



# Technology Assessment Report for Industrial Boiler Applications: NO<sub>x</sub> Combustion Modification

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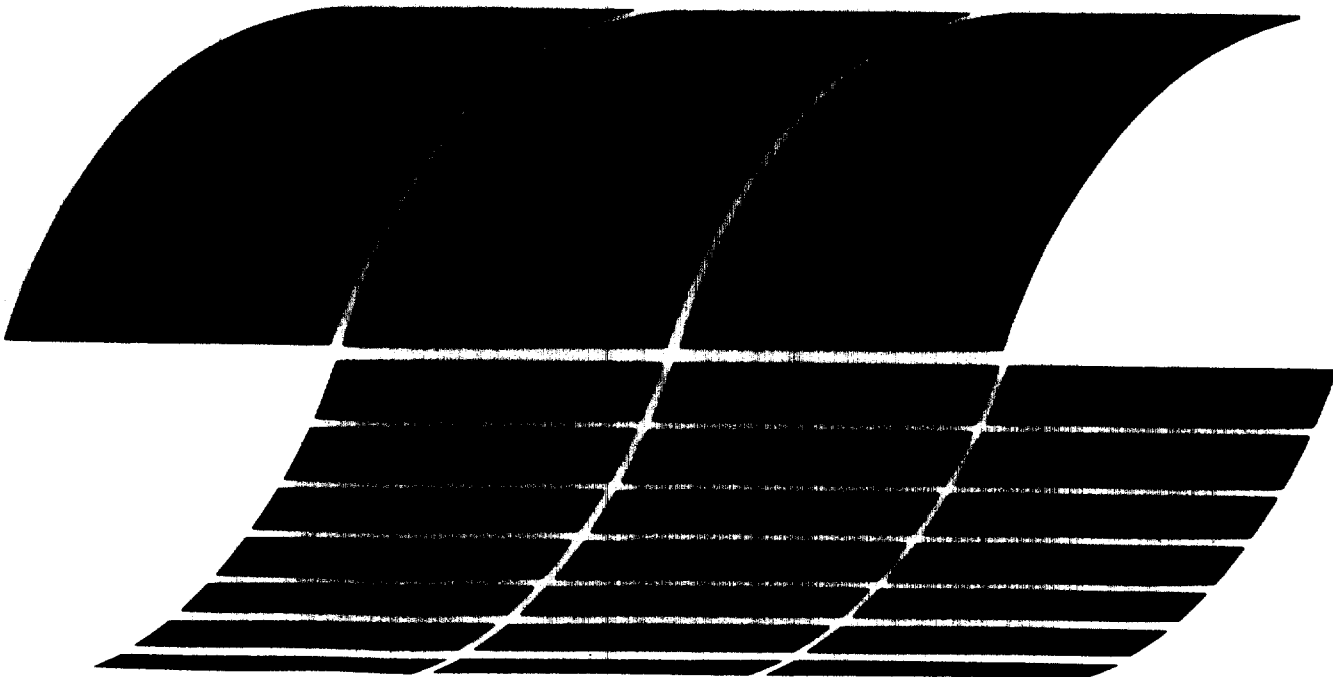
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**EPA-600/7-79-178f**

**December 1979**

# **Technology Assessment Report for Industrial Boiler Applications: NO<sub>x</sub> Combustion Modification**

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## PREFACE

The 1977 Amendments to the Clean Air Act required that emission standards be developed for fossil-fuel-fired steam generators. Accordingly, the U.S. Environmental Protection Agency (EPA) recently promulgated revisions to the 1971 new source performance standard (NSPS) for electric utility steam generating units. Further, EPA has undertaken a study of industrial boilers with the intent of proposing a NSPS for this category of sources. The study is being directed by EPA's Office of Air Quality Planning and Standards, and technical support is being provided by EPA's Office of Research and Development. As part of this support, the Industrial Environmental Research Laboratory at Research Triangle Park, N.C., prepared a series of technology assessment reports to aid in determining the technological basis for the NSPS for industrial boilers. This report is part of that series. The complete report series is listed below:

| Title                                                                                                 | Report No.        |
|-------------------------------------------------------------------------------------------------------|-------------------|
| The Population and Characteristics of Industrial/<br>Commercial Boilers                               | EPA-600/7-79-178a |
| Technology Assessment Report for Industrial Boiler<br>Applications: Oil Cleaning                      | EPA-600/7-79-178b |
| Technology Assessment Report for Industrial Boiler<br>Applications: Coal Cleaning and Low Sulfur Coal | EPA-600/7-79-178c |
| Technology Assessment Report for Industrial Boiler<br>Applications: Synthetic Fuels                   | EPA-600/7-79-178d |

| Title                                                                                                    | Report No.        |
|----------------------------------------------------------------------------------------------------------|-------------------|
| Technology Assessment Report for Industrial Boiler Applications: Fluidized-Bed Combustion                | EPA-600/7-79-178e |
| Technology Assessment Report for Industrial Boiler Applications: NO <sub>x</sub> Combustion Modification | EPA-600/7-79-178f |
| Technology Assessment Report for Industrial Boiler Applications: NO <sub>x</sub> Flue Gas Treatment      | EPA-600/7-79-178g |
| Technology Assessment Report for Industrial Boiler Applications: Particulate Collection                  | EPA-600/7-79-178h |
| Technology Assessment Report for Industrial Boiler Applications: Flue Gas Desulfurization                | EPA-600/7-79-178i |

These reports will be integrated along with other information in the document, "Industrial Boilers -- Background Information for Proposed Standards," which will be issued by the Office of Air Quality Planning and Standards.

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## METHOD 6—DETERMINATION OF SULFUR DIOXIDE EMISSIONS FROM STATIONARY SOURCES

### 1. Principle and Applicability

1.1 Principle. A gas sample is extracted from the sampling point in the stack. The sulfuric acid mist (including sulfur dioxide) and the sulfur dioxide are separated. The sulfur dioxide fraction is measured by the barium-thionitrate titration method.

1.2 Applicability. This method is applicable for the determination of sulfur dioxide emissions from stationary sources. The minimum detectable limit of the method has been determined to be 3.4 milligrams (mg) of  $\text{SO}_2/\text{m}^3$  ( $2.12 \times 10^{-4}$  lb/ft<sup>3</sup>). Although no upper limit has been established, tests have shown that concentrations as high as 80,000 mg/m<sup>3</sup> can be collected efficiently in two midge impingers, each containing 15 milliliters of 3 percent hydrogen peroxide, at a rate of 1.0 lpm for 20 minutes. Based on theoretical calculations, the upper concentration limit in a 2-liter sample is about 93,300 mg/m<sup>3</sup>.

Possible interferences are free ammonia, water-soluble cations, and fluorides. The cations and fluorides are removed by glass wool and an isopropanol bubbler, and hence do not affect the  $\text{SO}_2$  analysis. When samples are being taken from a gas stream with high concentrations of very fine particulate matter (such as in inlets to control devices), a high efficiency glass fiber filter must be used in place of the glass wool plug (i.e., the one in the probe) to remove the particulate matter.

The ammonia interference is removed by reacting with  $\text{SO}_2$  to form particulate sulfate and by reacting with the indicator. If free ammonia is present (this can be determined by knowledge of the process and nothing white particulate matter in the probe and isopropanol bubbler), alternative methods, subject to the approval of the Administrator, U.S. Environmental Protection Agency, are required.

### 2. Apparatus

2.1 Sampling. The sampling train is shown in Figure 6-1, and component parts are discussed below. The tester has the option of substituting sampling equipment described in Method 5 in place of the midge impinger equipment of Method 6. However, the Method 6 train must be modified to include a heated filter between the probe and isopropanol impinger, and the operation of the sampling train and sample analysis must be at the flow rates and solution volumes defined in Method 6. The tester also has the option of determining  $\text{SO}_2$  simultaneously with particulate matter and moisture determinations by (1) replacing the water in a Method 5 impinger system with 3 percent peroxide solution, or (2) by replacing the Method 5 water impinger system with a Method 5 isopropanol filter-peroxide system. The analysis for  $\text{SO}_2$  must be consistent with the procedure in Method 8.87.

2.1.1 Probe. Deteriorated glass, or stainless steel (other materials of construction may be used, subject to the approval of the Administrator), approximately 6-mm inside diameter, with a heating system to prevent water condensation and a filter (either in-stack or heated outside) to remove particulate matter, including sulfuric acid mist. A plug of glass wool is a satisfactory filter.

2.1.2 Bubbler and Impingers. One midge bubbler, with medium-coarse glass fiber and borosilicate or quartz glass wool packed to top (see Figure 6-1) to prevent sulfuric acid mist carryover, and three 30-ml midge impingers. The bubbler and midge impingers must be connected in series with leak-free glass connectors. Silicone grease may be used, if necessary, to prevent leakage.

At the option of the tester, a midge impinger may be used in place of the midge bubbler.

Other collection absorbers and flow rates may be used, but are subject to the approval of the Administrator. Also, collection efficiency must be shown to be at least 99 percent for each test run and must be documented in the report. If the efficiency is found to be acceptable after a series of three tests, further documentation is not required. To conduct the efficiency test, an extra absorber must be added and analyzed separately. This extra absorber must not contain more than 1 percent of the total  $\text{SO}_2$ .

2.1.3 Glass Wool. Deteriorated or quartz.

2.1.4 Stopcock Grease. Acetone-insoluble, heat-stable silicone grease may be used, if necessary.

2.1.5 Temperature Gauge. Dial thermometer, or equivalent, to measure temperature of gas leaving impinger train to within  $1^\circ\text{C}$  ( $2^\circ\text{F}$ ).

2.1.6 Drying Tube. Tube packed with 6- to 16-mesh indicating type silica gel, or equivalent, to dry the gas sample and to protect the meter and pump. If the silica gel has been used previously, dry at  $175^\circ\text{C}$  ( $350^\circ\text{F}$ ) for 2 hours. New silica gel may be used as received. Alternatively, other types of desiccants (equivalent or better) may be used, subject to approval of the Administrator. 87

2.1.7 Valve. Needle valve, to regulate sample gas flow rate. 87

2.1.8 Pump. Leak-free diaphragm pump, or equivalent, to pull gas through the train. Install a small surge tank between the pump and rate meter to eliminate the pulsation effect of the diaphragm pump on the rotameter. 87

2.1.9 Rate Meter. Rotameter, or equivalent, capable of measuring flow rate to within 2 percent of the selected flow rate of about 1000 cc/min.

2.1.10 Volume Meter. Dry gas meter, sufficiently accurate to measure the sample volume within 2 percent, calibrated at the selected flow rate and conditions actually encountered during sampling, and equipped with a temperature gauge (dial thermometer, or equivalent) capable of measuring temperature to within  $3^\circ\text{C}$  ( $5.4^\circ\text{F}$ ).

2.1.11 Barometer. Mercury, aneroid, or other barometer capable of measuring atmospheric pressure to within 2.5 mm Hg (0.1 in. Hg). In many cases, the barometric reading may be obtained from a nearby national weather service station, in which case the station value (which is the absolute barometric pressure) shall be requested and an adjustment for elevation differences between the weather station and sampling point shall be applied at a rate of minus 2.5 mm Hg (0.1 in. Hg) per 30 m (100 ft) elevation increase or vice versa for elevation decrease. 87

2.1.12 Vacuum Gauge and Rotameter. At least 760 mm Hg (30 in. Hg) gauge, and 0-40 cc/min rotameter to be used for leak check of the sampling train. 87

2.2.1 Wash bottles. Polyethylene or glass, 500 ml, two.

2.2.2 Storage Bottles. Polyethylene, 100 ml, to store impinger samples (one per sample).

### 3. Analysis

3.3.1 Pipettes. Volumetric type, 5-ml, 20-ml (one per sample), and 25-ml sizes.

3.3.2 Volumetric Flasks. 100-ml size (one per sample) and 1000-ml size 87

2.3.3 Burettes. 5- and 50-ml sizes.

2.3.4 Erlenmeyer Flasks. 250 ml-size (one for each sample, blank, and standard).

2.3.5 Dropping Bottle. 125-ml size, to add indicator.

2.3.6 Graduated Cylinder. 100-ml size.

2.3.7 Spectrophotometer. To measure absorbance at 362 nanometers.

### 3. Reagents

Unless otherwise indicated, all reagents must conform to the specifications established by the Committee on Analytical Reagents of the American Chemical Society. Where such specifications are not available, use the best available grade.

### 3.1 Sampling

3.1.1 Water. Deionized, distilled to conform to ASTM specification D1193-74, Type 3. At the option of the analyst, the  $\text{KMnO}_4$  test for oxidizable organic matter may be omitted when high concentrations of organic matter are not expected to be present.

3.1.2 Isopropanol. 80 percent. Mix 80 ml of isopropanol with 20 ml of deionized, distilled water. Check each lot of isopropanol for peroxide impurities as follows: shake 10 ml of isopropanol with 10 ml of freshly prepared 10 percent potassium iodide solution. Prepare a blank by similarly treating 10 ml of distilled water. After 1 minute, read the absorbance at 362 nanometers on a spectrophotometer. If absorbance exceeds 0.1, reject alcohol for use.

Peroxides may be removed from isopropanol by redistilling or by passage through a column of activated alumina; however, reagent grade isopropanol with suitably low peroxide levels may be obtained from commercial sources. Rejection of contaminated lots may, therefore, be a more efficient procedure.

3.1.3 Hydrogen Peroxide. 3 Percent. Dilute 30 percent hydrogen peroxide 1:9 (v/v) with deionized, distilled water (80 ml is needed per sample). Prepare fresh daily.

3.1.4 Potassium Iodide Solution. 10 Percent. Dissolve 10.0 grams KI in deionized, distilled water and dilute to 100 ml. Prepare when needed.

### 3.2 Sample Recovery

3.2.1 Water. Deionized, distilled, as in 3.1.1.

3.2.2 Isopropanol. 80 Percent. Mix 80 ml of isopropanol with 20 ml of deionized, distilled water.

### 3.3 Analysis

3.3.1 Water. Deionized, distilled, as in 3.1.1.

3.3.2 Isopropanol. 100 percent.

3.3.3 Thionitrate Indicator. 1-(o-arsenophenylazo)-2-naphthol-3,5-disulfonic acid, disodium salt, or equivalent. Dissolve 0.20 g in 100 ml of deionized, distilled water.

3.3.4 Barium Perchlorate Solution. 0.0100 N. Dissolve 1.93 g of barium perchlorate trihydrate ( $\text{Ba}(\text{ClO}_4)_3 \cdot 3\text{H}_2\text{O}$ ) in 200 ml distilled water and dilute to 1 liter with isopropanol. Alternatively, 1.22 g of  $[\text{BaCl}_2 \cdot 2\text{H}_2\text{O}]$  may be used instead of the perchlorate. Standardize as in Section 5.5.87

3.3.5 Sulfuric Acid Standard. 0.0100 N. Purchase or standardize to  $\pm 0.0002$  N against 0.0100 N NaOH which has previously been standardized against potassium acid phthalate (primary standard grade).

### 4. Procedure

#### 4.1 Sampling

4.1.1 Preparation of collection train. Measure 15 ml of 80 percent isopropanol into the midge bubbler and 15 ml of 3 percent hydrogen peroxide into each of the first two midge impingers. Leave the final midge impinger dry. Assemble the train as shown in Figure 6-1. Adjust probe heater to a temperature sufficient to prevent water condensation. Place crushed ice and water around the impingers.

4.1.2 Leak-check procedure. A leak check prior to the sampling run is optional; however, a leak check after the sampling run is mandatory. The leak-check procedure is as follows:

Temporarily attach a suitable (e.g., 0-40 cc/min) rotameter to the outlet of the dry gas meter and place a vacuum gauge at or near the probe inlet. Plug the probe inlet, pull a vacuum of at least 250 mm Hg (10 in. Hg), and note the flow rate as indicated by the rotameter. A leakage rate not in excess of 2 percent of the average sampling rate is acceptable.

NOTE: Carefully release the probe inlet plug before turning off the pump.

It is suggested (not mandatory) that the pump be leak-checked separately, either prior to or after the sampling run. If done prior to the sampling run, the pump leak-check shall precede the leak check of the sampling train described immediately above; if done after the sampling run, the pump leak-check shall follow the train leak-check. To leak check the pump, proceed as follows: Disconnect the drying tube from the probe-impinger assembly. Place a vacuum gauge at the inlet to either the drying tube or the pump, pull a vacuum of 250 mm (10 in.) Hg, plug or pinch off the outlet of the flow meter and then turn off the pump. The vacuum should remain stable for at least 30 seconds. 87

Other leak-check procedures may be used, subject to the approval of the Administrator, U.S. Environmental Protection Agency. The procedure used in Method 5 is not suitable for diaphragm pumps.

4.1.3 Sample collection. Record the initial dry gas meter reading and barometric pressure. To begin sampling, position the tip of the probe at the sampling point, connect the probe to the bubbler, and start the pump. Adjust the sample flow to a constant rate of approximately 1.0 liter/min as indicated by the rotameter. Maintain this constant rate ( $\pm 10$  percent) during the entire sampling run. Take readings (dry gas meter, temperatures at dry gas meter and at impinger outlet and rate meter) at least every 5 minutes. Add more ice during the run to keep the temperature of the gases leaving the last impinger at  $20^\circ\text{C}$  ( $68^\circ\text{F}$ ) or less. At the conclusion of each run, turn off the pump, remove probe from the stack, and record the final readings. Conduct a leak check as in Section 4.1.2. (This leak check is mandatory.) If a leak is found, void the test run, or use procedures acceptable to the Administrator to adjust the sample volume for the leakage. Drain the bath, and purge the remaining part of the train by drawing clean ambient air through the system for 15 minutes at the sampling rate. 87

Clean ambient air can be provided by passing air through a charcoal filter or through an extra midge impinger with 15 ml of 3 percent  $\text{H}_2\text{O}_2$ . The tester may opt to simply use ambient air, without purification.

4.2 Sample Recovery. Disconnect the impingers after purging. Discard the contents of the midge bubbler. Pour the contents of the midge impingers into a leak-free polyethylene bottle for shipment. Rinse the three midge impingers and the connecting tubes with deionized, distilled water, and add the washings to the same storage container. Mark the fluid level. Seal and identify the sample container.

4.3 Sample Analysis. Note level of liquid in container, and confirm whether any sample was lost during shipment; note this on analytical data sheet. If a noticeable amount of leakage has occurred, either void the sample or use methods, subject to the approval of the Administrator, to correct the final results.

Transfer the contents of the storage container to a 100-ml volumetric flask and dilute to exactly 100 ml with deionized, distilled water. Pipette a 20-ml aliquot of this solution into a 250-ml Erlenmeyer flask, add 80 ml of 100 percent isopropanol and two to four drops of thionitrate indicator, and titrate to a pink endpoint using 0.0100 N barium perchlorate. Repeat and average the titration volumes. Run a blank with each series of samples. Replicate titrations must agree within 1 percent or 0.2 ml, whichever is larger.

(NOTE.—Protect the 0.0100 N barium perchlorate solution from  $\text{CO}_2$  absorption at all times.)

### 5. Calibration

#### 5.1 Metering System

5.1.1 Initial Calibration. Before its initial use in the field, first leak check the metering system (drying tube, needle valve, pump, rotameter, and dry gas meter) as



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## SECTION 1

### EXECUTIVE SUMMARY

Industrial boilers produce more than 20 percent of all stationary combustion source nitrogen oxides ( $\text{NO}_x$ ) emissions.\* Combustion modification control techniques represent potentially viable means of controlling  $\text{NO}_x$ . The objective of this report is to assess combustion modification  $\text{NO}_x$  control technology in order to supply background information for the EPA Office of Air Quality Planning and Standards in their evaluation of alternative control systems for industrial boilers.

#### 1.1 INTRODUCTION

This report evaluates the effectiveness, applicability, and limitations of specific combustion modification  $\text{NO}_x$  controls for each major equipment/fuel category in the industrial boiler sector. The current baseline or normal operating level  $\text{NO}_x$  emission factors for these major boiler/fuel categories are compiled and the effectiveness of combustion modifications in reducing these  $\text{NO}_x$  emission levels are reviewed. Only limited, short term field test results (though well documented) are available to date, as  $\text{NO}_x$  controls are not currently widely practiced in the industrial boiler sector. This summary highlights some of the general trends observed after a thorough review of available, well documented, published data. These observations are meant to be only guidelines; there will certainly be exceptions, and much research and development work remains before  $\text{NO}_x$  control technology is well characterized for all of the diverse industrial boiler design and equipment types. Indeed, EPA's Industrial Environmental Research Laboratory at Research Triangle Park, N.C., is currently expanding the

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\*Reference 2-10

existing data base through a number of control development programs, including 30-day continuous monitoring field tests.

Industrial boilers are defined here as coal-, oil-, or natural gas-fired steam generators in the industrial sector with heat input capacities greater than 3 MW ( $10 \times 10^6$  Btu/hr). Major equipment/fuel categories for industrial boilers have been identified and are listed in Table 1-1, along with typical heat input capacities and average baseline  $\text{NO}_x$  emission levels.

## 1.2 $\text{NO}_x$ FORMATION MECHANISMS AND PRINCIPLES OF CONTROL

Oxides of nitrogen ( $\text{NO}_x$ ) formed in combustion processes are usually due either to thermal fixation of atmospheric nitrogen in the combustion air, leading to "thermal  $\text{NO}_x$ " or to the conversion of chemically bound nitrogen in the fuel, leading to "fuel  $\text{NO}_x$ ." For natural gas and distillate oil firing, nearly all  $\text{NO}_x$  emissions result from thermal fixation. With residual oil and coal, the contribution from fuel-bound nitrogen can be significant and, under certain operating conditions, predominate.

Both thermal and fuel  $\text{NO}_x$  appear to be kinetically or aerodynamically limited because emission rates are far below the levels which would prevail at equilibrium. Thus, the rate of formation of both thermal and fuel  $\text{NO}_x$  is dominated by combustion conditions and is amenable to suppression through combustion process modifications. Although the mechanisms are different, both thermal and fuel  $\text{NO}_x$  are promoted by rapid mixing of oxygen with the fuel. Additionally, thermal  $\text{NO}_x$  is greatly increased by long residence time at high temperature. The modified combustion conditions and control concepts which have been tried or suggested to limit  $\text{NO}_x$  formation are as follows:

- Decrease primary flame zone  $\text{O}_2$  level by:
  - Decreased overall  $\text{O}_2$  level
  - Controlled mixing of fuel and air
  - Use of fuel-rich primary flame zone
- Decrease time of exposure at high temperature by:
  - Decreased peak temperature
  - Decreased adiabatic flame temperature through dilution
  - Decreased combustion intensity
  - Increased flame cooling

TABLE 1-1. MAJOR INDUSTRIAL BOILER/FUEL CATEGORIES AND  
BASELINE NO<sub>x</sub> EMISSION LEVELS

| Fuel                      | Boiler Type                   | Typical Size<br>(Heat input<br>Capacity)<br>MM(106 Btu/hr) | No. of<br>Boilers<br>Tested | Average<br>NO <sub>x</sub> Baseline<br>Emission Level<br>mg NO <sub>2</sub> /J(1b/106 Btu) | AP-42 (Ref. 3-2)<br>NO <sub>x</sub> Baseline<br>Emission Level<br>mg NO <sub>2</sub> /J(1b/106 Btu) | Sources of Data<br>Used for<br>Selected Baseline<br>Emissions |
|---------------------------|-------------------------------|------------------------------------------------------------|-----------------------------|--------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| Pulverized Coal           | Single Wall<br>and Tangential | 59(200)<br>114(400)                                        | 4<br>2                      | 285(0.663)<br>285(0.663)                                                                   | 328(0.763)<br>328(0.763)                                                                            | Ref. 3-3, 3-4, 3-5<br>Ref. 3-3, 3-4, 3-5                      |
| Stoker Coal               | Spreader                      | 44(150), 25(85)                                            | 7,5                         | 265(0.616)                                                                                 | 273(0.635)                                                                                          | Ref. 3-2 through 3-6                                          |
|                           | Underfeed                     | 9(30)                                                      | 2                           | 150(0.349)                                                                                 | 273(0.635)                                                                                          | Ref. 3-3                                                      |
|                           | Chain Grate                   | 22(75)                                                     | 2                           | 140(0.326)                                                                                 | 273(0.635)                                                                                          | Ref. 3-4, 3-5                                                 |
| Residual Oil <sup>a</sup> | Firetube                      | 4.4(15)                                                    | 5                           | 115(0.267)                                                                                 | --                                                                                                  | Ref. 3-3, 3-4, 3-8                                            |
|                           | Watertube                     | 8.8(30)                                                    | 10                          | 160(0.372)                                                                                 | 171(0.398)                                                                                          | Ref. 3-3, 3-4, 3-8, 3-9                                       |
|                           | Watertube                     | 44(150)                                                    | 7                           | 160(0.372)                                                                                 | 171(0.398)                                                                                          | Ref. 3-3, 3-4                                                 |
| Distillate Oil            | Firetube                      | 4.4(15)                                                    | 6                           | 75(0.175)                                                                                  | 68(0.158)                                                                                           | Ref. 3-3, 3-4                                                 |
|                           | Watertube                     | 29(100)                                                    | 4,3                         | 55 <sup>b</sup> , 90 <sup>c</sup> (0.128 <sup>b</sup> , 0.209 <sup>c</sup> )               | --                                                                                                  | Ref. 3-3, 3-4, 3-9                                            |
|                           | Watertube                     | 44(150)                                                    | 1                           | 90 <sup>c</sup> (0.209 <sup>c</sup> )                                                      | --                                                                                                  | Ref. 3-3, 3-4                                                 |
| Natural Gas               | Firetube                      | 4.4(15)                                                    | 8                           | 40(0.093)                                                                                  | 75(0.174)                                                                                           | Ref. 3-3, 3-4, 3-10                                           |
|                           | Watertube                     | 29(100)                                                    | 9,11                        | 45 <sup>b</sup> , 110 <sup>c</sup> (0.105 <sup>b</sup> , 0.255 <sup>c</sup> )              | --                                                                                                  | Ref. 3-3, 3-4, 3-9                                            |
|                           | Watertube                     | 44(150)                                                    | 7                           | 120 <sup>c</sup> (0.280) <sup>c</sup>                                                      | --                                                                                                  | Ref. 3-3, 3-4                                                 |

<sup>a</sup>Includes No. 5 and No. 6 fuel oils.

<sup>b</sup>From boilers not equipped with air preheaters.

<sup>c</sup>From boilers equipped with air preheaters.

TABLE 1-2. SUMMARY OF COMBUSTION PROCESS MODIFICATION CONCEPTS

| Combustion Conditions                                  | Control Concept                                     | Effect on Thermal NO <sub>x</sub>                                               | Effect on Fuel NO <sub>x</sub>                                     | Primary Applicable Controls                  |                                          |                                                           |
|--------------------------------------------------------|-----------------------------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------------------|----------------------------------------------|------------------------------------------|-----------------------------------------------------------|
|                                                        |                                                     |                                                                                 |                                                                    | Operational Adjustments                      | Hardware Modification                    | Major Redesign                                            |
| Decrease primary flame zone O <sub>2</sub> level       | Decrease overall O <sub>2</sub> level               | Reduces O <sub>2</sub> rich, high NO <sub>x</sub> pockets in the flame          | Reduces exposure of fuel nitrogen intermediaries to O <sub>2</sub> | Low excess air firing                        | Flue gas recirculation (FGR)             |                                                           |
|                                                        | Delayed mixing of fuel and air                      | Flame cooling and dilution during delayed mixing reduces peak temp.             | Volatile fuel N reduces to N <sub>2</sub> in the absence of oxygen | Burner adjustments                           | Low NO <sub>x</sub> burners              | Optimum burner/firebox design                             |
|                                                        | Primary fuel-rich flame zone                        | Flame cooling in low O <sub>2</sub> , low temp. primary zone reduces peak temp. | Volatile fuel N reduces to N <sub>2</sub> in the absence of oxygen | Burners out of service; biased burner firing | Overfire air ports                       | Burner/firebox design for two stage combustion            |
| Decrease peak flame temperature                        | Decrease adiabatic flame temperature                | Direct suppression of thermal NO <sub>x</sub> mechanism                         | Ineffective                                                        | Reduced air preheat                          | Water injection, FGR                     |                                                           |
|                                                        | Decrease combustion intensity                       | Increased flame zone cooling yields lower peak temperature                      | Minor direct effect; indirect effect on mixing                     | Load reduction                               |                                          | Enlarged firebox, increased burner spacing                |
|                                                        | Increased flame zone cooling/ reduce residence time | Increased flame zone cooling yields lower peak temperature                      | Ineffective                                                        | Burner tilt                                  |                                          | Redesign heat transfer surfaces, firebox aerodynamics     |
| Chemically reduce NO <sub>x</sub> in post flame region | Inject reducing agent                               | Reduction                                                                       | Reduction                                                          |                                              | Ammonia injection possible on some units | Redesign convective section for NH <sub>3</sub> injection |

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- Controlled mixing of fuel and air or use of fuel-rich primary flame zone
- Decreased primary flame zone residence time
- Chemically reduced  $\text{NO}_x$  in postflame region by:
  - Injection of reducing agent

Table 1-2 relates these control concepts to applicable combustion process modifications and equipment types. The process modifications are further categorized according to their role in the control development sequence: operational adjustments, hardware modifications of existing equipment or through factory installed controls, and, major redesigns of new equipment. The controls for decreased  $\text{O}_2$  are also generally effective for peak temperature reduction but have not been repeated.

### 1.3 SYSTEMS OF $\text{NO}_x$ EMISSIONS REDUCTION FOR COAL-FIRED BOILERS

The combustion modification controls reviewed for possible application to industrial boilers included

- Low excess air (LEA)
- Staged combustion air (SCA)
  - Burners out of service (BOOS), not applicable to stokers
  - Overfire (OFA) or sidefire (SFA) air
- Low  $\text{NO}_x$  burners (LNB)
- Flue gas recirculation (FGR)
- Reduced air preheat (RAP)
- Load reduction (LR) or reduced combustion intensity (furnace redesign)
- Ammonia injection

The following subsections discuss the selection of the best control systems for coal-fired boilers.

#### 1.3.1 Candidate Best Systems of Control for Coal-Fired Boilers

In selecting the best system of  $\text{NO}_x$  emissions reduction, many factors have to be considered, including:

- Control effectiveness and applicability
- Reliability and availability
- Process impacts
- Capital and operating costs
- Energy impacts
- Environmental impacts

The effectiveness of controls in reducing  $\text{NO}_x$  emissions, and their applicability to industrial boilers as well as their reliability, were used to select preliminary candidate control systems. Techniques were considered if they were expected to be available for new boilers sold in 1983 or sooner. Performance data for these preliminary candidates were then carefully reviewed to identify any demonstrated or expected process or environmental impacts. For example, major impacts such as severe derating of the boiler can make a control option no longer viable. Environmental impacts were evaluated through the analysis of measured or postulated incremental emissions, other than  $\text{NO}_x$ , when controls are implemented. Finally, capital and operating costs, including energy impacts, were considered. These costs were used to decide between favorable alternative control options, or in the case of costly but highly effective techniques, to defer application until stringent control levels are absolutely necessary.

All of the above listed factors were considered by evaluating detailed field test results when available and through discussions with major equipment manufacturers and users, and control R&D groups. Throughout this report there is much attention directed toward retrofit field test applications. This is so because retrofit data are the only documented information currently available.

In the ensuing discussion of emission control technologies, candidate technologies were compared using three emission control levels labelled "moderate, intermediate, and stringent." These control levels were chosen only to encompass all candidate technologies and form bases for comparison of technologies for control of specific pollutants considering performance, costs, energy, and environmental effects.

From these comparisons, candidate "best" technologies for control of individual pollutants are recommended for consideration in subsequent industrial boiler studies. These "best technology" recommendations do not consider combinations of technologies to remove more than one pollutant and have not undergone the detailed environmental, cost, and energy impact assessments necessary for regulatory action. Therefore, the levels of "moderate, intermediate, and stringent" and the recommendation of "best technology" for individual pollutants are not to be construed as indicative of the regulations that will be developed for industrial



boilers. EPA will perform rigorous examination of several comprehensive regulatory options before any decisions are made regarding the standards for emissions from industrial boilers.

Tables 1-3 and 1-4 list the candidates for best systems of  $\text{NO}_x$  emissions reduction for pulverized coal-fired and stoker coal-fired boilers, respectively. Also summarized in these tables are the control effectiveness (percent  $\text{NO}_x$  reduction), operational impact, cost impact which includes energy impact, environmental impact, and commercial availability.

#### Low Excess Air

Reducing the excess air level in the furnace has generally been found to be an effective method of  $\text{NO}_x$  control for all fuels. In this technique, the combustion air is reduced to the minimum amount required for complete combustion, maintaining acceptable furnace cleanliness and steam temperature. With less oxygen available in the flame zone, both thermal and fuel  $\text{NO}_x$  formation are reduced. In addition, the reduced airflow reduces the quantity of flue gas released per unit time resulting in an improvement in boiler efficiency.

#### Overfire Air

Staged combustion through overfire air seeks to control  $\text{NO}_x$  by carrying out initial combustion in a primary, fuel-rich, combustion zone, then completing combustion, at lower temperatures, in a second, fuel lean zone. The overfire air technique involves firing the burners (or the combustion bed in the case of stokers) more fuel rich than normal while admitting the remaining combustion air through overfire air ports. Overfire air is very effective for  $\text{NO}_x$  reduction and may be used with all fuels.

#### Reduced Combustion Intensity

Reducing combustion intensity generally lowers thermal  $\text{NO}_x$  formation. Reduced combustion intensity can be brought about by load reduction (reduced firing rate) in existing units and by use of an enlarged firebox in new units.  $\text{NO}_x$  reduction field tests on industrial boilers have been mixed, on a retrofit basis, but the technique is probably best implemented as increased furnace plan area in new designs, based on results for new utility boilers.

TABLE 1-3. CANDIDATES FOR BEST SYSTEMS OF NO<sub>x</sub> EMISSIONS REDUCTION:  
PULVERIZED COAL-FIRED BOILERS

| Technique                    | Effectiveness <sup>a</sup><br>(% NO <sub>x</sub> Reduction) | Operational Impact                                                                                                                   | Cost Impact <sup>b</sup>                                        | Environmental Impact                                  | Availability                                                            |
|------------------------------|-------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------------------------|
| Low Excess Air               | 5 - 25                                                      | Increased boiler efficiency.                                                                                                         | Increased efficiency offsets capital and operating costs.       | Possible increased CO and organic emissions.          | Available                                                               |
| Overfire Air                 | 5 - 30                                                      | Possible increased slagging, corrosion. Perhaps slight decrease in boiler efficiency.                                                | Major modification. Marginal increase in cost for new units.    | Possible increased particulate and organic emissions. | Commercially offered but not demonstrated for this boiler/fuel category |
| Reduced Combustion Intensity | 5 - 25                                                      | None. Best implemented as increased furnace plan area in new designs.                                                                | Major modification. Marginal increase in cost for new units.    | None                                                  | Technology transfer required from utility industry                      |
| Low NO <sub>x</sub> Burners  | 45 - 60                                                     | None expected.                                                                                                                       | Potentially most cost-effective.                                | None expected.                                        | 1981 - 1983 <sup>c</sup>                                                |
| NH <sub>3</sub> Injection    | 40 - 60                                                     | Possible implementation difficulties. Fouling problems with high sulfur fuels, load restrictions. Close operator attention required. | Several fold higher than conventional combustion modifications. | Possible emissions of NH <sub>3</sub> and byproducts. | Commercially offered but not demonstrated                               |

<sup>a</sup>Effectiveness based on control applied singly

<sup>b</sup>Incremental cost impact noting capacity/cost of boiler to which control is applied.

<sup>c</sup>References 2-79, 3-30

TABLE 1-4. CANDIDATES FOR BEST SYSTEMS OF NO<sub>x</sub> EMISSIONS REDUCTION:  
STOKER COAL-FIRED BOILERS

| Technique                 | Effectiveness <sup>a</sup><br>(% NO <sub>x</sub> Reduction) | Operational Impact                                                                                                                                   | Cost Impact <sup>b</sup>                                                                             | Environmental Impact                                       | Availability                              |
|---------------------------|-------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|------------------------------------------------------------|-------------------------------------------|
| Low Excess Air            | 5 - 25                                                      | Possible grate overheating, clinker formation, increased corrosion. Close operator attention required.                                               | Increased efficiency should partially offset costs.                                                  | Possible increased CO, organic, and particulate emissions. | Available                                 |
| Overfire Air              | 5 - 25                                                      | Possible grate overheating, clinker formation, increased corrosion. Close operator attention required. Perhaps slight decrease in boiler efficiency. | Major modification of grate and OFA, probably costly. Present units have OFA for smoke control only. | Possible increased CO, organic, and particulate emissions. | R&D                                       |
| NH <sub>3</sub> Injection | 40 - 60                                                     | Possible implementation difficulties. Fouling problems with high sulfur fuels, load restrictions. Close operator attention required.                 | Several fold higher than conventional combustion modifications.                                      | Possible emissions of NH <sub>3</sub> and byproducts.      | Commercially offered but not demonstrated |

<sup>a</sup>Effectiveness based on control applied singly.

<sup>b</sup>Incremental cost impact noting capacity/cost of boiler to which control is applied.

### Low NO<sub>x</sub> Burners

Low NO<sub>x</sub> burners are generally designed to reduce flame turbulence, delay fuel air mixing, and establish fuel-rich zones where combustion initially takes place. The longer, less intense flames produced with low NO<sub>x</sub> burners, as compared to those of conventional burners, result in lower flame temperatures which reduce thermal NO<sub>x</sub> generation. Moreover, the reduced availability of oxygen in the initial combustion zone inhibits fuel NO<sub>x</sub> conversion. Low NO<sub>x</sub> burners represent a developing technology that promises highly effective NO<sub>x</sub> control at relatively low cost.

### Ammonia Injection

The technique reduces NO to N<sub>2</sub> and H<sub>2</sub>O with injection of ammonia (NH<sub>3</sub>) at flue gas temperatures ranging from 1070 to 1270K (1470 to 1830°F). However, the method is very temperature sensitive with maximum NO<sub>x</sub> reductions occurring in a very narrow temperature window around 1240 ± 50K (1770 ± 90°F). An elaborate NH<sub>3</sub> injection, monitoring and control system is required. The application of this technique, especially to the severe flue gas environment from coal combustion, is still several years away.

#### 1.3.2 Best Systems of Control for Coal-Fired Boilers

The best systems of control were selected based on the criteria discussed in the previous subsection, and are summarized in Table 1-5 for boilers with heat input capacity ≥ 29 MW (100 × 10<sup>6</sup> Btu/hr) and Table 1-6 for boilers < 29 MW (100 × 10<sup>6</sup> Btu/hr). Best systems were selected by boiler equipment type and suggested moderate, intermediate and stringent level of control. Control effectiveness, operational impact, cost including energy impact, environmental impact, and commercial availability have already been summarized in Tables 1-3 and 1-4. It should be noted that the suggested moderate control levels for the boiler/fuel categories considered are generally conservative in the sense that demonstrated control techniques have, in specific instances, achieved controlled NO<sub>x</sub> levels lower than the suggested moderate levels.

Spreader stoker boilers are listed in both Tables 1-5 (≥ 29 MW) and 1-6 (< 29 MW) because this design type is offered over a large range of heat input capacities. However, because their average baseline emission levels are relatively higher than those from other stoker designs, it is

TABLE 1-5. BEST CONTROL SYSTEMS FOR COAL-FIRED INDUSTRIAL BOILERS WITH  
HEAT INPUT  $\geq 29$  MW ( $100 \times 10^6$  Btu/Hr)<sup>a</sup>

| Boiler Equipment Type | Baseline<br>NO <sub>x</sub> Emissions<br>ng/J (lb/10 <sup>6</sup> Btu) | Moderate<br>301 ng/J (0.7 lb/10 <sup>6</sup> Btu) | Level of Control                                      |                                                                                               |
|-----------------------|------------------------------------------------------------------------|---------------------------------------------------|-------------------------------------------------------|-----------------------------------------------------------------------------------------------|
|                       |                                                                        |                                                   | Intermediate<br>258 ng/J (0.6 lb/10 <sup>6</sup> Btu) | Stringent<br>215 ng/J (0.5 lb/10 <sup>6</sup> Btu)                                            |
| Pulverized Coal-Fired | 285 (0.663) <sup>b</sup>                                               | No control necessary <sup>c</sup>                 | 1. Low excess air<br>2. Overfire air                  | 1. Overfire air**<br>2. Low NO <sub>x</sub> burner***<br>3. Ammonia injection <sup>d</sup> ** |
| Spreader Stoker       | 265 (0.616)                                                            | No control necessary                              | Low excess air                                        | Low excess air/<br>Overfire air***                                                            |

<sup>a</sup>Low excess air operation is recommended practice whenever controls are required. However combination of LEA and OFA is not recommended for pulverized coal tangential units (see Section 3.2.1.2).

<sup>b</sup>Wide range of baseline emissions reported (see Section 3.2.1.1)

<sup>c</sup>Some units may require low excess air.

<sup>d</sup>NH<sub>3</sub> injection required only for those units with unusually high baseline emissions.

\*Commercially offered but not demonstrated for this boiler/fuel category.

\*\*Commercially offered but not demonstrated.

\*\*\*Under research and development.

However combination of LEA and OFA

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TABLE 1-6. CANDIDATE BEST CONTROL SYSTEMS FOR COAL-FIRED INDUSTRIAL BOILERS WITH  
HEAT INPUT <29 MW (100 x 10<sup>6</sup> Btu/Hr)

| Boiler Equipment Type                       | Baseline<br>NOx Emissions<br>ng/J (1b/10 <sup>6</sup> Btu) |                                                   | Level of Control                                      |                                                    |
|---------------------------------------------|------------------------------------------------------------|---------------------------------------------------|-------------------------------------------------------|----------------------------------------------------|
|                                             |                                                            |                                                   |                                                       |                                                    |
| Spreader Stoker<br>Chain Grate<br>Underfeed | 265(0.616)<br>140(0.326)<br>150(0.349)                     | Moderate<br>215 ng/J (0.5 1b/10 <sup>6</sup> Btu) | Intermediate<br>172 ng/J (0.4 1b/10 <sup>6</sup> Btu) | Stringent<br>129 ng/J (0.3 1b/10 <sup>6</sup> Btu) |
|                                             |                                                            | Low excess air/overfire air***                    | Ammonia injection**                                   | Ammonia injection**                                |
|                                             |                                                            | No control necessary                              | No control necessary                                  | Low excess air                                     |
|                                             |                                                            | No control necessary                              | No control necessary                                  | Low excess air                                     |

\*\*Commercially offered but not demonstrated.

\*\*\*Under research and development.

recommended that spreader stokers be grouped with pulverized coal units as far as potentially achievable emission control levels are concerned. Spreader stokers are listed together with other stoker types in Table 1-6 solely because of similarities in designs and hence in applicable control techniques.

#### Pulverized Coal-Fired Boilers

Low excess air or overfire air form the best system for moderate (301 ng/J, 0.7 lb/10<sup>6</sup> Btu) and intermediate (258 ng/J, 0.6 lb/10<sup>6</sup> Btu) NO<sub>x</sub> control for pulverized coal-fired industrial boilers. The moderate control level was not set lower than 301 ng/J because of the broad range in baseline NO<sub>x</sub> emissions for the six units tested, ranging from 174 to 563 ng/J with most data from 201 to 296 ng/J, yielding an average baseline of 285 ng/J. No significant correlation of emission levels with (pulverized coal) boiler type or coal properties were evident from the limited data.

Staged combustion with low excess air and overfire air should achieve the stringent control level of 215 ng/J (0.5 lb/10<sup>6</sup> Btu). The low excess air and overfire air control system has the primary advantage over the other control systems because of its commercial availability and its effectiveness. The cost of the system is not prohibitive when overfire air ports are designed as a part of new boilers. In addition, careful operation of staged air injection is not expected to seriously affect emissions of other criteria pollutants. Burner stoichiometries in the range of 100 to 110 percent would be adequate to achieve a 20 percent NO<sub>x</sub> reduction. At these stoichiometry levels, oxidizing atmospheres would prevail in the furnace, thus minimizing concern over possible furnace slagging and boiler tube wastage. However, achieving the stringent NO<sub>x</sub> emission level of 215 ng/J with combined low excess air and overfire air may require burner stoichiometries be reduced below 100 percent in some cases. This low burner stoichiometry level would cause reducing atmospheres in parts of the furnace, thus creating the potential for corrosion of water tubes. Generally boiler manufacturers do not recommend burner operation with stoichiometry levels below 100 percent primarily because of increased corrosion potential. Therefore, low excess

overfire air is recommended as the stringent control technique with the provision that further field testing and demonstrations may be necessary.

Because of the possible operational problems associated with overfire air, low  $\text{NO}_x$  burners were selected as the first backup candidate for achieving the stringent control level. Reported  $\text{NO}_x$  reduction efficiencies for utility size units are of the order of 45 to 60 percent. Similar reduction efficiencies are projected for the industrial low  $\text{NO}_x$  burners under development. Therefore low  $\text{NO}_x$  burners are expected to easily meet the 215 ng/J control level, a 25 percent reduction from the average baseline level. Once developed, low  $\text{NO}_x$  coal-fired burners for industrial boilers could become the best control system because of the expected lower cost and other operational advantages over the staged combustion method of overfire air.

If low  $\text{NO}_x$  burners are not commercialized by 1983, ammonia injection is the alternative stringent control system. However,  $\text{NH}_3$  injection is several times more costly than conventional combustion modification controls. In addition, as a developing technology, there are several implementation and operational problems that need to be resolved. The optimal effectiveness for noncatalytic reduction of  $\text{NO}$  by  $\text{NH}_3$  occurs over a very narrow temperature range, around  $1240 \pm 50\text{K}$  ( $1770 \pm 90^\circ\text{F}$ ). Hence, precise location of the  $\text{NH}_3$  injection ports is crucial. Since the temperature profile in a boiler changes with load,  $\text{NO}_x$  control with  $\text{NH}_3$  may dictate load restrictions on the boiler. Other potential problems include fouling and emissions of  $\text{NH}_3$  and byproducts. However, a major strength of the technique is its potential for high  $\text{NO}_x$  removal (40 to 60 percent).

#### Stoker Coal-Fired Boilers

Spreader stokers are the only major stoker boiler types with average uncontrolled  $\text{NO}_x$  emissions above 258 ng/J ( $0.6 \text{ lb}/10^6 \text{ Btu}$ ). Low excess air and overfire air constitute the best candidate control system capable of reductions to 215 ng/J ( $0.5 \text{ lb}/10^6 \text{ Btu}$ ). However, close operator attention will be required to avoid the problems of grate overheat, clinker formation, and corrosion associated with firing at too low excess air levels. Potential environmental impacts as increased carbon monoxide, particulate, and organic emissions warrant further testing. Any  $\text{NO}_x$  reduction below 215 ng/J ( $0.5 \text{ lb}/10^6 \text{ Btu}$ ) can only



be achieved with  $\text{NH}_3$  injection (an unproven technique), possibly down to 129 ng/J ( $0.3 \text{ lb}/10^6 \text{ Btu}$ ).

The other major stoker types, chain grate and underfeed, have average uncontrolled  $\text{NO}_x$  emissions below 172 ng/J ( $0.4 \text{ lb}/10^6 \text{ Btu}$ ). Control of these units to 129 ng/J ( $0.3 \text{ lb}/10^6 \text{ Btu}$ ) is possible with low excess air. It should be emphasized that control data for stokers are limited, and low excess air and overfire air represent the only significant controls tested on stokers.

#### 1.4 SYSTEMS OF $\text{NO}_x$ EMISSIONS REDUCTION FOR OIL-FIRED BOILERS

The combustion modification  $\text{NO}_x$  control techniques considered for oil-fired boilers are the same as those for coal-fired units, as listed at the beginning of Subsection 1.3.

##### 1.4.1 Candidate Best Systems of Control for Oil-Fired Boilers

Using the selection procedure discussed earlier, candidate best control systems were identified and are listed in Table 1-7 for residual oil-fired boilers and Table 1-8 for distillate oil-fired boilers units. Also summarized in these tables are the control effectiveness (percent  $\text{NO}_x$  reduction), operational impact, cost impact which includes energy impact, environmental impact, and commercial availability. All of these candidates, except for flue gas recirculation and reduced air preheat have been described in the previous subsection on coal-firing.

Flue gas recirculation for  $\text{NO}_x$  control consists of extracting a portion of the flue gas and returning it to the furnace, admitting the flue gas through the burner windbox. Flue gas recirculation lowers the bulk furnace gas temperature and reduces oxygen concentration in the combustion zone. The former effect is probably dominant since flue gas recirculation has been found to be most effective in reducing thermal  $\text{NO}_x$ . Addition of flue gas recirculation to a boiler is a major modification: the fan, ductwork, dampers, and controls as well as possibly having to increase existing fan capacity due to increased draft loss, can represent a large investment.

Reducing the amount of combustion air preheat lowers the primary combustion zone peak temperature, generally lowering thermal  $\text{NO}_x$  production as a result. It is an effective technique applicable to the clean fuels: distillate oil and natural gas. However, to prevent severe energy penalties, an economizer should be substituted as a flue gas heat recovery device.

TABLE 1-7. CANDIDATES FOR BEST SYSTEMS OF NO<sub>x</sub> EMISSIONS REDUCTION:  
RESIDUAL OIL-FIRED BOILERS

| Technique                                | Effectiveness <sup>a</sup><br>(% NO <sub>x</sub> Reduction) | Operational Impact                                                                                                                   | Cost Impact <sup>b</sup>                                       | Environmental Impact                                  | Availability                                                            |
|------------------------------------------|-------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------------------------|
| Low Excess Air                           | 5 - 20                                                      | Increased boiler efficiency.                                                                                                         | Increased efficiency partially offsets costs.                  | Possible increased CO and organic emissions.          | Available                                                               |
| Staged Combustion                        | 20 - 40                                                     | Perhaps slight decrease in boiler efficiency.                                                                                        | Major modification, perhaps costly.                            | Possible increased particulate and organic emissions. | Commercially offered but not demonstrated for this boiler/fuel category |
| Low NO <sub>x</sub> Burners <sup>c</sup> | 20 - 50                                                     | None expected.                                                                                                                       | Potentially most cost-effective.                               | None expected.                                        | Commercially offered but not demonstrated                               |
| NH <sub>3</sub> Injection                | 40 - 70                                                     | Possible implementation difficulties. Fouling problems with high sulfur fuels, load restrictions. Close operator attention required. | Several fold higher than conventional combustion modification. | Possible emissions of NH <sub>3</sub> and byproducts. | Commercially offered but not demonstrated                               |

<sup>a</sup> Effectiveness based on control applied singly.

<sup>b</sup> Incremental cost impact noting capacity/cost of boiler to which control is applied.

TABLE 1-8. CANDIDATES FOR BEST SYSTEMS OF NO<sub>x</sub> EMISSIONS REDUCTION:  
DISTILLATE OIL- AND GAS-FIRED BOILERS

| Technique                                   | Effectiveness <sup>a</sup><br>(% NO <sub>x</sub> Reduction) | Operational Impact                                                                   | Cost Impact <sup>b</sup>                                                 | Environmental Impact                            | Availability                                                               |
|---------------------------------------------|-------------------------------------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------|-------------------------------------------------|----------------------------------------------------------------------------|
| Low Excess Air                              | 5 - 15 (oil),<br>5 - 10 (gas)                               | Increased boiler efficiency.                                                         | Increased efficiency should<br>offset some of costs.                     | Possible increased CO<br>and organic emissions. | Available                                                                  |
| Staged<br>Combustion                        | 20 - 40 (oil),<br>25 - 45 (gas)                             | Perhaps slight decrease in<br>boiler efficiency.                                     | Major modification, probably<br>costly.                                  | Possible increased<br>organic emissions.        | Commercially offered but not demonstrated<br>for this boiler/fuel category |
| Flue Gas<br>Recirculation                   | 40 - 70 (oil)<br>45 - 75 (gas)                              | Possible flame instability.<br>Can be eliminated with proper<br>engineering/testing. | Major modification, probably<br>costly.                                  | Possible increased<br>organic emissions.        | Available                                                                  |
| Reduced Air<br>Preheat                      | 20 - 55 (oil)<br>20 - 55 (gas)                              | Replacing air preheater with<br>economizer in new designs.                           | None, other than engineering<br>redesign of new units (if<br>necessary). | None                                            | Available                                                                  |
| Low NO <sub>x</sub><br>Burners <sup>c</sup> | 20 - 50                                                     | None expected.                                                                       | Potentially most cost-<br>effective.                                     | None expected.                                  | Commercially offered but not demonstrated                                  |

<sup>a</sup> Effectiveness based on control applied singly.

<sup>b</sup> Incremental cost impact noting capacity/cost of boiler to which control is applied.

#### 1.4.2 Best Systems of Control for Oil-Fired Boilers

Best systems of control for residual oil- and distillate oil-fired boilers are summarized in Tables 1-9 and 1-10, respectively. Best systems were selected by boiler equipment type and suggested moderate, intermediate, and stringent level of control.

##### Residual Oil-Fired Boilers

Since baseline  $\text{NO}_x$  emissions from residual oil-fired firetube boilers averaged only 115 ng/J ( $0.267 \text{ lb}/10^6 \text{ Btu}$ ) no controls are generally necessary to meet the moderate control level of 129 ng/J ( $0.3 \text{ lb}/10^6 \text{ Btu}$ ). Low excess air firing should achieve the intermediate level of control, 108 ng/J ( $0.25 \text{ lb}/10^6 \text{ Btu}$ ). Low excess air operation should also increase boiler efficiency. The same caution about possible increased CO and organic emissions discussed for coal-firing under low excess air apply here also. Stringent control, 86 ng/J ( $0.2 \text{ lb}/10^6 \text{ Btu}$ ), will require either low  $\text{NO}_x$  burners or staged combustion, neither one of which is demonstrated technology for the small firetube designs. Low  $\text{NO}_x$  burners were selected as the first choice because of their potential for being the most cost-effective, high-reduction combustion modification technique.

The generally larger watertube boilers with higher  $\text{NO}_x$  emissions will also need the same controls, low excess air, low  $\text{NO}_x$  burners, and staged combustion, only sooner (e.g., moderate level). Staged combustion is a demonstrated technique for the large multiburner watertube boilers. However, if low  $\text{NO}_x$  burners are commercialized in time for stringent control, 86 ng/J ( $0.2 \text{ lb}/10^6 \text{ Btu}$ ), they should prove more cost-effective. The only other alternative for stringent control is ammonia injection. Although demonstrated and in limited commercial operation for oil- and gas-firing in Japan, this control system represents a severalfold more costly alternative for  $\text{NO}_x$  reduction than the other two systems. In addition, operational problems and potential emissions of  $\text{NH}_3$  and byproducts cause environmental concern.

It should be noted that the above discussed controlled emission levels for residual oil firing may be difficult to achieve for boilers firing high nitrogen content fuel (e.g.,  $>0.3$  weight percent nitrogen). Indeed there is a possible trend of increasing total  $\text{NO}_x$  emissions with fuel nitrogen content, unlike the behavior exhibited by coal-fired

TABLE 1-9. BEST CONTROL SYSTEM FOR RESIDUAL OIL-FIRED INDUSTRIAL BOILERS<sup>a</sup>

| Boiler Equipment Type | Baseline<br>NO <sub>x</sub> Emissions<br>ng/J (lb/106 Btu) | Level of Control                                                               |                                                           |                                                             |
|-----------------------|------------------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------------------|-------------------------------------------------------------|
|                       |                                                            | Moderate<br>129 ng/J (0.3 lb/106 Btu)                                          | Intermediate<br>108 ng/J (0.25 lb/106 Btu)                | Stringent<br>86 ng/J (0.2 lb/106 Btu)                       |
| Firetube              | 115 (0.267)                                                | No control necessary                                                           | Low excess air                                            | 1. Low NO <sub>x</sub> burners**<br>2. Staged combustion*** |
| Watertube             | 160 (0.372)                                                | 1. Low excess air<br>2. Low NO <sub>x</sub> burners**<br>3. Staged combustion* | 1. Low NO <sub>x</sub> burners**<br>2. Staged combustion* | 1. Low NO <sub>x</sub> burners**<br>2. Ammonia injection**  |

<sup>a</sup>Low excess air is recommended practice whenever controls are required.

\*Commercially offered but not demonstrated for this boiler/fuel category.

\*\*Commercially offered but not demonstrated.

\*\*\*Research and development.

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TABLE 1-10. BEST CONTROL SYSTEMS FOR DISTILLATE OIL-FIRED INDUSTRIAL BOILERS<sup>a</sup>

| Boiler Equipment Type                        | Baseline<br>NO <sub>x</sub> Emissions<br>ng/J (lb/10 <sup>6</sup> Btu) | Level of Control                                 |                                                                                                                  |                                                                                            |
|----------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------|------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
|                                              |                                                                        | Moderate<br>86 ng/J (0.2 lb/10 <sup>6</sup> Btu) | Intermediate<br>65 ng/J (0.15 lb/10 <sup>6</sup> Btu)                                                            | Stringent<br>43 ng/J (0.1 lb/10 <sup>6</sup> Btu)                                          |
| Firetube                                     | 75 (0.175)                                                             | No control necessary                             | Low excess air                                                                                                   | 1. Flue gas recirculation<br>2. Low NO <sub>x</sub> burners**                              |
| Watertube not equipped<br>with air preheater | 55 (0.128)                                                             | No control necessary                             | No control necessary                                                                                             | 1. Flue gas recirculation<br>2. Low NO <sub>x</sub> burners**<br>3. Staged combustion air* |
| Watertube equipped with<br>air preheater     | 90 (0.209)                                                             | Low excess air                                   | 1. Reduced air preheat<br>2. Flue gas recirculation<br>3. Low NO <sub>x</sub> burners**<br>4. Staged combustion* | 1. Reduced air preheat<br>2. Reduced air preheat<br>+ Low NO <sub>x</sub> burners**        |

<sup>a</sup>Low excess air operation is recommended practice whenever controls are required

\*Commercially offered but not demonstrated for this boiler/fuel category.

\*\*Commercially offered but not demonstrated.

boilers. A possible controlled (low excess air operation)  $\text{NO}_x$  level is 200 ng/J ( $0.47 \text{ lb}/10^6 \text{ Btu}$ ) for high nitrogen content residual oil.

#### Distillate Oil-Fired Boilers

$\text{NO}_x$  emissions from distillate oil combustion are primarily from thermal  $\text{NO}_x$  formation. The relatively low uncontrolled baseline  $\text{NO}_x$  emissions of distillate oil-fired boilers permit achievement of very low controlled  $\text{NO}_x$  levels: 86, 65, and 43 ng/J (0.2, 0.15, and  $0.1 \text{ lb}/10^6 \text{ Btu}$ ). These control levels can in most cases be met with commercially available techniques. Table 1-10 lists the best control systems for moderate, intermediate, and stringent control of distillate oil-fired boilers. The preferred control systems are low excess air, reduced air preheat, flue gas recirculation, and low  $\text{NO}_x$  burners, in that order, lowering  $\text{NO}_x$  down to 65 ng/J ( $0.15 \text{ lb}/10^6 \text{ Btu}$ ). Distillate oil- and natural gas-fired boilers not equipped with air preheaters (all firetubes, some watertubes) exhibited significantly lower  $\text{NO}_x$  emissions than those with air preheaters, irrespective of boiler heat input capacity. Those boilers without air preheat can reach 43 ng/J ( $0.1 \text{ lb}/10^6 \text{ Btu}$ ) with just flue gas recirculation, while air preheater- equipped boilers require combined reduced air preheat and flue gas recirculation.

Replacing the air preheater with an economizer in a new boiler is the best way to implement reduced air preheat with no energy loss. Flue gas recirculation, combined with reduced air preheat, is the best stringent control technique because of its demonstrated high effectiveness for clean fuels (distillate oil and natural gas). Potential operational problems such as flame instability should be eliminated with proper engineering and testing. Environmental impacts such as possible increased organic emissions are expected to be minimal, although further investigation is definitely called for.

#### 1.5 SYSTEMS OF $\text{NO}_x$ EMISSION REDUCTION FOR GAS-FIRED BOILERS

The  $\text{NO}_x$  emissions characteristics and control strategies for gas-fired boilers are nearly identical to those for distillate oil-fired units. Therefore, the discussion in the previous subsection on distillate oil-firing is directly relevant here and will not be repeated. Table 1-8

summarizes the candidates for best system of reduction, while Table 1-11 summarizes the best control systems and levels of control achievable.

## 1.6 ENERGY IMPACT

Although energy considerations were certainly included in the selection of best controls discussed in Sections 1.3 through 1.5, a general summary of energy impacts of combustion modification  $\text{NO}_x$  controls is useful here. Of the control methods reviewed, low excess air is the most fuel efficient. Low excess air should be used with most control methods to increase thermal efficiency and reduce  $\text{NO}_x$  emissions. Staged combustion air ports can be located so that thermal efficiency is not decreased if they are used with low excess and only one type of fuel is burned. For boilers that burn several fuels, several air ports would be needed and these ports may not always be in just the optimal location. Except for increased fan power use, boilers could be designed so that flue gas recirculation would not decrease thermal efficiency significantly. In some tests this was not always the case. Low  $\text{NO}_x$  burners are the most promising new technology. Ignoring  $\text{NH}_3$  and carrier gas, ammonia injection appears to have only a minor energy impact though for raw material consumption, operational, and environmental reasons it might not be desirable. For new distillate oil- and gas-fired boilers, economizers are recommended over air preheaters as energy saving devices.

In summary, combustion modification  $\text{NO}_x$  controls for new industrial boilers should only have a minor energy impact. In fact, with proper boiler design and control implementation, it might even be possible in some cases to significantly lower  $\text{NO}_x$  emissions and use less energy.

## 1.7 COST IMPACT

Although cost considerations were certainly included in the selection of best controls discussed in Sections 1.3 through 1.5, a general summary of cost impacts of combustion modification  $\text{NO}_x$  controls is useful here.

The primary contributions of combustion modification  $\text{NO}_x$  controls to steam costs changes are the equipment modification costs and changes in thermal efficiency and fan power demand. For firetube boilers annualized equipment costs are usually higher than costs due to efficiency or fan power demand changes. For watertube boilers, the opposite is usually true. For both firetube and watertube boilers, all costs are important and any factors that can lower any of these costs will be beneficial. In



TABLE 1-11. BEST CONTROL SYSTEMS FOR NATURAL GAS-FIRED INDUSTRIAL BOILERS<sup>a</sup>

| Boiler Equipment Type                     | Baseline<br>NO <sub>x</sub> Emissions<br>ng/J (lb/10 <sup>6</sup> Btu) | Level of Control                                 |                                                       |                                                                             |
|-------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------|-------------------------------------------------------|-----------------------------------------------------------------------------|
|                                           |                                                                        | Moderate<br>86 ng/J (0.2 lb/10 <sup>6</sup> Btu) | Intermediate<br>65 ng/J (0.15 lb/10 <sup>6</sup> Btu) | Stringent<br>43 ng/J (0.1 lb/10 <sup>6</sup> Btu)                           |
| Firetube                                  | 40 (0.093)                                                             | No control necessary                             | No control necessary                                  | No control necessary                                                        |
| Watertube not equipped<br>with air heater | 45 (0.105)                                                             | No control necessary                             | No control necessary                                  | Low excess air                                                              |
| Watertube equipped with<br>air heater     | 110 (0.256)                                                            | 1. RAPb<br>2. FGR<br>3. SCA*<br>4. LNB**         | 1. RAP + FGRb<br>2. RAP + LNB**<br>3. RAP + SCA*      | 1. RAP + FGRb<br>2. RAP + LNB**<br>3. RAP + NH <sub>3</sub> **<br>injection |

<sup>a</sup>Low excess air operation is recommended practice whenever controls are required.

bRAP = Reduced Air Preheat

FGR = Flue Gas Recirculation

SCA = Staged Combustion Air

LNB = Low NO<sub>x</sub> Burners

\*Commercially offered but not demonstrated for this boiler/fuel category.

\*\*Commercially offered but not demonstrated.

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many cases, using the lowest possible excess air will lower the cost impact. Of course, the boiler should be designed to give the highest possible thermal efficiency and lowest fan power requirements. Careful design can result in better fuel efficiency than was assumed in the economic analysis presented in this report.

Figures 1-1, 1-2, and 1-3 summarize the cost effectiveness of typical combustion modification  $\text{NO}_x$  controls for representative coal-, residual oil-, and distillate oil-/natural gas- fired industrial boilers. The estimated annualized control cost is plotted as a function of achievable  $\text{NO}_x$  control level.

Of the  $\text{NO}_x$  controls covered in this report, low excess air is the method recommended to be considered first since it can reduce fuel costs. Low  $\text{NO}_x$  burners are a promising technique since they should allow both low  $\text{NO}_x$  and low excess air operation, and thus save fuel while lowering  $\text{NO}_x$  emissions. Staged combustion is the next best method, unless fuel switching problems make it impractical. If staged combustion cannot be used, flue gas recirculation is the next most cost-effective technique. Ammonia injection is the least cost effective technique and load changing may make it very impractical. Also, whenever possible, an economizer is preferred over an air preheater as a fuel saving device since it does not raise  $\text{NO}_x$  levels.

In summary, combustion modification  $\text{NO}_x$  controls, once proven and demonstrated, should be a cost effective means of control for industrial boilers raising steam costs up to only 1 to 2 percent in most cases. However, the initial investment required, especially for small boilers, may be a large fraction of the cost of the boiler itself, up to 25 percent when controls are installed on a new boiler and up to 50 percent when retrofitting the controls on an existing boiler. Factory installed controls on new boilers should prove more cost effective than retrofit controls.

## 1.8 ENVIRONMENTAL IMPACT

Although environmental considerations were certainly included in the selection of best control discussed in Sections 1.3 through 1.5, a general summary of environmental impacts of combustion modification  $\text{NO}_x$  controls is useful here.

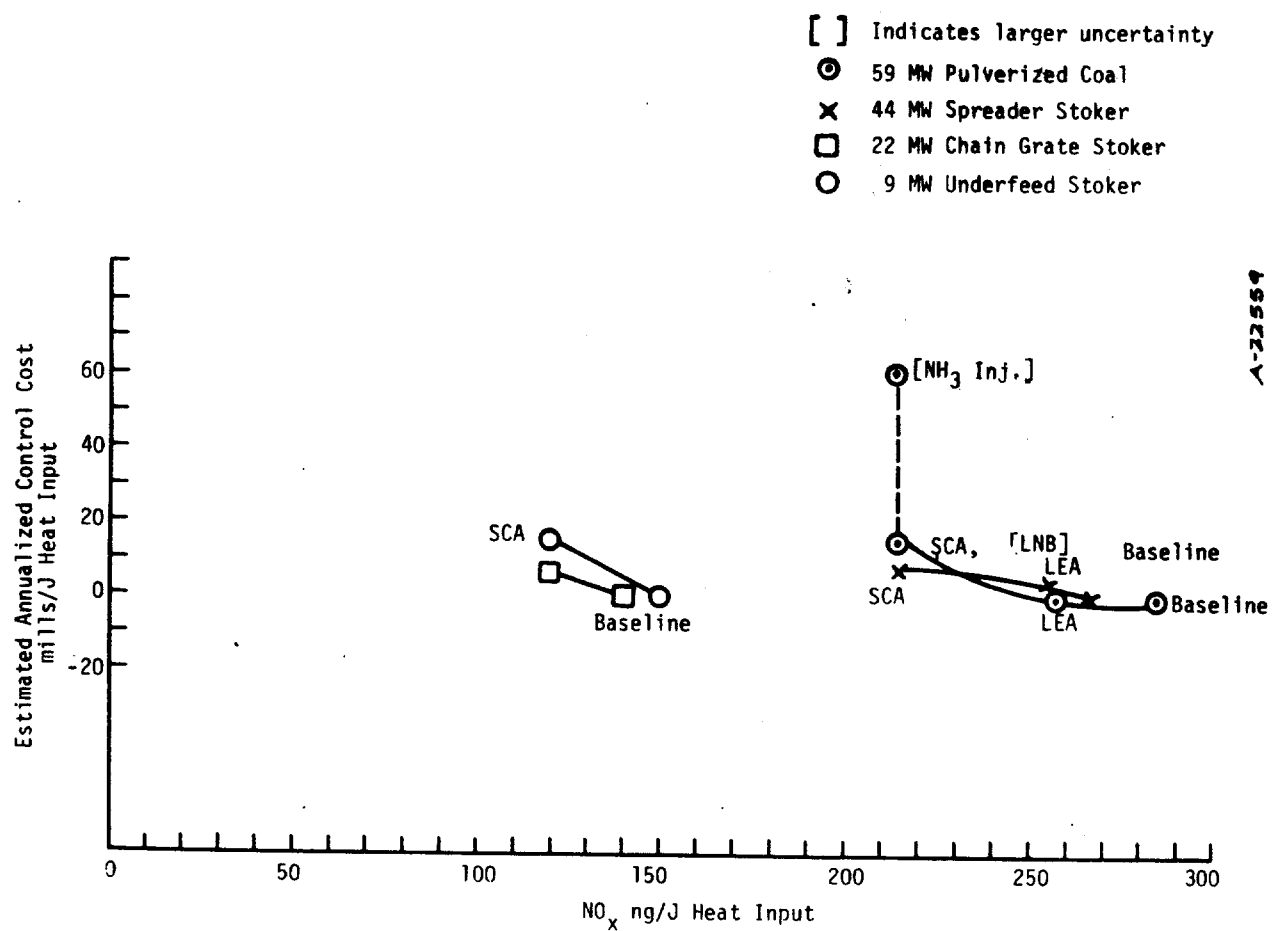


Figure 1-1. Estimated annualized control cost versus NO<sub>x</sub> level for coal-fired boilers (costs are only first estimates).

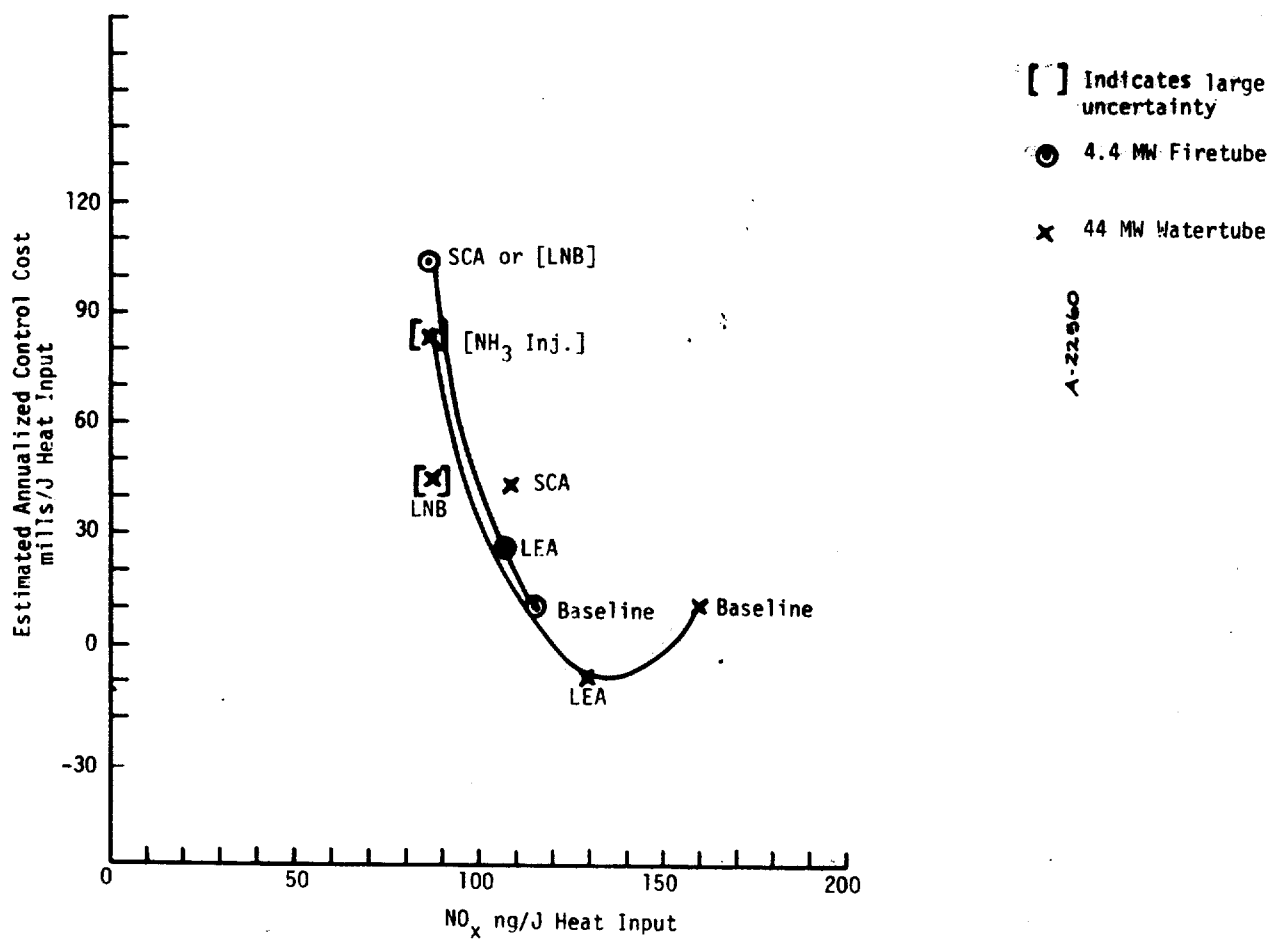


Figure 1-2. Estimated annualized control cost versus NO<sub>x</sub> emission level for residual oil-fired boilers (costs are only first estimates).

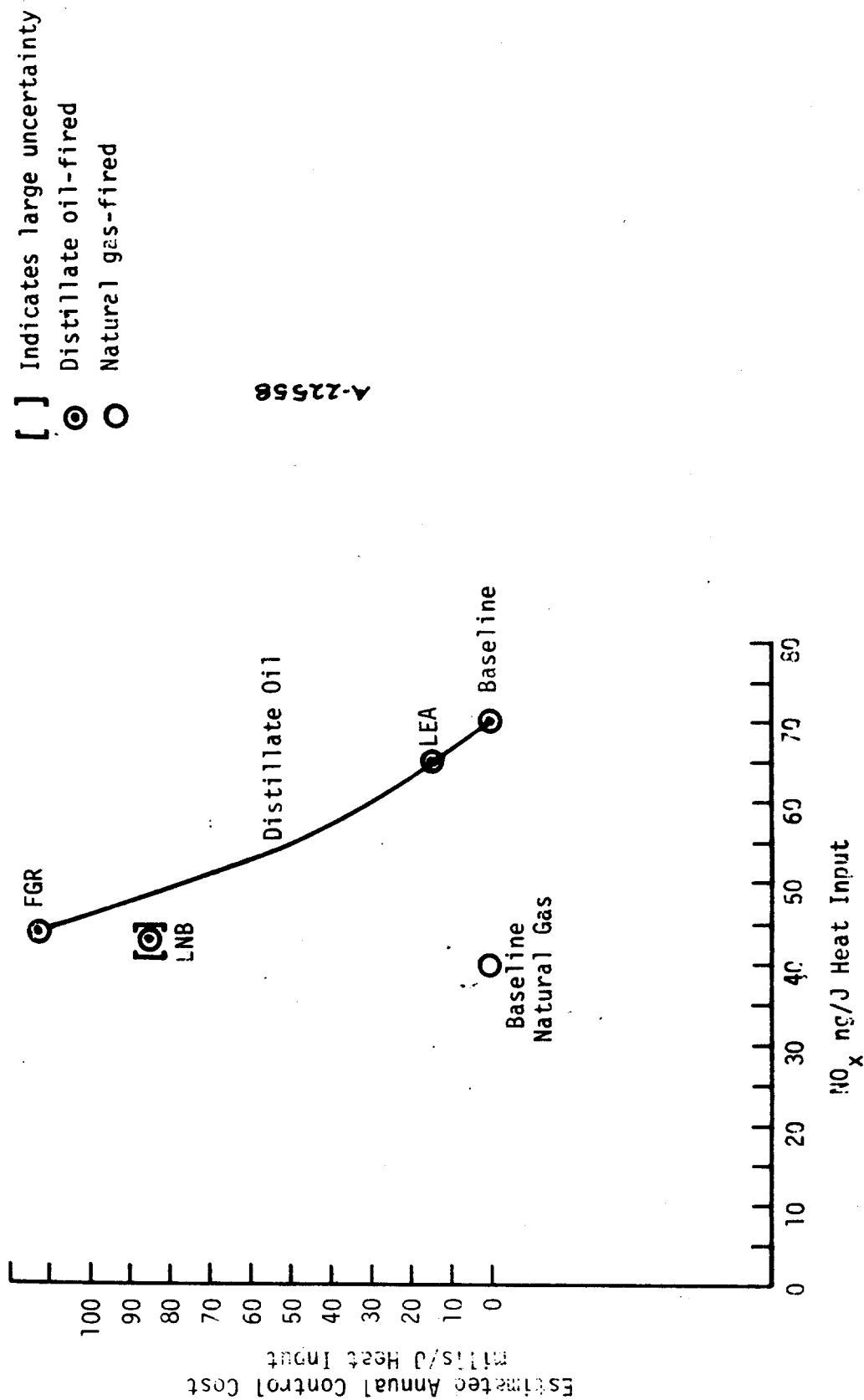


Figure 1-3. Estimated annualized control cost versus NO<sub>x</sub> emission levels for distillate oil and natural gas fired 4.4 MW firetube boiler (costs are first estimates only).

In general, no serious environmental impacts are expected for the control techniques recommended in this report. However, more field testing is required to quantify and establish that statement.

Tables 1-12 through 1-15 compare the recommended  $\text{NO}_x$  control techniques, the levels of control achievable, and the resulting incremental changes in other pollutant emissions. Where actual data are not available, a postulated effect is presented.

Carbon monoxide levels generally increase with  $\text{NO}_x$  control, although this can be minimized if not eliminated with judicious application of the control. Actual test data shows unburned hydrocarbon emissions to be decreased more often than increased, though the data are variable. Sulfate emissions decrease with decreasing oxygen content; particulate emissions decrease due to an (assumed) increase in particulate control device collection efficiency. The best  $\text{NO}_x$  control device for industrial boilers firing coal appear to be low excess air and staged combustion (overfire air), but information is too limited to be conclusive.

Low excess air and staged combustion (overfire air) appears to have little effect on incremental emissions from residual oil-fired boilers. For distillate oil- and natural gas-fired boilers, flue gas recirculation, staged combustion, and reduced air preheat appear to be the best methods available.

Incremental emissions are potentially increased by  $\text{NO}_x$  controls. More data are needed to quantify the incremental emissions for each control technique and to determine if any significant environmental impact may result.

TABLE 1-12. POSTULATED EFFECT OF CANDIDATE NO<sub>x</sub> CONTROL SYSTEMS ON INCREMENTAL EMISSIONS FROM COAL-FIRED INDUSTRIAL BOILERS

| Boiler                     | NO <sub>x</sub> Control Technique | Level of Control | Change in Incremental Emissions |      |                 |             |
|----------------------------|-----------------------------------|------------------|---------------------------------|------|-----------------|-------------|
|                            |                                   |                  | CO                              | UHC  | SO <sub>3</sub> | Particulate |
| Coal-Fired Boiler ≥ 29 MM  | Low Excess Air                    | Moderate         | +                               | -    | (-)             | (-)a        |
|                            |                                   | Intermediate     | +                               | -    | -               | -           |
|                            |                                   | Stringent        | +                               | v    | -               | -           |
|                            | Overfire Air                      | Intermediate     | +                               | (+)  | (-)             | (-)a        |
|                            |                                   | Stringent        | +                               | +    | -               | (-)a        |
|                            | Low NO <sub>x</sub> Burners       | Stringent        | (+)                             | (+)  | (-)             | (-)a        |
| Coal-Fired Boilers < 29 MM | Ammonia Injection <sup>b</sup>    | Stringent        | (NE)                            | (NE) | (+)             | (NE)        |
|                            | Low Excess Air                    | Intermediate     | -                               | +    | (-)             | -           |
|                            |                                   | Stringent        | v                               | (+)  | (-)             | (-)a        |

( ) No data available  
 - Some decrease  
 + Some increase  
 ++ Significant increase  
 v Variable results  
 NE No effect  
<sup>a</sup> Assuming dust control devices are utilized, otherwise (+)  
<sup>b</sup> Ammonia injection may cause ammonia and byproduct emissions

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Consequently, the gaps in the information concerning measured parameter data used to calculate coal-fired trace element emissions will affect the adequacy of this emissions inventory.

For coal-fired utility systems, the gaps in the information concerning the parameters of these equations are associated mainly with the trace element enrichment measured in fly ash out a control device. The number of data points for measured trace element enrichment out an ESP (Table 3-8) range from 8 (for selenium) to 14 (for manganese), while the number of data points for measured trace element enrichment out a wet scrubber or multiple cyclone range from only 1 to 3<sup>1</sup>. Other parameters used in these equations such as trace element content in coal, heating values of coal, particulate removal efficiencies, etc., were derived from extensive sets of data and have no apparent information gaps.

For oil-fired electricity generation SCCP (including internal combustion sources), there are also numerous gaps in the information concerning the test data for trace element and benzo(a)pyrene emissions. However, as with coal-fired sources, these gaps are not relevant to the adequacy of the trace element emissions inventory because the emission levels were calculated based on a parameterized equation (see Section 3.1.4) rather than measured emission levels. The reason for using the parameterized equation to estimate emissions from oil-fired sources is because there are more data points (per trace element) for trace element content in oil than for test data measuring trace element emissions.

Other parameters used in this equation, such as heating value of the fuel oil and the amount of fuel oil consumed, were derived from extensive sets of data and have no apparent information gaps.

Test data for BaP emissions for oil-fired SCCP, including internal combustion engines and turbines, are limited to only one data point (see Table 4-6).

Table 4-15 summarizes the extent of information concerning the noncriteria pollutant emissions of this study in terms of the number of



TABLE 1-14. POSTULATED EFFECT OF CANDIDATE NO<sub>x</sub> CONTROL SYSTEMS ON INCREMENTAL EMISSIONS FROM DISTILLATE OIL-FIRED INDUSTRIAL BOILERS

| NO <sub>x</sub> Control Technique | Level of Control | Change in Incremental Emissions |      |                 |                  |
|-----------------------------------|------------------|---------------------------------|------|-----------------|------------------|
|                                   |                  | CO                              | UHC  | SO <sub>3</sub> | Particulate      |
| Low Excess Air                    | Moderate         | (+)                             | (+)  | (-)             | (-) <sup>a</sup> |
|                                   | Intermediate     | ++                              | -    | (-)             | (-) <sup>a</sup> |
|                                   | Stringent        | (++)                            | (+)  | (-)             | (-) <sup>a</sup> |
| Flue Gas Recirculation            | Moderate         | (+)                             | (+)  | (-)             | (-) <sup>a</sup> |
|                                   | Intermediate     | (+)                             | (+)  | (-)             | (-) <sup>a</sup> |
|                                   | Stringent        | +                               | +    | (-)             | (-) <sup>a</sup> |
| Overfire Air                      | Moderate         | (+)                             | (+)  | (-)             | (-) <sup>a</sup> |
|                                   | Intermediate     | +                               | +    | (-)             | -                |
|                                   | Stringent        | +                               | +    | -               | -                |
| Reduced Air Preheat               | Intermediate     | (NE)                            | (NE) | (-)             | (+)              |
|                                   | Stringent        | (NE)                            | (NE) | (-)             | (+)              |
| Low NO <sub>x</sub> Burners       | Stringent        | (+)                             | (+)  | (-)             | (-) <sup>a</sup> |

( ) No data available

- Some decrease

+ Some increase

++ Significant increase

<sup>a</sup> Assuming dust control devices are utilized. Otherwise (+)

NE No Effect

TABLE 1-15. POSTULATED EFFECT OF CANDIDATE NO<sub>x</sub> CONTROL SYSTEMS ON INCREMENTAL EMISSIONS FROM GAS-FIRED INDUSTRIAL BOILERS

| NO <sub>x</sub> Control Technique | Level of Control | Change in Incremental Emissions <sup>a</sup> |     |
|-----------------------------------|------------------|----------------------------------------------|-----|
|                                   |                  | CO                                           | UHC |
| Low Excess Air                    | Moderate         | +                                            | (+) |
|                                   | Intermediate     | +                                            | -   |
|                                   | Stringent        | +                                            | (+) |
| Flue Gas Recirculation            | Moderate         | (+)                                          | (+) |
|                                   | Intermediate     | (+)                                          | (+) |
|                                   | Stringent        | -                                            | (+) |
| Overfire Air                      | Moderate         | +                                            | (+) |
|                                   | Intermediate     | +                                            | (+) |
|                                   | Stringent        | -                                            | -   |
| Reduced Air Preheat               | Moderate         | +                                            | -   |
|                                   | Intermediate     | +                                            | (+) |
|                                   | Stringent        | +                                            | (+) |
| Low NO <sub>x</sub> Burners       | Stringent        | (+)                                          | (+) |

( ) No data available

- Some decrease

+ Some increase

++ Significant increase

<sup>a</sup> SO<sub>3</sub> and particulate not present in natural gas combustion products

## SECTION 2

### EMISSION CONTROL TECHNIQUES

This section presents a survey of applicable combustion modifications to reduce  $\text{NO}_x$  emissions from industrial boilers. Industrial boilers can be defined as coal-, oil- or natural gas-fired steam generators with heat input capacities usually ranging from 3 to 73 MW (10 to  $250 \times 10^6$  Btu/hr). In fact, the current New Source Performance Standards (NSPS) for utility boilers cover units  $>73$  MW ( $>250 \times 10^6$  Btu/hr) input (Reference 2-1). However, for the purposes of this study, industrial units larger than 73 MW ( $250 \times 10^6$  Btu/hr) are also covered. Indeed, nearly 14 percent of the total population of steam generators in the industrial sector have capacities greater than 73 MW ( $250 \times 10^6$  Btu/hr).

This section provides a review of current available knowledge of the effectiveness, applicability and limitations of specific combustion modifications for each major equipment/fuel category in the industrial boiler sector. Major equipment and fuel categories for industrial boilers have been identified as follows:

- Coal-fired
  - Pulverized coal, field-erected watertube
  - Packaged and field erected stoker-fed watertube
- Oil-fired
  - Residual oil, packaged and field erected watertube
  - Residual oil, packaged firetube
  - Distillate oil, packaged and field erected watertube
  - Distillate oil, packaged firetube

- Gas-fired
  - Packaged and field erected watertube
  - Packaged firetube

The category of stokers includes packaged underfeed units and field erected spreader and chain grate units. These boiler categories include the standard boiler types identified in the current EPA study of which this work is a part (Reference 2-3).

However, the above list contains three additional industrial boiler categories. These are gas- and distillate oil-fired watertube units and residual oil-fired firetube units. These additional boiler types have been selected primarily on two criteria. First, these boiler types have different  $\text{NO}_x$  emissions characteristics and hence have different control options. Second, a significant number of boilers within these three categories have been extensively tested with combustion modifications. This will be borne out in the subsequent sections. Thus a separate discussion of these units is warranted.

The main discussion on combustion modifications for  $\text{NO}_x$  control of industrial boilers is preceded by a brief overview of the mechanisms of  $\text{NO}_x$  formation and the basic concepts for its reduction.

## 2.1 $\text{NO}_x$ FORMATION MECHANISM AND PRINCIPLES OF CONTROL

Oxides of nitrogen formed in combustion processes are usually due either to thermal fixation of atmospheric nitrogen in the combustion air, leading to "thermal  $\text{NO}_x$ ", or to the conversion of chemically bound nitrogen in the fuel, leading to "fuel  $\text{NO}_x$ ".\* For natural gas and light distillate oil firing, nearly all  $\text{NO}_x$  emissions result from thermal fixation. With residual oil, crude oil, and coal, the contribution from fuel-bound nitrogen can be significant and, under certain operating conditions, predominant. A brief discussion of each of these two mechanisms of  $\text{NO}_x$  formation follows.

### 2.1.1 Thermal $\text{NO}_x$

The detailed chemical mechanism by which molecular nitrogen in the combustion air is converted to nitric oxide is not fully understood.

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\*The term  $\text{NO}_x$  includes all oxides of nitrogen, primarily NO and  $\text{NO}_2$ . However, field test data have shown that over 95 percent of the  $\text{NO}_x$  formed in steam generators leaves the stack as NO (Reference 2-4).

In practical combustion equipment, particularly for liquid or solid fuels, the kinetics of the  $N_2$ - $O_2$  system are coupled to the kinetics of hydrocarbon oxidation and both are influenced, if not dominated, by effects of turbulent mixing in the flame zone. It is, however, generally accepted that thermal  $NO_x$  forms at high temperatures in an excess of  $O_2$ . The most widely accepted set of reactions that describes this phenomenon is the chain mechanism proposed by Zeldovich (Reference 2-5):



Reaction (2-1) has a large activation energy (317 kJ/mol) and is generally believed to be rate determining. Oxygen atom concentrations are assumed to have reached equilibrium according to:



where M denotes any third substance (usually  $N_2$ ).

Experimental measurements of NO formation in heated mixtures of  $N_2$ ,  $O_2$  and Ar at atmospheric pressures have shown that NO concentration is strongly dependent on temperature (Reference 2-6). Thermal  $NO_x$  formation is also dependent on the  $N_2$  concentration, the residence time, and the square root of  $O_2$  concentration according to the following equation (Reference 2-6):

$$[NO] = k_1 e^{(-k_2/T)} [N_2] [O_2]^{1/2} t$$

where:  $[ ]$  = mole fraction  
 $T$  = temperature (K)  
 $t$  = residence time

$k_1, k_2$  = constants

Therefore, the formation of thermal  $NO_x$  can be reduced by four tactics: (1) reduce nitrogen level, (2) reduce oxygen level, (3) reduce peak temperature, and (4) reduce time of exposure at peak temperature. In

typical hydrocarbon-air flames, the  $N_2$  mole fraction is of the order 0.7 and is relatively difficult to modify. Therefore, field practice has focused on reducing oxygen level, peak temperature, and time of exposure in the  $NO_x$ -producing region of the combustor (Reference 2-7). These parameters are in turn dependent on secondary combustion variables such as combustion intensity and internal mixing in the flame zone -- effects which are ultimately determined by primary equipment and fuel parameters over which the combustion engineer has some control.

Combustion modification techniques such as lowered excess air and staged combustion have been used to lower local  $O_2$  concentrations. Flue gas recirculation and reduced air preheat have been used in boilers to lower peak flame temperatures. Flue gas recirculation reduces residence time at peak temperatures, although the primary effect is through temperature reduction and lowered  $O_2$  concentration.

Controlling the mixing between fuel, combustion air and recirculated products has also been found to reduce thermal  $NO_x$  formation. Burner swirl, combustion air velocity, fuel injection angle and velocity, burner divergent angle and confinement ratio all affect the mixing between fuel combustion air and recirculated products. Unfortunately, generalizing these effects is difficult, because the interactions are complex. Increasing swirl, for example, may both increase entrainment of cooled combustion products (hence lowering peak temperatures) but it may also increase fuel/air mixing (raising local combustion intensity). Thus, the net effect of increasing swirl can be to either raise or lower  $NO_x$  emissions, depending on other system parameters (Reference 2-10).

#### 2.1.2 Fuel $NO_x$

The role of fuel-bound nitrogen as a source of  $NO_x$  emissions from combustion sources has been recognized since 1968 (Reference 2-8). Although the relative contribution of fuel and thermal  $NO_x$  to total  $NO_x$  emissions from sources firing nitrogen-containing fuels has not been definitively established, recent estimates indicate that fuel  $NO_x$  is significant and may even predominate. In fact, laboratory studies under controlled operating conditions have shown that fuel  $NO_x$  can account for 50 percent of the total  $NO_x$  for residual oil and up to 80 percent for

coal (Reference 2-9). Therefore, as coal is increasingly used as a national energy source, the control of fuel  $\text{NO}_x$  will become more important.

The following discussion is directed mainly toward fuel  $\text{NO}_x$  formation from coal, though fuel  $\text{NO}_x$  is also a problem with other nitrogen-containing fuels as well. A recent review of published data indicated that, in general, anywhere from 20 to 90 percent of fuel nitrogen in oil is converted to  $\text{NO}_x$  while the percentage of fuel nitrogen converted to  $\text{NO}_x$  in coal ranges from 5 to 60 (Reference 2-10). Figure 2-1 illustrates the nitrogen content of various U.S. coals, expressed as ng  $\text{NO}_2$  produced per Joule for 100 percent conversion of the fuel nitrogen. The figure clearly shows that if all coal-bound nitrogen was converted to  $\text{NO}_x$ , emissions for all coals would exceed the coal-fired utility boiler NSPS of 301 ng/J ( $0.7 \text{ lb}/10^6 \text{ Btu}$ ) implemented in 1971. Fortunately, only a fraction of the fuel nitrogen is converted to  $\text{NO}_x$  for both oil and coal firing (Reference 2-11, 2-12). Furthermore, the percentage of fuel nitrogen conversion appears to decrease as the fuel nitrogen content increases. Recent data from combustion of coal in utility boilers exhibited fuel nitrogen conversion ranging from 6.5 percent to 15 percent, with the possible correlation of conversion increasing with the ratio of coal oxygen to coal nitrogen (References 2-72 and 2-73). An EPA field test program on industrial boilers confirmed the trend of increasing fractional conversion of fuel nitrogen with decreasing nitrogen content. An average conversion of 46 percent was found for residual oil, and nearly 100 percent for distillate oil (Reference 2-20).

Thus, although fuel  $\text{NO}_x$  emissions undoubtedly increase with increasing fuel nitrogen content, the emissions increase is not proportional (Reference 2-11). In fact, data on tangential coal-fired boilers indicate only a slight increase in total  $\text{NO}_x$  emissions as fuel nitrogen increases. This is shown in Figure 2-2 (Reference 2-13). One recent report comparing two similar wall-fired utility boilers claimed a 23 percent reduction in fuel  $\text{NO}_x$  with a 15 percent reduction in fuel nitrogen, on a ng nitrogen/J heat input basis (Reference 2-70). However the lower  $\text{NO}_x$  producing coal also had a higher moisture content which would have tended to reduce  $\text{NO}_x$  emissions. The data collected on

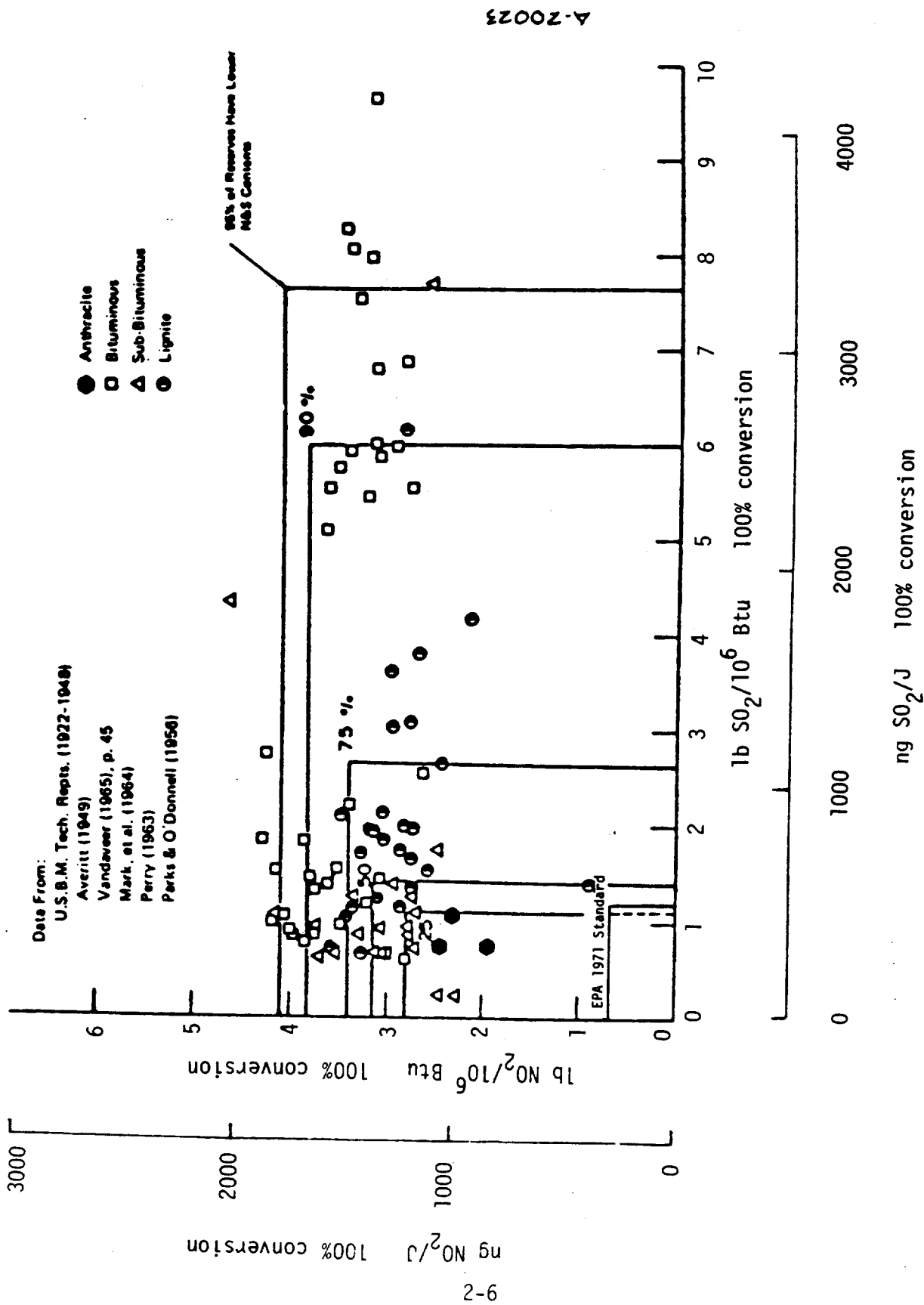
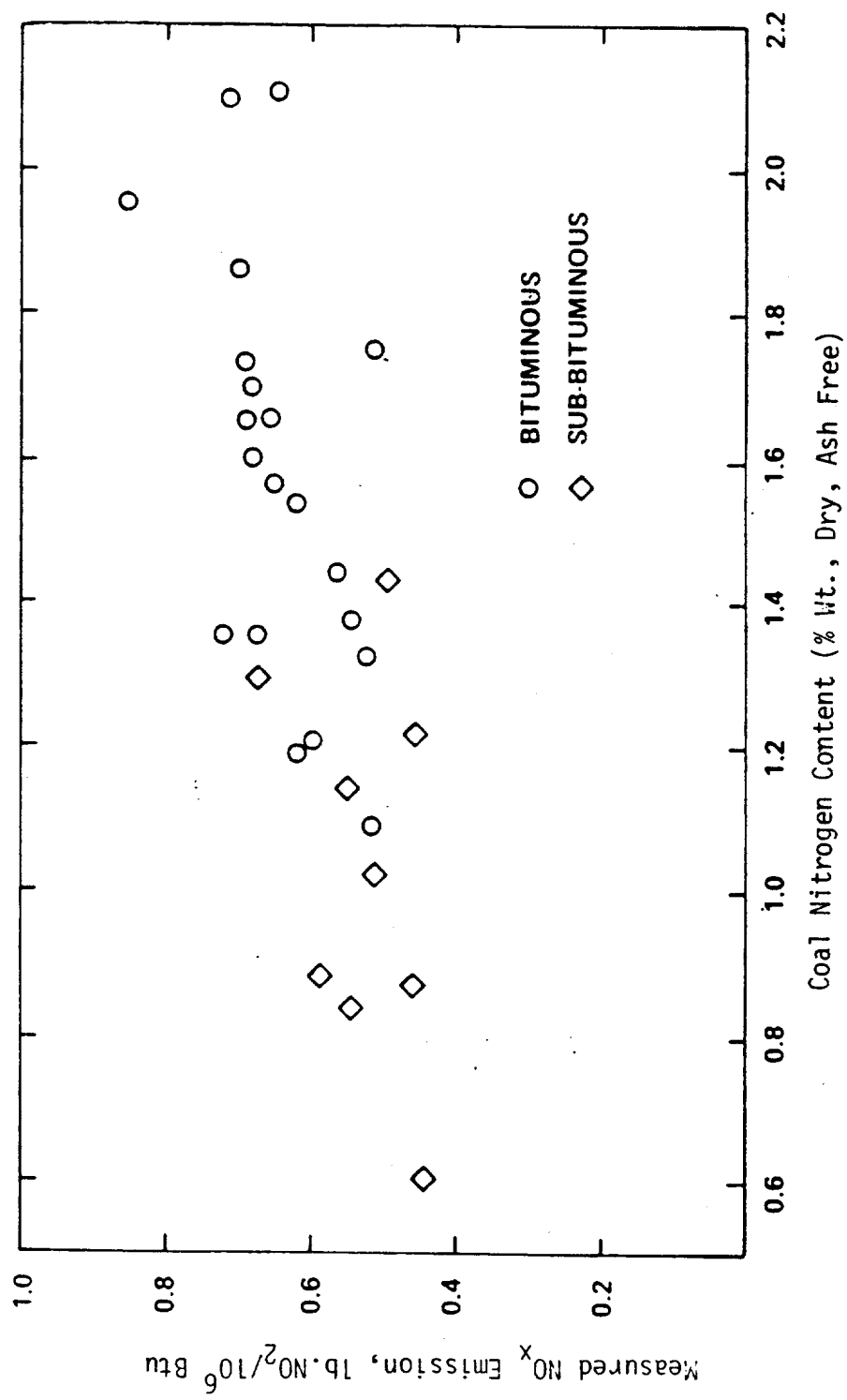


Figure 2-1. Nitrogen and sulfur content of U.S. coal reserves (Reference 2-12).





industrial boilers by KVB under an EPA sponsored field test program indicated that no direct correlation between total  $\text{NO}_x$  emissions and coal fuel nitrogen, per se, exists (Reference 2-20). The tentative generalizations that can be made at this time are that the higher nitrogen fuels do produce more  $\text{NO}_x$  in the order coal, residual oil, distillate oil, natural gas, but within a given fuel category, e.g. coal, no definite conclusions can be drawn. Since field experience is not definitive, a review of the current fundamental theories of fuel  $\text{NO}_x$  formation may be profitable in developing control strategy.

In general, fuel  $\text{NO}_x$  formation is the product of oxidation of the nitrogen in the volatiles and in the char of the coal. The oxidation of char nitrogen to NO proceeds much more slowly than the oxidation of volatilized nitrogen. In fact, based on a combination of experimental and empirical modeling studies, it is now believed that 60 to 80 percent of the fuel  $\text{NO}_x$  results from volatile nitrogen oxidation (References 2-11 and 2-14). Conversion of the char nitrogen to NO is in general lower, by factors of two to three, than conversion of total coal nitrogen (Reference 2-15).

Regardless of the precise mechanism of fuel  $\text{NO}_x$  formation, several general trends are evident, particularly for coal combustion. As expected, fuel nitrogen conversion to NO is highly dependent on the fuel/air ratio for the range existing in typical combustion equipment (Reference 2-16). This behavior is due largely to volatile NO formation, while oxidation of the char nitrogen is relatively insensitive to fuel/air changes.

In contrast to thermal  $\text{NO}_x$ , fuel  $\text{NO}_x$  production is relatively insensitive to small changes in combustion zone temperature (Reference 2-15). Char nitrogen oxidation appears to be a very weak function of temperature, and although the amount of nitrogen volatiles appears to increase as temperature increases, this is believed to be partially offset by a decrease in percentage conversion (Reference 2-15). Furthermore, operating restrictions severely limit the magnitude of actual temperature changes attainable in current systems.

As described above, fuel  $\text{NO}_x$  emissions are a strong function of fuel/air mixing. In general, any change which increases the mixing between the fuel and air during coal devolatilization will dramatically

increase volatile nitrogen conversion and increase fuel NO. In contrast, char NO formation is only weakly dependent on initial mixing and therefore may represent a lower limit on the emission level which can be achieved through burner modifications (Reference 2-10).

In principle, the best strategy for fuel NO<sub>x</sub> abatement combines low excess air firing, optimum burner design, and staged combustion. Assuming suitable stage separation, low excess air (LEA) may have little effect on fuel NO, but it increases system efficiency. Before using LEA firing, the need to get good carbon burnout and low CO emissions must be considered.

Optimum burner design ensures locally fuel-rich conditions during devolatilization, which promotes reduction of volatilized nitrogen compounds to N<sub>2</sub>. Staged combustion produces overall fuel-rich conditions during the first 1 to 2 seconds and promotes the reduction of NO to N<sub>2</sub> through reburning reactions. High secondary air preheat also appears desirable, because it promotes more complete nitrogen volatilization in the fuel-rich initial combustion stage. This leaves less char nitrogen to be subsequently oxidized in the fuel-lean second stage. Unfortunately, it also tends to favor thermal NO formation, and at present there is no general agreement on which effect dominates (Reference 2-10).

### 2.1.3 Principles of Control

In summary of the above discussion, both thermal and fuel NO<sub>x</sub> are far below the levels which would prevail at equilibrium at peak temperature. Thus, the rate of formation of both thermal and fuel NO<sub>x</sub> is dominated by combustion conditions and is amenable to suppression through combustion process modifications. Although the mechanisms are different, both thermal and fuel NO<sub>x</sub> are promoted by rapid mixing of oxygen with the fuel. Additionally, thermal NO<sub>x</sub> is greatly increased by increased residence time at high temperature. The modified combustion conditions and control concepts which have been tried or suggested to combat the formation mechanisms are as follows:

- Decrease primary flame zone O<sub>2</sub> level by:
  - Decreased overall O<sub>2</sub> level
  - Controlled mixing of fuel and air
  - Use of fuel-rich primary flame zone

- Decrease time of exposure at high temperature by:
  - Decreased peak temperature:
    - Decreased adiabatic flame temperature through dilution
    - Decreased combustion intensity
    - Increased flame cooling
    - Controlled mixing of fuel and air or use of fuel-rich primary flame zone
  - Decreased primary flame zone residence time
- Chemically reduce  $\text{NO}_x$  in post-flame region by:
  - Injection of reducing agent

Table 2-1 relates these control concepts to applicable combustion process modifications and equipment types. The process modifications are further categorized according to their role in the control development sequence: operational adjustments, hardware modifications of existing equipment or through factor installed controls, and, major redesigns of new equipment. The controls for decreased  $\text{O}_2$  are also generally effective for peak temperature reduction but have not been repeated.

Table 2-2 summarizes the availability and status of the primary controls shown in Table 2-1 as applicable to the major boiler fuel type categories identified earlier. The following subsections review the status and performance of each of these applicable controls.

## 2.2 COAL-FIRED BOILERS

Industrial coal-fired boilers are of both the pulverized and stoker types. Pulverized coal-fired boilers are usually limited to sizes greater than 29 MW heat input ( $100 \times 10^6$  Btu/hr) (Reference 2-17) and account for 3.9 percent of the total industrial boiler population (Reference 2-2). Stokers, instead, range from less than 0.3 MW to 120 MW of heat input ( $1$  to  $400 \times 10^6$  Btu/hr) and account for 11.25 percent of the total industrial boiler population (Reference 2-2).

Two basic designs exist for industrial boilers burning pulverized coal: single wall and tangential. However, cyclone boilers are often included in this fuel type category even though the coal they burn is not pulverized but crushed.

As already discussed in Subsection 2.1 on  $\text{NO}_x$  formation mechanisms, and will be further elaborated in this subsection as well as Section 3, there are insufficient emissions data on coal-fired industrial

TABLE 2-1. SUMMARY OF COMBUSTION PROCESS MODIFICATION CONCEPTS (REFERENCE 2-10)

| Combustion Conditions                                  | Control Concept                                     | Effect on Thermal NO <sub>x</sub>                                               | Effect on Fuel NO <sub>x</sub>                                     | Primary Applicable Controls                  |                                          |                                                           |
|--------------------------------------------------------|-----------------------------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------------------|----------------------------------------------|------------------------------------------|-----------------------------------------------------------|
|                                                        |                                                     |                                                                                 |                                                                    | Operational Adjustments                      | Hardware Modification                    | Major Redesign                                            |
| Decrease primary flame zone O <sub>2</sub> level       | Decrease overall O <sub>2</sub> level               | Reduces O <sub>2</sub> rich, high NO <sub>x</sub> pockets in the flame          | Reduces exposure of fuel nitrogen intermediaries to O <sub>2</sub> | Low excess air firing                        | Flue gas recirculation (FGR)             |                                                           |
|                                                        | Delayed mixing of fuel and air                      | Flame cooling and dilution during delayed mixing reduces peak temp.             | Volatile fuel N reduces to N <sub>2</sub> in the absence of oxygen | Burner adjustments                           | Low NO <sub>x</sub> burners              | Optimum burner/firebox design                             |
|                                                        | Primary fuel-rich flame zone                        | Flame cooling in low O <sub>2</sub> , low temp. primary zone reduces peak temp. | Volatile fuel N reduces to N <sub>2</sub> in the absence of oxygen | Burners out of service; biased burner firing | Overfire air ports                       | Burner/firebox design for two stage combustion            |
| Decrease peak flame temperature                        | Decrease adiabatic flame temperature                | Direct suppression of thermal NO <sub>x</sub> mechanism                         | Ineffective                                                        | Reduced air preheat                          | Water injection, FGR                     |                                                           |
|                                                        | Decrease combustion intensity                       | Increased flame zone cooling yields lower peak temperature                      | Minor direct effect; indirect effect on mixing                     | Load reduction                               |                                          | Enlarged firebox, increased burner spacing                |
|                                                        | Increased flame zone cooling/ reduce residence time | Increased flame zone cooling yields lower peak temperature                      | Ineffective                                                        | Burner tilt                                  |                                          | Redesign heat transfer surfaces, firebox aerodynamics     |
| Chemically reduce NO <sub>x</sub> in post flame region | Inject reducing agent                               | Decomposition                                                                   | Decomposition                                                      |                                              | Ammonia injection possible on some units | Redesign convective section for NH <sub>3</sub> injection |

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TABLE 2-2. APPLICABILITY OF COMBUSTION MODIFICATION NO<sub>x</sub> CONTROLS FOR MAJOR INDUSTRIAL BOILER EQUIPMENT/FUEL TYPES

| Fuel                                                              | Coal                                       |                                           | Oil and Natural Gas                       |                                           |                                           |
|-------------------------------------------------------------------|--------------------------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|
| Equipment Type                                                    |                                            |                                           |                                           |                                           |                                           |
| Combustion Modification                                           | Packaged and Field Erected Stokers         | Field Erected Pulverized Coal             | Field Erected Watertube                   | Packaged Watertube                        | Packaged Firetube                         |
| Low Excess Air (LEA)                                              | Available but not implemented <sup>a</sup> | Available, implemented on limited basis   | Available, implemented on limited basis   | Available but not implemented             | Available but not implemented             |
| Load Reduction (LR)                                               | Available but not implemented              | Available but not implemented             | Available but not implemented             | Available but not implemented             | Available but not implemented             |
| Staged Combustion with Overfire Air Injection (OFA)               | Available but not implemented              | Implemented on limited basis              | Available but not implemented             | Not available R&D <sup>b</sup> status     | Not available R&D <sup>b</sup> status     |
| Staged Combustion with Burners out of Service (BOOS) <sup>c</sup> | Not applicable                             | Available but not implemented             | Available but not implemented             | Not applicable for single burner boilers  | Not applicable                            |
| Flue gas Recirculation (FGR)                                      | Not applicable                             | Not available. limited research           | Available                                 | Available                                 | Available                                 |
| Low NO <sub>x</sub> Burners (LNB)                                 | Not applicable                             | Not available. R&D <sup>b</sup> status    | Commercially offered but not demonstrated | Commercially offered but not demonstrated | Commercially offered but not demonstrated |
| Ammonia Injection                                                 | Not available. Limited research            | Commercially offered but not demonstrated | Commercially offered but not demonstrated | Commercially offered but not demonstrated | Commercially offered but not demonstrated |
| Reduced Air Preheat (RAP)                                         | Not available. Limited research            | Not available. Fuel penalty too high      | Available                                 | Available                                 | Not applicable                            |
| New Furnace Design (Decreased Heat Release Rate)                  | Not available. Limited research            | Available but not implemented             | Not available. Limited research           | Not available. Limited research           | Not available. Limited research           |

<sup>a</sup>Means that control technique is commercially available, but is not presently being implemented for emission control.

<sup>b</sup>R&D, Research and Development.

<sup>c</sup> BOOS is considered a retrofit NO<sub>x</sub> control measure.

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boilers to warrant a breakdown of baseline or achievable control levels based on coal type. The few boiler and coal types tested are not adequate to establish the significance of any trends. In fact, as discussed earlier, some of the so-called data trends are conflicting. Variations in emissions from boiler to boiler (of the same firing type, etc.) are often greater than possible variations due to coal type (see, for example, Table 7-2).

Of the four single wall pulverized coal-fired boilers analyzed, three showed baseline (normal operation) emissions of 174, 216 and 244 ng/J (0.405, 0.502, and 0.567 lb/10<sup>6</sup> Btu) as NO<sub>2</sub> and the fourth showed baseline emissions of 563 ng/J (1.31 lb/10<sup>6</sup> Btu) as NO<sub>2</sub> (References 2-18 and 2-19).<sup>\*</sup> These boilers ranged in size from 46.7 to 117 MW (160 to 400 x 10<sup>6</sup> Btu/hr) with the fourth boiler having an input capacity of 76.2 MW (260 x 10<sup>6</sup> Btu/hr). The large baseline emissions of the fourth unit could not be explained by any significant differences in fuel properties, boiler characteristics, or operating conditions. One cyclone boiler tested emitted 494 ng/J (1.15 lb/10<sup>6</sup> Btu) as NO<sub>2</sub> at baseline (References 2-18 and 2-20). Cyclone boilers are generally large NO<sub>x</sub> producers; thus these high NO<sub>x</sub> levels are not surprising. A 66 MW (225 x 10<sup>6</sup> Btu/hr) and a 94 MW (320 x 10<sup>6</sup> Btu/hr) tangential coal-fired boiler were also tested. Baseline emissions were 234 and 296 ng/J (0.544 and 0.688 lb/10<sup>6</sup> Btu) as NO<sub>2</sub>, respectively (Reference 2-18). Because of the small number of boilers tested and the small difference in the average NO<sub>x</sub> emissions from tangential and single wall industrial boilers, their NO<sub>x</sub> emissions will be averaged together in this study.

Emission data from industrial boilers burning pulverized coal are limited to the six units above. However, large industrial boilers are similar in design to utility boilers. Based on this similarity in design, a direct comparison of NO<sub>x</sub> emissions can be made. Control techniques applicable to utility boilers can often be applied to large industrial boilers.

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<sup>\*</sup>Note: NO<sub>x</sub> emission data discussed in this report are all listed in Section 7 along with boiler and fuel characteristics.

Stokers are classified according to the method of feeding fuel to the furnace (Reference 2-17). The four major types are:

- Spreader
- Underfeed
- Chain grate or traveling grate
- Vibrating grate

The type of stoker used in a given application is usually dependent on the type of coal burned and the response time required for load changes. For example underfeed stokers are best equipped to burn caking coals and spreader stokers most easily follow fluctuating loads.

Generally stokers emit lower uncontrolled  $\text{NO}_x$  emissions than pulverized coal-fired boilers. Reported baseline  $\text{NO}_x$  emissions vary from 153 to 336 ng/J (0.356 to 0.781 lb/10<sup>6</sup> Btu) as  $\text{NO}_2$  for spreader stokers, 136 to 163 ng/J (0.317 to 0.379 lb/10<sup>6</sup> Btu) as  $\text{NO}_2$  for underfeed stokers and 100 ng/J to 178 ng/J (0.233 to 0.414 ng/J) as  $\text{NO}_2$  for chain grate stokers (Reference 2-18 through 2-21).

The following subsections summarize the  $\text{NO}_x$  control techniques via combustion modifications for these two major coal-fired industrial boiler types: pulverized coal and stokers.

#### 2.2.1 Applicable Control Techniques for Pulverized Coal-Fired Boilers

Field test data on combustion modifications to reduce  $\text{NO}_x$  emissions from industrial boilers firing pulverized coal are very limited. However, due to the basic similarity in equipment design between the industrial and utility size boilers, applicable combustion modifications established for the smaller utility steam generators are also applicable for the larger industrial size units. Added limitations are present though when implementing these controls on the smaller boilers. These limitations are discussed for each of the control techniques.

Table 2-3 lists the combustion modifications which are applicable to pulverized coal-fired boilers. Combustion modifications for which no actual data exist for the industrial boiler size range have also been included. The effectiveness and limitations of these individual techniques are based on data reported for utility size boilers. The information on the number of industrial size boilers tested clearly shows that the data on control techniques for these units are indeed very



TABLE 2-3. COMBUSTION MODIFICATION NO<sub>x</sub> CONTROLS FOR PULVERIZED COAL-FIRED INDUSTRIAL BOILERS

| Control Technique                 | Description of Technique                                      | Number of Industrial Boilers Tested | Effectiveness of Control (Percent NO <sub>x</sub> Reduction) | Range of Application                                                                           | Commercial Availability/R&D Status                                                | Comments                                                                                                                                    |
|-----------------------------------|---------------------------------------------------------------|-------------------------------------|--------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Low Excess Air (LEA)              | Reduction of combustion air.                                  | 6                                   | 0-25<br>(avg. 8.9)                                           | Excess oxygen reduced to 5.2% on the average                                                   | Available                                                                         | Added benefits of technique include increase in boiler efficiency, limited by increase in CO, HC and smoke emissions.                       |
| Burners Out of Service (BOOS)     | One or more burners on air only. Remainder firing fuel rich.  | 2                                   | 27-39<br>(avg. 33)                                           | Applicable only for boilers with minimum of 4 burners.                                         | Available. However, extensive engineering work necessary prior to implementation. | Limited by the number of burners available. Load reduction required in most cases. Possible increased slagging, corrosion.                  |
| Overfire Air Injection (OFA)      | Secondary air from OFA ports above fuel rich firing burners   |                                     | 5-30                                                         | Burner stoichiometry as low as 100%                                                            | Commercially offered but not demonstrated for industrial size boilers.            | Requires installation of OFA ports, etc. Possible increased slagging, corrosion.                                                            |
| Flue Gas Recirculation            | Recirculation of flue gas to burner windbox                   |                                     | 0-20                                                         | Up to 25% of the flue gas recirculated.                                                        | Not offered because relatively ineffective.                                       | Requires installation of FGR ducts, fan, etc. Can cause combustion instability. Burner windbox may need extensive modifications.            |
| Low NO <sub>x</sub> Burners (LNB) | New burner designed utilizing controlled air-fuel mixing      |                                     | 45-60                                                        | Prototype LNB limited to size ranges above 100 MBtu/hr.                                        | Still in the development stage. Prototype LNB available from major boiler mfrs.   | Active R&D efforts underway.                                                                                                                |
| Ammonia Injection                 | Injection of NH <sub>3</sub> in convective section of boiler. |                                     | 40-60                                                        | Limited by furnace geometry. NH <sub>3</sub> injection rate limited to 1.5 NH <sub>3</sub> /NO | Commercially offered but not demonstrated                                         | Probably best suited as a new design feature than a retrofit application. Possible implementation and operational problems.                 |
| Reduced Load                      | Reduction of fuel and air flow to the boiler.                 |                                     | Varies from 45% reduction to 4% increase in NO <sub>x</sub>  | Applicable to all boilers. Load can be reduced to 25% of capacity.                             | Available now but not implemented because of adverse operational impacts          | Load reduction not effective because of increase in excess O <sub>2</sub> . Best implemented with increase in furnace size for new boilers. |

limited. In fact, the boilers that were tested were only tested for a short period of time (generally <3 hours).

#### 2.2.1.1 Low Excess Air

Reducing the excess air level in the furnace has generally been found to be an effective method for  $\text{NO}_x$  control. In this technique, the combustion air is reduced to the minimum amount required for complete combustion, while maintaining acceptable furnace cleanliness, and steam temperature. With less oxygen available in the flame zone, both thermal and fuel  $\text{NO}_x$  formation are reduced. In addition, the reduced airflow lowers the quantity of flue gas released resulting in an improvement in boiler efficiency.

Low excess air operation is a relatively simple technique to implement. It is applicable to all boiler types and requires only reducing airflow to the burner windbox. However, in a multiburner unit, modifications to the windbox might be necessary to improve air distribution to individual burners during low excess air operation. Lowering excess air reduces the safety margin for complete combustion. Therefore, close monitoring of flue gas  $\text{O}_2$  and CO may be necessary.

Baseline excess oxygen levels for single wall and tangential pulverized coal-fired boilers investigated ranged from 4.5 to 8.6 percent and averaged 6.3 percent (References 2-18 and 2-19). In these boilers excess oxygen was reduced to 5.2 percent lowering  $\text{NO}_x$  emission by 8.6 percent on the average.

The lone cyclone boiler (117 MW,  $400 \times 10^6$  Btu/hr) tested was the least amenable to excess oxygen reduction because of the initial low baseline  $\text{O}_2$  level. The excess oxygen measured 3.4 percent at baseline and was reduced only to 3.1 percent for LEA firing.  $\text{NO}_x$  emissions were reduced 5 percent for this test (References 2-4 and 2-18).

These excess oxygen levels were probably not representative of the actual excess oxygen in the flue gas leaving the furnace. Air infiltration into the boiler ducts for balanced draft boilers can dilute the flue gas and cause oxygen readings to be higher than actual. However, field investigations found that these units were, in general, being fired with more than adequate excess air in order to assume complete combustion and provide a margin of safety.

Combustion with low excess air is a favorite  $\text{NO}_x$  control technique because it not only reduces  $\text{NO}_x$  by 25 ppm on the average for each percent reduction in excess oxygen, but it also increases boiler efficiency and furthermore is relatively easy to implement.

#### 2.2.1.2 Overfire Air Injection (OFA)

The injection of air above the top burner level through OFA ports together with a reduction in air flow to the burners is one of two techniques used to obtain staged combustion in industrial size pulverized coal-fired boilers. The other technique, burners out of service, is discussed below in Section 2.2.1.3.

New utility tangential coal-fired boilers currently come equipped with overfire air ports to help meet 1971 NSPS for  $\text{NO}_x$  emissions. Overfire air ports on wall-fired boilers are not as common as for the tangentially fired units. However, Babcock and Wilcox (B&W) has recently installed two 190 MW ( $650 \times 10^6$  Btu/hr) pulverized coal-fired industrial boilers equipped with OFA ports and compartmented windboxes to limit  $\text{NO}_x$  emissions to 300 ng/J ( $0.7 \text{ lb}/10^6 \text{ Btu}$ ) (References 2-22 and 2-23). In these boilers, 105 percent of the total air requirement is added to the burners, 10 percent through the OFA ports. Automatic controls determine the difference between the total air requirements for the total fuel flow to the furnace and the total air flow to the individual burner compartments. This difference in air flow is then fed through the OFA ports.

The combination of the compartmented windbox and careful airflow control also improves the thermal efficiency of these new B&W units. B&W provides oxygen analyzers on all new coal-fired industrial boilers. Overfire air cannot be implemented on cyclone boilers because the cyclone furnace cannot be fired substoichiometrically.

No detailed OFA test data have been reported for pulverized coal-fired industrial boilers. Therefore the information listed in Table 2-3 reflects results from utility boiler data (Reference 2-24). Overfire air has been very effective in reducing  $\text{NO}_x$  for boilers of this size. In fact, 30 percent reductions have been reported for utility

boilers of the tangential firing type. Potential limitations of the technique include (References 2-25 and 2-26):

- Furnace tube wastage due to local reducing conditions when firing high sulfur coal
- Tendency for slag accumulation in the furnace
- Additional excess air may be required to ensure complete combustion resulting in a decrease in boiler efficiency.

Experience with utility boilers indicates, however, that these potential problems can be overcome with proper implementation of staged combustion (Reference 2-24.)

Overfire air is more attractive in original designs than in retrofit applications. Additional duct work, furnace penetration, and extra fan capacity may be required. In addition, physical obstructions outside of the boiler may make retrofit installation difficult and costly. There may also be insufficient height between the top row of burners and the furnace exit to permit accommodation of overfire air ports and the enlarged combustion zone created by the staged combustion technique (Reference 2-25).

#### 2.2.1.3 Burners Out of Service (BOOS)

Burners out of service is the other technique used to obtain staged combustion in industrial pulverized coal-fired boilers. It is primarily employed as a retrofit  $\text{NO}_x$  control measure for existing utility sized boilers. Ideally, all of the fuel flow is diverted from a selected number of burners to the remaining firing burners. Since airflow is maintained relatively unchanged among all burners a staged combustion effect is obtained. For the technique to be significantly effective the top burners must be set on air only. The technique, however, has several limitations for pulverized coal-fired boilers. These limitations can be summarized as follows:

1. Individual burners cannot be shut off because coal flow must be terminated at a pulverizer. Since each pulverizer serves a minimum of two burners, at least two burners must be removed from service.
2. Indiscriminate selection of burners out of service is often not possible because pulverizers may serve burners located on two separate levels

3. In many cases burners/pulverizers which operate during BOOS cannot handle increased coal flow necessitating a significant reduction in the boiler steam rating
4. Register adjustments are often necessary to divert some airflow from top burners to lower burners. If satisfactory staging conditions cannot be obtained simply by adjusting burner registers, a compartmental windbox becomes necessary.

These limitations were clearly evident in the tests conducted on one pulverized coal-fired industrial size boiler (76 MW heat input) equipped with 4 burners in square matrix (Reference 2-20). To implement the BOOS technique the pulverizer serving the top two burners was shut off necessitating a 50 percent reduction in boiler load. In addition, airflow could not be easily controlled to individual burners so that burner swirl and coal air mixing were affected. The resultant  $\text{NO}_x$  reduction was 39 percent.

From this experience, it is evident that to implement the BOOS technique with this burner pattern and the number of available burners necessitates a reduction in the capacity of the boiler by up to 50 percent. It is expected that this will often be the case for industrial boilers because of the limited number of burners and pulverizers.

Since a reduction in boiler load is not desirable and often not feasible, BOOS is not always a viable technique. A potential alternative involves the installation of overfire air ports above existing burners if there is space for the overfire air ports (already discussed in Section 2.2.1.2).

#### 2.2.1.4 Low $\text{NO}_x$ Burners (LNB)

Prototype low  $\text{NO}_x$  pulverized coal-fired burners have been developed primarily for reducing  $\text{NO}_x$  emissions from utility boilers. Their principal characteristics are reduced flame turbulence, delayed fuel air mixing, and establishment of fuel-rich zones where combustion initially takes place (Reference 2-24). Prototype dual register burners developed by Babcock and Wilcox (B&W) (References 2-27 and 2-28) and the dual throat burners developed by Foster Wheeler (FW) (References 2-29 and 2-30) are being installed in new utility size coal-fired boilers. This technology applies only to wall-fired boilers.  $\text{NO}_x$  reductions reported

in Table 2-3 are based on results from B&W and FW utility application testing because no industrial size low  $\text{NO}_x$  coal burner has yet been developed.

Energy and Environmental Research Corporation (EER), under a research contract to EPA, is developing advanced low  $\text{NO}_x$  burner concepts such as distributed fuel/air mixing, as illustrated in Figure 2-3 (References 2-31 and 2-32). Field evaluation programs, also sponsored by EPA, involving several manufacturers and R&D groups, are being planned (Reference 2-79).

A low  $\text{NO}_x$  burner for industrial boiler application is under commercial development by Peabody Engineering Corporation. Peabody is constructing a variation of a standard dual register type burner. The  $50 \times 10^6$  Btu/hr burner may become one of several burners to be tested in an EPA test program. Basically, the burner is designed to reduce the air in the primary combustion zone. The resultant reduced flame temperatures also serve to lower  $\text{NO}_x$  emissions. Once completed, the burner presumably will not be restricted in size range and may be suitable for many pulverized coal facilities (Reference 2-33).

In some applications low  $\text{NO}_x$  burners may have several advantages over other combustion modifications such as staged combustion with OFA or BOOS. For example, one utility boiler manufacturer claims that low  $\text{NO}_x$  burners will maintain the furnace in an oxidizing environment, hence, minimizing slagging and reducing the potential for furnace corrosion when firing high sulfur coal (Reference 2-27). Also, more complete carbon utilization may be achieved due to better coal/air mixing in the furnace. Finally, lower oxygen levels may be obtained with all the combustion air admitted through the burners (Reference 2-24).

Since the burners generally alter the flame configuration, care must be taken when applying the burners to existing boilers. For instance, the dual register coal burners have a longer flame length. The burner can be installed only in those boilers which are large enough to avoid cold wall impingement.

It is estimated that low  $\text{NO}_x$  burners will not be fully commercialized for the utility boilers for two more years. Its application for industrial size pulverized coal-fired steam generators is also a few years away.

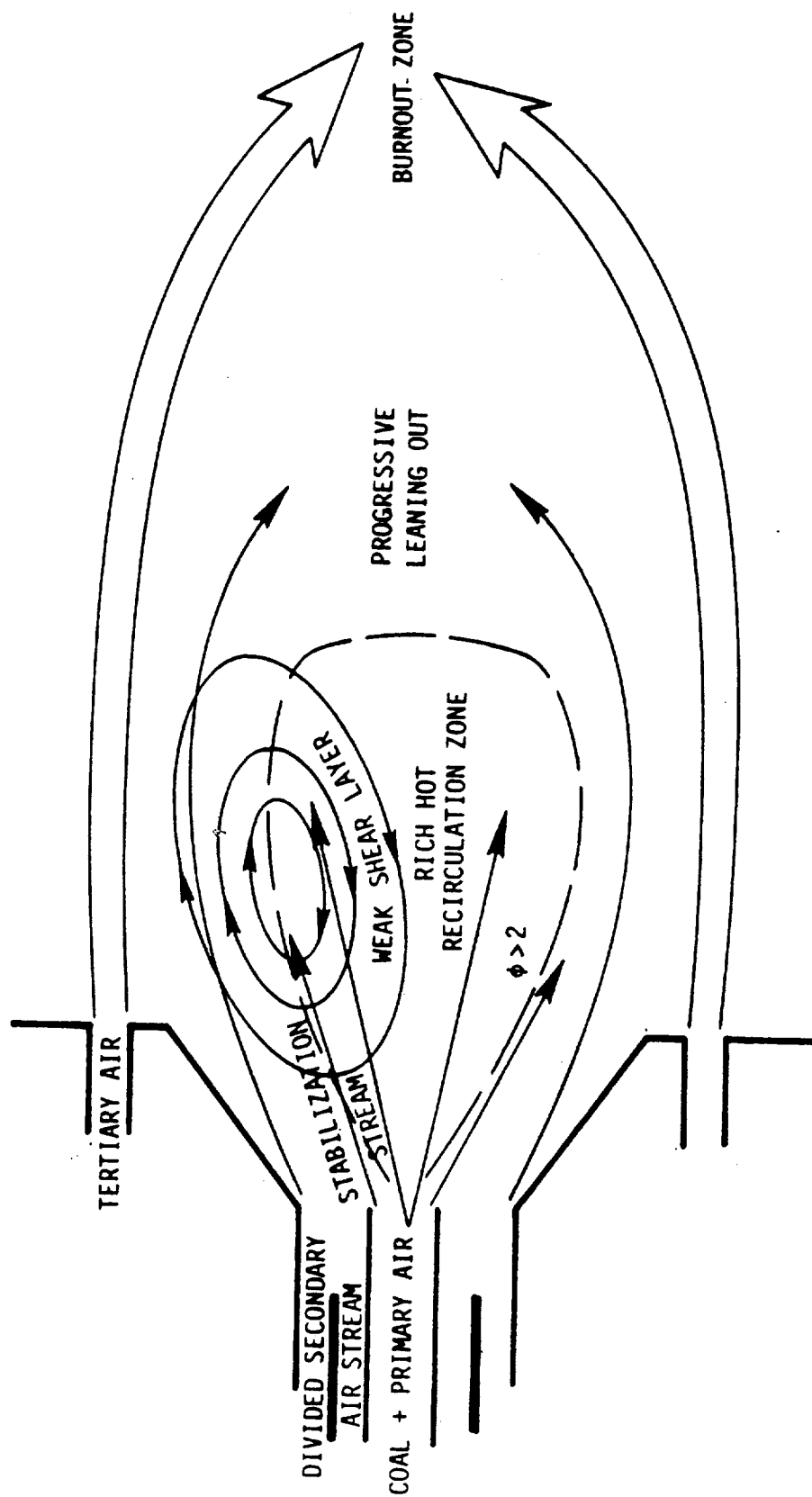


Figure 2-3. Distributed fuel/air mixing concept (Reference 2-31).

#### 2.2.1.5 Flue Gas Recirculation (FGR)

Flue gas recirculation for  $\text{NO}_x$  control consists of extracting a portion of the flue gas from the economizer outlet and returning it to the furnace, admitting the flue gas through the burner windbox. Figure 2-4 shows a schematic of a typical FGR installation. Flue gas recirculation lowers the bulk furnace gas temperature and reduces oxygen concentration in the combustion zone (Reference 2-24).

Flue gas recirculation through the windbox and, to a lesser degree, through the furnace hopper has been found to be very effective for  $\text{NO}_x$  control on gas- and oil-fired utility boilers (References 2-26 and 2-34). However, the technique was relatively ineffective on coal-fired units because FGR mainly affects thermal  $\text{NO}_x$ , not fuel  $\text{NO}_x$  (Reference 2-35). Table 2-3 gives performance data on FGR with low excess air (LEA) on opposed wall coal-fired utility boiler. These data show that for this boiler, combined flue gas recirculation and low excess air can only reduce  $\text{NO}_x$  emissions by 20 percent (Reference 2-35). Similar results have been reported elsewhere (Reference 2-10). The technique of low excess air alone can often achieve similar reductions, as discussed earlier.

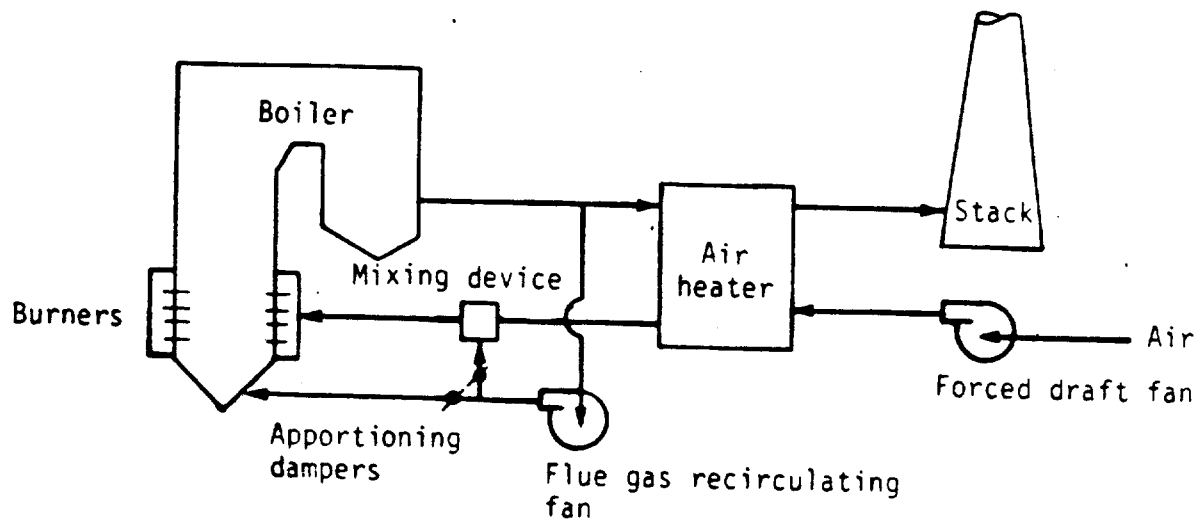


Figure 2-4. Typical flue gas recirculation system for  $\text{NO}_x$  control.



TABLE B-5. REPRESENTATIVE UTILITY BAGHOUSE  
COST ACCOUNTS  
(\$10<sup>3</sup>, 1978)

| Coal type<br>Boiler size (MWe)<br>(10 <sup>6</sup> Btu/hr) | Eastern<br>500<br>(4690) | Western<br>500<br>(4506) |
|------------------------------------------------------------|--------------------------|--------------------------|
| Air-to-cloth ratio<br>m/min                                | 0.55                     | 0.55                     |
| Gas Flow, 10 <sup>3</sup> m <sup>3</sup> /min (actual)     | 45.72                    | 45.42                    |
| Collector and supports                                     | 5,109                    | 5,103                    |
| Ducting and supports                                       | 714                      | 714                      |
| Ash handling equipment                                     | 478                      | 477                      |
| Insulation                                                 | 1,339                    | 1,337                    |
| Other field costs                                          | 3,515                    | 3,515                    |
| Total field                                                | 11,155                   | 11,146                   |
| Engineering, miscellaneous and<br>contingency              | 1,450                    | 1,448                    |
| Capital investment (CI)                                    | 12,600                   | 12,590                   |
| Annual O&M                                                 | 374                      | 373                      |
| Capital recovery factor                                    | 0.1175                   | 0.1175                   |
| Annualized cost                                            | 1,860                    | 1,852                    |

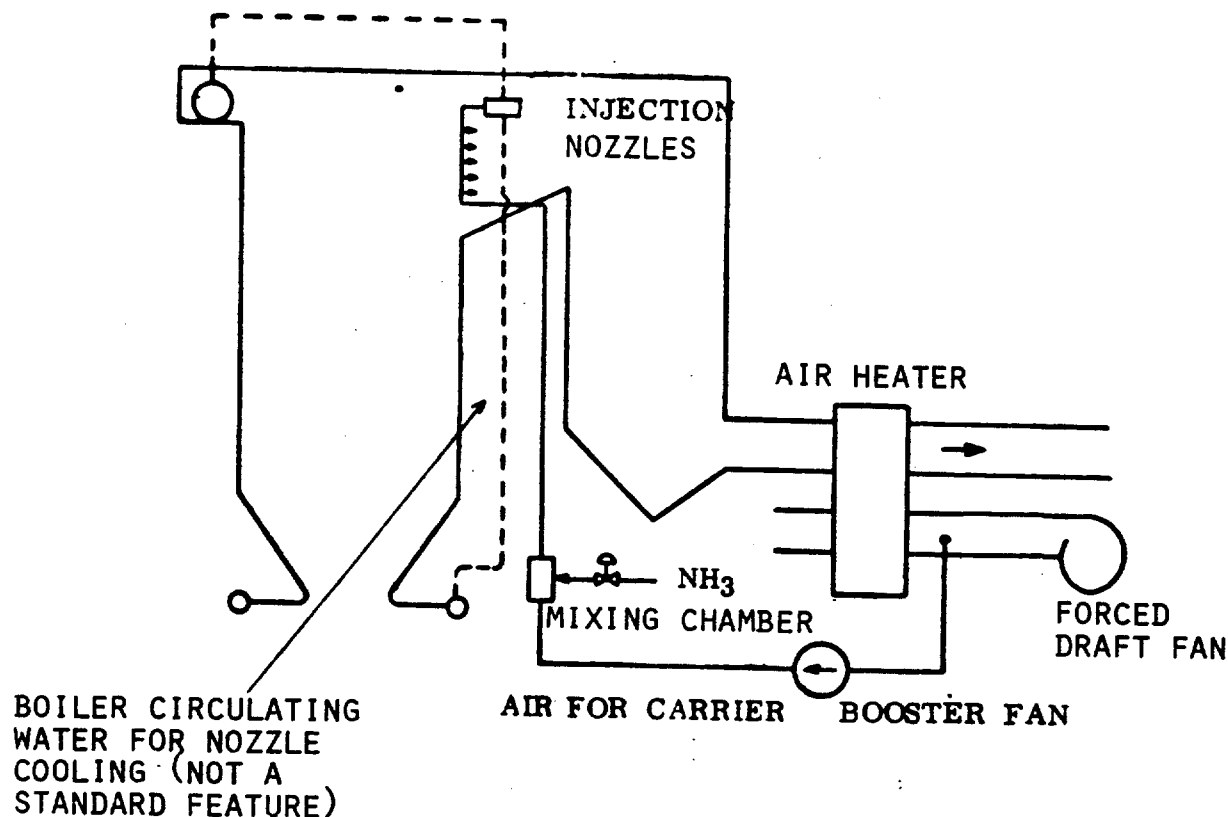


Figure 2-5. Schematic diagram of the NH<sub>3</sub> injection system (Reference 2-38).

approximately 1070 to 1290K (1470 to 1856°F). However, optimal NO reduction occurs over a very narrow temperature range, around  $1240 \pm 50\text{K}$  ( $1770 \pm 90^\circ\text{F}$ ).

The NO<sub>x</sub> reduction effectiveness reported in Table 2-3 reflects results from full-scale application of the ammonia injection process in gas- and oil-fired industrial boilers in Japan (Reference 2-39). No full-scale retrofit on a coal-fired unit has been accomplished so far. However, in subscale tests it was found that the flue gas environment from coal combustion does not markedly affect the effectiveness of the process any more than that relative to gas and oil combustion products (Reference 2-40).

Ammonia injection has numerous limitations which have so far prevented its full-scale commercialization as a NO<sub>x</sub> reduction technique

on coal-fired boilers. These limitations can be summarized as follows: (References 2-37, 2-39 and 2-41).

- Performance is very sensitive to flue gas temperature, and is maximized only within a 50K temperature gradient from the optimum temperature of about 1240K. This temperature sensitivity may require special procedures for load following boilers.
- Performance is very sensitive to flue gas residence time at optimum temperatures. High flue gas quench rates are expected to reduce process performance.
- Costs of the process can be much higher than for other combustion controls
- Successful retrofit application is highly dependent on the geometry of convective section
- Byproduct emissions such as ammonium bisulfate might cause operational problems, especially in coal-fired boilers

Although  $\text{NH}_3$  injection is currently being commercially offered, it is not demonstrated technology. Therefore, it should be considered to be still at the development stage (Reference 2-76). This technique might prove to be, however, the only alternative in controlling  $\text{NO}_x$  emission from cyclone-fired boilers which are not amenable to other combustion modifications. Therefore, its use can potentially achieve  $\text{NO}_x$  emission levels which would otherwise not be obtainable with current state-of-the-art controls (Reference 2-39).

#### 2.2.1.7 Load Reduction

Thermal  $\text{NO}_x$  formation generally increases as the volumetric heat release rate or combustion intensity increases (Reference 2-10). Reduced combustion intensity can be brought about by load reduction, or derating, in existing units and by use of an enlarged firebox in new units.

However, during field tests on industrial boilers burning pulverized coal,  $\text{NO}_x$  emissions were found to increase in some instances when these boilers were operated below 60 percent of capacity (Reference 2-20). A load reduction of approximately 30 percent from the baseline rating of 80 percent capacity increased  $\text{NO}_x$  emissions from three boilers by 13 percent on the average. The reduced heat input was accompanied in all cases by an increase in excess oxygen averaging 0.7 percent. One

cyclone units, however, showed a drop in  $\text{NO}_x$  emissions by 6 percent for a load reduction of 25 percent (Reference 2-4). Thus, it seems that in many cases any beneficial effects resulting from load reduction were offset by the increase in excess air required at the reduced load.

Reduced firing rate often leads to several operating problems. Aside from the limiting of capacity, low load operation usually requires higher levels of excess air to maintain steam temperature and to control smoke and CO emissions. The steam temperature control range is also reduced substantially for those industrial boilers producing superheated steam. This will reduce the operating flexibility of the unit and its response to changes in load. The combined results are reduced operating efficiency due to higher excess air and reduced load following capability due to a reduction in control range (Reference 2-10).

When the unit is designed for a reduced heat release rate, the problems associated with derating are largely avoided. The use of an enlarged firebox produces  $\text{NO}_x$  reductions similar to load reduction on existing units. This technique of larger firebox has been implemented on new coal-fired utility boilers since about 1970 (Reference 2-24). Generally, the size of these fireboxes has increased 30 percent partly in response to 1971 NSPS for utility boilers and partly to facilitate combustion of lower grade coals (Reference 2-42). Therefore, the technique can also be considered available for large industrial size pulverized coal-fired boilers. Babcock and Wilcox (B&W) is currently considering power furnace loading as one of several techniques for reducing  $\text{NO}_x$  emissions from their industrial boilers (Reference 2-43).

#### 2.2.2 Applicable Control Techniques for Stokers

$\text{NO}_x$  emissions from stokers are significantly lower than those from pulverized coal. These lower emissions have been attributed to the lower combustion intensity and to the partial staged combustion that naturally occurs during combustion on fuel beds (Reference 2-17).

Four methods have been used to modify the combustion of a stoker in order to reduce  $\text{NO}_x$  emissions. These methods are (1) reduced undergrate air or low excess air, (2) overfire air, (3) reduced air preheat, and (4) reduced heat input (References 2-4, 2-18, 2-19 and 2-21). Ammonia injection is potentially applicable although it has not yet been demonstrated on an industrial stoker. The boiler geometry and the flue

gas temperature profile in a stoker should permit the implementation of the  $\text{NH}_3$  injection process in a similar manner as for a pulverized coal-fired unit. Table 2-4 lists information on the performance and limitation of each of these techniques.

The information is based on limited data. A search for additional data from boiler manufacturers and researchers has not revealed any other applicable combustion modification for  $\text{NO}_x$  control for stokers (References 2-44 through 2-48).

#### 2.2.2.1 Low Excess Air (LEA)

Figure 2-6 is a schematic of a spreader stoker furnace showing where combustion air is introduced in this type of boiler. Overfire air is generally controlled independently from undergrate air. Low excess air tests performed in the field consisted of reducing the undergrate airflow while maintaining the OFA flow approximately as in normal operation.

Recently EPA field tests of 17 stokers indicate that the excess oxygen levels at baseline operating conditions averaged about 9 percent (References 2-4, 2-18 through 2-21). During low excess air tests, the average excess oxygen level was reduced to 6.4 percent. Such reduction lowered  $\text{NO}_x$  emission levels approximately 10 percent for each 1 percent reduction in excess oxygen (Reference 2-4, 2-20, 2-21, 2-48, and 2-49).

The minimum achievable excess air is limited by several factors. Except for the water-cooled vibrating grate, the only cooling of the grate is by the flow of air past it. If this air is cut back too much, the grate can overheat. There is also the danger of creating local reducing zones as the air is cut back and forming harmful corrosion products. Another problem noticed during field tests has been the formation of clinkers as the excess oxygen was reduced, the CO emissions tend to rise. However, test results indicate that if excess oxygen levels are maintained above 5 percent, CO emissions will tend to stay below 150 ppm (Reference 2-18, 2-20 2-21 and 2-49). Limited data show CO emissions for underfeed stokers to be less sensitive to excess air levels than for spreader stokers (References 2-4, 2-18 and 2-20).

Fuel combustion with lowest possible levels of excess air assures maximum boiler efficiency unless the air is decreased to the point where unburned carbon losses are greatly increased. From the limited amount of data it can be tentatively generalized that if the airflow is maintained

TABLE 2-4. COMBUSTION MODIFICATION NO<sub>x</sub> CONTROLS FOR STOKER COAL-FIRED INDUSTRIAL BOILERS

| Control Technique             | Description of Technique                                              | Number of Industrial Boilers Tested | Effectiveness of Control (Percent NO <sub>x</sub> Reduction)                       | Range of Application                                                                                    | Commercial Availability/R&D Status                                                                 | Comments                                                                                                                                                                                                                                        |
|-------------------------------|-----------------------------------------------------------------------|-------------------------------------|------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Low Excess Air (LEA)          | Reduction of air flow under stoker bed.                               | 15                                  | 5-25                                                                               | Excess O <sub>2</sub> limited to 5-6% minimum                                                           | Available now but need R&D on lower limit of excess air.                                           | Danger of overheating grate, clinker formation, corrosion, and high CO emissions.                                                                                                                                                               |
| Staged Combustion (LEA + OFA) | Reduction of under grate air flow and increase of over-fire air flow. | 5                                   | 5-25                                                                               | Excess O <sub>2</sub> limited 5% minimum.                                                               | Most stokers have OFA ports as smoke control devices but may need better air flow control devices. | Need research to determine optimal location and orientation of OFA ports for NO <sub>x</sub> emission control. Overheating grate, corrosion and high CO emission can occur if under grate air flow is reduced below acceptable level as in LEA. |
| Reduced Load                  | Reduction of coal and air feed to the stoker.                         | 13                                  | Varies from 49% decrease to 25% increase in NO <sub>x</sub> (average 15% decrease) | Has been used down to 25% load.                                                                         | Available                                                                                          | Only for stokers that can reduce load without increasing excess air. Not a desirable technique because of loss in boiler efficiency.                                                                                                            |
| Reduced Air Preheat (RAP)     | Reduction of combustion air temperature                               | 1                                   | 8                                                                                  | Combustion air temperature reduced from 473K to 453K.                                                   | Available now if boiler has combustion air heater.                                                 | Not a desirable technique because of loss in boiler efficiency.                                                                                                                                                                                 |
| Ammonia Injection             | Injection of NH <sub>3</sub> in convective section of boiler.         |                                     | 40-60 (from gas-and oil-fired boiler experience).                                  | Limited by furnace geometry. Feasible NH <sub>3</sub> injection rate limited to 1.5 NH <sub>3</sub> /NO | Not available. Needs investigation of full scale application.                                      | Probably best suited as a new design feature than a retrofit application. Possible implementation and operational problems                                                                                                                      |

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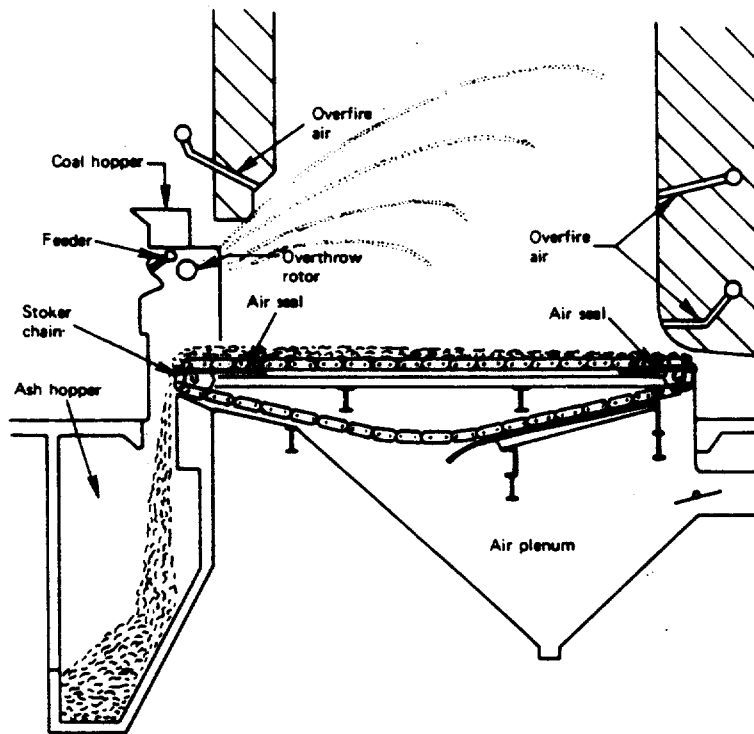


Figure 2-6. Air injection in a traveling-grade spreader stoker (Reference 2-17).

such that the excess oxygen level measures approximately 6 percent, no serious optional or emission problem should result. Of course, this generalization would require verification. Indeed, the minimum excess oxygen level for a particular boiler could be higher than 6 percent.  $\text{NO}_x$  emission reductions of about 5-25 percent and increases in boiler efficiency of one percent can be expected with LEA provided fuel burnout does not change during the process (References 2-4 and 2-20).

Research and developmental work on redesigning the grate and stoker would be necessary if lower excess oxygen levels are required. In addition a solution to the clinker formation problem will also be needed for this type of operation.

#### 2.2.2.2 Staged Combustion

One of the reasons  $\text{NO}_x$  emission from stokers is lower than those from pulverized coal-fired boilers is the partial staged combustion nature of combustion of fuel beds (Reference 2-50). Volatile matter leaves the

fuel bed as the coal is fed into the grate and burns above the bed level. The solids are subsequently burned with lower combustion intensity.

An increased staged combustion effect beyond what seems to occur naturally in the stoker furnace seems difficult to obtain. However, augmented staged combustion control can be effected by injecting air above the fuel bed through the overfire air ports (OFA) and reducing the undergrate airflow.

Figure 2-6 shows the relative location of these airflows. A reduction of 10 to 25 percent in  $\text{NO}_x$  has been achieved by this method without increasing CO emission (References 2-4, 2-18, 2-20 and 2-49). Most stokers have OFA ports as smoke control devices. Therefore, the location or orientation of the OFA ports may not be the optimum in order to achieve best  $\text{NO}_x$  reductions. For example, one test showed a 25 percent reduction in  $\text{NO}_x$  emissions by using two oil burners as overfire air ports (Reference 2-4). However, these burner ports were located far above the existing stoker OFA ports. Other OFA tests, using only the existing OFA ports located closer to the fuel bed rather than the burner ports, lowered  $\text{NO}_x$  emission only 10 percent.

This method suffers from the same disadvantages of LEA because reduced undergrate airflow is absolutely necessary to achieve any staging effect. Therefore limitations applicable to the technique of LEA such as grate overheating, corrosion, and clinker formation can also limit the application of the staged combustion technique.

#### 2.2.2.3 Reduced Load

Underfeed stokers tend to produce lower  $\text{NO}_x$  emissions than spreader stokers. One reason has been attributed to the fact that underfeed stokers generally have larger fireboxes and consequently lower volumetric and surface heat release rates (References 2-4 and 2-20). Reducing the boiler load will lower the volumetric and surface heat release rate; therefore it is equivalent to having a larger firebox. One test on a spreader stoker shows a 10 percent reduction in  $\text{NO}_x$  emission by reducing the load from 70 to 60 percent of maximum continuous rating (References 2-18 and 2-20). On most other tests as the load was reduced, the excess air had to be increased, causing a net rise in  $\text{NO}_x$  emissions. These results suggest that the technique will be effective in



reducing  $\text{NO}_x$  emissions only if the excess air can be maintained at the original level measured during the higher load condition.

The technique, although an applicable one, has numerous possible disadvantages. These include derating of the boiler and loss in boiler efficiency as a consequence of the requirements to increase the excess air level (Reference 2-20).

#### 2.2.2.4 Reduced Air Preheat (RAP)

There is only limited data on reduced air preheat applied to industrial stokers. Based on tests on only one boiler, a small reduction of the combustion air temperature from approximately 366 to 355K (200°F to 180°F) reduced  $\text{NO}_x$  emissions by an average of 8 percent (References 2-18 and 2-20). Some researchers claim that the coal bed preheats the air before the combustion occurs and thus defeats the purpose of the method (Reference 2-50). This technique is of course limited to stokers equipped with combustion air preheaters. Only larger ( $>29$  MW,  $100 \times 10^6$  Btu/hr) stokers tend to have air preheaters. In addition, significant losses in boiler efficiencies will occur if flue gas temperatures leaving the stack are increased as a consequence of bypassing air preheaters. Economizers could be added to avoid efficiency losses.

#### 2.2.2.5 Ammonia Injection

Ammonia injection should be applicable to stoker boilers as well as pulverized coal-fired units. However, the geometry of the ducting in the convective section is crucial. The ammonia injection ports must be located in that portion of the furnace where the flue gas temperature ranges from 1070 to 1290K (1470 to 1860°F).

The information on ammonia injection listed in Table 2-4 is the same as that in Table 2-3. The performance of the ammonia injection process has not been investigated on stokers; therefore the potential  $\text{NO}_x$  reductions listed in Table 2-4 are based on reported results on gas- and oil-fired industrial boilers (References 2-39).

### 2.3 OIL-FIRED BOILERS

Oil-fired industrial boilers fall into two major categories: firetube and watertube. Firetube boilers can be further divided into Scotch, horizontal return, tubular and firebox designs. Watertube boilers are identified as either packaged or field-erected units. Packaged boilers, both watertube and firetube, are usually equipped with a single

burner. Field-erected units are usually equipped with an array of burners and are generally of larger capacity than the packaged units.

Oil-fired firetube boilers are designed with a maximum of 9 MW heat input ( $30 \times 10^6$  Btu/hr). These boilers account for 7.2 percent of the total industrial boiler population (Reference 2-2). Industrial watertube boilers can be as large as utility boilers, however the packaged watertube units are usually limited to 73 MW ( $250 \times 10^6$  Btu/hr) of heat input (Reference 2-51). Oil-fired watertube boilers account for 35.3 percent of total industrial boiler population -- 8.7 percent are packaged units and 26.6 percent are field-erected boilers (Reference 2-2).

Table 2-5 lists the baseline  $\text{NO}_x$  emissions from oil-fired industrial boilers measured during an EPA test program (Reference 2-4 and 2-20). Regardless of the boiler type, it is evident that boilers burning residual oil produce more  $\text{NO}_x$  emissions than the ones firing distillate oil. Also for any particular class of boilers the range of  $\text{NO}_x$  emissions for residual oil is often wider than the range of emissions for distillate oil. The larger amount and variation of fuel nitrogen in the residual oil accounts for both these observations. Fuel analyses performed as a part of this test program showed that residual oil generally contained 0.10 to 1.0 percent fuel nitrogen while distillate oil contains less than 0.05 percent on the average (Reference 2-20).

Combustion modification  $\text{NO}_x$  control techniques for oil-fired boiler are as follows:

- Low excess air (LEA)
- Staged combustion air (SCA)
- Burners out of service (BOOS)
- Flue gas recirculation (FGR)
- Reduced air preheat (RAP)
- Load reduction (LR)
- Low  $\text{NO}_x$  burners (LNB)
- Ammonia injection

These techniques can be applied singly or in appropriate combination, especially for ammonia injection which can be implemented with any other combustion modification. Also, the BOOS technique can only be applied to multiburner units and is usually confined to retrofit applications.

Table 2-6 summarizes the information on the performance, applicability and

TABLE 2-5. NO<sub>x</sub> EMISSIONS AT BASELINE AND AT LOW EXCESS AIR FROM OIL-FIRED INDUSTRIAL BOILERS (REFERENCES 2-4, 2-20, 2-52 AND 2-53)

| Equipment Type            | No. Boilers Tested | Residual Oil     |                                             |                                                   |                  |                              |
|---------------------------|--------------------|------------------|---------------------------------------------|---------------------------------------------------|------------------|------------------------------|
|                           |                    | Baseline         |                                             |                                                   | Low Excess Air   |                              |
|                           |                    | O <sub>2</sub> % | NO <sub>x</sub> Emissions ng/J <sup>a</sup> | NO <sub>x</sub> Emissions lb/10 <sup>6</sup> Btua | O <sub>2</sub> % | NO <sub>x</sub> Reductions % |
| Firetube                  | 5                  | 5.2              | 95.5 - 170<br>(115.0)                       | 0.222 - 0.395<br>(0.275)                          | 3.2              | 7                            |
| Watertube W/O Air Preheat | 9                  | 5.9              | 87.5 - 362<br>(190)                         | 0.203 - 0.843<br>(0.442)                          | 4.0              | 13                           |
| Watertube W/ Air Preheat  | 8                  | 5.8              | 66.8 - 188<br>(134)                         | 0.155 - 0.438<br>(0.312)                          | 4.6              | 12                           |
| All Boiler Types          | 22                 | 5.7              | 66.8 - 362<br>(155)                         | 0.155 - 0.843<br>(0.360)                          | 4.0              | 11                           |

| Equipment Type            | No. Boilers Tested | Distillate Oil   |                                             |                                                   |                  |                              |
|---------------------------|--------------------|------------------|---------------------------------------------|---------------------------------------------------|------------------|------------------------------|
|                           |                    | Baseline         |                                             |                                                   | Low Excess Air   |                              |
|                           |                    | O <sub>2</sub> % | NO <sub>x</sub> Emissions ng/J <sup>a</sup> | NO <sub>x</sub> Emissions lb/10 <sup>6</sup> Btua | O <sub>2</sub> % | NO <sub>x</sub> Reductions % |
| Firetube                  | 2                  | 5.4              | 96.5 - 107<br>(102)                         | 0.224 - 0.248<br>(0.236)                          | 3.2              | 18                           |
| Watertube W/O Air Preheat | 3                  | 5.5              | 44.7 - 59.5<br>(51.8)                       | 0.103 - 0.138<br>(0.120)                          | 3.2              | 6                            |
| Watertube W/ Air Preheat  | 2                  | 5.4              | 69.0 - 102<br>(86.5)                        | 0.160 - 0.237<br>(0.199)                          | 4.5              | 12                           |
| All Boiler Types          | 7                  | 5.8              | 44.7 - 107<br>(72.6)                        | 0.104 - 0.248<br>(0.169)                          | 3.7              | 11                           |

<sup>a</sup>NO<sub>x</sub> emissions are given as a range, with the average in parentheses.

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TABLE 2-6. COMBUSTION MODIFICATION NO<sub>x</sub> CONTROLS FOR OIL-FIRED INDUSTRIAL BOILERS

| Control Technique                             | Description of Technique                                     | No. of Boilers Tested                             | Effectiveness of Control (Percent NO <sub>x</sub> Reduction)        |                                                                     | Range of Application                                                                                                                                 | Availability/<br>R&D Status                                                                                           | Comments                                                                                                   |
|-----------------------------------------------|--------------------------------------------------------------|---------------------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
|                                               |                                                              |                                                   | Residual                                                            | Distillate Oil                                                      |                                                                                                                                                      |                                                                                                                       |                                                                                                            |
| Low Excess Air (LEA)                          | Reduction of combustion air                                  | 22 residual oil boilers, 7 distillate oil boilers | 0 to 28<br>11 average<br>or 10 ng/J/<br>% O <sub>2</sub> reduction. | 0 to 24<br>11 average<br>or 10 ng/J/<br>% O <sub>2</sub> reduction. | Generally excess O <sub>2</sub> can be reduced to 2.5% representing a 3% drop from baseline.                                                         | Available.                                                                                                            | Added benefits included increase in boiler efficiency. Limited by increase in CO, HC, and smoke emissions. |
| Staged Combustion Air                         | Fuel rich firing burners with secondary combustion air ports | 3 residual boilers, 1 distillate oil boilers      | 20-50                                                               | 17-44                                                               | 70-90% burner stoichiometries can be used with proper installation of secondary air ports                                                            | Technique is applicable on packaged and field-erected units. However, not commercially available for all design types | Best implemented on new units. Retrofit is probably not feasible for most units especially packaged ones.  |
| Burners Out of Service (BOOS)                 | One or more burners on air only. Remainder firing fuel rich. | 8 boilers                                         | 10 to 30                                                            | N/A                                                                 | Applicable only for boilers with minimum of 4 burners. Best suited for square burner pattern with top burner as BOOS. Only for retrofit application. | Available. Retrofit requires careful selection of BOOS pattern and control of air flow.                               | Retrofit often requires boiler derating unless fuel delivery system is modified.                           |
| Flue Gas Recirculation (FGR)                  | Recirculation of portion of flue gas to burners              | One distillate oil boilers. Two residual boilers. | 15 - 30                                                             | 58 to 73                                                            | Up to 25-30% of flue gas recycled. Can be implemented on all design types.                                                                           | Available. Requires extensive modifications to the burner and windbox.                                                | Best suited for new units. Costly to retrofit. Possible flame instability at high FGR rates.               |
| Flue Gas Recirculation plus staged combustion | Combined techniques of FGR and staged combustion             | Only one package watertube                        | 25 to 53                                                            | 73 to 77                                                            | Max. FGR rates set at 25% for distillate oil and 20% for residual oil.                                                                               | Combined techniques are still at experimental stage. Needs more R&D feasible only for new units.                      | Retrofit may not be feasible. Best implemented on new units                                                |

Continued

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TABLE 2-6. CONCLUDED

| Control Technique                 | Description of Technique                                                           | No. of Boilers Tested                                         | Effectiveness of Control (Percent NO <sub>x</sub> Reduction) |                                                 | Range of Application                                                                                 | Availability/ R&D Status                                                                  | Comments                                                                                                                                                                                      |
|-----------------------------------|------------------------------------------------------------------------------------|---------------------------------------------------------------|--------------------------------------------------------------|-------------------------------------------------|------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                   |                                                                                    |                                                               | Residual                                                     | Distillate Oil                                  |                                                                                                      |                                                                                           |                                                                                                                                                                                               |
| Load Reduction (LR)               | Reduction of air and fuel flow to all burners in service                           | 17 residual oil-fired boilers, 7 distillate oil-fired boilers | 33% decrease to 25% increase in NO <sub>x</sub>              | 31% decrease to 17% increase in NO <sub>x</sub> | Applicable to all boiler types and sizes. Load can be reduced to 25% of maximum                      | Available now as a retrofit application. Better implemented with improved fire-box design | Technique not effective when it necessitates an increase in excess O <sub>2</sub> levels, LR possible implemented in new designs as reduced combustion intensity (enlarged furnace plan area) |
| Low NO <sub>x</sub> Burners (LNB) | New burner designs with controlled air/fuel mixing and increased heat dissipation. | Large number tested in Japan                                  | 20-50%                                                       | 20-50%                                          | New burners described generally applicable to all boilers. More specific information needed.         | Commercially offered but not demonstrated                                                 | Specific emissions data from industrial boilers equipped with LNB are lacking                                                                                                                 |
| Ammonia Injection                 | Injection of NH <sub>3</sub> as a reducing agent in the flue gas.                  | 5 (4 Japanese installations, 1 domestic)                      | 40-70%                                                       | 40-70%                                          | Applicable for large package and field-erected watertube boilers. Not feasible for firetube boilers. | Commercially offered but not demonstrated                                                 | Some increased maintenance of air heater/economizer parts might be necessary when burning high sulfur oil. Technique is very costly.                                                          |
| Reduced Air Preheat (RAP)         | Bypass of combustion air preheater                                                 | 2 residual oil-fired boilers                                  | 5-16%                                                        | --                                              | Combustion air temp. can be reduced to ambient conditions (340K)                                     | Available. Not implemented because of significant loss in thermal efficiency.             | Application of this technique on new boilers necessitated installation of heat recovery systems in the flue gas                                                                               |

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availability of these techniques for oil-fired industrial boilers. The following subsections high-light the major points of interest for each of the controls considered.

### 2.3.1 Low Excess Air (LEA)

Low excess air, as for coal-fired boilers, is an effective means of achieving reductions in  $\text{NO}_x$  with increased boiler efficiency for oil-fired units. The technique is applicable to all oil-fired industrial boilers and is easy to implement both in a retrofit case and in new boilers.

Firetube and small watertube industrial boilers are generally equipped with constant speed forced draft fans which supply air to the windbox. Air control is achieved by adjusting the vanes at the inlet to the fan. A reduction in air flow to the burner(s) is achieved by closing these vanes. The reduced air-fuel ratio lowers the excess air level in the furnace. Large oil-fired multiburner watertube boilers are equipped with variable speed forced draft and induced fans which can be controlled to vary the amount of air flow to the boiler. However, these units will probably require the use of compartmental windboxes in addition to fan control for even distribution of air flow to each burner.

Table 2-5 summarizes the performance of the LEA technique on specific industrial boiler equipment types burning fuel oil. In general, the data show that LEA is equally effective for residual and distillate oil-fired boilers.  $\text{NO}_x$  was reduced by approximately 11 percent for both fuels. The data also show that for residual oil-fired boilers LEA is slightly more effective when applied on watertube than on firetube units. The reverse is true for distillate oil-fired boilers. However, the data base is not sufficiently large to verify the significance of these trends.

Reducing the excess oxygen in the flue gas by decreasing the air flow to the burner can lead to a rapid increase in  $\text{CO}$ , hydrocarbon and smoke emissions. However, the field test data for many boilers has shown that as long as the excess  $\text{O}_2$  is maintained above 3.0 percent these emissions were not increased (Reference 2-18).

In addition to reducing  $\text{NO}_x$  emissions the technique of LEA is cost effective because it increases boiler efficiency. In fact, the thermal efficiency of all oil-fired units tested increased 0.7 percent on the average with LEA combustion (Reference 2-20).

Application of low excess air combustion requires not only means of adjusting air flow at various boiler loads, but also installation of flue gas  $O_2$  and CO monitors. Attempts to adjust for LEA without controls may lead to a loss rather than a gain in efficiency. Alarms should also be installed to provide a safety system in case the air flow to the boiler is inadequate.

Low excess air combustion should be considered a standard operating practice for industrial boilers. In fact, because of the increased fuel efficiency the technique is often implemented strictly as a fuel economy device.

### 2.3.2 Staged Combustion

The concept of staged combustion consists of injecting secondary air downstream of a first stage combustion zone which is characterized by substoichiometric levels of combustion air. Stage combustion can be effected by use of secondary air ports/injectors or by burners out of service. Which of these techniques can be implemented on oil-fired boilers will depend on the type of furnace design.

The diversity of air injection systems designs applicable to oil-fired industrial boilers warrants a separate discussion for each of the major equipment design types previously identified.

#### 2.3.2.1 Firetube Boilers

Figure 2-7 shows a schematic of an experimental retrofit application of the staged combustion technique, staged combustion air injection (SCA), on a firetube boiler burning residual oil.

The retrofit design consists of eight stainless steel pipes connected through a ring manifold to a forced draft fan. The air injection pipes penetrate the furnace opposite from the burner and are equipped with "fish tail" orifice to assist in mixing the air with the combustion products. A separate fan provides air to the manifold independent of the burner air. This technique assures control of burner stoichiometry while supplying enough air downstream of the burner to complete combustion. The retractable injection nozzles permitted the analysis of the effect of injection air location on the performance of the staged combustion technique at various burner air-fuel ratios.

TABLE 5-16. BaP NATIONWIDE EMISSIONS AND EMISSIONS FACTORS

| SCCP                                       | Nationwide Emissions <sup>a</sup><br>Mg/yr | BaP Emission Factor <sup>a</sup> (mean)<br>pg/J |
|--------------------------------------------|--------------------------------------------|-------------------------------------------------|
| <u>Utility</u>                             |                                            |                                                 |
| Pulverized dry bottom -<br>bituminous coal | 0.55                                       | 0.066                                           |
| Residual Oil                               | 0.10                                       | 0.027                                           |
| <u>Industrial</u>                          |                                            |                                                 |
| Spreader Stoker -<br>bituminous coal       | 0.02                                       | 0.03                                            |
| Residual Oil                               | 0.07                                       | 0.027                                           |
| Underfeed Stoker - wood                    | -                                          | -                                               |
| <u>Comm/Inst.</u>                          |                                            |                                                 |
| Underfeed Stoker -<br>bituminous coal      | 0.09                                       | 1.29                                            |
| Distillate oil                             | 0.02                                       | 0.70                                            |
| Underfeed Stoker - wood                    | -                                          | -                                               |
| <u>Residential</u>                         |                                            |                                                 |
| Underfeed Stoker -<br>bituminous coal      | 19                                         | 100                                             |
| Distillate oil                             | 0.14                                       | 0.054                                           |
| Wood                                       |                                            |                                                 |
| Stoves                                     | 27                                         | 494 <sup>b</sup>                                |
| Fireplaces                                 | 1.0                                        | 95.1 <sup>b</sup>                               |

<sup>a</sup>Based on small number of samples (see Tables 4-6, 4-20, 4-29, and 4-37).

<sup>b</sup>Includes BaP and perylenes.



could be partly attributed to removal of burner baffles under the staged combustion tests. The significant  $\text{NO}_x$  reduction achieved indicates that the staged combustion technique can be very effective in reducing  $\text{NO}_x$  emissions from firetube boilers burning residual oil. This technique is expected to be less effective for distillate oil combustion because of the lower fuel  $\text{NO}_x$  formation with this fuel.

Staged combustion air (SCA) injection should be considered still in the development stage. More testing is required to resolve the combustion instability at the high boiler loads and to establish the reliability of the system for long-term operation. In addition, the design of the SCA system as shown in Figure 2-7 might not be feasible altogether because of operational complexity and incremental cost.

#### 2.3.2.2 Packaged Watertube

Two retrofit designs of the staged combustion technique have been investigated for single burner packaged watertube boilers. Figures 2-8 and 2-9 show the schematic of two secondary air injection systems.

In the first retrofit application (Figure 2-8), the staged combustion air was injected from the side of the furnace. The application was possible because the configuration of the waterwalls was not of the tangent type. That is, refractory brick spacing existed between furnace waterwall tubes. Consequently air could be injected without having to modify or remove any of the furnace tubes. This type of waterwall tube design is typical of oil boiler furnaces. Modern manufacturing methods utilize tangent tube construction for better radiant heat transfer.

Figure 2-9 shows an alternate method of injecting staged air combustion in a modern design "D" type package watertube boiler. Holes were drilled in the windbox and four retractable air injection lances were installed directly in the furnace. The tangent tube design of this furnace did not permit side air injection. The movable lances permitted injection of air at varying distances downstream of the burner. This injection system was designed for the purpose of conducting experimental tests and should not be considered as an established method of injecting secondary air in this boiler type. However, it may be possible to design the tube arrangement in new boilers such that air injection ports could be installed on the side of the furnace.

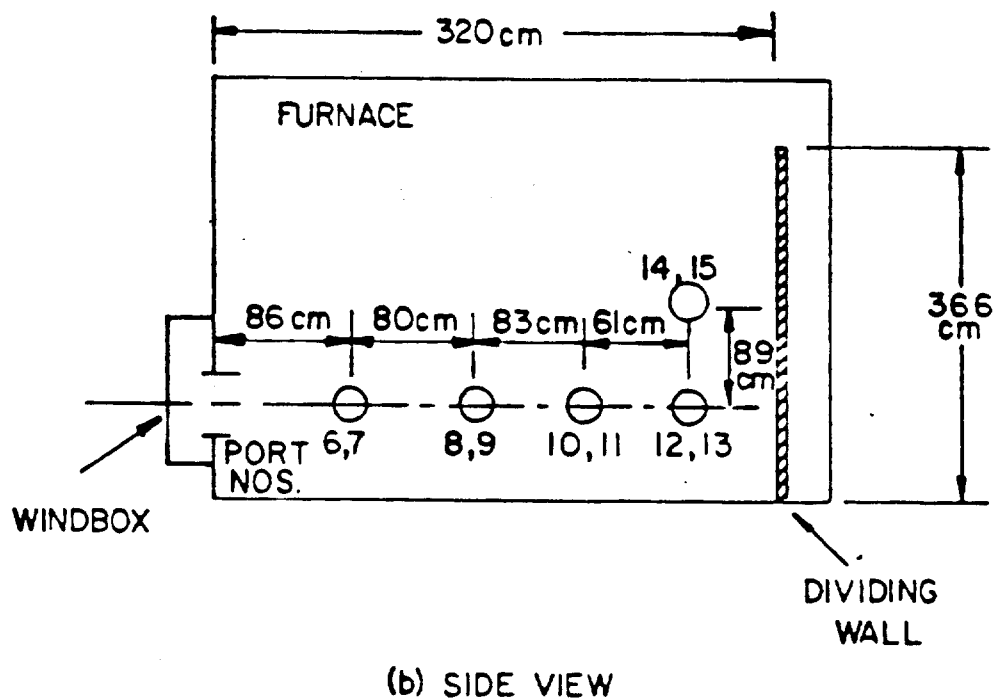
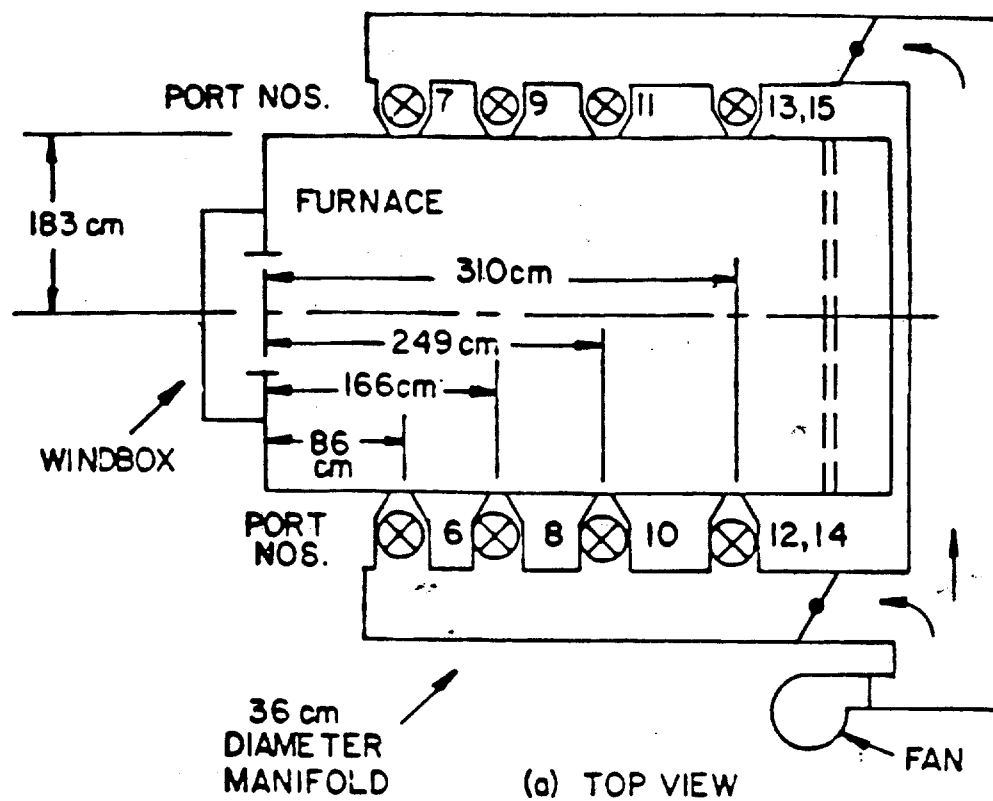


Figure 2-8. Schematic of staged air system installed for single burner packaged watertube oil-fired boilers (Reference 2-55).

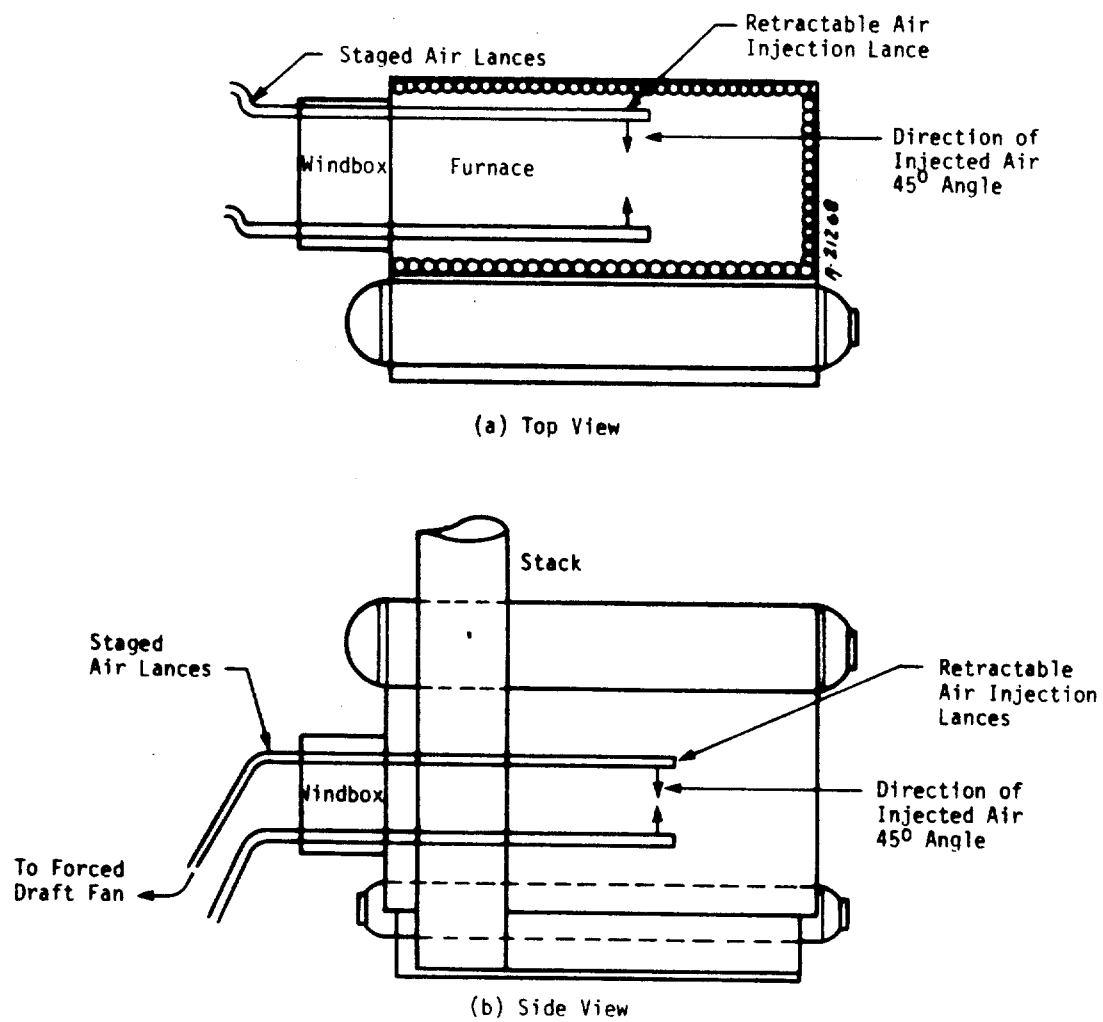


Figure 2-9. Schematic of stage air system installed on "D" type packaged watertube boiler (Reference 2-55).

Results on the performance of staged combustion on single burner watertube boilers suggest that two conditions are required to achieve substantial  $\text{NO}_x$  reductions (References 2-20 and 2-55).

- Burner stoichiometries must be set between 90 and 100 percent. That is, air flow to the burner windbox must be below theoretical air needed for complete combustion.
- Secondary air must be injected sufficiently downstream from the burner exit to allow for cooling of combustion gases. This downstream distance varies with burner type and size.

Carefully installed and operated staged injection air will result in significant  $\text{NO}_x$  reductions (40-45 percent) from residual oil-fired package boilers. However, as in the case with firetube boilers it is estimated that more field data on the long term effects of SCA in these units is necessary before this technique can be considered demonstrated.

#### 2.3.2.3 Field Erected Watertube

For field erected watertube boilers, normally equipped with more than one burner, staged combustion can be obtained with the techniques of overfire air (OFA) or burners out of service (BOOS).

The technique of OFA has already been described for coal-fired boilers (Section 2.2.1.2). Overfire air injection above the top burner level is applicable to new as well as existing oil-fired boilers. However, as in the case for coal-fired units the technique is more attractive in original designs than in retrofit applications for cost considerations. Information on  $\text{NO}_x$  reduction from oil-fired industrial boilers using OFA is very limited. However, application of the technique on utility boilers burning oil has resulted in 24 percent  $\text{NO}_x$  reduction (Reference 2-24). Overfire air is a viable  $\text{NO}_x$  reduction technique for new multiburner industrial units burning oil. Furthermore, it is considered demonstrated and commercially available.

Burners out of service is the simplest method of achieving staged combustion with these units. However, this technique is usually limited to retrofit applications. The method of implementing BOOS has already been described in Section 2.2.1.3 for coal-fired units. The application to oil-fired units is essentially the same except that oil-fired units have better control over the number or location of the burner(s) to be used as air injection ports. This is possible for oil and also gas units

because the fuel flow can be terminated at each individual burner and not at a set of burners as in the pulverized coal-fired units. Furthermore, fuel feed rates to the active burners can be adjusted over a broader range for oil- and gas-fired boilers. Numerous field test data on burners out of service have been gathered on industrial boilers.  $\text{NO}_x$  emissions were reduced 25-40 percent during these tests (References 2-4 and 2-20).

On existing units, operation with BOOS requires that the unit be derated unless modification to the fuel delivery system is made. In addition, adjustments to the air flow controls, such as burner registers, might also be required to achieve the required burner stoichiometry without increasing smoke and combustible emissions. Furthermore, there is no optimum BOOS pattern applicable to all existing boilers (Reference 2-20).

### 2.3.3 Flue Gas Recirculation (FGR)

Recycling a portion of the flue gas back to the primary combustion zone reduces  $\text{NO}$  formation by lowering the bulk furnace gas temperature and reducing oxygen concentration. Figures 2-10 through 2-12 show schematics of typical FGR retrofit applications on a firetube and two packaged watertube boilers, respectively. The systems are nearly identical consisting of an FGR fan assembly and associated ducting connecting the stack to the windbox.

One investigator reported that the technique is more effective for watertube boilers than for firetube boilers when burning the same fuel because of the generally higher combustion intensity of the watertubes (Reference 2-52). However,  $\text{NO}_x$  reductions for both firetube and watertube reached a maximum of 20 percent when burning a residual oil. Another investigator reported that FGR is more effective for steam atomized oil combustion than for air atomized oil combustion (References 2-20 and 2-55). In fact, in a watertube boiler burning steam atomized residual oil, maximum  $\text{NO}_x$  reduction was 20 percent. When burning the same oil with air atomization only 16 percent  $\text{NO}_x$  reduction was achieved.

For oil-fired boilers FGR is more effective when burning light distillate oil because thermal  $\text{NO}_x$  predominates. In fact,  $\text{NO}_x$  reductions of up to 73 percent were obtained with FGR when burning a No. 2 distillate oil (Reference 2-55).

In a retrofit application, flue gas recirculation rates approaching or above 30 percent can cause severe flame instability, flame pulsation,

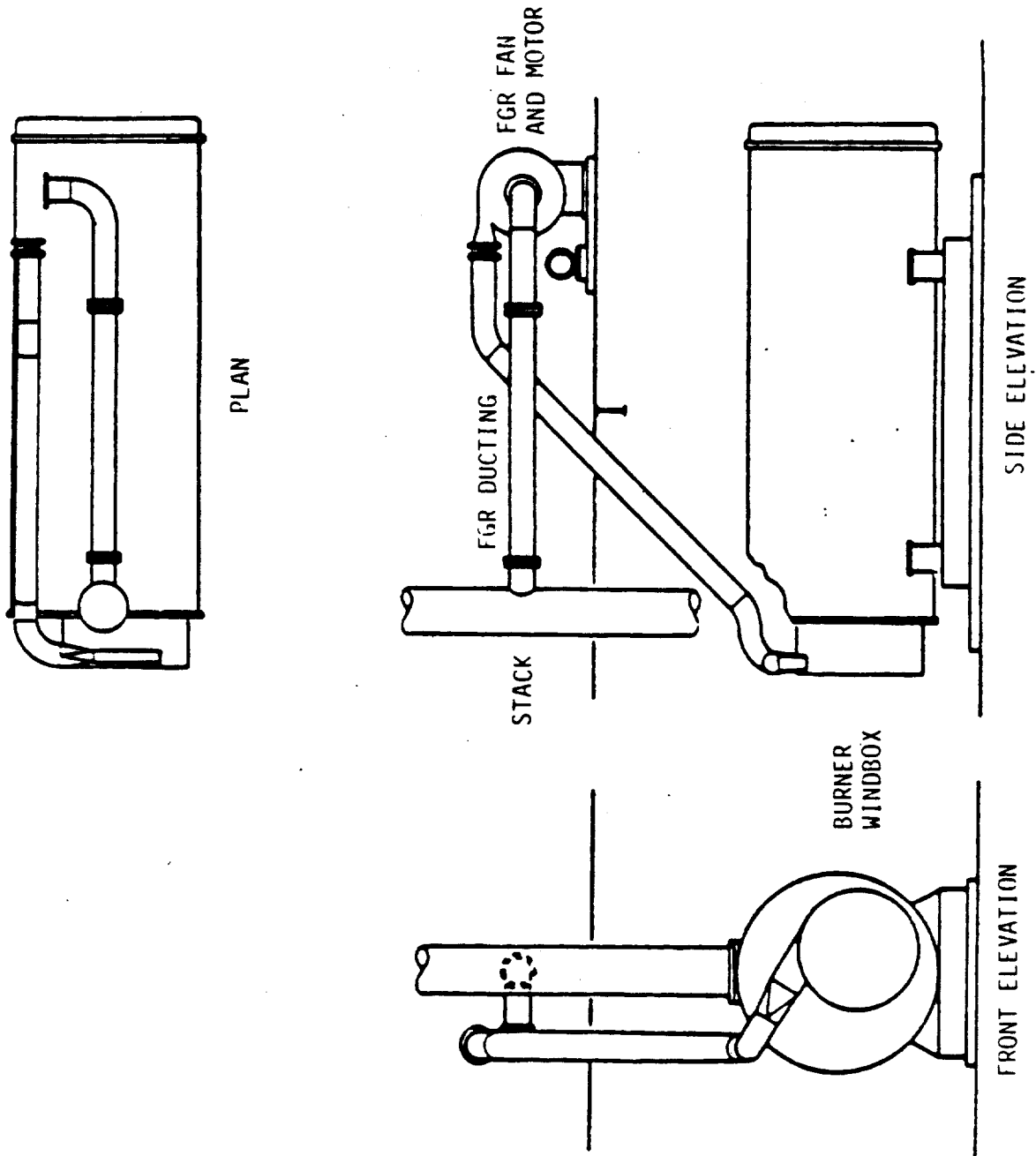
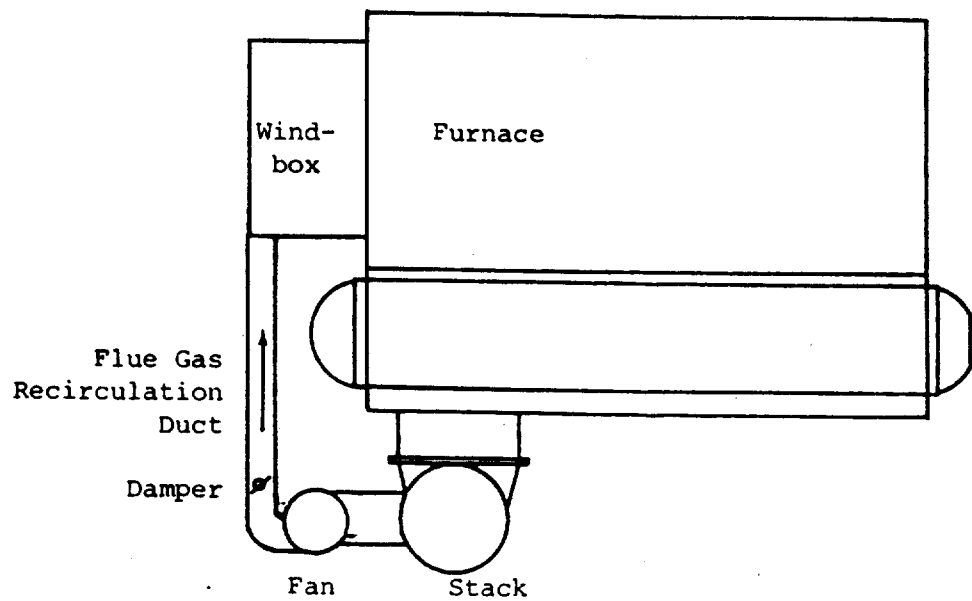
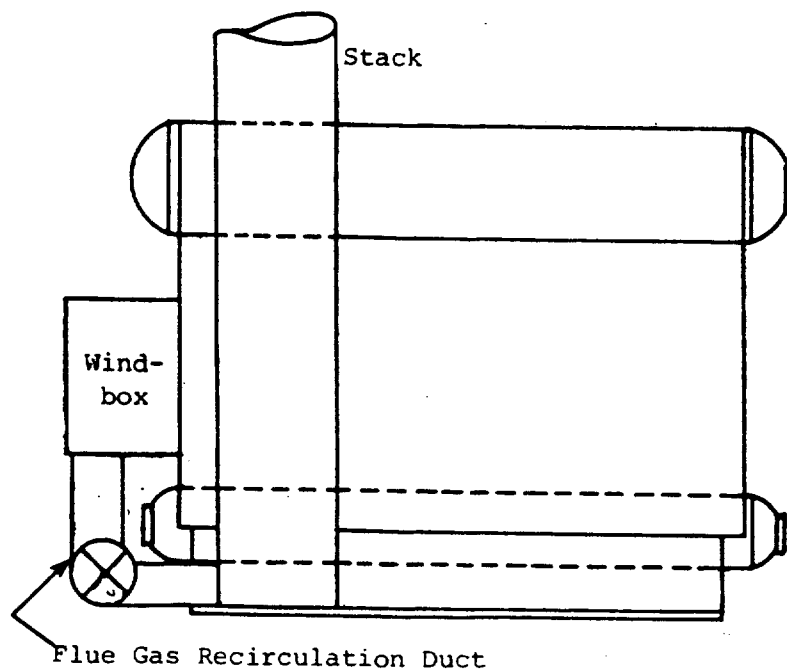


Figure 2-10. Layout of flue gas recirculation system for a firetube boiler (Reference 2-54).



(a) Top View



(b) Side View

Figure 2-11. Layout of flue gas recirculation system for a packaged watertube boiler (Reference 2-55).

Table V

## APPENDIX E

## Fireplace Atmospheric Emissions

## POM Quantification

POM QUANTIFICATION (ng)

POM quantification is reported in nanograms. The samples were collected by the methods described in the Procedure section, Page 13.

| Component                  | NAS<br>Notation | SAMPLE        |                |              |
|----------------------------|-----------------|---------------|----------------|--------------|
|                            |                 | Alder<br>69-5 | D. Fir<br>76-5 | Pine<br>8605 |
| Anthracene/Phenanthrene    |                 | 52,450        | 59,600         | 52,100       |
| Methyl anthracenes         |                 | 21,300        | 32,900         | ---          |
| Fluoranthene               |                 | 16,100        | 27,200         | 21,400       |
| Pyrene                     |                 | 18,900        | 24,700         | 21,750       |
| Methyl Pyrene/Fluoranthene |                 | 17,800        | 13,400         | 450          |
| Benzo(c)phenanthrene       | ***             | 4,300         | 3,800          | 2,450        |
| Chrysene/Benz(a)anthracene | *               | 11,900        | 17,800         | 7,950        |
| Methyl chrysenes           | *               | 5,300         | 9,200          | 28,300       |
| Benzo fluoranthenes        | **              | 5,400         | 7,300          | 3,000        |
| Benzo(a)pyrene             | ***             | 5,200         | 8,900          | 12,400       |
| Benzo(e)pyrene             |                 |               |                |              |
| Perylene                   |                 | ---           | ---            | ---          |
| -Methylcholanthrenes       | ****            | 3,300         | 9,600          | 5,650        |
| Indene(1,2,3-cd)pyrene     | *               | 1,300         | 2,600          | 3,050        |
| Benzo(ghi)perylene         |                 | 2,800         | 3,200          | 3,000        |
| Dibenzo(a,h)anthracene     | ***             | ---           | ---            | ---          |
| Diebenzo(c,g)carbazole     | ***             | ---           | ---            | ---          |
| Dibenz(ai and ah)pyrenes   | ***             | ---           | ---            | ---          |
| Coronene                   |                 | ---           | ---            | ---          |
| TOTAL                      |                 | 166,000       | 220,000        | 162,000      |



equipment vibration and blowouts. These problems were found to be significantly alleviated by extensive burner and windbox modifications (References 2-20 and 2-52).

In general, FGR is definitely an applicable control technique for oil-fired industrial boilers. It is most effective on boilers burning distillate oil. When burning residual oil, steam atomization is preferred. The technique is commercially available for new boilers for which burners have been designed to accommodate the additional flue gas flow. In fact, one manufacturer has recently installed two 14.7 MW ( $50 \times 10^6$  Btu/hr) units equipped with FGR systems in Southern California (References 2-56 and 2-57). No information on the performance on these units has been reported. However, the  $\text{NO}_x$  emissions of these units are designed to meet the stringent regulations of the South Coast Air Basin of 225 ppm at 3 percent  $\text{O}_2$  for oil combustion (approximately 126 ng  $\text{NO}_2/\text{J}$ ).

#### 2.3.4 Combined Flue Gas Recirculation and Staged Combustion

The packaged watertube boiler shown in Figure 2-9 was also tested with combined SCA and FGR. Tests were run to determine whether the effectiveness of the two techniques are additive (References 2-20 and 2-55). Combining SCA with FGR gave no increased reduction over that with FGR or SCA alone when burning distillate oil. However, the combined techniques had a pronounced effect when burning residual oil. Thus staged combustion alone reduced  $\text{NO}_x$  emissions of residual oil 42 percent, FGR alone reduced  $\text{NO}_x$  emissions 11 percent while FGR with SCA reduced the  $\text{NO}_x$  emission 55 percent.

Fitting a boiler with both SCA and FGR may not prove to be cost effective. The combined technique is not considered commercially available because staged combustion is still experimental for firetube and packaged watertube boilers.

#### 2.3.5 Reduced Air Preheat (RAP)

Reducing the amount of combustion air preheat lowers the primary combustion zone peak temperature, generally lowering thermal  $\text{NO}_x$  production as a result. The technique can be implemented only on boilers equipped with air preheaters. These boilers are of the watertube type and generally have designed heat input capacities of greater than 15 MW ( $50 \times 10^6$  Btu/hr) (Reference 2-20). No retrofit work is required in some instances.

As evidenced by the data contained in Table 2-5, baseline  $\text{NO}_x$  emission data from distillate oil-fired watertube boilers equipped with air preheaters had greater  $\text{NO}_x$  emissions than those units not equipped with air preheaters. Unit capacity was not a factor. No similar reduction occurred for those units burning residual oil, perhaps because of the greater variation in fuel nitrogen content of the various oils being burned.

The data reported in Table 2-6 reflects results of RAP tests on two residual oil-fired boilers. For one boiler where the initial baseline  $\text{NO}_x$  emissions was below 200 ppm at 3 percent  $\text{O}_2$  (112 ng/J) the technique was ineffective. For the other boiler with initial baseline emissions over 330 ppm at 3 percent  $\text{O}_2$  (185 ng/J), RAP reduced  $\text{NO}_x$  emissions at a rate of 33 ppm (19 ng/J) per 50K ( $90^\circ\text{F}$ ) reduction in combustion air temperature (Reference 2-20).

Although available, the technique is rarely applied because very few industrial size oil-fired boilers are equipped with air preheaters. Furthermore, when RAP can be implemented, the fuel penalty involved due to loss in efficiency makes the technique very unattractive. Reducing the air preheat temperatures as a means of reducing nitrogen oxide emissions from oil-firing will result in a decrease in boiler efficiency by about 2.5 percent per 50K ( $90^\circ\text{F}$ ) increase in stack temperature (Reference 2-20 and 2-58). Because of this significant loss in boiler efficiency, the heat loss would have to be recovered if RAP is to be used as a  $\text{NO}_x$  control technique. Enlarging the surface area of existing economizers or installation of an economizer in place of an air preheater can be used to recover the heat loss due to the RAP technique for  $\text{NO}_x$  control. For new boilers, installation of an economizer is technically feasible and also offers economic advantages over the air preheater (Reference 2-59).

#### 2.3.6 Load Reduction

Reducing boiler load is accomplished by reducing the heat input into the furnace. Both heat release rate (also known as combustion intensity) and peak flame temperature are lowered, reducing the thermal  $\text{NO}_x$  formation. However, the reduced mass flow through the burners at the reduced load condition can cause improper fuel-air mixing, thus creating CO and soot emission with additional operational problems. This situation is alleviated by increasing the air flow to excess air levels

higher than normally maintained at the higher boiler loads. This increase in air flow causes more oxygen availability, thus favoring increase in fuel  $\text{NO}_x$  formation. The net effect of reduced thermal  $\text{NO}$  and increased fuel  $\text{NO}$  is often no change in  $\text{NO}_x$  concentration in the flue gas.

This was essentially the result of the load reduction tests conducted in an EPA program on 24 oil-fired industrial boilers (References 2-4, 2-20 and 2-53). The data often show a split with some boilers increasing  $\text{NO}_x$  emissions at reduced loads and other boilers decreasing them. For firetube boilers burning distillate oil, the  $\text{NO}_x$  emissions ranged from a 10 percent decrease to a 7 percent increase for each 10 percent load reduction. Five distillate oil-fired boilers without air preheat shown an average increase in  $\text{NO}_x$  emission of 3.8 percent while the remaining two with air preheat showed an average decrease in  $\text{NO}_x$  emissions of 26 percent.  $\text{NO}_x$  emissions from firetube and watertube units burning residual oil showed average decreases in  $\text{NO}_x$  emission factors regardless of whether the air was preheated or not.

Reducing boiler load will usually reduce the thermal efficiency of the boiler because of the increase in excess air needed to maintain good fuel air mixing. A more desirable way to achieve a reduction in combustion intensity would be to increase the size of the firebox. The enlarged firebox would provide reduced heat release rates without necessitating an increase in excess air levels. Naturally, the increased firebox design will only apply to new boilers. This technique is being implemented on utility size boilers (Reference 2-24).

#### 2.3.7 Low $\text{NO}_x$ Burners (LNB)

Low  $\text{NO}_x$  burners firing fuel oil can generally be classified by the method of fuel injection and the method of combustion air delivery. A recent EPA study (Reference 2-60) further classifies the burners as:

- Good-mixing\*
- Divided flame
- Self-recirculating

---

\*Controlled-mixing is probably a less confusing term, but "good-mixing" was the term used by the EPA report and will be retained here.

- Staged-combustion
  - Two stage combustion
  - Off stoichiometric combustion

The good-mixing and divided flame type burners primarily reduce thermal  $\text{NO}_x$ , either by rapid quenching of the flame, or by an increase in the surface area of the flame for increased heat dissipation. The self-recirculation and various staged-combustion type burners reduce both thermal and fuel  $\text{NO}_x$ . This is accomplished through the recycling of combustion gas, which is lean in oxygen, or substoichiometric air injected in the primary combustion zone with stoichiometric and excess air added at the point of fuel discharge into the furnace.

Seven types of low  $\text{NO}_x$  burners for industrial boilers are presently under development or in commercial use in Japan. A summary of the limited information regarding each of these burners is presented in Table 2-7. Available information on the operations, performance, applicability and availability of each of these burners is discussed in the following sections. Unfortunately, actual emissions data for low  $\text{NO}_x$  burners for industrial boilers are generally not available. The percentage  $\text{NO}_x$  reductions presented here are only the expected performance as cited in the references, usually with no baseline emission levels given.

#### Nippon/TRW Burner

The Nippon/TRW burner is designed to allow for an initial fuel-air mixing zone, established through precise control of the radial injection and atomization of the fuel into the combustion air. A second mixing zone allows for heterogeneous mixing of fuel droplets, followed by the primary flame front and post combustion zone (Reference 2-61).

The intermixing of fuel and air produces a radial conical flame pattern as shown in Figure 2-13. The combination of the recirculation of combustion products and good-mixing of fuel and air leads to reduced  $\text{NO}_x$  emissions by rapid quenching of the flame with cooler combustion gases. Figure 2-13 also shows the flame as being a thin annular configuration for increased heat dissipation and lower flame temperatures. Both phenomena reduce thermal  $\text{NO}_x$  production.

Figure 2-14 presents the results of the demonstration/commercialization tests performed by Nippon/TRW. The sensitivity of  $\text{NO}_x$  emission

TABLE 2-7. LOW NO<sub>x</sub> BURNERS FOR OIL AND GAS FIRING

| Manufacturer Developer                | Burner Type              | Effectiveness of (Percent NO <sub>x</sub> Reduction) | Applicability | Availability                           | Comments                                                                            |
|---------------------------------------|--------------------------|------------------------------------------------------|---------------|----------------------------------------|-------------------------------------------------------------------------------------|
| Nippon/TRW                            | Good mixing <sup>a</sup> | 17-23% w/heavy oil, fuel nitrogen content of 0.3%    | Oil & gas     | Commercialized early 1975 in Japan     | Lower steam atomization but higher burner throat ΔP, High excess O <sub>2</sub>     |
| TRW/Civiltech                         | Good mixing <sup>a</sup> | 17-23% w/heavy oil, fuel nitrogen content of 0.3%    | Oil & gas     | Late 1979                              | First generation burner tested in Japan. Second generation being developed for U.S. |
| Ishikawajima-Narima                   | Divided flame            | 30-50% reduction depending on application            | Oil & gas     | Commercially available in Japan (1973) | Requires burner tip modification only                                               |
| Tokoyo Gas                            | Staged Combustion        | 50% reduction                                        | Gas           | Continuing development                 | Flame stability problems                                                            |
| Kawasaki                              | Staged Combustion        | 20-50% depending on fuel rate                        | Oil & gas     | N/A                                    | N/A                                                                                 |
| Coen                                  | Staged Combustion        | N/A                                                  | Oil & gas     | Available on a very limited basis      | Staged combustion design. All proprietary data                                      |
| Energy and Environmental Research/EPA | Staged Combustion        | Up to 50%                                            | Oil           | Still at R&D stage                     | Currently being tested in a field operating firetube                                |

<sup>a</sup>Controlled mixing is probably a better term, but "good mixing" was the term used by the EPA study (Reference 2-60) and will be retained here.

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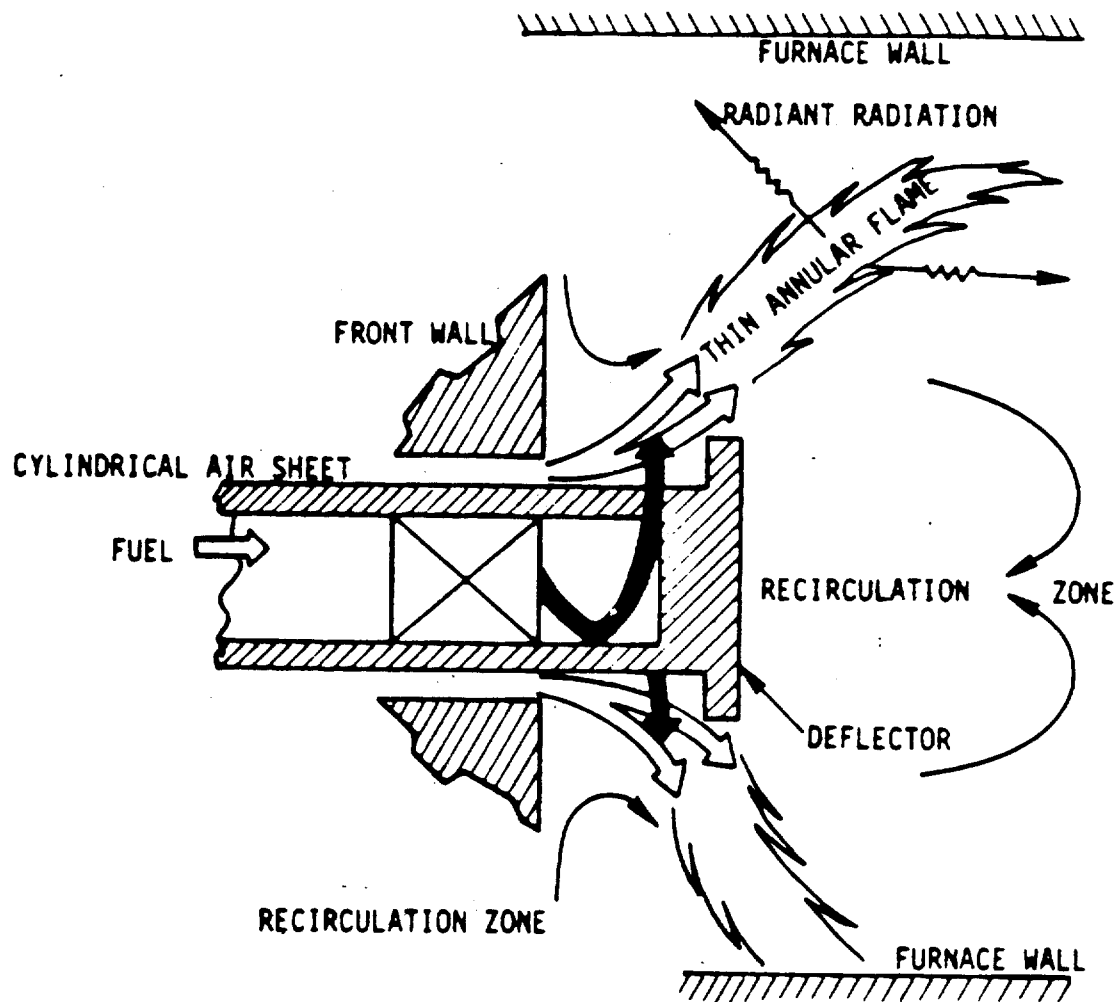


Figure 2-13. The Nippon/TRW burner (Reference 2-62).

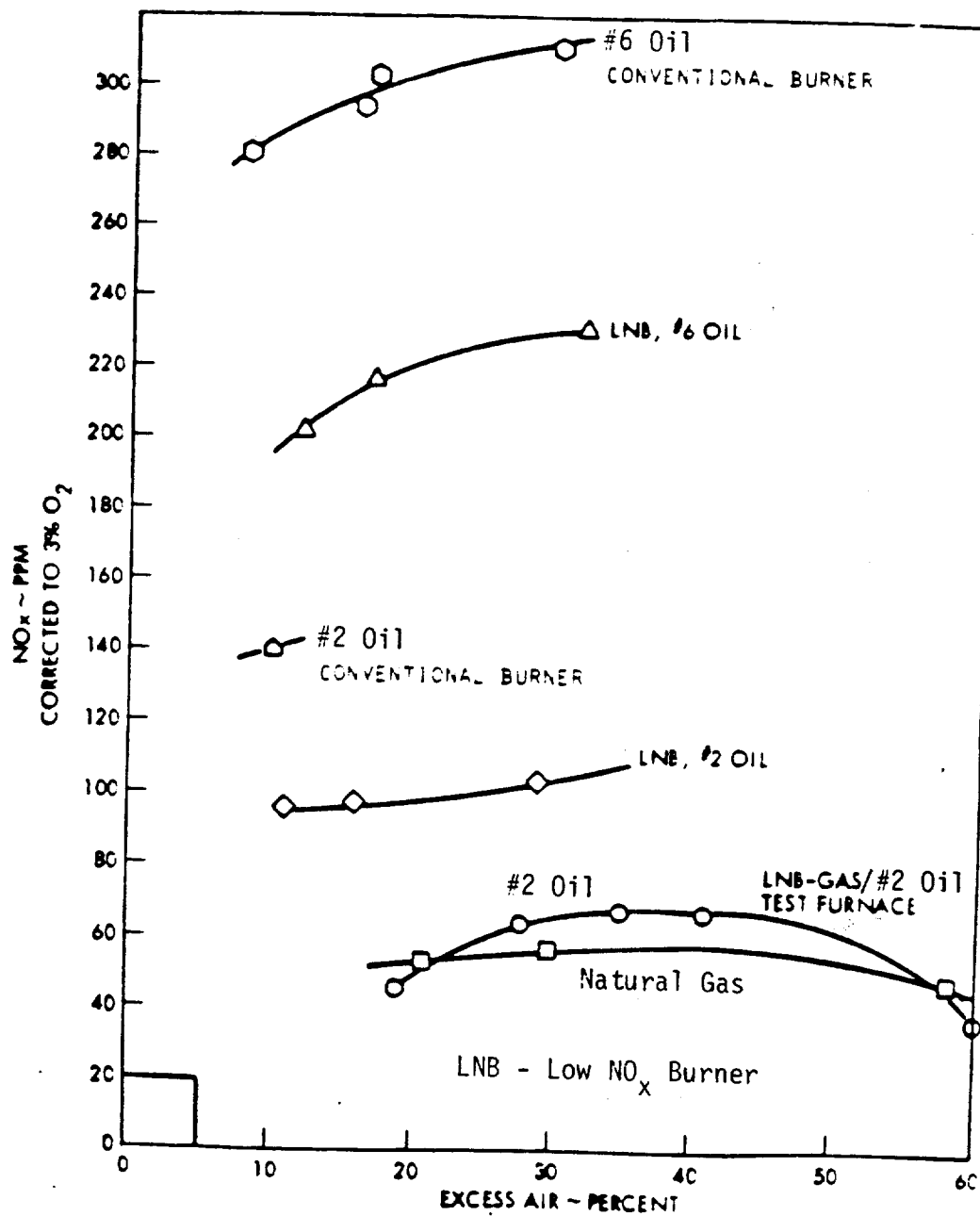


Figure 2-14. Performance results of the Nippon/TRW low NO<sub>x</sub> burner (LNB) (Reference 2-61).

concentrations as affected by fuel nitrogen is clearly seen. Figure 2-14 also demonstrates the low  $\text{NO}_x$  burner capabilities compared to a conventional burner. These tests were conducted after the burner was installed in an existing packaged boiler without modification to the safety control equipment, combustion air or fuel-handling system. The test results show a 35 percent decrease in  $\text{NO}_x$  emissions for No. 2 fuel oil and a 30 percent decrease for heavy oil (analysis unknown). When the low  $\text{NO}_x$  burner was in operation, all  $\text{NO}_x$  emissions were below 220 ppm corrected at 3 percent excess oxygen (123 ng/J, 0.287 lb/10<sup>6</sup> Btu). The burner has been commercially available in Japan since early 1975 (Reference 2-62).

#### TRW/Civiltech Burner

The TRW/Civiltech burner represents the second generation burner being developed based on experience obtained with the Nippon/TRW LNB (Reference 2-63). Problems experienced during testing in Japan have led to a program to refine the original burner design. The second generation burner is being designed to achieve:

- Reasonably low excess air requirements during partial load operations
- Wider range of applicability, with burner heat input capacities of 3 to 73 MW (10 to 250 x 10<sup>6</sup> Btu/hr)

As of this writing, the TRW burner is being commercially offered, though as yet undemonstrated. A preliminary timetable calls for commercial application near the end of 1979 (References 2-61, 2-63, and 2-77). An EPA sponsored field demonstration is currently underway and actual operating data should soon be available (Reference 2-78).

#### Ishikawajima-Harima Heavy Industries (IHI) Burner

Ishikawajima-Harima Heavy Industries developed several burner configurations which are effective in reducing  $\text{NO}_x$ . The basic principle of the burners is a divided flame, as shown in Figure 2-15. The flame produced has a radial conical pattern which increases the radiation surface area and the rate of heat dissipation. The reduced flame temperature results in reductions in  $\text{NO}_x$  emissions.

The burner variations shown in Figure 2-15 were tested on a furnace simulator. The results are shown in Figure 2-16.  $\text{NO}_x$  concentrations are shown to be reduced by 30 to 50 percent of the emissions from



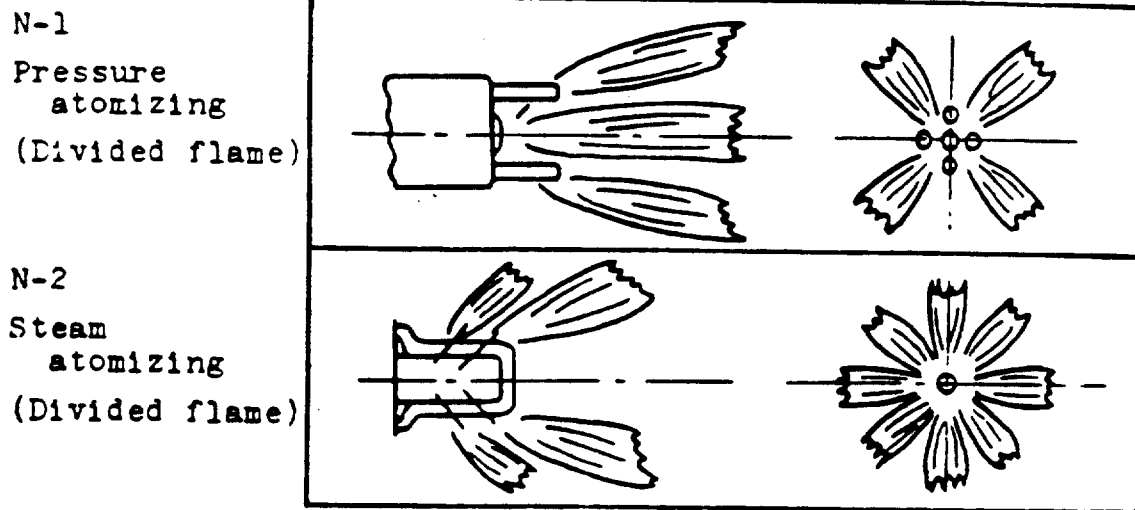
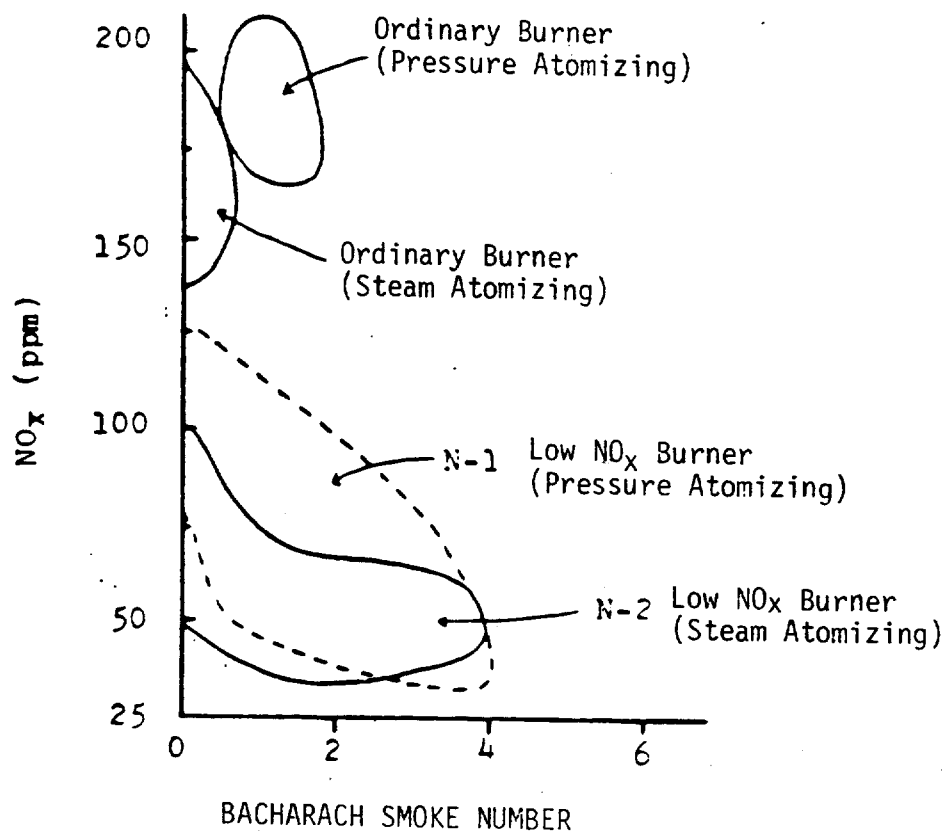


Figure 2-15. Ishikawajima-Harima divided flame burner (Reference 2-64).



NOTE: Enclosed regions represent data bands.

Figure 2-16. Effect of flame division on NO<sub>x</sub> and smoke concentrations (Ishikawajima-Harima burner) (Reference 2-64).

conventional burners. Field tests on large boilers, 130 MW ( $400 \times 10^6$  Btu/hr) and larger have also been conducted and the results are presented in Figure 2-17. It is significant to note that combinations of  $\text{NO}_x$  reduction capability of the IHI burner are reduced as the use of other control methods, such as flue gas recirculation or staged combustion is increased.

The burner is commercially available for oil and gas fuel applications. The primary advantage to this burner is that it requires only the replacement of the conventional burner tip with the IHI flame divider, a minor modification.

#### Tokoyo Gas Company Burner

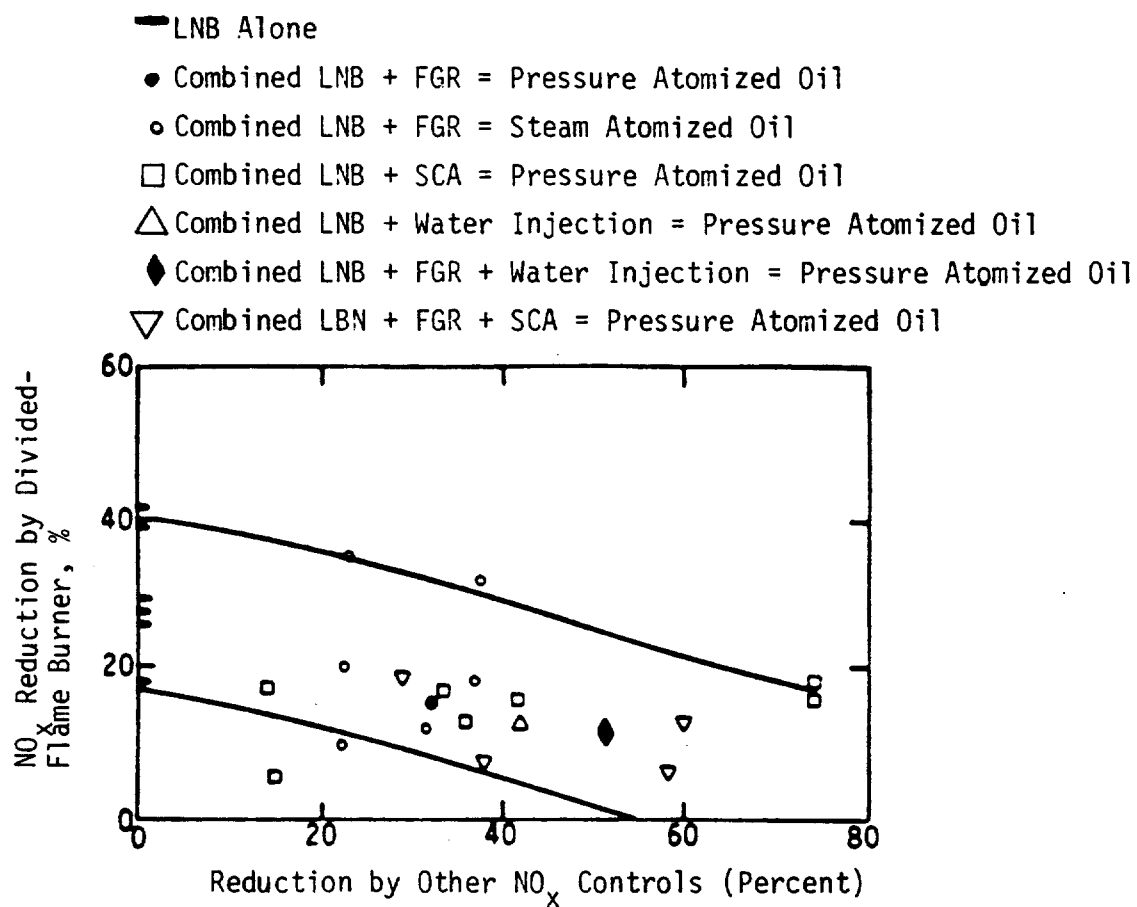
Tokoyo Gas company developed one of the first two-stage combustion type burners (Reference 2-65). The principle of the burner is shown in Figure 2-18. The primary air ports admit a predetermined air volume followed by stoichiometric addition as shown.

Experimental test results showed the presence of HCN and  $\text{NH}_3$  intermediates, the radicals which Fenimore determined were precursors to the formation of "prompt NO" (Reference 2-66). To reduce the concentration of these radicals, a catalyst was inserted between the first and second combustion zones. The burner operates at the limit of fuel-rich combustion, resulting in some flame stability problems (Reference 2-65).

Tests conducted on a firetube boiler with a capacity of 5.5 MW ( $18.6 \times 10^6$  Btu/hr) resulted in  $\text{NO}_x$  emissions approximately 50 percent of those from conventional burners. Because of the flame stability problems, however, the burner is still in the development stages (Reference 2-65).

#### Kawasaki Heavy Industries Burner

A two-staged combustion burner, utilizing a precombustion zone, has been designed by Kawasaki Heavy Industries (Reference 2-60). The precombustion chamber is placed in the windbox with secondary combustion air added at the point of discharge into the furnace, as shown in Figure 2-19. The injection of the fuel oil results in an eddy effect, as in self-recirculating burners, resulting in fuel rich combustion. The fuel is vaporized and partially combusted. Secondary air is added, at the desired overall stoichiometry, at the burner tip. Reportedly, this



LNB = Low NO<sub>x</sub> Burner  
 FGR = Flue Gas Recirculation  
 SCA = Staged Combustion Air

Figure 2-17. Effect of combined combustion modifications NO<sub>x</sub> controls on the performance of the Ishikawajima-Harima low NO<sub>x</sub> burner) (Reference 2-64).

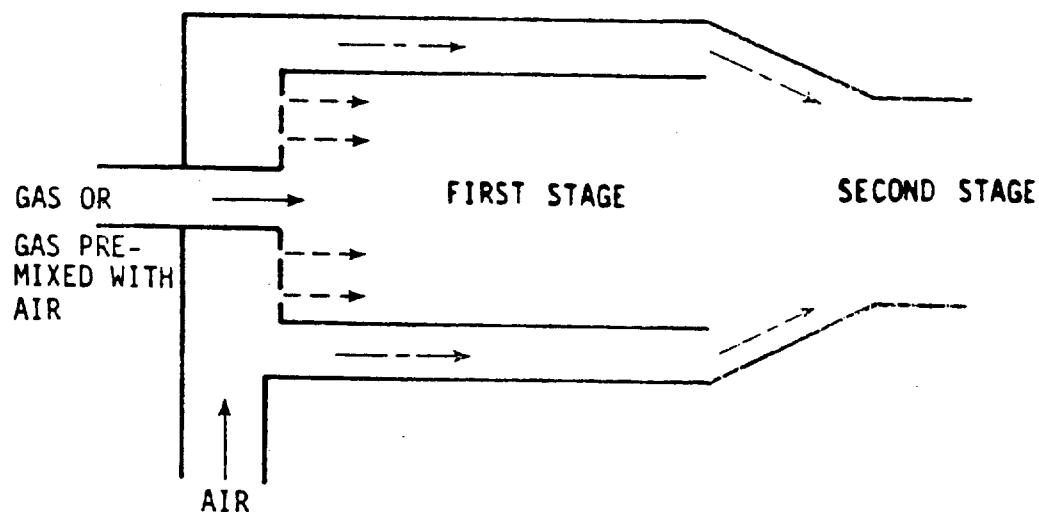


Figure 2-18. Schematic of Tokoyo Gas Company two-stage combustion type burner for low  $\text{NO}_x$  formation (Reference 2-60).

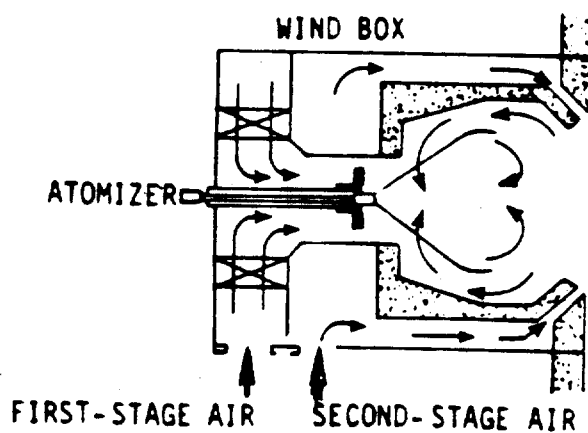


Figure 2-19. Kawasaki two-stage combustion-type burner for oil (Reference 2-60).

configuration reduces both thermal and fuel  $\text{NO}_x$ . The degree of reduction is shown in Figure 2-20.

#### Coen Burner

All test and descriptive information regarding the Coen low  $\text{NO}_x$  burner is considered proprietary (Reference 2-67). The information given was limited to burner concept (staged combustion) and applicable fuels (gas and oil). It was also stated that the burner was commercially available on an extremely limited basis. The flame is elongated, making the application to existing boilers difficult without substantial derating. All burners sold will be tested as part of a burner development program. Widespread commercial availability is not expected in the near future (Reference 2-67).

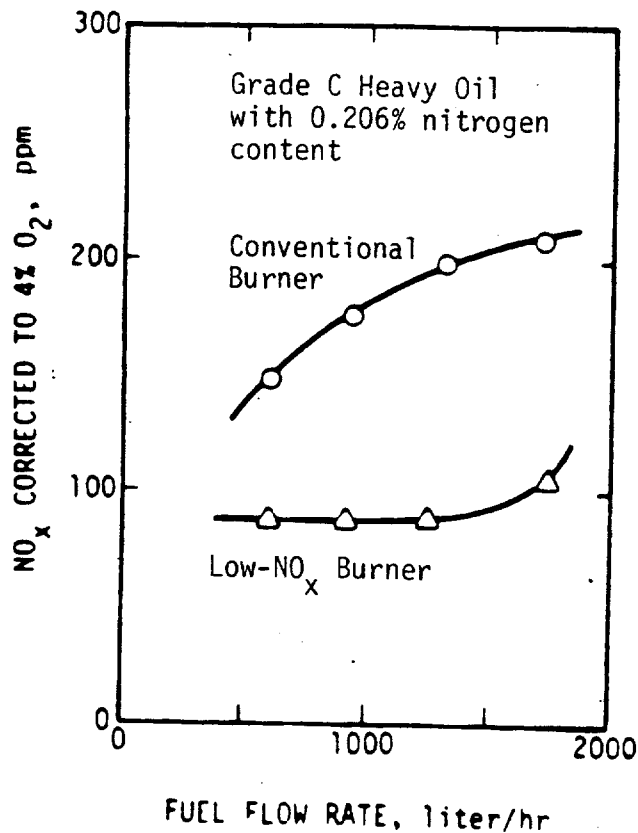


Figure 2-20. Effect of Kawasaki low  $\text{NO}_x$  burner on  $\text{NO}_x$  emissions (Reference 2-60).

## Energy and Environmental Research Co. (EER) EPA Burner

EER recently tested an oil-fired low  $\text{NO}_x$  burner in a firetube boiler. Reductions in  $\text{NO}_x$  emission levels of greater than 50 percent have been achieved without the need to modify the boiler in any way (Reference 2-68). Apparently the burner has not been fully demonstrated because additional testing is underway to investigate the effect of oil atomization. Preliminary results with this burner have been very encouraging; however there is no indication on future availability.

### 2.3.8 Ammonia Injection

The non-catalytic reduction of NO in the flue gas with  $\text{NH}_3$  is commercially available in Japan. Four industrial steam generators ranging in size from 41 to 252 MW ( $140$  to  $860 \times 10^6$  Btu/hr) have been successfully retrofitted in Japan. Reported  $\text{NO}_x$  reductions ranging from approximately 40 to 65 percent depending on the temperature of the injection location (Figure 2-21).

Since the commercial application of ammonia injection process in Japan, one domestic application on an oil recovery boiler in Southern California has taken place. Reported  $\text{NO}_x$  reductions ranged from 50 to 70 percent with the unit burning a heavy crude oil (Reference 2-69). The technique is particularly attractive because it can be in combination with any other combustion modification. Thus, significant  $\text{NO}_x$  reductions can be achieved.

For firetube boilers the injection system would need to be placed in the firebox as it is shown in Figure 2-22 because optimum temperatures occur at this location. The system represents an experimental retrofit application for a pilot scale test program. For watertube boilers the injection system will have to be located at the entrance of the convective section where flue gas temperatures are optimum for the NO reduction reaction to occur.

Due to the expected high cost of this technique compared with other combustion modifications, the ammonia injection process will probably not be feasible on small size boilers such as firetubes and package watertubes. In addition, since these industrial units are generally not base loaded, that is they do not operate at a steady continuous load, the variable heat input will cause significant flue gas temperature fluctuations which will reduce the performance of the control technique.

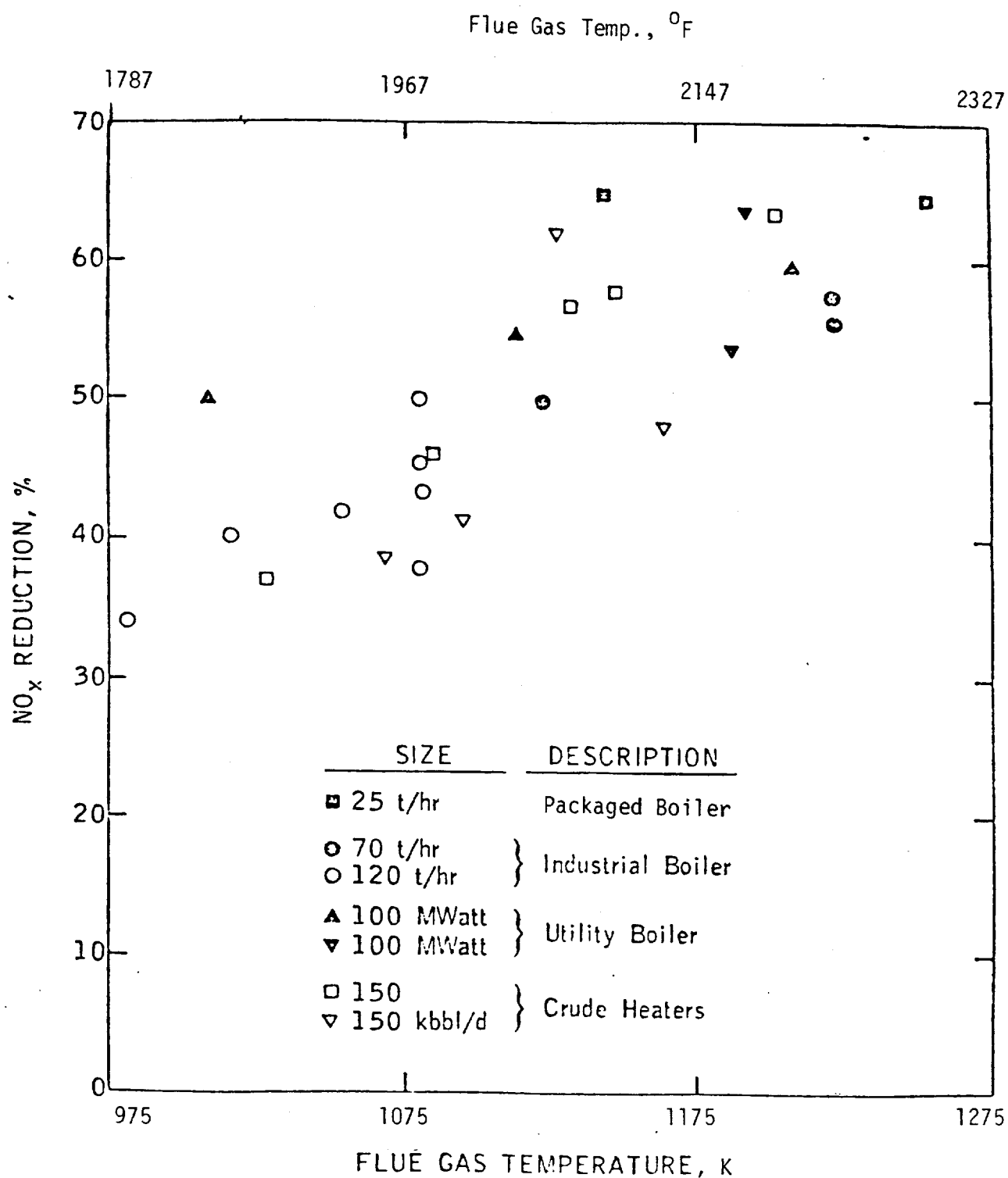


Figure 2-21. Ammonia injection system performance on commercial units as functions of temperature (Reference 2-70).

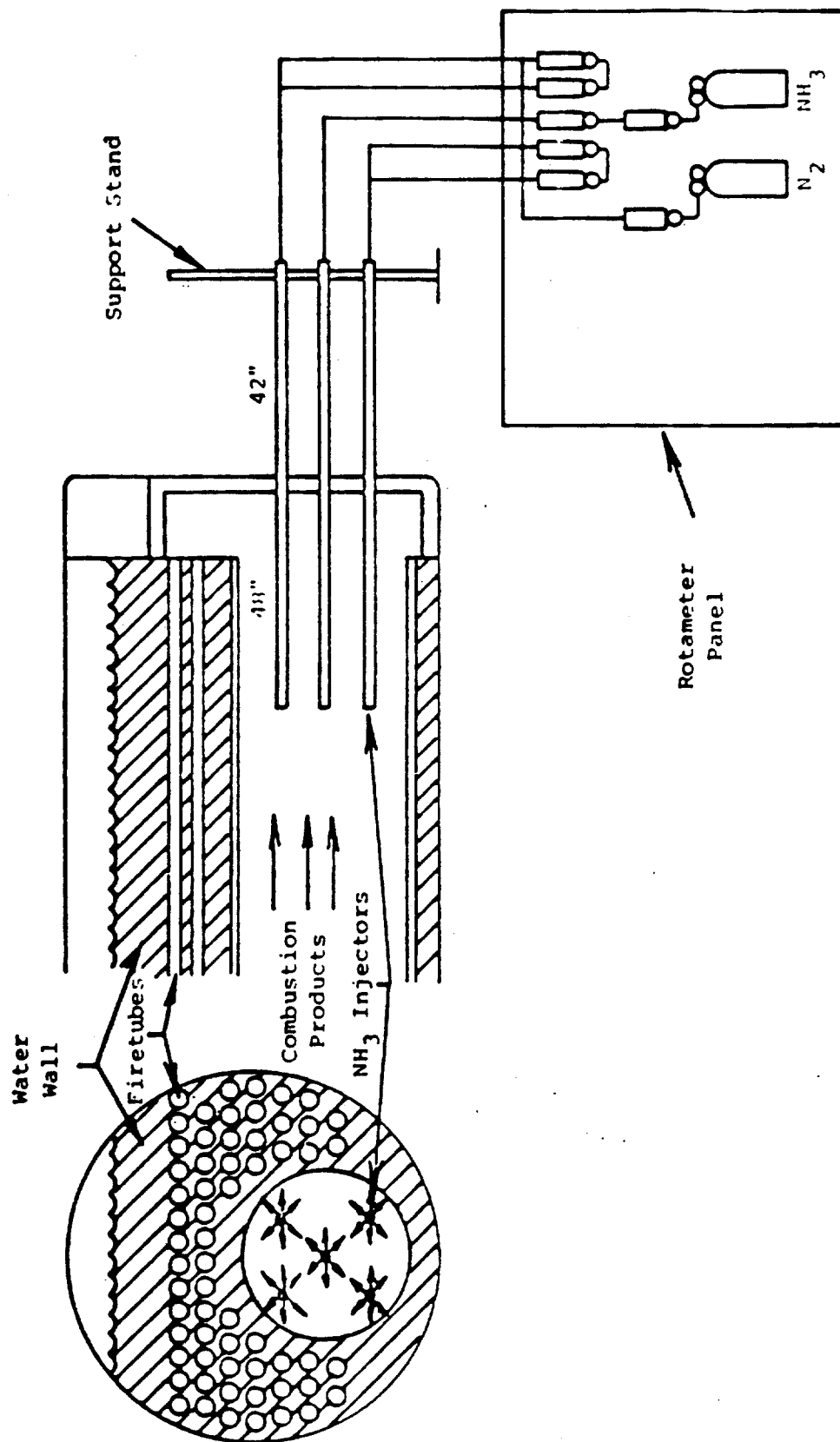


Figure 2-22. Schematic of ammonia injection system on a firetube boiler (Reference 2-18).



From an operational standpoint, the ammonia injection process is best suited for units burning low sulfur oil. The absence of  $\text{SO}_3$  in the flue gas will eliminate the concern for corrosive deposits caused by the formation of ammonium sulfates.

## 2.4 GAS-FIRED BOILERS

Gas-fired industrial boilers are of the same basic design as oil-fired boilers. In fact, approximately one-fourth of all industrial boilers are capable of burning gas and oil individually or in combination (Reference 2-44). Gas-fired boiler designs are categorized as firetubes, and packaged or field-erected watertubes. Of the total population of installed units, gas-fired firetubes comprise 11.3 percent, packaged watertubes 8.6 percent and field-erected watertubes 13.6 percent (Reference 2-2).

Table 2-8 lists baseline  $\text{NO}_x$  emission from gas-fired industrial boilers tested by EPA (References 2-4, 2-20 and 2-53). The data show a definite increase in  $\text{NO}_x$  emissions for boilers equipped with air preheaters. There appears to be no difference between  $\text{NO}_x$  emissions of firetube boilers and those of small single burner watertube boilers without air preheat.

All of the combustion modifications applicable for oil-fired units are also applicable to boilers burning natural gas. Table 2-9 summarizes the available information on the performance, applicability and availability of these techniques for gas-fired units.

The following subsections highlight the major points of interest for each of the techniques considered.

### 2.4.1 Low Excess Air (LEA)

Implementation of LEA firing on gas-fired units is similar to that on oil-fired units because the boiler equipment is essentially the same. Low excess air reduces  $\text{NO}_x$  emissions approximately 12 percent for firetube boilers, 8 percent for watertube boilers, without preheated air and about 15 percent for watertube boilers with preheated air. Test data also shows that excess oxygen level could in general be reduced to around 3.0 percent without excessive emissions of CO or HC (References 2-4 and 2-20 and 2-53).

TABLE 2-8. BASELINE NO<sub>x</sub> EMISSION FROM NATURAL GAS-FIRED INDUSTRIAL BOILERS

| Type of Boiler                | Number of Boilers | Excess O <sub>2</sub><br>(Weighted Average) | Range of NO <sub>x</sub><br>Emissions ng/J<br>(Weighted Average) | Range of NO <sub>x</sub><br>Emissions lb/10 <sup>6</sup> Btu<br>(Weighted Average) |
|-------------------------------|-------------------|---------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------------------------|
| Firetube                      | 8                 | 3.6 - 11.5<br>(6.5)                         | 28.6 - 55.1<br>(41)                                              | 0.066 - 0.128<br>(0.095)                                                           |
| Watertube without air preheat | 9                 | 2.9 - 8.9<br>(5.3)                          | 30.1 - 97.9<br>(47)                                              | 0.070 - 0.228<br>(0.116)                                                           |
| Watertube with air preheat    | 11                | 1.9 - 13.1<br>(5.7)                         | 49.0 - 190.1<br>(113)                                            | 0.114 - 0.444<br>(0.263)                                                           |

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TABLE 2-9. COMBUSTION MODIFICATION NO<sub>x</sub> CONTROLS FOR GAS-FIRED INDUSTRIAL BOILERS

| Control Technique                                  | Description of Technique                                                                     | Number of Industrial Boilers Tested | Effectiveness of Control (Percent NO <sub>x</sub> Reduction) | Range of Application                                                                                                                | Commercial Availability/R&D Status                                                                               | Comments                                                                                                                                                    |
|----------------------------------------------------|----------------------------------------------------------------------------------------------|-------------------------------------|--------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Low Excess Air (LEA)                               | Reduction in air-fuel ratio by reducing air flow to the windbox                              | 28                                  | 5 to 35                                                      | Generally excess O <sub>2</sub> can be safely reduced to 3.0%. This reduction represents a 2.5% drop from baseline.                 | Method and control equipment currently available.                                                                | Generally practiced because of increased boiler efficiency. Best NO <sub>x</sub> reductions reported for large multiburner units.                           |
| Staged combustion air (SCA)                        | Injection of secondary air downstream of the burner(s) in the direction of the flue gas path | 3                                   | 5 to 46                                                      | 70-90% burner stoichiometries can be maintained. Applicable to all units, however requires extensive equipment modification.        | Technique is still experimental especially for small fire-tube and water-tube units.                             | Found to be less effective on firetube boilers than watertube boilers. Generally less effective for gas-fired units.                                        |
| Burners out of Service (BOOS)                      | One or more burners on air only. Remainder firing fuel rich.                                 | 3                                   | 17 to 44                                                     | Applicable only to multiburner units. Best suited for square burner pattern.                                                        | Technique is available. Retrofit application only. Requires careful selection of BOOS and control of air flow.   | May require modification of gas delivery system and burners to avoid derating.                                                                              |
| Flue Gas Recirculation (FGR)                       | Recirculation of flue gas to the burner windbox. Requires motor, fan and connecting ducting. | 3                                   | 48 to 86                                                     | Flue gas recirculation rates possible up to 45%. Technique is applicable to all boiler types except ones equipped with ring burners | Available now. Best suited for new boilers. Retrofit application would result in extensive burner modifications. | Flame instability problem is not severe except for ring burners. Minor burner modifications can guarantee stable flames. Most effective on watertube units. |
| Staged combustion and Flue Gas Recirculation (FGR) | Combined techniques of staged combustion air and FGR                                         | 1                                   | 76                                                           | Applicable to all boilers with some restrictions as individual techniques.                                                          | FGR is an available technique. SCA for small package units is still at R&D stage.                                | No added benefit of SCA to FGR performance. Combined methods are not additive in their effect.                                                              |

Continued

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TABLE 2-9. CONCLUDED

| Control Technique                 | Description of Technique                                                           | Number of Industrial Boilers Tested | Effectiveness of Control (Percent NO <sub>x</sub> Reduction) | Range of Application                                                                                                        | Commercial Availability/R&D Status                                                                                     | Comments                                                                                                                                    |
|-----------------------------------|------------------------------------------------------------------------------------|-------------------------------------|--------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Load Reduction (LR)               | Reduction of both fuel and air flow to burners. Or design with enlarged firebox.   | 21                                  | 32% decrease to 82% increase in (10.5% average reduction)    | Tests to 20% of rated capacity. Applicable to all units.                                                                    | Technique available. However, retrofit application is not feasible due to initial low load factor of industrial units. | Least effective on fire-tube boilers because of lower combustion intensity. Applicable for new watertube units with increased firebox size. |
| Reduced Air Preheat (RAP)         | Bypass of combustion air preheater.                                                | 2                                   | 20-55 ng/J-1/ temperature per 50K reduction in air temp.     | Applicable only on units equipped with air preheaters (large watertube units). This application is very limited.            | Technique available but not implemented because of significant loss in efficiency.                                     | Implementation would require other designs to recover loss of heat. Technique is not desirable because of loss in efficiency.               |
| Low NO <sub>x</sub> Burners (LNB) | New burner designs with controlled air/fuel mixing and increased heat dissipation. | N/A                                 | 20-50                                                        | New burners generally applicable to all boilers. More information is needed.                                                | Commercially offered but not demonstrated                                                                              | Specific emissions data from industrial boilers equipped with LNB are lacking.                                                              |
| Ammonia Injection                 | Injection of NH <sub>3</sub> as a reducing agent in the flue gas.                  | 5<br>(4 Japanese, 1 domestic)       | 40-70                                                        | Applicable for large package and field-erected watertube boilers. Not cost effective for fire-tube boilers because of size. | Commercially offered but not demonstrated                                                                              | Should be fewer problems than with coal- or oil-firing technique very costly.                                                               |

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In summary, LEA is not a uniformly effective  $\text{NO}_x$  control technique for gas-fired boilers. However, combustion with LEA remains desirable because of increased boiler efficiency.

#### 2.4.2 Staged Combustion Air (SCA)

Staged combustion air on gas-fired boilers is applied in the same manner as on oil-fired boilers. The firetube and single burner watertubes for which SCA was implemented with oil firing were also used to investigate the effectiveness of the technique for gas firing. SCA on gas-fired multiburner watertube was also investigated implementing the BOOS technique. The following sections summarize the performance, applicability and availability of the various methods of implementing SCA on the major gas-fired industrial boilers.

##### 2.4.2.1 Firetube Boilers

A schematic of the staged air injection system for firetube boilers is shown in Figure 2-7. In the EPA study,  $\text{NO}_x$  emissions were reduced 25 percent at a burner stoichiometry of 90 percent and overall excess air of 2.9 percent (Reference 2-53). Secondary air was most effective when injected downstream of the burner at a distance equivalent to 1.5 firebox diameters.

As in the case for oil-fired firetubes, more testing is needed to assess the feasibility of this technique. The probable high cost both as a retrofit and a new boiler design feature associated with the modest  $\text{NO}_x$  reductions make SCA unattractive for gas-fired firetube boilers.

##### 2.4.2.2 Packaged Watertube Boilers

$\text{NO}_x$  emissions from the "D" type watertube boiler (Figure 2-9) with staged combustion averaged 6 percent of baseline levels. The optimum location of the injected air was found to be at a distance of at least 1.2 m (4 feet) from a gas gun burner. Only marginally better  $\text{NO}_x$  reduction was achieved by increasing this distance to 2.1 m (7 feet) (References 2-20 and 2-55).

$\text{NO}_x$  reductions for the other single burner watertube boiler (Figure 2-8) averaged only approximately 30 percent when the secondary air was injected at approximately 1 m (3 feet) and 3 m (9 feet) from the burner exit plane. Injection of secondary air between 1 and 3 meters from the ring burner caused only a slight reduction in  $\text{NO}_x$  emissions (References 2-20 and 2-55).

Staged combustion was less effective for the second watertube boiler because the combustion air was preheated. The high preheat temperatures reduced the effectiveness of SCA in lowering thermal  $\text{NO}_x$ . When the primary combustion air temperature was reduced,  $\text{NO}_x$  emissions were reduced 69 percent with staged air injection (Reference 2-55). This indicates that  $\text{NO}_x$  emissions from gas-fired boilers are more sensitive to combustion air temperature than oil-fired boilers.

The same study also indicated that the type of gas burner -- gun or ring -- influenced the location of the secondary injection air for optimum  $\text{NO}_x$  reductions. For the gun type burner,  $\text{NO}_x$  emissions decreased as the air was injected further away from the burner exit plane. This reduction levels off at a distance corresponding to approximately 7 cm per thousand Joules of heat input. For the ring type burner,  $\text{NO}_x$  reduction peaked at two staged air injection locations: 0.8 and 3.0 meters approximately. These distances correspond to approximately 2 and 7 cm per thousand Joules of heat input respectively. Thus, for the ring burner, it seems that the staged air could also be injected much closer to the burner with similar  $\text{NO}_x$  reduction results (References 2-20 and 2-55).

Staged combustion air for small gas-fired watertube boilers is still at the experimental stage. If ever developed for these units, SCA will be used with new units burning oil instead of gas because the technique is more effective for the liquid fuels containing nitrogen. More pilot and field studies are necessary to confirm some of the trends described above to define safe operating limits of the technique when the boiler is operating at various loads.

#### 2.4.2.3 Multiburner Watertube

Staged combustion can be implemented on multiburner units by utilizing secondary air ports or by the BOOS method. For gas-fired boilers BOOS reduced  $\text{NO}_x$  emissions to a maximum of 30 percent by terminating the fuel flow to half of the available burners (Reference 2-20).

As in the case with oil firing the optimum BOOS selection varies for all existing boilers. Similarly, limitations such as boiler derate when many burners are set on air only are also applicable to gas-fired units as for oil-fired units. Operational impact such as corrosion and soot formation are very much reduced with gas-fired boilers.

#### 2.4.3 Flue Gas Recirculation (FGR)

Three natural gas-fired boilers were retrofitted with FGR, two by Ultrasystems (Reference 2-53) and the third by KVB (References 2-20 and 2-55). Figures 2-10 through 2-12 show schematics of the FGR system in two applications. In all cases the burner windbox was breached to install the FGR duct. The recycled flue gas was mixed with both primary and secondary air.

The firetube boiler has a gas "ring" burner embedded in the refractory throat (see Figure 2-23). Apparently, this burner permitted flue gas recirculation rates up to 55 percent without flame instability. Nitrogen oxide reductions were approximately 50 percent for 25 percent FGR and 70 percent for 50 percent FGR. Excess carbon monoxide emissions reached significant levels only at very low (less than 1.5 percent) excess  $O_2$  levels (Reference 2-53).

For the 73 MW ( $250 \times 10^6$  Btu/hr) "D" type boiler,  $NO_x$  reductions on the order of 70 percent were achieved with FGR rates as high as 45 percent. Flame stability could apparently be maintained with the typical gas fired "ring" burner installed in this watertube unit. Figure 2-24 shows a schematic of the burner (Reference 2-53).

The third package watertube boiler retrofitted with FGR was a 5 MW "D" type unit equipped with a ring burner similar to the one shown in Figure 2-24. Installation of FGR caused severe flame stability problems even at low recirculation rates. These problems were alleviated by using a gas gun burner instead of the ring type. However, flue gas recirculation rates were still limited to 20 percent. Using the gas burner,  $NO_x$  emissions were reduced 52 percent with 8 percent FGR and 75 percent with 20 percent FGR (Reference 2-55).

There seems to be no clear trend between gas burner type and flame stability with FGR. However, it is evident that FGR installation will necessitate, in most cases, extensive burner modifications to alleviate the flame instability. There is some indication that the burner shown in Figure 2-23 may not require any modification.

Flue gas recirculation for gas-fired industrial boilers is definitely available and is an effective technique. However, use of FGR may necessitate use of different burner configuration.

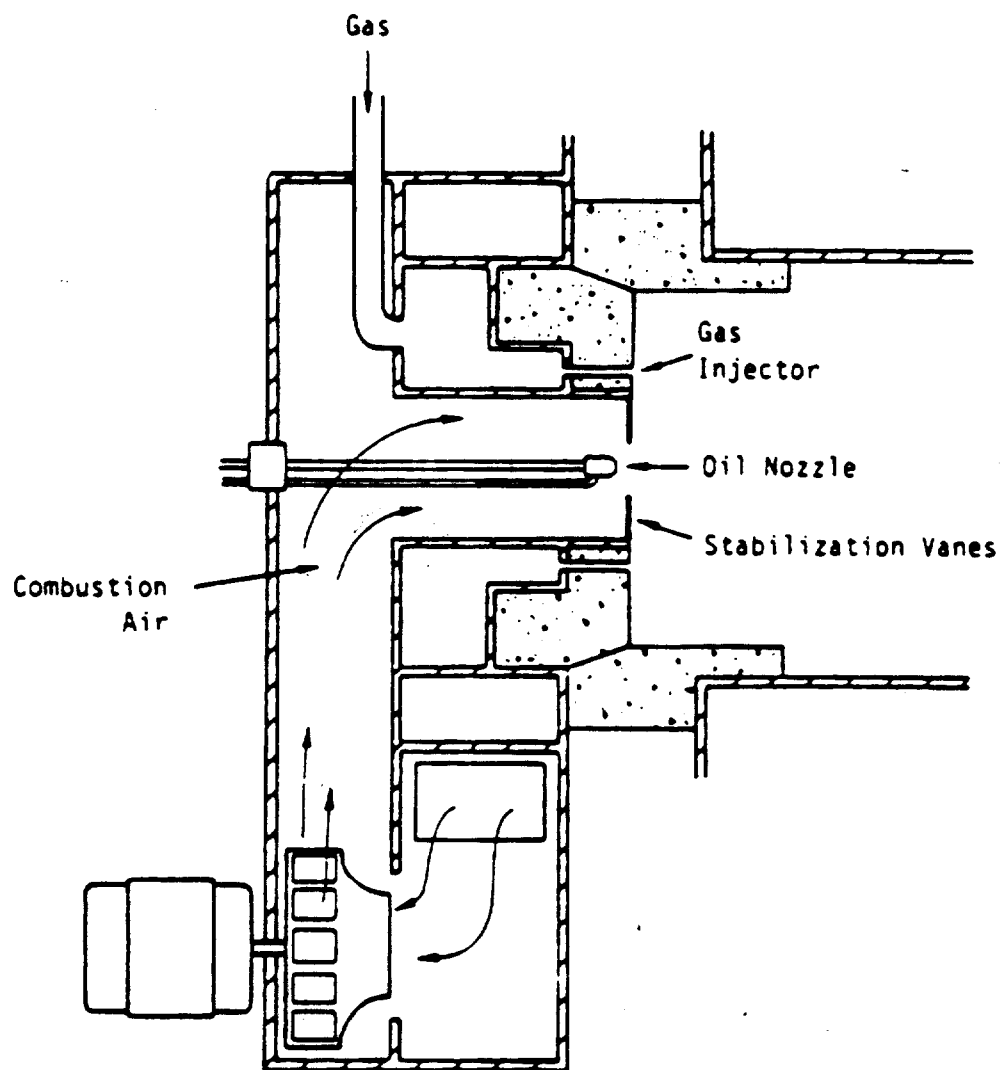


Figure 2-23. Schematic of the windbox burner arrangement of a firetube burner (Reference 2-53).



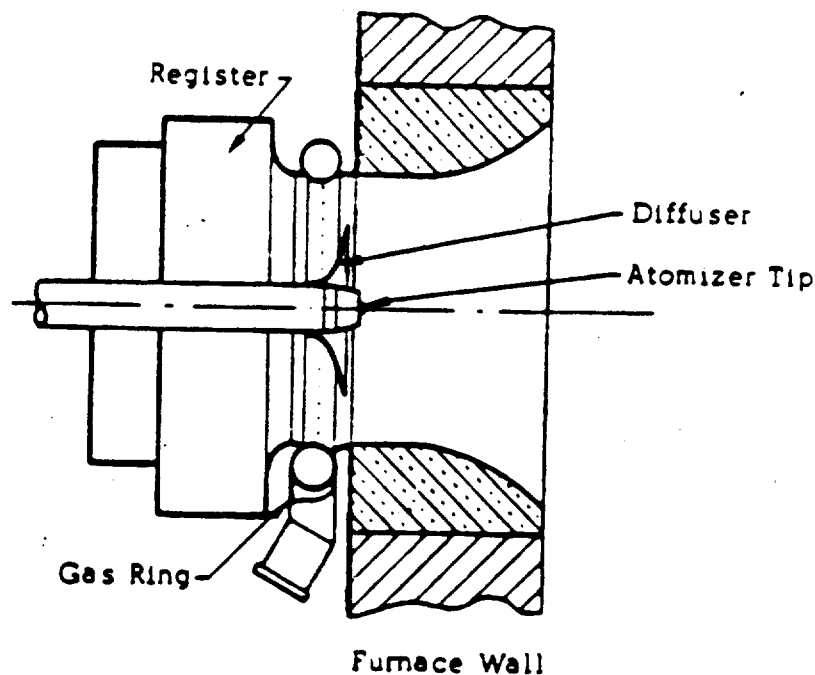


Figure 2-24. Schematic of register burner installed in a watertube boiler (Reference 2-53).

#### 2.4.4 Combined Flue Gas Recirculation and Staged Combustion

Data for natural gas are limited to only one boiler, the 5 MW ( $17.5 \times 10^6$  Btu/hr) "D" type packaged unit retrofitted with FGR and SCA in an EPA Test Program (References 2-20 and 2-55). These data indicate that the addition of staged air injection does not further decrease  $\text{NO}_x$  emissions beyond the levels achieved with FGR (76 percent).

The combined FGR and SCA does not present any operational impact in addition to those caused by the single application of either technique. There is no incentive in adding SCA to FGR when there is no additional  $\text{NO}_x$  reduction.

#### 2.4.5 Load Reduction

Load reduction gave an average  $\text{NO}_x$  emission reduction of 3.4 percent for firetubes; 6.4 percent for watertube boilers without air preheaters and 35 percent for boilers with air preheat (References 2-20

TABLE 4-11. QUANTITIES OF TRACE ELEMENTS IN WASTEWATER EMISSIONS FROM ELECTRICITY GENERATION COMBUSTION SOURCES IN 1978

| Source Category        | 1978 Emissions in Mg/Yr |       |       |      |      |      |        |      |      |       |  |
|------------------------|-------------------------|-------|-------|------|------|------|--------|------|------|-------|--|
|                        | As                      | Be    | Cd    | Cr   | Mn   | Mo   | Ni     | Se   | V    | Hg    |  |
| Ash pond overflow      | 753                     | <3.99 | 3.19  | 3.19 | 26.2 | 35.1 | 16.0   | 3.19 | 3.19 | 3.19  |  |
| Cooling tower blowdown | 2800                    | 100   | 902   | 4510 | 3010 | 2610 | 601    | 812  | 601  |       |  |
| Boiler blowdown        | 3.00                    | 0.62  | 1.27  | 1.75 | 1.81 | 2.62 | 2.93   | 1.93 | 0.19 |       |  |
| Coal pile runoff       | 3.15                    | 0.95  | <0.32 | 0.32 | 517  | --   | 46.0   | 0.13 | --   | <0.32 |  |
| Chemical cleaning      |                         |       |       |      |      |      |        |      |      |       |  |
| Acid                   | 4.49                    | 1.36  | 4.08  | 395  | 2610 | --   | 24,200 | 0.14 | --   | <1.36 |  |
| Alkaline               | 2.72                    | 1.36  | <1.36 | 1.36 | 5.44 | --   | 214    | 0.27 | --   | <1.36 |  |
| Water treatment        |                         |       |       |      |      |      |        |      |      |       |  |
| Clarification          | --                      | --    | --    | 32.1 | --   | --   | 16.8   | --   | --   | --    |  |
| Demineralization       | --                      | --    | --    | 19.5 | --   | --   | 11.6   | --   | --   | --    |  |
| Total                  | 3570                    | <110  | 914   | 5020 | 6170 | 2650 | 25,100 | 820  | 556  | 6.21  |  |

Continuing research and development effort in U.S. is directed primarily toward oil-fired burners. Commercial application of these burners is targeted for late 1979 and beyond.

#### 2.4.8 Ammonia Injection

The design and application of the ammonia injection process does not vary significantly with the fuel burned. Therefore, the basic design of the injection system shown in Figure 2-5 for a coal-fired watertube boiler is also applicable to gas-fired boilers. Application to the smaller firetube units would be similar to that of Figure 2-22, as discussed in Section 2.3.8 for oil-fired units.

The ammonia injection process is easier to operate and maintain with gas firing. This advantage is due primarily to the less severe flue gas environment from combustion of natural gas. For example, the absence of sulfur oxides eliminates the possibility of sulfate formation with unreacted ammonia. In addition, the absence of particulate emissions will reduce the maintenance of the injection grid to remove accumulated deposits. Finally, gas-fired boilers do not produce water wall deposits like those in coal- and residual oil-fired boilers and thus the fluctuation in flue gas temperatures caused by these deposits is eliminated.

Ammonia injection is a control technology which is commercially offered but not demonstrated. The effectiveness varies from 40 to 70 percent  $\text{NO}_x$  reduction depending on the application (Figure 2-21). As in the case of oil-fired units, ammonia injection will probably not be suitable for small units such as firetubes and package watertubes because of the significant incremental cost to the equipment and to its operation. In addition, many small units operate at continuously changing loads depending on plant steam demand. The variation in load will cause temperature fluctuations which degrade the performance of the process.

## REFERENCES FOR SECTION 2

- 2-1. "Electric Utility Steam Generating Units, Proposed Standards of Performance and Announcement of Public Hearings on Proposed Standards," Federal Register 43 (182), September 19, 1978.
- 2-2. "Task 2 Summary Report -- Preliminary Summary of Industrial Boiler Population," prepared by PEDCo in support of OAQPS work on NSPS for industrial boilers, June 29, 1978. Also Section 3 of Task 2 Report, "The Industrial Steam Generator Industry," August 1978.
- 2-3. "Task 7 Summary Report -- Technical and Economic Bases for Evaluation of Emission Reduction Technology," prepared by PEDCo in support of OAQPS work on NSPS for industrial boilers, June 2, 1978. Also as revised August 3, 1978.
- 2-4. Cato, G. A., et al., "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers -- Phase I," EPA-600/2-74-078a, NTIS-PB 238 920/AS, October 1974.
- 2-5. Zeldovich, J., "The Oxidation of Nitrogen in Combustion and Explosions," Acta Physicochim, U.S.S.R. (Moscow), Vol. 21, pp. 4, 1946.
- 2-6. Mackinnon, D. J., "Nitric Oxide Formation at High Temperature," Journal of the Air Pollution Control Association, Vol. 24, No. 3, March 1974.
- 2-7. Bartz, D. R., et al., "Control of Oxides of Nitrogen from Stationary Sources in the South Coast Air Basin," California ARB 2-1471, September 1974.
- 2-8. Shaw, J. T., and A. C. Thomas, "Oxides of Nitrogen in Relation to the Combustion of Coal," presented at the Seventh International Conference on Coal Science, Prague, June 1968.
- 2-9. Pershing, D. W., et al., "Influence of Design Variables on the Production of Thermal and Fuel NO from Residual Oil and Coal Combustion," AIChE Symposium Series, No. 148, Vol. 71, pp. 12-29, 1975.
- 2-10. Mason, H. B., et al., "Preliminary Environmental Assessment of Combustion Modification Techniques: Volume II. Technical Results," EPA-600/7-77-119b, NTIS-PB 276 681/AS, October 1977.
- 2-11. Pohl, J. H., and A. F. Sarofim, "Devolatilization and Oxidation of Coal Nitrogen," presented at 16th International Symposium on Combustion, M.I.T., Cambridge, Massachusetts, August 1976.

- 2-12. United States Senate, Committee on Public Works, "Air Quality and Stationary Source Emissions Control," Serial No. 94-4, March 1975.
- 2-13. Habelt, W. W., and B. M. Howell, "Control of NO Formation in Tangentially Coal-Fired Steam Generators," in Proceedings of the NO<sub>x</sub> Control Technology Seminar, EPRI SR-39, NTIS-PB 253 611, February 1976.
- 2-14. Pershing, D. W. and J. O. L. Wendt, "The Effect of Coal Combustion on Thermal and Fuel NO<sub>x</sub> Production from Pulverized Coal Combustion," presented at Central States Section, The Combustion Institute, Columbus, Ohio, April 1976.
- 2-15. Pershing, D. W., "Nitrogen Oxide Formation in Pulverized Coal Flames," PhD Dissertation, University of Arizona, 1976.
- 2-16. Pohl, J. H. and A. F. Sarofim, "Fate of Coal Nitrogen During Pyrolysis and Oxidation," in Proceedings of the Stationary Source Combustion Symposium, Vol. I, Fundamental Research, EPA 600/2-76-152a, NTIS-PB 256 320/AS, June 1976.
- 2-17. Giammar, R. D. and R. B. Engdahl, "Technical, Economic and Environmental Aspects of Industrial Stoker -- Fuel Boilers," presented at 71st Annual Meeting of the Air Pollution Control Association, Houston, Texas, June 25-30, 1978.
- 2-18. Hunter, S. C. and J. J. Buening, "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers -- Phase I and II (Data Supplement)," EPA-600/2-77-122, NTIS-PB 270 112/6BE, June 1977.
- 2-19. Maloney, K. L., et al., "Low Sulfur Western Coal Use in Existing Small and Intermediate Size Boilers," EPA-600/7-78-153a, NTIS-PB 287-937/AS, July 1978.
- 2-20. Cato, G. A., et al., "Field Testing: Application of Combustion Modification to Control Pollutant Emissions from Industrial Boilers -- Phase II," EPA-600/2-76-086a, NTIS-PB 253 500/AS, April 1976.
- 2-21. Gabrielson, J. E., et al., "Field Test of Industrial Stoker Coal-Fired Boilers for Emissions Control and Efficiency Improvement -- Site A," EPA-600/7-78-136a, NTIS-PB 285-172/AS, July 1978.
- 2-22. Harstine, G. E., and D. C. Williams, "Industrial Pulverized Coal-Fired Boiler Designed to Meet Today's Challenge," paper presented at American Power Conference, Chicago, Illinois, April 24-26, 1978.

- 2-23. Schwieger, R. G., et al., "Plant Design Today -- A New Challenge," Power Magazine, pp. 34, November 1976.
- 2-24. Lim, K. J., et al., "Environmental Assessment of Utility Boiler Combustion Modification NO<sub>x</sub> Controls," Acurex Draft Report TR-78-105, EPA Contract No. 68-02-2160, April 1978.
- 2-25. Campobenedetto, E. J., Babcock & Wilcox Co., Letter to K. J. Lim, Acurex Corporation, November 15, 1977.
- 2-26. Rawdon, A. H. and S. A. Johnson, "Control of NO<sub>x</sub> Emissions from Power Boilers," presented at Annual Meeting of the Institute of Fuel, Adelaide, Australia, November 1974.
- 2-27. Brackett, C. E. and J. A. Barsin, "The Dual Register Pulverized Coal Burner, a NO<sub>x</sub> Control Device," in Proceedings of the NO<sub>x</sub> Control Technology Seminar, EPRI SR-39, NTIS-PB 253 661, February 1976.
- 2-28. Campobenedetto, E. J., "The Dual Register Pulverized Coal Burner -- Field Test Results," presented to Engineering Foundation Conference on Clean Combustion of Coal, New Hampshire, July 31 - August 5, 1977.
- 2-29. Vatsky, J. and R. P. Walden, "NO<sub>x</sub> -- A Progress Report," Heat Engineering, Volume 47, No. 8, July-September 1976.
- 2-30. Vatsky, J., "Attaining Low NO<sub>x</sub> Emissions by Combining Low Emission Burners and Off-Stoichiometric Firing," presented at the 70th Annual AIChE Meeting, New York, November 15, 1977.
- 2-31. Gershman, R., et al., "Design and Scale-up of Low Emission Burners for Industrial and Utility Boilers," in Proceedings of the Second Stationary Source Combustion Symposium Vol. V, Addendum, EPA-600/7-77-073e, NTIS-PB 274 897/AS, July 1977.
- 2-32. "Low NO<sub>x</sub> Burner Development," in NO<sub>x</sub> Control Review, D. G. Lachapelle, ed., Volume 3, No. 2, pp. 1, Spring 1978.
- 2-33. Fletcher, R. J., Peabody Engineering Corp., Telecommunication with R. S. Merril, Acurex Corp., July 21, 1978.
- 2-34. Norton, D. M., et al., "Status of Oil-Fired NO<sub>x</sub> Control Technology," in Proceedings of the NO<sub>x</sub> Control Technology Seminar, EPRI SR-39, NTIS-PB 253 661, February 1976.
- 2-35. Thompson, R. E., and M. W. McElroy, "Effectiveness of Gas Recirculation and Staged Combustion in Reducing NO<sub>x</sub> on a 560-MW Coal-Fired Boiler," EPRI FP-257, NTIS-PB 260 582, September 1976.

- 2-36. Lyon, R. K., "Method for the Reduction of Concentrations on NO in Combustion Effluents Using Ammonia," United States Patent No. 3,900,554, August 1975.
- 2-37. Muzio, L. J., et al., "Homogenous Gas Phase Decomposition of Oxides of Nitrogen," EPRI Report FP-253, NTIS-PB 257 555, August 1976.
- 2-38. "Non-Catalytic NO<sub>x</sub> Reduction Process Applied to Large Utility Boilers," Mitsubishi Heavy Industries, Ltd., November 1977.
- 2-39. Bartok, W., "Non-Catalytic Reduction of NO<sub>x</sub> with NH<sub>3</sub>" Proceedings of the Second Stationary Source Combustion Symposium Volume II, EPA-600/7-77-073b, NTIS-PB 271 756, July 1977.
- 2-40. Muzio, L. J., et al., "Non-Catalytic NO Removal with Ammonia," EPRI Final Report FP-735, Research Project 835-1, April 1978.
- 2-41. Lyon, R. K., and J. P. Longwell, "Selective Non-Catalytic Reduction of NO<sub>x</sub> by NH<sub>3</sub>," in Proceedings of the NO<sub>x</sub> Control Technology Seminar, EPRI SR-39, NTIS-PB 253 661, February 1976.
- 2-42. Copeland, J. O., Draft of "Standards Support and Environmental Impact Statement, Volume I: Proposed Standards of Performance for Electric Utility Steam Generating Units (Nitrogen Oxides)," EPA, December 1977.
- 2-43. Broz, L. D., Acurex Corp., Trip Report to D. Blann, Acurex Corp., Tour of Babcock & Wilcox Co. plant in Wilmington, N.C. arranged by ABMA and EPA/IERL-RTP, September 21, 1978.
- 2-44. Giammar, R. D., Battelle Columbus Laboratory, Columbus, Ohio, Telecommunication with H. I. Lips, Acurex Corp., July 19, 1978.
- 2-45. Axtman, W. H., ABMA, Arlington, Va., Telecommunication with H. I. Lips, Acurex Corp., July 21, 1978.
- 2-46. Broz, L. D., Acurex Corp., Raleigh, N.C., Telecommunication with H. I. Lips, Acurex Corp., Mtn. View, Ca., July 21, 1978.
- 2-47. Jordan, J., Worley Equipment Inc., Chicago, Ill., Telecommunication with H. I. Lips, Acurex Corp., July 18, 1978.
- 2-48. Reschly, Detroit Stoker Co., Monroe, Michigan, Telecommunication with H. I. Lips, Acurex Corp., July 18, 1978.
- 2-49. Higginbotham, E. B., Acurex Corp., Unpublished data supplied to H. I. Lips, Acurex Corp., December 1978.
- 2-50. Fennelly, P. F., et al., "Screening Study to Obtain Information Necessary for the Development of Standards of Performance for Solid-Fueled Boilers ( 63 x 10<sup>6</sup> kcal/hr Input)," GCA-TR-76-23-G, July 1976.

- 2-51. Locklin, D. W., et al., "Design Trends and Operating Problems in Combustion Modification of Industrial Boilers," EPA-650/2-74-032, NTIS-PB 235 712, April 1974.
- 2-52. Heap, M. P., et al., "Reduction of Nitrogen Oxide Emissions from Field Operating Package Boilers, Phase III," EPA-600/2-77-025, NTIS-PB 269 277, January 1977.
- 2-53. Cichanowicz, J. E., et al., "Pollutant Control Technique for Packaged Boilers. Phase I, Hardward Modifications and Alternate Fuels," Ultrasystems Draft Report, EPA Contract No. 68-02-1498, November 1976.
- 2-54. Muzio, L. J., et al., "Package Boiler Flame Modification for Reducing Nitric Oxide Emissions -- Phase II of III," EPA-R2-73-292, NTIS-PB 236 752/2BA, June 1974.
- 2-55. Carter, W. A., et al., "Emissions Reduction on Two Industrial Boiler with Major Combustion Modifications," EPA 600/7-78-099a, NTIS-PB 283 109, June 1978.
- 2-56. Morton, W., E. Keeler Co., Williamsport, Pa., Telecommunication with R. J. Milligan, Acurex Corp., July 26, 1978.
- 2-57. Hester, C., Acurex Corp., Raleigh, N.C., Trip Report to D. Blann, Acurex Corp., Raleigh, N.C., Tour of E. Keeler Co. plant in Williamsport, Pa., September 20, 1978.
- 2-58. Cato, G. A., et al., "Reference Guideline for Industrial Boiler Manufacturers to Control Pollution with Combustion Modification," EPA-600/8-77-003b, NTIS-PB 276 715/AS, November 1977.
- 2-59. Schwieger, B., "Industrial Boilers: What's Happening Today," Power Magazine, Vol. 121, No. 2 pp. S.1-S.24, February 1977 and Vol. 122, No. 2 pp. S.1-S.24, February 1978.
- 2-60. Ando, J., et al., "NO<sub>x</sub> Abatement for Stationary Sources in Japan," EPA-600/7-77-103b, NTIS-PB 276 948/AS, September 1977.
- 2-61. Koppang, R. R., "A Status Report on the Commercialization and Recent Development History of the TRW Low NO<sub>x</sub> Burner," TRW Internal Report, January 1976.
- 2-62. Ando, J., et al., "NO<sub>x</sub> Abatement for Stationary Source in Japan," EPA-600/2-76-013b, NTIS-PB 250 586/AS, January 1976.
- 2-63. Koppang, R. R., TRW, Inc., Redondo Beach, California, Telecommunication with R. S. Merrill, Acurex Corp., July 21, 1978.
- 2-64. Ando, J., et al., "Nitrogen Oxide Abatement Technology in Japan -- 1973," EPA-R2-73-284, NTIS-PB 222 143, June 1974.



- 2-65. Kido, N., Japan National Research Institute for Pollution and Resources, Unpublished data supplied to K. J. Lim, Acurex Corp., August 1978.
- 2-66. Fenimore, C. P., "Formation of Nitric Oxide in Premixed Hydrocarbon Flames," Proceedings of the 13th Symposium (International) on Combustion, The Combustion Institute, Pittsburg, Pa., 1971.
- 2-67. Eaton, S., Coen Company, Telecommunications with R. S. Merrill, Acurex Corp., July 10, 1978 and August 8, 1978.
- 2-68. Cichanowicz, J. E., et al., "NO<sub>x</sub> Control Techniques for Package Boiler: Comparison of Burner Design, Fuel Modification and Combustion Modification," in Proceedings of the Second Stationary Source Combustion Symposium, EPA-600/7-77-073e, NTIS-PB 274 897/AS, July 1977.
- 2-69. Air and Water Pollution Report, "Exxon Corp. Stationary NO<sub>x</sub> Emissions Significantly Reduced at Plant," February 20, 1978.
- 2-70. Barsin, J. A., "Pulverized Coal Firing NO<sub>x</sub> Control," presented at Second EPRI NO<sub>x</sub> Control Technology Seminar, Denver, Colorado, November 8-9, 1978.
- 2-71. Commercial Application of Exxon Thermal DeNO<sub>x</sub> Process, Sales Brochure, Exxon Inc., 1978.
- 2-72. Habelt, W. W., "The Influence of the Coal Oxygen to Coal Nitrogen Ratio on NO<sub>x</sub> Formation," presented at the 70th Annual AIChE Meeting, New York, November 13-17, 1977.
- 2-73. Marshall, J. J., and A. P. Selker, "The Role of Tangential Firing and Fuel Properties in Attaining Low NO<sub>x</sub> Operation for NO<sub>x</sub> Control Technology Seminary, Denver, Colorado, November 8-9, 1978.
- 2-74. Krippene, B. C., "Burner and Boiler Alternations for NO<sub>x</sub> Control," presented to Central States Section, The Combustion Institute, Madison Wisconsin, March 26-27, 1974.
- 2-75. Barr, W. H., et al., "Modifying Large Boilers to Reduce Nitric Oxide Emissions, Chem. Eng. Prog., Vol. 73, pp. 59-68, July 1977.
- 2-76. Castaldini, C., et al., "Technical Assessment of Exxon's Thermal DeNO<sub>x</sub> Process," Acurex Final Report 79-301, EPA Contract 68-02-2611, April 1979.
- 2-77. Boughton, M., TRW, Inc., Redondo Beach, CA, Telecommunication with K. J. Lim, Acurex Corp., May 21, 1979.
- 2-78. Matthews, B. J., TRW, Inc., Redondo Beach, CA, letter to W. Peters, EPA, IERL-RTP, NC, March 23, 1979.

- 2-79. Martin, G. B., "Field Evaluation of Low NO<sub>x</sub> Coal Burners on Industrial and Utility Boilers," in Proceedings of the Third Stationary Source Symposium, Volume I, EPA-600/7-79-050a, February 1979.

## SECTION 3

### CANDIDATES FOR BEST SYSTEMS OF EMISSION REDUCTION

This section identifies and discussed alternative combustion modification control techniques capable of achieving moderate, intermediate, and stringent levels of  $\text{NO}_x$  control. These control levels are based on uncontrolled baseline emission levels and the capabilities of combustion modification controls. Candidate systems of emission reduction may involve either single or combined applications of the techniques characterized in Section 2. The selection of candidate control systems for each industrial boiler/fuel category was based on an assessment of the effectiveness, commercial availability or R&D status, operational impact and reliability of each control system. Energy, environmental, and cost impacts are also considered; however detailed evaluation is deferred to later sections of this report.

#### 3.1 CRITERIA FOR SELECTION

In selecting the best system of  $\text{NO}_x$  emission reduction, many factors have to be considered, including

- Control effectiveness and applicability
- Reliability and availability
- Process impacts
- Environmental impacts
- Capital and operating costs, including energy impacts

The effectiveness of controls in reducing  $\text{NO}_x$  emissions, and their applicability to industrial boilers as well as their reliability, were used to select preliminary candidate control systems. Techniques were considered if they were expected to be available for new boilers sold in 1983 or sooner (Reference 3-1). Performance data for these preliminary candidates were than carefully reviewed to identify any demonstrated or

expected process or environmental impacts. For example, major impacts such as severe derating of the boiler can make a control option no longer viable. Environmental impacts were evaluated through the analysis of measured or postulated incremental emissions, other than  $\text{NO}_x$ , when controls are implemented. Finally, capital and operating costs, including energy impacts, were considered. These costs were used to decide between favorable alternative control options, or in the case of costly but highly effective techniques, to defer application until stringent control levels are absolutely necessary.

All of the above listed factors were considered by evaluating detailed field test results when available and through discussions with major equipment manufacturers and users, and control R&D groups.

In the ensuing discussion of emission control technologies, candidate technologies were compared using three emission control levels labelled "moderate, intermediate, and stringent." These control levels were chosen only to encompass all candidate technologies and form bases for comparison of technologies for control of specific pollutants considering performance, costs, energy, and environmental effects.

From these comparisons, candidate "best" technologies for control of individual pollutants are recommended for consideration in subsequent industrial boiler studies. These "best technology" recommendations do not consider combinations of technologies to remove more than one pollutant and have not undergone the detailed environmental, cost, and energy impact assessments necessary for regulatory action. Therefore, the levels of "moderate, intermediate, and stringent" and the recommendation of "best technology" for individual pollutants are not to be construed as indicative of the regulations that will be developed for industrial boilers. EPA will perform rigorous examination of several comprehensive regulatory options before any decisions are made regarding the standards for emissions from industrial boilers.

Two factors were primarily considered in selecting these levels of control. The first criterion is the baseline uncontrolled emission level for each industrial boiler/fuel category. The second is the recorded or estimated  $\text{NO}_x$  reduction effectiveness of each combustion modification control. Careful consideration of the uncontrolled baseline  $\text{NO}_x$  level

and the percent reduction in emissions that is attributable to selected control systems determines the degree of control.

Baseline emission factors are extremely important because they ultimately determine what control levels are achievable and which control are appropriate. For example, if a conservative or high baseline emission level is used, then the selected control levels based on reported  $\text{NO}_x$  reduction will also be conservative and easier to obtain. On the other hand, if a low baseline  $\text{NO}_x$  level is used, a selected moderate control level may prove difficult to achieve. As a review of the limited emission data will show (see Section 7), baseline (and controlled) emissions levels were quite variable in some cases and well defined in other cases. So the general caution is that the baseline (and controlled) emission levels should be considered only tentative because of the limited data. However, it should be noted that the moderate control levels suggested here for the boiler/fuel categories considered are generally conservative in the sense that demonstrated control techniques have, in specific instances, achieved controlled  $\text{NO}_x$  levels lower than the suggested moderate levels.

Table 3-1 lists the baseline  $\text{NO}_x$  emission factors selected after review of all available data. The table also compares these selected levels to the previously suggested emission factors (Reference 3-29) contained in EPA Document AP-42 (Reference 3-2). Emissions data for pulverized coal-fired industrial boilers are limited to six units (References 3-3 through 3-5). These emissions ranged from 174 ng/J to 563 ng/J and the size of the units ranged from 47 MW to 147 MW (160 to 500 x  $10^6$  Btu/hr) of heat input<sup>a</sup>. There was no general correlation between  $\text{NO}_x$  emission levels and boiler size/type or coal characteristics.

The  $\text{NO}_x$  emission levels given in AP-42 (Reference 3-2) for coal-fired stokers consist of only one number (273 ng/J) which was derived from data on spreader stokers only. That number is in good agreement with the  $\text{NO}_x$  baseline level (265 ng/J) selected in this study for spreader stokers, as shown in Table 3-1. However, the AP-42 number is in very poor agreement with the reported averages for the underfeed and the chain grate

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<sup>a</sup>Note:  $\text{NO}_x$  emission data discussed in this report are all listed in Section 7, along with boiler and fuel characteristics.

TABLE 3-1. COMPARISON OF BASELINE NO<sub>x</sub> EMISSION LEVELS

| Fuel                      | Boiler Type                   | Typical Size<br>(Heat Input<br>Capacity)<br>MM(10 <sup>6</sup> Btu/hr) | No. of<br>Boilers<br>Tested | Average<br>NO <sub>x</sub> Baseline<br>Emission Level<br>mg NO <sub>2</sub> /J(1b/10 <sup>6</sup> Btu) | AP-42 (Ref. 3-2)<br>NO <sub>x</sub> Baseline<br>Emission Level<br>mg NO <sub>2</sub> /J(1b/10 <sup>6</sup> Btu) | Sources of Data<br>Used for<br>Selected Baseline<br>Emissions |
|---------------------------|-------------------------------|------------------------------------------------------------------------|-----------------------------|--------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| Pulverized Coal           | Single Wall<br>and Tangential | 59(200)<br>114(400)                                                    | 4<br>2                      | 285(0.663)<br>285(0.663)                                                                               | 328(0.763)<br>328(0.763)                                                                                        | Ref. 3-3, 3-4, 3-5<br>Ref. 3-3, 3-4, 3-5                      |
| Stoker Coal               | Spreader                      | 44(150), 25(85)                                                        | 7,5                         | 265(0.616)                                                                                             | 273(0.635)                                                                                                      | Ref. 3-2 through 3-6                                          |
|                           | Underfeed                     | 9(30)                                                                  | 2                           | 150(0.349)                                                                                             | 273(0.635)                                                                                                      | Ref. 3-3                                                      |
|                           | Chain Grate                   | 22(75)                                                                 | 2                           | 140(0.326)                                                                                             | 273(0.635)                                                                                                      | Ref. 3-4, 3-5                                                 |
| Residual Oil <sup>a</sup> | Firetube                      | 4.4(15)                                                                | 5                           | 115(0.267)                                                                                             | --                                                                                                              | Ref. 3-3, 3-4, 3-8                                            |
|                           | Watertube                     | 8.8(30)                                                                | 10                          | 160(0.372)                                                                                             | 171(0.398)                                                                                                      | Ref. 3-3, 3-4, 3-8, 3-9                                       |
|                           | Watertube                     | 44(150)                                                                | 7                           | 160(0.372)                                                                                             | 171(0.398)                                                                                                      | Ref. 3-3, 3-4                                                 |
| Distillate Oil            | Firetube                      | 4.4(15)                                                                | 6                           | 75(0.175)                                                                                              | 68(0.158)                                                                                                       | Ref. 3-3, 3-4                                                 |
|                           | Watertube                     | 29(100)                                                                | 4,3                         | 55 <sup>b</sup> , 90 <sup>c</sup> (0.128 <sup>b</sup> , 0.209 <sup>c</sup> )                           | --                                                                                                              | Ref. 3-3, 3-4, 3-9                                            |
|                           | Watertube                     | 44(150)                                                                | 1                           | 90 <sup>c</sup> (0.209 <sup>c</sup> )                                                                  | --                                                                                                              | Ref. 3-3, 3-4                                                 |
| Natural Gas               | Firetube                      | 4.4(15)                                                                | 8                           | 40(0.093)                                                                                              | 75(0.174)                                                                                                       | Ref. 3-3, 3-4, 3-10                                           |
|                           | Watertube                     | 29(100)                                                                | 9,11                        | 45 <sup>b</sup> , 110 <sup>c</sup> (0.105 <sup>b</sup> , 0.255 <sup>c</sup> )                          | --                                                                                                              | Ref. 3-3, 3-4, 3-9                                            |
|                           | Watertube                     | 44(150)                                                                | 7                           | 120 <sup>c</sup> (0.280) <sup>c</sup>                                                                  | --                                                                                                              | Ref. 3-3, 3-4                                                 |

<sup>a</sup>Includes No. 5 and No. 6 fuel oils.  
<sup>b</sup>From boilers not equipped with air preheaters.  
<sup>c</sup>From boilers equipped with air preheaters.

units. This stands to reason as spreader stokers are known to be higher  $\text{NO}_x$  emitters than underfeed units (Reference 3-3). This study incorporates new data made available since Document AP-42 and updates were published.

All other selected  $\text{NO}_x$  baseline emission data generally agree with the AP-42 emission levels except that for natural gas-fired firetube boilers which show a difference of 35 ng/J. This disparity is due to two reasons. The first is that Document AP-42 gives a range for natural gas-fired firetube boilers and the final value chosen by that document is from the high end of that range. The second reason is that the AP-42 emission factor is derived from a more limited data base than that reviewed in this study. This, as well as other emission data, is well documented in Section 7 of this report.

The  $\text{NO}_x$  emission factors selected in this study agree with the results for industrial boilers from a recent study to update EPA Document AP-42 emission factors (Reference 3-14).

In addition to the original seven standard boiler/fuel categories recommended by PEDCo (Reference 3-28), three other categories were considered: residual oil-fired firetube boilers and distillate oil- and gas-fired watertube boilers. Furthermore, for the latter two categories, a distinction was made between boilers equipped with air preheaters and those that are not. The baseline  $\text{NO}_x$  emissions for these three additional categories are clearly different from the original seven; therefore they should be treated separately when assessing the feasibility of reducing emissions to a predetermined control level. Finally, four additional size variations of the above 10 standard boiler/fuel categories were requested by EPA to further aid in the economic assessment of controls, bringing the total boiler/fuel cases treated to 14 (Reference 3-32).

With the baseline emission levels of each industrial boiler/fuel category established (to the extent possible as limited data permitted), the capabilities of the available control techniques were carefully reviewed to select the best control options and establish achievable control levels. Tables 3-2 through 3-5 summarize the performance of the candidate control systems for pulverized coal-, stoker coal-, residual oil-, distillate oil-, and gas-fired boilers, respectively. These

TABLE 3-2. CANDIDATES FOR BEST SYSTEMS OF NO<sub>x</sub> EMISSIONS REDUCTION:  
PULVERIZED COAL-FIRED BOILERS

| Technique                    | Effectiveness <sup>a</sup><br>(% NO <sub>x</sub> Reduction) | Operational Impact                                                                                                                   | Cost Impact <sup>b</sup>                                        | Environmental Impact                                  | Availability                                                            |
|------------------------------|-------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------------------------|
| Low Excess Air               | 5 - 25                                                      | Increased boiler efficiency.                                                                                                         | Increased efficiency offsets capital and operating costs.       | Possible increased CO and organic emissions.          | Available                                                               |
| Overfire Air                 | 5 - 30                                                      | Possible increased slagging, corrosion. Perhaps slight decrease in boiler efficiency.                                                | Major modification. Marginal increase in cost for new units.    | Possible increased particulate and organic emissions. | Commercially offered but not demonstrated for this boiler/fuel category |
| Reduced Combustion Intensity | 5 - 25                                                      | None. Best implemented as increased furnace plan area in new designs.                                                                | Major modification. Marginal increase in cost for new units.    | None                                                  | Technology transfer required from utility industry                      |
| Low NO <sub>x</sub> Burners  | 45 - 60                                                     | None expected.                                                                                                                       | Potentially most cost-effective.                                | None expected.                                        | 1981 - 1983 <sup>c</sup>                                                |
| NH <sub>3</sub> Injection    | 40 - 60                                                     | Possible implementation difficulties. Fouling problems with high sulfur fuels, load restrictions. Close operator attention required. | Several fold higher than conventional combustion modifications. | Possible emissions of NH <sub>3</sub> and byproducts. | Commercially offered but not demonstrated                               |

<sup>a</sup>Effectiveness based on control applied singly

<sup>b</sup>Incremental cost impact noting capacity/cost of boiler to which control is applied.

<sup>c</sup>References 2-79, 3-30



TABLE 3-3. CANDIDATES FOR BEST SYSTEMS OF NO<sub>x</sub> EMISSIONS REDUCTION:  
STOKER COAL-FIRED BOILERS

| Technique                 | Effectiveness <sup>a</sup><br>(% NO <sub>x</sub> Reduction) | Operational Impact                                                                                                                                   | Cost Impact <sup>b</sup>                                                                             | Environmental Impact                                       | Availability                              |
|---------------------------|-------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|------------------------------------------------------------|-------------------------------------------|
| Low Excess Air            | 5 - 25                                                      | Possible grate overheating, clinker formation, increased corrosion. Close operator attention required.                                               | Increased efficiency should partially offset costs.                                                  | Possible increased CO, organic, and particulate emissions. | Available                                 |
| Overfire Air              | 5 - 25                                                      | Possible grate overheating, clinker formation, increased corrosion. Close operator attention required. Perhaps slight decrease in boiler efficiency. | Major modification of grate and OFA, probably costly. Present units have OFA for smoke control only. | Possible increased CO, organic, and particulate emissions. | R&D                                       |
| NH <sub>3</sub> Injection | 40 - 60                                                     | Possible implementation difficulties. Fouling problems with high sulfur fuels, load restrictions. Close operator attention required.                 | Several fold higher than conventional combustion modifications.                                      | Possible emissions of NH <sub>3</sub> and byproducts.      | Commercially offered but not demonstrated |

<sup>a</sup> Effectiveness based on control applied singly.

<sup>b</sup> Incremental cost impact noting capacity/cost of boiler to which control is applied.

TABLE 3-4. CANDIDATES FOR BEST SYSTEMS OF NO<sub>x</sub> EMISSIONS REDUCTION:  
RESIDUAL OIL-FIRED BOILERS

| Technique                   | Effectiveness <sup>a</sup><br>(% NO <sub>x</sub> Reduction) | Operational Impact                                                                                                                   | Cost Impact <sup>b</sup>                                       | Environmental Impact                                  | Availability                                                            |
|-----------------------------|-------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------------------------|
| Low Excess Air              | 5 - 20                                                      | Increased boiler efficiency.                                                                                                         | Increased efficiency partially offsets costs.                  | Possible increased CO and organic emissions.          | Available                                                               |
| Staged Combustion           | 20 - 40                                                     | Perhaps slight decrease in boiler efficiency.                                                                                        | Major modification, perhaps costly.                            | Possible increased particulate and organic emissions. | Commercially offered but not demonstrated for this boiler/fuel category |
| Low NO <sub>x</sub> Burners | 20 - 50                                                     | None expected.                                                                                                                       | Potentially most cost-effective.                               | None expected.                                        | Commercially offered but not demonstrated                               |
| NH <sub>3</sub> Injection   | 40 - 70                                                     | Possible implementation difficulties. Fouling problems with high sulfur fuels, load restrictions. Close operator attention required. | Several fold higher than conventional combustion modification. | Possible emissions of NH <sub>3</sub> and byproducts. | Commercially offered but not demonstrated                               |

<sup>a</sup> Effectiveness based on control applied singly.

<sup>b</sup> Incremental cost impact noting capacity/cost of boiler to which control is applied.

TABLE 3-5. CANDIDATES FOR BEST SYSTEMS OF NO<sub>x</sub> EMISSIONS REDUCTION:  
DISTILLATE OIL- AND GAS-FIRED BOILERS

| Technique                      | Effectiveness <sup>a</sup><br>(% NO <sub>x</sub> Reduction) | Operational Impact                                                                   | Cost Impact <sup>b</sup>                                                 | Environmental Impact                            | Availability                                                               |
|--------------------------------|-------------------------------------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------|-------------------------------------------------|----------------------------------------------------------------------------|
| Low Excess Air                 | 5 - 15 (oil),<br>5 - 10 (gas)                               | Increased boiler efficiency.                                                         | Increased efficiency should<br>offset some of costs.                     | Possible increased CO<br>and organic emissions. | Available                                                                  |
| Staged<br>Combustion           | 20 - 40 (oil),<br>25 - 45 (gas)                             | Perhaps slight decrease in<br>boiler efficiency.                                     | Major modification, probably<br>costly.                                  | Possible increased<br>organic emissions.        | Commercially offered but not demonstrated<br>for this boiler/fuel category |
| Flue Gas<br>Recirculation      | 40 - 70 (oil)<br>45 - 75 (gas)                              | Possible flame instability.<br>Can be eliminated with proper<br>engineering/testing. | Major modification, probably<br>costly.                                  | Possible increased<br>organic emissions.        | Available                                                                  |
| Reduced Air<br>Preheat         | 20 - 55 (oil)<br>20 - 55 (gas)                              | Replacing air preheater with<br>economizer in new designs.                           | None, other than engineering<br>redesign of new units (if<br>necessary). | None                                            | Available                                                                  |
| Low NO <sub>x</sub><br>Burners | 20 - 50                                                     | None expected.                                                                       | Potentially most cost-<br>effective.                                     | None expected.                                  | Commercially offered but not demonstrated                                  |

<sup>a</sup> Effectiveness based on control applied singly.

<sup>b</sup> Incremental cost impact noting capacity/cost of boiler to which control is applied.

TABLE 5-7. TRACE ELEMENT COLLECTION EFFICIENCIES FOR FABRIC FILTERS<sup>a</sup>

| Element         | Collection Efficiency, % |                       |  |
|-----------------|--------------------------|-----------------------|--|
|                 | Method 5 <sup>b</sup>    | Impactor <sup>c</sup> |  |
| As              | 99.94                    | 99.94                 |  |
| Be              | NR <sup>d</sup>          | NR                    |  |
| Cd              | NR                       | NR                    |  |
| Cr <sup>e</sup> | 99.70                    | 99.94                 |  |
| Hg <sup>e</sup> | 67.14                    | >99.77                |  |
| Mn              | 99.94                    | 99.78                 |  |
| Mo              | NR                       | NR                    |  |
| Ni <sup>e</sup> | 99.51                    | >99.71                |  |
| Se <sup>e</sup> | 93.41                    | 99.40                 |  |
| V               | 99.95                    | 99.77                 |  |
| Ash             | 99.63                    | 99.68                 |  |

<sup>a</sup>This plant is a pulverized coal-fired utility boiler fired with 0.3% S sub-bituminous coal. Samples analyzed by NAA. Reference 13.

<sup>b</sup>Samples collected by EPA Method 5.

<sup>c</sup>Samples collected by low pressure impactor.

<sup>d</sup>NR - Not reported.

<sup>e</sup>Volatile elements. Method 5 collection efficiencies include volatile fraction collected in impingers. Impactor values do not. Collection of volatile fraction not considered adequate.

TABLE 3-6. SUGGESTED NO<sub>x</sub> CONTROL LEVELS FOR INDUSTRIAL BOILERS

| Fuel                                       | Control Level, ng NO <sub>2</sub> /J (1b NO <sub>2</sub> /10 <sup>6</sup> Btu) |              |           |
|--------------------------------------------|--------------------------------------------------------------------------------|--------------|-----------|
|                                            | Moderate                                                                       | Intermediate | Stringent |
| Coal: Units >29 MW Heat Input <sup>a</sup> | 301 (0.7)                                                                      | 258 (0.6)    | 215 (0.5) |
| Coal: Units <29 MW Heat Input              | 215 (0.5)                                                                      | 172 (0.4)    | 129 (0.3) |
| Residual Oil                               | 129 (0.3)                                                                      | 108 (0.25)   | 86 (0.2)  |
| Distillate Oil and Gas                     | 86 (0.2)                                                                       | 65 (0.15)    | 43 (0.1)  |

<sup>a</sup>It is suggested that spreader stokers be placed at these moderate, intermediate, and stringent levels, regardless of heat input capacity.

example, reduced air preheat and FGR are required for distillate oil- and gas-fired watertube boilers with air preheaters.

The following sections discuss the alternative  $\text{NO}_x$  emission control systems for industrial boilers necessary to reduce emissions to the three levels of control. For each boiler/fuel category, the best candidate  $\text{NO}_x$  control systems are identified for the moderate, intermediate, and stringent control levels.

### 3.2 CANDIDATE CONTROL SYSTEMS FOR COAL-FIRED INDUSTRIAL BOILERS

$\text{NO}_x$  formation from coal combustion is primarily from fuel  $\text{NO}_x$ . In fact, laboratory studies under controlled operating conditions have shown that fuel  $\text{NO}_x$  can account for up to 80 percent of the total  $\text{NO}_x$  from combustion of coal (Reference 3-11). In principle, the best strategy for fuel  $\text{NO}_x$  abatement combines low excess air firing, optimum burner design, and staged combustion.

Tables 3-7 and 3-8 list the candidates for best control system for coal-fired industrial boilers with heat inputs greater than and less than 29 MW ( $100 \times 10^6$  Btu/hr) heat input, respectively. These control systems were selected from the candidates summarized in Tables 3-2 and 3-3. Coal-fired units are divided at 29 MW ( $100 \times 10^6$  Btu/hr) heat input since the larger units tend to have higher  $\text{NO}_x$  emissions levels. Pulverized coal-fired boilers and spreader stokers are generally larger than 29 MW ( $100 \times 10^6$  Btu/hr) of heat input (References 3-3, 3-11). However, spreader stoker units smaller than 29 MW are not uncommon. Underfeed and chain grate stokers generally have heat input capacities of less than 29 MW, and generally produce lower  $\text{NO}_x$  emission levels than the larger spreader stokers and pulverized coal units. Cyclone boilers have not been included since sales of these units have halted since 1974 (Reference 3-31). Their baseline  $\text{NO}_x$  emissions are extremely high (approximately 650 ng/J, 1.51 lb/ $10^6$  Btu), and not easily amenable to control (Reference 3-13).

The following subsections present the criteria for selecting the control systems presented in Tables 3-7 and 3-8 and the order in which they were selected. Each subsection pertains to the individual boiler equipment type identified.

TABLE 3-7. BEST CONTROL SYSTEMS FOR COAL-FIRED INDUSTRIAL BOILERS  
WITH HEAT INPUT  $\geq 29$  MW ( $100 \times 10^6$  Btu/Hr)<sup>a</sup>

| Boiler Equipment Type | Baseline<br>NO <sub>x</sub> Emissions<br>ng/J (lb/10 <sup>6</sup> Btu) | Moderate<br>301 ng/J (0.7 lb/10 <sup>6</sup> Btu) | Level of Control                                           | Stringent<br>215 ng/J (0.5 lb/10 <sup>6</sup> Btu)                                                                                    |
|-----------------------|------------------------------------------------------------------------|---------------------------------------------------|------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|
|                       |                                                                        | No control necessary <sup>c</sup>                 |                                                            |                                                                                                                                       |
| Pulverized Coal-Fired | 285 (0.663) <sup>b</sup>                                               | No control necessary                              | 1. Low excess air<br>2. Overfire air<br><br>Low excess air | 1. Overfire air*<br>2. Low NO <sub>x</sub> burner***<br>3. Ammonia injection <sup>d**</sup><br><br>Low excess air/<br>Overfire air*** |
| Spreader Stoker       | 265 (0.616)                                                            | No control necessary                              |                                                            |                                                                                                                                       |

<sup>a</sup>Low excess air operation is recommended practice whenever controls are required. However combination of LEA and OFA is not recommended for pulverized coal tangential units (see Section 3.2.1.2).  
<sup>b</sup>Wide range of baseline emissions reported (see Section 3.2.1.1)  
<sup>c</sup>Some units may require low excess air.  
<sup>d</sup>NH<sub>3</sub> injection required only for those units with unusually high baseline emissions.

\*Commercially offered but not demonstrated for this boiler/fuel category.

\*\*Commercially offered but not demonstrated.

\*\*\*Under research and development.

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TABLE 3-8. BEST CONTROL SYSTEMS FOR COAL-FIRED INDUSTRIAL BOILERS  
WITH HEAT INPUT <29 MW (100 x 10<sup>6</sup> Btu/Hr)

| Boiler Equipment Type | Baseline<br>NOx Emissions<br>ng/J (lb/10 <sup>6</sup> Btu) | Level of Control                                  |                                                    |
|-----------------------|------------------------------------------------------------|---------------------------------------------------|----------------------------------------------------|
|                       |                                                            | Moderate<br>215 ng/J (0.5 lb/10 <sup>6</sup> Btu) | Stringent<br>129 ng/J (0.3 lb/10 <sup>6</sup> Btu) |
| Spreader Stoker       | 265(0.616)                                                 | Low excess air/overfire air***                    | Ammonia injection**                                |
| Chain Grate           | 140(0.326)                                                 | No control necessary                              | Low excess air                                     |
| Underfeed             | 150(0.349)                                                 | No control necessary                              | Low excess air                                     |

\*\*Commercially offered but not demonstrated.

\*\*\*Under research and development.



### 3.2.1 Pulverized Coal-Fired Boilers

Industrial size pulverized coal-fired boilers can be subdivided into two categories based on the firing mode of the burners in the furnace: tangential and single wall firing. No significant differences in  $\text{NO}_x$  emission levels were observed between these two firing types (see Section 7) although recent data indicate a difference in  $\text{NO}_x$  emissions for utility size units of these two firing types (References 3-14 and 3-15).

As stated earlier, information on baseline as well as controlled  $\text{NO}_x$  emissions from pulverized coal-fired industrial size boilers is very limited. Therefore the selection of the applicable control systems for each of the three control levels relied heavily on utility boiler experience with combustion modifications (Reference 3-13).

#### 3.2.1.1 Moderate Control Level

No control should be necessary to achieve the moderate control level of 301 ng/J as the selected baseline  $\text{NO}_x$  emission level is 285 ng/J. The moderate control level was set at 301 ng/J and not any lower because of the broad range in baseline  $\text{NO}_x$  emissions for the six units tested, ranging from 174 to 563 ng/J with most data between 201 and 296 ng/J, yielding an average baseline of 285 ng/J. No significant correlation of emission levels with boiler type or size or coal characteristics were evident from a review of the data presented in Table 7-2 (see Section 7).

#### 3.2.1.2 Intermediate Control Level

Combustion modifications capable of reducing  $\text{NO}_x$  emission from 285 to the intermediate control level of 258 ng/J (10 percent reduction) include low excess air and overfire air. Low excess air (LEA) operation should be capable of achieving the intermediate control level in all but a few cases. Overfire air (OFA) should satisfy the remaining cases. Combination of LEA with OFA has been known to reduce  $\text{NO}_x$  emissions from utility boilers by 30 percent; however it is not recommended for tangential boilers (Reference 3-13). Combustion Engineering, the manufacturer of tangential boilers, recommends using normal overall furnace excess air levels with OFA operation to ensure no coincident increase of unburned carbon in the flyash or carbon monoxide emissions from their units (References 3-33 and 3-34).

The LEA and OFA control system has the primary advantage over the other control systems because of its commercial availability and its effectiveness. The cost of the system is not prohibitive when  $\text{NO}_x$  ports are designed as a part of new boilers. In addition, careful operation of staged air injection is not expected to seriously affect emissions of other criteria pollutants<sup>a</sup>. Burner stoichiometries in the range of 100 to 110 percent would be adequate to achieve a 20 percent  $\text{NO}_x$  reduction (Reference 3-15). At these stoichiometry levels the oxidizing atmospheres would prevail in the furnace, thus minimizing concern over possible furnace slagging and boiler tube wastage.

#### 3.2.1.3 Stringent Control Level

Achieving the stringent  $\text{NO}_x$  emission level of 215 ng/J represents a 25 percent reduction from baseline. Combined low excess air and overfire air operation can achieve this level of control. However, burner stoichiometries would have to be reduced below 100 percent in some cases (Reference 3-13). This low burner stoichiometry level would cause reducing atmospheres in parts of the furnace, thus creating the potential for corrosion of water tubes (Reference 3-13). Generally boiler manufacturers do not recommend burner operation with stoichiometry levels below 100 percent primarily because of increased corrosion potential. Therefore LEA/OFA is recommended as the stringent control technique with the proviso that further field testing and demonstrations may be necessary.

Because of the possible operational problems associated with OFA, low  $\text{NO}_x$  burners (LNB) were selected as the first backup candidate for achieving the stringent control level. Reported  $\text{NO}_x$  reductions for utility size units are of the order of 45 to 60 percent (References 3-16 and 3-17). Similar reduction efficiencies are projected for industrial low  $\text{NO}_x$  burners under development. Therefore LNB is expected to easily meet the 215 ng/J control level, a 25 percent reduction from the average baseline level. Once developed, low  $\text{NO}_x$  coal-fired burners for industrial boilers could become the candidate control system because of the expected lower cost and other operational advantages over the staged

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<sup>a</sup>The effect of combustion modifications on other criteria pollutants is discussed in Section 6.

combustion method of OFA. One such burner is being developed by Peabody Engineering Corporation and will be tested by Energy and Environmental Research Corp. (EER) (Reference 3-18).

If low  $\text{NO}_x$  burners are not commercialized by 1983, ammonia injection is the alternative stringent control system. Also ammonia injection may be required for those pulverized coal-fired units with unusually high baseline  $\text{NO}_x$  emissions. However,  $\text{NH}_3$  injection is several times more costly than conventional combustion modification controls. In addition, as a developing technology, there are several implementation and operational problems that need to be resolved. The optimal effectiveness for noncatalytic reduction of NO by  $\text{NH}_3$  occurs in a very narrow temperature range, approximately  $1240 \pm 50\text{K}$  ( $1770 \pm 90^\circ\text{F}$ ). Hence, precise location of the  $\text{NH}_3$  injection ports is crucial. Since the temperature profile in a boiler changes with load,  $\text{NO}_x$  control with  $\text{NH}_3$  may dictate load restrictions on the boiler. Other potential problems include fouling and emissions of  $\text{NH}_3$  and byproducts. However, the major strengths of the technique are its potential for high  $\text{NO}_x$  removal (40 to 60 percent), and its applicability as an additional control that can be combined with conventional combustion techniques for extremely large  $\text{NO}_x$  reductions (Reference 3-19).

### 3.2.2 Spreader Stoker Boilers

Field test data of  $\text{NO}_x$  combustion modifications on spreader stoker fed coal-fired boilers come from four EPA-sponsored programs (References 3-3 through 3-7, and 3-35). The coal in a spreader stoker boiler burns partly in a suspended state and partly on a moving or vibrating grate. The combustion of coal in the suspended state apparently causes  $\text{NO}_x$  emissions to be generally higher than for other stoker types which feed and combust coal directly on a moving grate. Baseline uncontrolled  $\text{NO}_x$  emission averaged 265 ng/J for twelve spreader stoker industrial boilers (References 3-3 through 3-7, and 3-35). No significant correlation was observed between  $\text{NO}_x$  emission levels and unit capacity or fuel properties (e.g., coal type, fuel nitrogen), as a review of the data in Section 7 will show.

Spreader stokers generally range in size from 2.9 MW ( $10 \times 10^6$  Btu/hr) to 146 MW ( $500 \times 10^6$  Btu/hr) heat input

(Reference 3-14). The smaller units, i.e., those under 29 MW ( $100 \times 10^6$  Btu/hr), may have to meet stricter control levels than the larger units, according to Table 3-6. The candidate control systems are summarized in Tables 3-7 and 3-8).

Spreader stoker boilers are listed in both Tables 3-7 ( $\geq 29$  MW) and 3-8 ( $< 29$  MW) because this design type is offered over a large range of heat input capacities. However, because their average baseline emission levels are relatively higher than those from other stoker designs, it is recommended that spreader stokers be grouped with pulverized coal units as far as potentially achievable emission control levels are concerned. Spreader stokers are listed together with other stoker types in Table 3-8 solely because of similarities in designs and hence in applicable control techniques.

No control is necessary for meeting the moderate control level of 301 ng/J for spreader stokers larger than 29 MW. The intermediate control level (258 ng/J) may be easily achieved by low excess air (LEA) firing. Operating with LEA would result in increased boiler efficiency. Such problems as grate overhear, clinker formation, and corrosion should be minimized by limiting excess oxygen to 6 percent or more. For stringent control (215 ng/J), LEA and overfire air operation will probably be required. This can be accomplished by reducing undergrate air and increasing overfire airflow through the OFA ports normally installed in stokers. However, close operator attention will be required to avoid the problems of grate overhear, clinker formation, and corrosion associated with firing at too low excess air levels. Presently installed OFA ports were intended only for smoke control. New units should incorporate OFA ports designed for  $\text{NO}_x$  control. Potential environmental impacts as increased CO, particulate, and organic emissions warrant further testing. To date, LEA and OFA represent the only significant  $\text{NO}_x$  controls tested on stokers.

According to Table 3-8, smaller spreader stokers ( $< 29$  MW heat input) are faced with stricter control levels, 215, 172, and 129 ng/J (0.5, 0.4 and  $0.3 \text{ lb}/10^6 \text{ Btu}$ ) for moderate, intermediate, and stringent control, respectively. The moderate level can be met with LEA and OFA. However, the only control option for the intermediate and stringent level

is ammonia injection, which as described earlier, is not demonstrated technology for coal-firing. Therefore, it is recommended that spreader stokers, regardless of capacity, be aligned with pulverized coal units as far as potentially achievable control levels are concerned, as illustrated in Table 3-7.

### 3.2.3 Chain Grate and Underfeed Stokers

Chain grate and underfeed stokers have generally less than 29 MW ( $100 \times 10^6$  Btu/hr) heat input capacity. Neither stoker type requires any controls until the stringent level of 129 ng/J is needed. This can be achieved for chain grate (baseline 140 mg/J) and underfeed (baseline 150 ng/J) by reducing the excess air. Tests on new units indicate that  $\text{NO}_x$  reductions of 10 to 30 percent are possible with low excess air. Hence LEA is the recommended technique (and the only effective technique tested for underfeed stokers).

Stricter levels of control for chain grate and underfeed stokers were not suggested in Table 3-8 because of the very limited number of units tested (two each), and the lack of availability of effective control techniques (besides low excess air operation).

### 3.3 CANDIDATE BEST CONTROL SYSTEMS FOR RESIDUAL OIL-FIRED INDUSTRIAL BOILERS

Residual oil contains varying amounts of fuel bound nitrogen. During an extensive EPA-sponsored industrial boiler field test program the nitrogen found in residual oils (No. 5 and No. 6) varied from 0.1 to 0.52 percent (Reference 3-4). However, residual oils used in industrial boilers may have nitrogen contents as high as 1.0 percent. Baseline  $\text{NO}_x$  emissions from boilers burning residual oil are strongly affected by the nitrogen content of the fuel. Boiler design factors such as heat input capacity and combustion air temperature do not affect total  $\text{NO}_x$  emissions as much as nitrogen content of the oil.

Thus the contribution of fuel NO to total  $\text{NO}_x$  emissions is comparable to the contribution from thermally generated  $\text{NO}_x$ . Combustion modification controls which are most effective in reducing fuel  $\text{NO}_x$  are essentially the same used for coal-fired units. These are primarily low excess air firing and staged combustion. Both these controls limit the oxygen availability in the primary combustion zone, thus reducing the

formation of both fuel and thermal  $\text{NO}_x$ . Table 3-9 lists the best systems of combustion modification for residual oil-fired industrial boilers. These units have been separated into two main categories, firetube and watertube, based on the uncontrolled baseline emission factors. Firetube boilers are generally lower than 9 MW heat input ( $30 \times 10^6$  Btu/hr) (Reference 3-12). These units usually have lower combustion intensities than watertube units of the same size, contributing to lower thermal  $\text{NO}$  formation (Reference 3-8). Baseline  $\text{NO}_x$  emissions for firetube boilers averaged 115 ng/J while watertube units averaged 160 ng/J.

The following subsections summarize the candidate  $\text{NO}_x$  combustion modification control systems shown in Table 3-9.

### 3.3.1 Firetube Boilers

Since baseline  $\text{NO}_x$  emissions from firetube boilers burning residual oil averaged only 115 ng/J, no controls are generally necessary for these units to meet the moderate control level of 129 ng/J. However, controls are necessary to reduce  $\text{NO}_x$  emissions to the intermediate and stringent levels of 108 and 86 ng/J respectively.

#### 3.3.1.1 Intermediate Control Level

Since firetube boilers require only a 6 percent  $\text{NO}_x$  reduction to reach the intermediate level of control (108 ng/J), low excess air firing should easily be adequate. Low excess air operation should also increase boiler efficiency. The same caution about possible increased CO and organic emissions discussed earlier for coal-firing under LEA apply here also.

#### 3.3.1.2 Stringent Control Level

To meet the stringent control level of 86 ng/J, low  $\text{NO}_x$  burners are the most attractive method of control. Staged combustion has been investigated on one (3.5 MW,  $12 \times 10^6$  Btu/hr) firetube boiler with reductions in  $\text{NO}_x$  emissions of up to 50 percent (References 3-8 and 3-20). However, staged combustion cannot be easily implemented on these small packaged firetubes, and no feasible air injection system is under development for commercial application.

TABLE 3-9. BEST CONTROL SYSTEM FOR RESIDUAL OIL-FIRED INDUSTRIAL BOILERS<sup>a</sup>

| Boiler Equipment Type | Baseline<br>NO <sub>x</sub> Emissions<br>ng/J (lb/10 <sup>6</sup> Btu) | Level of Control                                                               |                                                           |                                                             |
|-----------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------------------|-------------------------------------------------------------|
|                       |                                                                        | Moderate<br>129 ng/J (0.3 lb/10 <sup>6</sup> Btu)                              | Intermediate<br>108 ng/J (0.25 lb/10 <sup>6</sup> Btu)    | Stringent<br>86 ng/J (0.2 lb/10 <sup>6</sup> Btu)           |
| Firetube              | 115 (0.267)                                                            | No control necessary                                                           | Low excess air                                            | 1. Low NO <sub>x</sub> burners**<br>2. Staged combustion*** |
| Watertube             | 160 (0.372)                                                            | 1. Low excess air<br>2. Low NO <sub>x</sub> burners**<br>3. Staged combustion* | 1. Low NO <sub>x</sub> burners**<br>2. Staged combustion* | 1. Low NO <sub>x</sub> burners**<br>2. Ammonia injection**  |

<sup>a</sup>Low excess air is recommended practice whenever controls are required.

\*Commercially offered but not demonstrated for this boiler/fuel category.

\*\*Commercially offered but not demonstrated.

\*\*\*Research and development.

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Thus low  $\text{NO}_x$  burners (LNB) remain as a potentially viable technique. Low  $\text{NO}_x$  burners reduce  $\text{NO}_x$  emissions primarily by operating on one of the following principles:

- Controlled mixing (to permit rapid quenching of the flame and reduce residence time at peak flame temperature)
- Divided flame (to provide more rapid cooling of flame)
- Self-recirculation (to dilute combustion gases and reduce peak flame temperature)
- Staged combustion (to reduce available excess oxygen)

As expected from the discussion in Section 2, the self-recirculation and staged combustion burner types are more effective with residual oil (high fuel nitrogen) combustion. Reductions in  $\text{NO}_x$  ranging from 20 to 50 percent have been reported with commercialized Japanese LNB and experimental domestic LNB. The Kawasaki two-stage combustion type LNB and the LNB being developed by EER, as discussed in Section 2, are two candidate burners for controlling  $\text{NO}_x$  from residual oil-fired boilers. However, neither burner is presently commercially available. The TRW burner which is commercially offered but not demonstrated may prove to be effective. Note, though, that the heat input capacity per burner of these LNBs may be too large for application to the smaller packaged firetubes. However, they represent potentially the most cost-effective method of high  $\text{NO}_x$  reduction with little expected adverse operational or environmental impact.

### 3.3.2 Watertube Boilers

As shown in Table 3-9 the baseline uncontrolled  $\text{NO}_x$  emissions from packaged and field erected watertube boilers averaged approximately 160 ng/J. The capacity of the boiler and the temperature of the combustion air did not have a significant effect on the baseline emission level (References 3-3, 3-4, 3-9). Combustion modification  $\text{NO}_x$  controls are necessary to reduce emissions to all three levels of control.

The following subsections discuss the criteria for selecting the control systems listed in order of priority in Table 3-9 for each of the control levels investigated.

#### 3.3.2.1 Moderate Control Level

The moderate  $\text{NO}_x$  control level of 129 ng/J can be obtained by operating the watertube boiler with a 3 percent excess oxygen level or



lower. Section 2 indicated that  $\text{NO}_x$  emissions were reduced 18 to 23 percent by reducing excess oxygen to the range of 3.1 to 4.2 percent. Achieving the moderate emission level represents a 19 percent reduction.

Operation of watertube boilers with excess oxygen levels in the flue gas on the order of 3 percent is a feasible and demonstrated method of achieving  $\text{NO}_x$  reductions. The technique has additional advantages such as increased boiler thermal efficiency, reduced fan power requirements and reduced sulfur trioxide formation for both residual oil and coal combustion -- a cause of acid smut emissions, corrosion and fouling (Reference 3-21). Furthermore, low excess air operation also seems to reduce particulate emissions. One EPA study reported approximately 30 percent drop in particulate emissions when burning residual oil (Reference 3-4). Operation at low excess air levels (less than 15 percent) is not favored by industrial boiler operators because of possible smoke emissions during rapid heat changes and possible formation of combustibles with unburned fuel creating a safety hazard. These disadvantages of LEA operation can be avoided by installing controls and implementing a comprehensive maintenance program. The increased costs due to more sophisticated controls and increased maintenance can be balanced by the fuel savings through increased boiler efficiency.

Burner manufacturers currently offer burners that can operate at very low excess oxygen levels (3 to 5 percent). These burners are of the axial flow type. Windbox air distribution is carefully controlled, and low-turbulent air is mixed with the fuel. The carefully controlled air flow eliminates the necessity of high excess air to assure complete mixing and combustion (Reference 3-21).

Alternative control systems include low  $\text{NO}_x$  burners and staged combustion. Low  $\text{NO}_x$  burners represent a better alternative for package single burner watertube units because staged air injection is not feasible. The two staged air injection designs presented in Section 2 are considered experimental. In fact, one boiler manufacturer indicated that operation of such a system would be too complicated for a packaged industrial unit (Reference 3-21).

Staged air injection for multiburner field erected watertube boilers might be the next best control system after the LEA technique.

Overfire air injection through  $\text{NO}_x$  ports is a demonstrated technology and fully capable of achieving 20 percent  $\text{NO}_x$  reductions. Low  $\text{NO}_x$  burners for multiple burner industrial size boilers could be undesirable because of possible flame interaction between burners and potential loss in  $\text{NO}_x$  reduction effectiveness.

In general, LEA is the best candidate  $\text{NO}_x$  control system capable of achieving 129 ng/J emissions for watertube boilers burning residual oil with a nitrogen content less than 0.5 percent. Of course, higher nitrogen content oils increase baseline emissions, necessitating larger emissions reductions to achieve the moderate control level.

#### 3.3.2.2 Intermediate Control Level

The intermediate control level of 108 ng/J ( $0.25 \text{ lb}/10^6 \text{ Btu}$ ) necessitates reductions greater than 30 percent. Technologies potentially capable of achieving these reductions include low  $\text{NO}_x$  burners and staged combustion. As in the case for moderate control level, LNB is probably preferred for packaged boilers while overfire air (one form of staged combustion) is preferred for multiburner units. Several low  $\text{NO}_x$  burner designs are still at the R&D stage; however, full demonstrations and commercialization are expected in the near future. In fact, one manufacturer (TRW) is currently offering an LNB system, with field demonstrations underway or imminent. Overfire air is currently being implemented on utility size units as a staged combustion technique.

control techniques if they are to achieve the stringent control level when operating singly. It is difficult to predict whether low  $\text{NO}_x$  burners like the Kawasaki, EER, or TRW units can achieve 50 percent reduction for all watertube boilers. With little information available on these and other developing burners, such assurance does not exist at the present time. However, LNBs were still chosen as the best stringent control system based on their potential for cost-effective control with little expected adverse impacts.

For staged combustion to achieve 46 percent  $\text{NO}_x$  reduction, it would mean burner operation with 70 to 90 percent stoichiometry. However, prolonged tests with areas of the boilers in severe reducing atmospheres caused by 70 percent burner stoichiometries have not been conducted. But based on utility boiler experience, burner stoichiometries less than 90 percent may not be acceptable because of increased corrosion and tube wastage. Therefore, staged combustion as a single technique control system would probably not be feasible considering operational problems.

The only other alternative to low  $\text{NO}_x$  burners for stringent control would be ammonia injection. Although the technique has seen limited commercial operation in Japan, this control system represents a several fold more costly alternative for  $\text{NO}_x$  reduction than the other two previously described systems. In addition, ammonia emissions will inevitably create some operational problems for high sulfur oil-fired boilers. These problems would lead to increased boiler maintenance, increasing operating cost over and above expected control costs. Furthermore potential emissions of  $\text{NH}_3$  and byproducts cause environmental concern.

### 3.3.3 Effects of Fuel Nitrogen

It should be noted that the above discussed controlled emission levels for residual oil firing may be difficult to achieve for boilers firing high nitrogen content fuel (e.g., >0.3 weight percent nitrogen). Indeed, Figure 3-1 indicates a possible trend of increasing total  $\text{NO}_x$  emissions with fuel nitrogen content, unlike the behavior exhibited by coal-fired boilers. A possible explanation may be the following: (1) the fractional conversion of fuel nitrogen to fuel  $\text{NO}_x$  increases with decreasing fuel nitrogen content, and (2) residual oil generally has much

lower fuel nitrogen content than does coal (Reference 3-4). For high nitrogen content residual oil, a possible moderate controlled (low excess air operation)  $\text{NO}_x$  level is 200 ng/J (0.47 lb/10<sup>6</sup> Btu). Note in Figure 3-1 that combustion air preheat appears to have no effect on  $\text{NO}_x$  emissions from residual oil-fired boilers, as expected.

#### 3.4 CANDIDATE BEST CONTROL SYSTEMS FOR DISTILLATE OIL-FIRED INDUSTRIAL BOILERS

$\text{NO}_x$  emissions from distillate oil combustion are primarily from thermal  $\text{NO}_x$  formation. Distillate oils generally contain less than 0.05 percent of fuel bound nitrogen. The emissions data used here are primarily from an EPA sponsored study in which fuel nitrogen content of the oil varied from 0.013 to 0.045 percent (Reference 3-4).

Combustion modifications which are primarily effective in reducing thermal  $\text{NO}_x$  formation are:

- Flue gas recirculation (FGR)
- Reduced air preheat (RAP)
- Load reduction with reduced oxygen
- Low  $\text{NO}_x$  burners
- Staged combustion

The relatively low uncontrolled baseline  $\text{NO}_x$  emissions of distillate oil-fired industrial boilers are reflected in the suggested  $\text{NO}_x$  control levels of 86, 65, and 43 ng/J for moderate, intermediate, and stringent control, respectively.

As will be observed in the following subsections, these control levels can in most cases be met with commercially available techniques. Table 3-10 lists the best candidates for  $\text{NO}_x$  emission control for each of the three control levels. However, it is interesting to note that watertube boilers with preheated combustion air tend to have significantly higher  $\text{NO}_x$  emissions than those without preheated air. Furthermore, this behavior was irrespective of unit capacity (Reference 3-3).

Firetube boilers usually have lower combustion intensities than watertube units; consequently, the formation of thermal  $\text{NO}_x$  would be expected to be lower (Reference 3-3). However, this was not the case for the boilers tested, though the differences measured were not large.

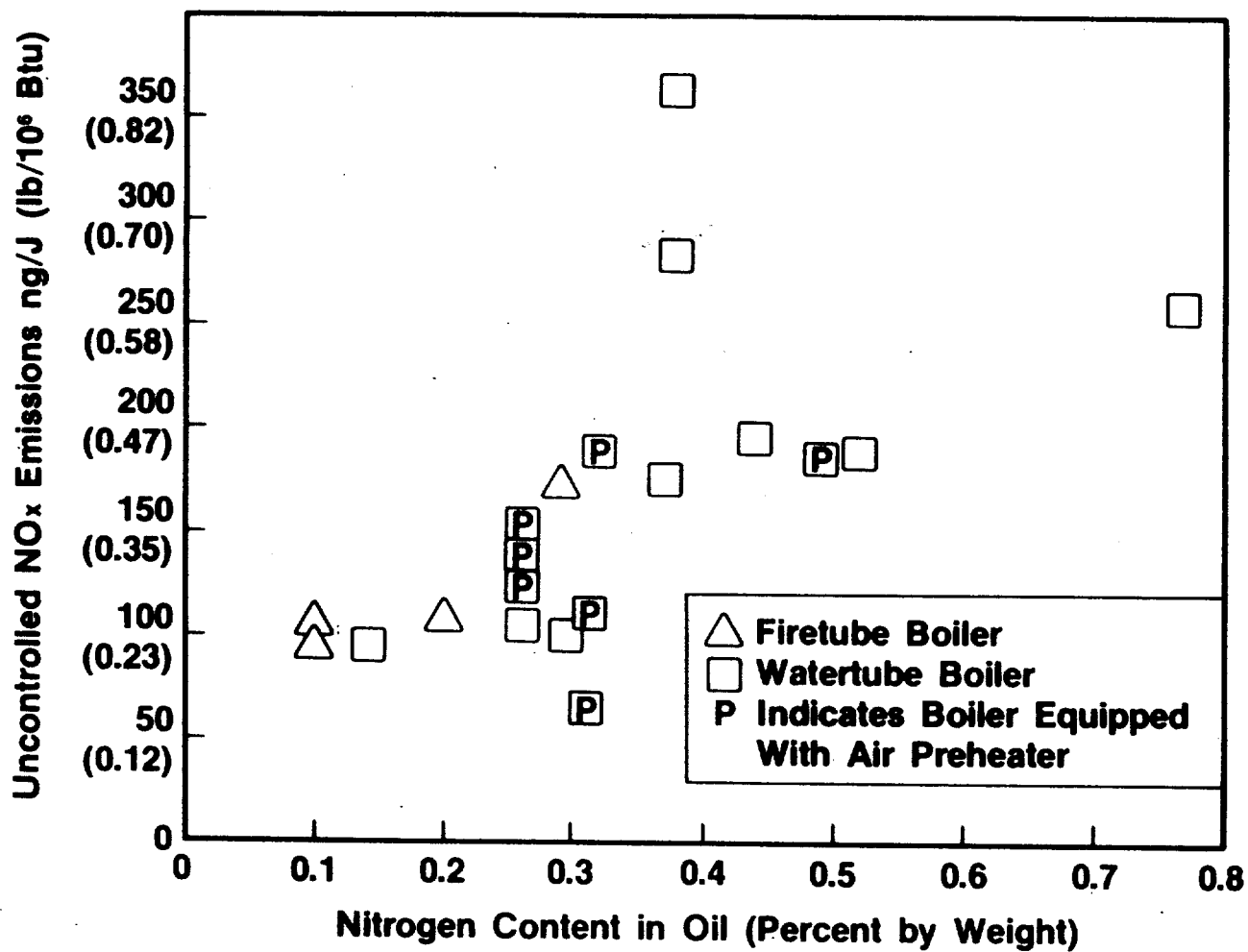


Figure 3-1. Effect of fuel nitrogen content on NO<sub>x</sub> emissions from residual oil-fired industrial boilers.

TABLE 3-10. BEST CONTROL SYSTEMS FOR DISTILLATE OIL-FIRED INDUSTRIAL BOILERS<sup>a</sup>

| Boiler Equipment Type                        | Baseline<br>NO <sub>x</sub> Emissions<br>ng/J (lb/10 <sup>6</sup> Btu) | Level of Control                                 |                                                                                                                  |                                                                                                                 |
|----------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------|------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|
|                                              |                                                                        | Moderate<br>86 ng/J (0.2 lb/10 <sup>6</sup> Btu) | Intermediate<br>65 ng/J (0.15 lb/10 <sup>6</sup> Btu)                                                            | Stringent<br>43 ng/J (0.1 lb/10 <sup>6</sup> Btu)                                                               |
| Firetube                                     | 75 (0.175)                                                             | No control necessary                             | Low excess air                                                                                                   | 1. Flue gas recirculation<br>2. Low NO <sub>x</sub> burners**                                                   |
| Watertube not equipped<br>with air preheater | 55 (0.128)                                                             | No control necessary                             | No control necessary                                                                                             | 1. Flue gas recirculation<br>2. Low NO <sub>x</sub> burners**<br>3. Staged combustion air*                      |
| Watertube equipped with<br>air preheater     | 90 (0.209)                                                             | Low excess air                                   | 1. Reduced air preheat<br>2. Flue gas recirculation<br>3. Low NO <sub>x</sub> burners**<br>4. Staged combustion* | 1. Reduced air preheat<br>+ flue gas recirculation<br>2. Reduced air preheat<br>+ Low NO <sub>x</sub> burners** |

<sup>a</sup>Low excess air operation is recommended practice whenever controls are required

\*Commercially offered but not demonstrated for this boiler/fuel category.

\*\*Commercially offered but not demonstrated.

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The following subsections discuss the criteria for relating the candidates for best  $\text{NO}_x$  control systems and the priority in which they have been listed in Table 3-10.

### 3.4.1 Firetube Boilers

Emissions from six firetube boilers burning distillate oil averaged approximately 75 ng/J (Reference 3-3). However, only two of these boilers were tested with combustion modifications. In addition, the combustion modifications used were limited to low excess air and load reduction. The effectiveness of other combustion modification control systems selected for firetube boilers is based on results obtained on watertube boilers. The effectiveness of the controls does not vary significantly between these two equipment types.

With such a low average baseline  $\text{NO}_x$  level (75 ng/J), firetube boilers should not need any controls to meet the moderate control level (86 ng/J) for distillate oil firing.

#### 3.4.1.1 Intermediate Control Level

Low excess air combustion on two firetube boilers reduced  $\text{NO}_x$  emissions 18 percent on the average (Reference 3-3). Excess oxygen was reduced in both cases from the baseline level of approximately 5.7 percent to 3.2 percent. Operation of the boiler burning distillate oil with a 3 percent excess oxygen level allows complete fuel-air mixing which in turn keeps combustible emissions at a minimum. This expected 18 percent  $\text{NO}_x$  reduction should be sufficient for the firetube boilers to meet the 65 ng/J intermediate control emission level. Operation of distillate oil burners below 3 percent excess oxygen is often feasible especially with today's designed LEA burners (Reference 3-21). The increased boiler efficiency and subsequent fuel saving due to LEA operation would also compensate for the cost of the system. Expenditures caused by LEA operation include the installation and operation of control equipment, including CO and  $\text{O}_2$  monitors.

Thus, LEA is the best candidate control for  $\text{NO}_x$  reduction for firetube boilers required to meet the intermediate  $\text{NO}_x$  emission control level of 65 ng/J. Other, more elaborate and costly techniques are not necessary.

#### 3.4.1.2 Stringent Control Level

The 40 percent  $\text{NO}_x$  reduction from baseline emissions required by the stringent control level eliminates the use of LEA, although LEA is still desirable because of increased boiler efficiency. The best control system for this  $\text{NO}_x$  reduction performance is flue gas recirculation. Flue gas recirculation is a very effective control system with reported  $\text{NO}_x$  reductions of up to 73 percent for watertube boilers (References 3-3 and 3-4, and 3-9). Potential operational problems such as flame instability should be eliminated with proper engineering and testing. Environmental impacts such as possible increased organic emissions are expected to be minimal, although further investigation is definitely desirable.

Flue gas recirculation was selected over low  $\text{NO}_x$  burners primarily because of the commercial availability of FGR. However, LNB designs capable of 40 percent  $\text{NO}_x$  reduction, once commercially available and demonstrated, will be much more cost effective. Reductions in  $\text{NO}_x$  emissions for low  $\text{NO}_x$  burners have been reported in the 20 to 50 percent range.

Additional  $\text{NO}_x$  control candidates would be ammonia injection and staged combustion. Although both of these techniques are feasible, they may prove to be inapplicable to firetube boilers because of equipment limitations. In addition, the cost of ammonia injection might prove to be more than the cost of the boiler itself.

In summary, flue gas recirculation is the preferred stringent control technique with low  $\text{NO}_x$  burners as the second option for distillate oil-fired firetube boilers.

#### 3.4.2 Watertube Boilers Without Air Preheaters

Watertube boilers firing distillate oil and not equipped with air preheaters are usually smaller than 15 MW ( $50 \times 10^6$  Btu) heat input, although a 58 MW unit has been tested (References 3-3 and 3-4).  $\text{NO}_x$  emissions from these equipment types averaged approximately 55 ng/J (References 3-3 and 3-4). This baseline emission level is lower than both the moderate and intermediate control levels of 86 and 65 ng/J, respectively, so no controls are needed. However, to meet stringent levels some form of  $\text{NO}_x$  control will be needed.



$\text{NO}_x$  reduction to 43 ng/J can be met by reducing the baseline level of 55 ng/J by 22 percent. This reduction should be easily achievable with flue gas recirculation (up to 70 percent  $\text{NO}_x$  reduction) or low  $\text{NO}_x$  burners (20 to 50 percent). Low excess air combustion reduced  $\text{NO}_x$  emissions from watertube boilers only about 4 to 12 percent when excess oxygen was lowered from approximately 5.5 to 3.5 percent. Although burner operation with excess oxygen lower than 3.5 percent is possible (Reference 3-21) it is unclear whether higher  $\text{NO}_x$  reductions could be achieved.

Flue gas recirculation was selected as the best candidate for stringent control based on its commercial availability and recorded performance. Recirculation rates of less than 30 percent are deemed sufficient to achieve this control level. At this rate, no major operational impacts are expected if the burner is modified to allow for the increased excess flowrate.

Low  $\text{NO}_x$  burners will probably be more cost effective since they are commercially available and demonstrated. They may become the candidate best system of control for reducing  $\text{NO}_x$  emissions to 43 ng/J. Low  $\text{NO}_x$  burners are especially attractive for single burner units such as packaged watertubes because the incremental cost for one LNB is considered minimal. However, the prototype low  $\text{NO}_x$  burners under current development may be of too large capacity for the smaller package units.

Staged combustion is another alternative control system. Staged combustion may prove to be more attractive than LNB for multiburner units. However, watertube boilers not equipped with air preheaters are generally of the package type with only one burner. For these units, air injection by means of ports down stream from the burner can be used to achieve staged combustion (see Section 2). Control of  $\text{NO}_x$  with this type of staged combustion is considered still at the experimental stage and more costly than control with LNB.

In summary, flue gas recirculation is considered the preferred method for stringent control of distillate oil-fired watertubes not equipped with air preheaters.

### 3.4.3 Watertube Boilers Equipped with Preheaters

Watertube boilers with preheated combustion air are generally larger than 15 MW ( $50 \times 10^6$  Btu/hr) heat input (Reference 3-3).

Baseline  $\text{NO}_x$  emissions from a limited number of these units averaged about 90 ng/J (Reference 3-4). Currently available combustion modification control systems are capable of achieving the moderate, intermediate, and stringent control levels for distillate oil firing.

#### 3.4.3.1 Moderate Control Level

Low excess air firing should be more than adequate to reduce the baseline  $\text{NO}_x$  emissions of 90 ng/J to the moderate control level of 86 ng/J with increased boiler efficiency and minimal adverse impacts.

#### 3.4.3.2 Intermediate Control

Combustion air temperature were not be reduced during the test program on the watertube boilers equipped with air preheaters. Therefore the effect of reduced air preheat (RAP) on these units cannot be clearly defined. However, based on results with natural gas, another clean fuel, it is speculated that RAP can reduce  $\text{NO}_x$  emissions by the 30 percent required by the intermediate control level of 65 ng/J. The loss in efficiency caused by the increased flue gas temperature can be averted for new units by installing an economizer instead of an air preheater. Economizers offer some operational advantages over air preheaters as well as reduced  $\text{NO}_x$  emissions (Reference 3-21). The primary advantage is the lower capital cost, sometimes nearly one-half of that of an air preheater (Reference 3-25).

Therefore, RAP or ambient temperature combustion air for new watertube boilers designed to fire distillate oil was selected as the best system for intermediate control. Alternative controls include flue gas recirculation, low  $\text{NO}_x$  burners, and staged combustion.

Flue gas recirculation is a very effective and available technique, but is also very costly, therefore it should be considered as an alternative to RAP only if replacing the air preheater with an economizer in a new unit is not feasible.

The remaining alternatives are low  $\text{NO}_x$  burners and staged combustion. For single burner packaged units, LNB is probably considered more desirable. However, LNB performance and operation have not been thoroughly demonstrated. Similarly, overfire air injection for multiburner units is a very attractive control system, probably more so than LNB. Staged combustion can reduce  $\text{NO}_x$  from watertube boilers firing distillate oil by 30 to 40 percent on the average (References 3-4 and 3-9).

In general, watertube boilers with ambient combustion air temperature are capable of meeting the intermediate emission level of 65 ng/J with minimal adverse impacts. Therefore it is recommended that new units be designed with an economizer instead of an air preheater. Alternative control candidates include FGR or LNB for packaged single burner boilers and OFA for multiburner units. Staged combustion for packaged watertube boilers is also a candidate, although, this control system is still at the experimental stage.

#### 3.4.3.3 Stringent Control Level

The stringent control level of 43 ng/J can be obtained by combining reduced air preheat (RAP) with another combustion modification such as FGR or LNB. The RAP plus FGR control system was selected as the best candidate again based on availability, even though its cost is generally expected to be higher than for RAP plus LNB control systems.

Alternative control systems include the use of ammonia injection combined with one other combustion modification. Reduced air preheat is preferred because it is expected to have the least operational and cost impact considering the flue gas heat recovery with an economizer. For boilers which must be equipped with air preheaters, FGR or LNB may still be adequate. Otherwise, costly  $\text{NH}_3$  injection may also be required.

### 3.5 CANDIDATE BEST CONTROL SYSTEMS FOR NATURAL GAS-FIRED INDUSTRIAL BOILERS

Formation of  $\text{NO}_x$  from the combustion of natural gas is entirely from thermal fixation of nitrogen in the combustion air. Combustion parameters primarily affecting thermal  $\text{NO}_x$  formation are peak flame temperature, oxygen concentration and exposure time at peak flame

temperatures. The following are applicable combustion modification controls which effectively reduce thermal  $\text{NO}_x$ :

- Flue gas recirculation
- Reduced air preheat
- Staged combustion and low excess air
- Load reduction with reduced oxygen
- Low  $\text{NO}_x$  burners

Table 3-11 lists the candidate best systems of combustion modification for natural gas-fired industrial boilers. Natural gas-fired boilers have been categorized into three main types: firetubes, watertubes not equipped with air preheaters, and watertubes equipped with air preheaters. This characterization was made because the baseline  $\text{NO}_x$  emissions of each of these types were significantly different, as well as because of alternate available control strategies.

Firetube boilers are the lowest emitters with approximately 40 ng/J emission level. These boilers are usually not equipped with air preheaters because of their small size, making heat recovery too costly to implement. Watertube boilers without preheated combustion air exhibited average  $\text{NO}_x$  emissions of 45 ng/J, while those units with air preheaters emitted significantly higher  $\text{NO}_x$ , 110 ng/J.

The following discussion summarizes the reasons for the selection and the order of the combustion modification systems for each of these major natural gas-fired industrial boilers, as shown in Table 3-11.

#### 3.5.1 Firetube Boilers

The low baseline  $\text{NO}_x$  emissions (40 ng/J) from firetube boilers require no controls for meeting the moderate, intermediate, or stringent levels for gas-fired boilers.

It is not considered cost-effective to require further control beyond the stringent level of 43 ng/J because of the firetube boiler's small size with very low baseline  $\text{NO}_x$  emissions level.

#### 3.5.2 Watertube Boilers Without an Air Preheater

Watertube boilers not equipped with air preheaters usually have heat input capacities lower than 15 MW ( $50 \times 10^6$  Btu/hr), although some larger units do exist (Reference 3-4). However, increasing concern about energy saving and fuel economy has resulted in numerous industrial boiler

TABLE 3-11. BEST CONTROL SYSTEMS FOR NATURAL GAS-FIRED INDUSTRIAL BOILERS<sup>a</sup>

| Boiler Equipment Type                  | Baseline<br>NO <sub>x</sub> Emissions<br>ng/J (lb/10 <sup>6</sup> Btu) | Level of Control                                 |                                                       |                                                                             |
|----------------------------------------|------------------------------------------------------------------------|--------------------------------------------------|-------------------------------------------------------|-----------------------------------------------------------------------------|
|                                        |                                                                        | Moderate<br>86 ng/J (0.2 lb/10 <sup>6</sup> Btu) | Intermediate<br>65 ng/J (0.15 lb/10 <sup>6</sup> Btu) | Stringent<br>43 ng/J (0.1 lb/10 <sup>6</sup> Btu)                           |
| Firetube                               | 40 (0.093)                                                             | No control necessary                             | No control necessary                                  | No control necessary                                                        |
| Watertube not equipped with air heater | 45 (0.105)                                                             | No control necessary                             | No control necessary                                  | Low excess air                                                              |
| Watertube equipped with air heater     | 110 (0.256)                                                            | 1. RAPb<br>2. FGR<br>3. SCA*<br>4. LNB**         | 1. RAP + FGRb<br>2. RAP + LNB**<br>3. RAP + SCA*      | 1. RAP + FGRb<br>2. RAP + LNB**<br>3. RAP + NH <sub>3</sub> **<br>Injection |

<sup>a</sup>Low excess air operation is recommended practice whenever controls are required.

bRAP = Reduced Air Preheat

FGR = Flue Gas Recirculation

SCA = Staged Combustion Air

LNB = Low NO<sub>x</sub> Burners

\*Commercially offered but not demonstrated for this boiler/fuel category.

\*\*Commercially offered but not demonstrated.

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manufacturers offering flue gas heat recovery devices such as air preheaters or economizers (Reference 3-21). This section addresses only those boilers not equipped with air preheaters.

Baseline  $\text{NO}_x$  emissions from these boiler types were found to be very low (45 ng/J), requiring no combustion modification to meet the moderate or intermediate  $\text{NO}_x$  control levels of 86 and 65 ng/J, respectively. With such a low baseline  $\text{NO}_x$  level, low excess air firing should certainly be adequate for meeting the stringent control level of 43 ng/J.

### 3.5.3 Watertube Boilers with Air Preheaters

Baseline  $\text{NO}_x$  emissions from gas-fired watertube boilers equipped with combustion air preheaters are significantly higher than similar boilers using ambient temperature combustion air (110 versus 45 ng/J). Section 2 has shown that if the air preheater is bypassed,  $\text{NO}_x$  reductions of up to 55 percent can be obtained, thus reducing the emission level from approximately 110 to 50 ng/J, nearly the level of units without air preheaters.

Therefore, substantial control levels can be achieved by bypassing air preheaters on existing units and building new boilers without air preheaters. However, in both cases the flue gas heat loss must be recovered by some other means; otherwise the control becomes very unattractive due to large boiler efficiency losses (one percent for every 20K or 42°F increase in stack temperature). One alternate flue gas heat recovery device is the economizer. As is the case for distillate oil-fired boilers, the economizer offers smaller capital investment and lower fan power requirements than an air preheater.

The following subsections describe the criteria used in selecting the order of control systems shown in Table 3-11 for gas-fired boilers with combustion air preheaters.

#### 3.5.3.1 Moderate Control Level

As discussed above, replacement of air preheaters with economizers helps to reduce  $\text{NO}_x$  levels, and is also cost effective. Therefore, for new gas-fired watertube boilers the best system of control to achieve an emission level of 86 ng/J (or lower) is to install economizers in place of air preheaters. Retrofit changes are not considered viable due to boiler design differences as well as high costs.

If an air preheater is installed, three other options can be considered. These are flue gas recirculation, staged combustion, and low  $\text{NO}_x$  burners. Flue gas recirculation is a very effective and available technique, but also very costly, and should be considered as an alternative to RAP only if replacing the air preheater with an economizer in a new unit is not feasible. Staged combustion together with low excess air was selected as another option because it is a demonstrated technology and is commercially available for utility size units. However, the choice between LNB or staged combustion highly depends on the boiler configuration. Single burner units might be more amenable to LNB than staged combustion because of the lower expected cost (see Section 4). However, staged combustion technology is presently available while LNB technology for natural gas combustion still needs demonstration in the U.S. (References 3-26, 3-27).

In summary, reduced air preheat through replacement of the air preheater with an economizer is the preferred, cost-effective method for moderate control of gas-fired watertube boilers. For a new unit, there should be no adverse process, cost, or environmental impact.

#### 3.5.3.2 Intermediate Control Level

When combined with no air preheat, flue gas recirculation, low  $\text{NO}_x$  burners, and staged combustion are candidate control systems to achieve the intermediate control level of 65 ng/J. Flue gas recirculation (FGR) was again selected as the best candidate control as for distillate oil-firing because of its significant effectiveness and its commercial availability. For single burner units, however, low  $\text{NO}_x$  burners may prove to be much more cost effective and would be selected as the best control even though demonstrated gas-fired low  $\text{NO}_x$  burners are not yet commercially available. For multiburner units, staged combustion combined with LEA might be preferred over low  $\text{NO}_x$  burners primarily because of its known effectiveness (25 to 45 percent  $\text{NO}_x$  reduction) and its nearer-term availability.

#### 3.5.3.3 Stringent Control Level

$\text{NO}_x$  emissions from gas-fired industrial boilers can be reduced to 43 ng/J only if the combustion air is not preheated. In most cases the combination of no air preheat and flue gas recirculation can reduce the  $\text{NO}_x$  emissions to this level because of the high effectiveness of flue

gas recirculation with natural gas fuel (up to 75 percent). This control system of RAP and flue gas recirculation is the preferred one because of its current availability and effectiveness.

Low  $\text{NO}_x$  burners are not yet demonstrated. In addition, their performance (up to 50 percent  $\text{NO}_x$  reduction) would not be sufficient to lower  $\text{NO}_x$  emissions to 43 ng/J. However, when low  $\text{NO}_x$  burners are combined with reduced air preheat, the stringent control level may be achievable. There are no reported tests to verify this.

A third alternative is ammonia injection combined with reduced air preheat. But this system is not thoroughly demonstrated and furthermore is significantly more costly than the flue gas recirculation/reduced air preheat system. In addition, there are environmental concerns with possible ammonia and byproduct emissions. Furthermore implementation and operational problems need to be resolved.

### 3.6 SUMMARY

Alternative emission control systems which achieve moderate, intermediate, and stringent levels of  $\text{NO}_x$  control have been selected. These control levels were based on uncontrolled baseline emission levels and the capabilities of combustion modification controls. Tables 3-7 through 3-11 summarize the candidates for best control systems and emission levels achievable for each of the major industrial boiler/fuel categories. Tables 3-2 through 3-5 highlight the main performance characteristics of candidate control systems. Selection criteria for these candidate best control systems were based on the effectiveness, commercial availability or R&D status, operational impact, and reliability of each system. Energy, environmental, and cost impacts were also considered.

Results to date indicate that low excess air (LEA) or overfire air (OFA) form the best system for moderate (301 ng/J) and intermediate (258 ng/J)  $\text{NO}_x$  control for pulverized coal-fired industrial boilers. However, those boilers with high baseline  $\text{NO}_x$  emissions may need to use a combination of OFA and LEA to achieve the intermediate control level. Staged combustion combined with low excess air can achieve the stringent control level of 215 ng/J. Alternative controls include low  $\text{NO}_x$  burners (LNB) and ammonia injection; both techniques are under development.



Spreader stokers are the only major stoker boiler types with average uncontrolled  $\text{NO}_x$  emissions above 258 ng/J. Low excess air and overfire air constitute the best candidate control system capable of reductions to 215 ng/J. Any  $\text{NO}_x$  reduction beyond this level can only be achieved with  $\text{NH}_3$  injection (an unproven technique), possibly down to 129 ng/J. The other major stoker types, chain grate and underfeed, have average uncontrolled  $\text{NO}_x$  emissions below 172 ng/J. Control of these units to 129 ng/J is possible with LEA.

The candidate best control systems for residual oil-fired industrial boilers are low excess air, low  $\text{NO}_x$  burners, and staged combustion. The low  $\text{NO}_x$  burners under development are projected to reduce  $\text{NO}_x$  emissions to the stringent level (86 ng/J). An alternative control is  $\text{NH}_3$  injection (an unproven technique). Candidate best control systems for distillate oil- or gas-fired boilers are reduced air preheat, flue gas recirculation, and low  $\text{NO}_x$  burners, in that order, lowering  $\text{NO}_x$  to 65 ng/J. Reduced air preheat combined with flue gas recirculation or with low  $\text{NO}_x$  burners may potentially reduce  $\text{NO}_x$  emissions to 43 ng/J.

### REFERENCES FOR SECTION 3

- 3-1 Sedman, C, EPA/OAQPS, and R. Stern, EPA/IERL-RTP, Comments to Industrial Boiler Contractors at RTP Program Review, August 30, 1978, as transcribed by C. Hester, Acurex Corp., "Minutes of August 30 Industrial Boiler Status Assessment Meeting," October 2, 1978.
- 3-2 "Compilation of Air Pollution Emission Factors," U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Publication AP-42, NTIS-PB 275-525, April 1973 and Supplements and No. 3, NTIS-PB 235-736, July 1974, and No. 6, NTIS-PB 254 274, April 1976.
- 3-3 Cato, G. A., et al., "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers -- Phase I," EPA-650/2-74-078a, NTIS-PB 238 920/AS, October, 1974.
- 3-4 Cato, G. A., et al., "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers -- Phase II," EPA-600/2-76-086a, NTIS PB-253 500/AS, April 1976.
- 3-5 Maloney, K. L., et al., "Low-Sulfur Western Coal Use in Existing Small and Intermediate Size Boilers," EPA-600/7-78-153a, NTIS-PB 287-937/AS, July 1978.
- 3-6 Goldberg, P. M., and E. B. Higginbotham, "Field Testing of an Industrial Stoker Coal-Fired Boiler -- Effects of Combustion Modification NO<sub>x</sub> Control on Emissions -- Site A," Acurex Report TR-79-25/EE, EPA Contract No. 68-02-2160, Acurex Corporation, Mountain View, California, August 1979.
- 3-7 Gabrielson, J.E., "Field Tests of Industrial Stoker Coal-Fired Boilers for Emissions Control and Efficiency Improvement-Site A," EPA-600/7-78-136a, NTIS-PB 285-172/AS, July 1978.
- 3-8 Heap, M. P., et al., "Reduction of Nitrogen Oxide Emissions from Field Operating Package Boilers, Phase III," EPA-600/2-77-025, NTIS-PB 269 277, January 1977.
- 3-9 Carter, W. A., et al., "Emissions Reduction on Two Industrial Boilers with Major Combustion Modifications," EPA 600/7-78-099a, NTIS-PB 283-109, June 1978.
- 3-10 Cichanowicz, J. E., et al., "Pollutant Control Techniques for Package Boilers. Phase I Hardware Modification and Alternate Fuels," EPA Draft Report under EPA Contract No. 68-02-1498, November, 1976.

- 3-11 Pershing, D. W., et al., "Influence of Design Variables on the Production of Thermal and Fuel NO from Residual Oil and Coal Combustion," AIChE Symposium Series, No. 148, Vol. 71, pp. 12-29, 1975.
- 3-12 "Task 2 Summary Report -- Preliminary Summary of Industrial Boiler Population," prepared by PEDCo in support of OAQPS work on NSPS for industrial boilers, June 29, 1978. Also Section 3 of Task 2 Report, "The Industrial Steam Generator Industry," August 1978.
- 3-13 Lim, K. J., et al., "Environmental Assessment of Utility Boiler Combustion Modification NO<sub>x</sub> Controls," Acurex Draft Report TR-78-105 under EPA Contract No. 68-02-2160, April, 1978.
- 3-14 Milligan, R. J., et al., "Update of NO<sub>x</sub> Emission Factors for AP-42," Acurex Draft Report TR-78-306 under EPA Contract No. 68-02-2611, Task 34, October 1978.
- 3-15 Crawford, A. R., et al., "Field testing: Application of Combustion Modifications to Control NO<sub>x</sub> Emissions for Utility Boilers," EPA 650/2-74-066, NTIS-PB 237 344/AS, June 1974.
- 3-16 Vatsky, J., "Attaining Low NO<sub>x</sub> Emissions by Combining Low Emission Burners and Off-Stoichiometric Firing," Paper No. 51d, 70th Annual AIChE Meeting, New York, November 1977.
- 3-17 Compobenedetto, E. J., "The Dual Register Pulverized Coal Burner - Field Test Results," presented to Engineering Foundation Conference on Clean Combustion of Coal, New Hampshire, August 1977.
- 3-18 Fletcher, R. J., Peabody Engineering Corp., Telecommunication with R. S. Merrill, Acurex Corp., July 21, 1978.
- 3-19 Bartok, W., "Non-Catalytic Reduction of NO<sub>x</sub> with NH<sub>3</sub>," Proceedings of the Second Stationary Source Combustion Symposium Volume II, EPA-600/7-77-073b, NTIS-PB 271 756/AS, July 1977.
- 3-20 Muzio, L. J., et al., "Package Boiler Flame Modification for Reducing Nitric Oxide Emissions -- Phase II of III," EPA-R2-73-292-B, NTIS-PB 236 752, June 1974.
- 3-21 Schwieger, B., "Industrial Boilers -- What's Happening Today," Power Magazine, Vol. 121, No. 2, pp. S.1-S.24, February 1977, and Vol. 122, No. 2 pp. S.1-S.24, February 1978.
- 3-22 Morton, B., F. Keeler Co., Williamsport, PA, Telecommunication with H. I Lips, Acurex Corp., August 8, 1978.
- 3-23 Ando, J., et al., "NO<sub>x</sub> Abatement for Stationary Sources in Japan," EPA-600/7-77-103b, NTIS-PB 276 948/AS, September 1977.
- 3-24 Ando, J., et al., "NO<sub>x</sub> Abatement for Stationary Sources in Japan," EPA-600/2-76-013b, NTIS PB 250 586/AS, January 1976.

- 3-25 Lindsay, J., Zurn Industries, Telecommunication with C. Castaldini, Acurex Corp., August 17, 1978.
- 3-26 Koppang, R. R., TRW, Telecommunication with R. S. Merrill, Acurex Corp., July 21, 1978.
- 3-27 Eaton, S., Coen Co., Telecommunication with R. S. Merrill, Acurex Corp., August 9, 1978.
- 3-28 "Recommendation for Standard Boilers," prepared by PEDCo in support of OAQPS work on NSPS for industrial boilers, August 30, 1978.
- 3-29 Broz, L. D., Acurex Corp., C. B. Sedman, EPA/OAQPS, and J. D. Mobley, EPA/IERL-RTP, Letter to Industrial Boiler Contractors, September 26, 1978.
- 3-30 Fletcher, R. J., Peabody Engineering Corp, Telecommunication with R. S. Merrill, Acurex Corp., July 21, 1978
- 3-31 Mason, H. B., et al., "Preliminary Environmental Assessment of Combustion Modification Techniques: Volume II. Technical Results," EPA-600/7-77-119b, NTIS-PB 276 681/AS, October 1977.
- 3-32 Mobley, J. D., EPA IERL-RTP, N.C., Letter to Industrial Boiler Contractors, April 27, 1979.
- 3-33 Habelt, W. W., Howel, B. M., "Control of NO<sub>x</sub> Formation in Tangentially Coal-Fired Steam Generators," presented at Electric Power Research Institute NO<sub>x</sub> Control Technology Seminar, San Francisco, California, February, 1976.
- 3-34 Marshall, J. J., and A. P. Selker, "The Role of Tangential Firing and Fuel Properties in Attaining Low NO<sub>x</sub> Operation for Coal-Fired Steam Generation", presented at Second Electric Power Research Institute NO<sub>x</sub> Control Technology Seminar, Denver, Colorado, November 1978.
- 3-35 Lips, H. I., and E. B. Higginbotham, "Field Testing of an Industrial Stoker Coal-Fired Boiler -- Effects of Combustion Modification NO<sub>x</sub> Control on Emissions -- Site B," Acurex Report TR-79-18/EE, EPA Contract No. 68-02-2160, Acurex Corporation, Mountain View, California, August 1979.

## SECTION 4

### COST IMPACT

The cost impact of combustion modification techniques for controlling  $\text{NO}_x$  emissions from industrial boilers is discussed in this section. The controls considered are those discussed in Section 3 as candidates for best  $\text{NO}_x$  emissions control system. Selection criteria for the best control system were based on the effectiveness, commercial availability or R&D status, operational impact, and reliability of each system. Estimates of the energy, environmental, and cost impacts were also considered. This section examines the cost impacts in greater detail.

#### 4.1 COST ANALYSIS

In the evaluation of  $\text{NO}_x$  controls for industrial boilers, the cost of boiler systems with controls are compared to the costs of uncontrolled and State Implementation Plan (SIP) controlled systems. (SIP control levels are summarized in Table 5-1.) Section 4.1.1 reviews the components that go into control costs, while Section 4.1.2 reviews the cost basis and assumptions.

##### 4.1.1 Components of Control Costs

Nitrogen oxides control techniques can have two major cost components. First, the control methods will usually require additional hardware, increasing the cost of the boiler to the user. Second, the cost of producing steam will probably be increased due both to the increased capital charge to be annualized (referred to as annualized capital cost) and any changes in operating, maintenance, and energy costs (referred to collectively as annualized operating costs). The price of steam will not always rise with addition of controls; for example, as will be shown later, low excess air operation can decrease the cost of steam in some cases.

The capital and operating costs of  $\text{NO}_x$  controls discussed here are engineering estimates based on limited published costs and discussions

with equipment vendors. The largest component of operating costs are often due to increased energy consumption. These changes in energy consumption are discussed in Section 5 and those values are used in estimating the changes in steam cost due to  $\text{NO}_x$  controls.

Indeed, it has been found for  $\text{NO}_x$  controls for utility boilers that losses in boiler efficiency (increased fuel consumption) can add up to over half the cost-to-control (Reference 4-1). For example, a 0.25 percent loss in boiler efficiency with staged combustion can translate to one third of the control cost. Unfortunately, these changes in boiler efficiency with  $\text{NO}_x$  controls have not been precisely established for utility or industrial boilers. Therefore, although equipment and operating costs are discussed here in as great detail as available data permit, the large unknown in energy costs should be noted when discussing control costs. In other words, a very small variation in boiler efficiency loss can lead to a very large fluctuation in control costs. In many cases, then, a detailed discussion of equipment cost estimates, etc. can become moot.

Since  $\text{NO}_x$  control techniques are not widely used on industrial boilers, very little is known about long term operation. Thus one area of concern is how  $\text{NO}_x$  controls affect day-to-day operation. Industrial boilers are operated with a minimal amount of operator attention and run under changing loads. Therefore the combustion modifications that are made for  $\text{NO}_x$  control may also require that the boiler control system (e.g., air and fuel flow controls) be modified. The cost of an additional boiler control system has been estimated and included in the presented prices, but without long term tests, a true modification cost can not be given. Also, since the actual costs depend on site and use of boiler, only estimated prices for a typical boiler can be given.

The costs of the following control techniques are discussed in this section: low excess air (LEA), staged combustion air (SCA) -- usually overfire air (OFA) or sidefire air (SFA), flue gas recirculation (FGR), low  $\text{NO}_x$  burners (LNB), reduced air preheat (RAP), and ammonia injection. The following paragraphs describe the required and/or recommended equipment needed when implementing these combustion modification techniques. The costs for the required and/or recommended equipment are included in the prices that will be listed.

Low excess air operation may require an oxygen trim system consisting of a flue gas  $O_2$  analyzer along with the control equipment for regulating air flow. This is in addition to the normal air flow control system. Wind box modifications may also be required for multi-burner boilers.

Staged combustion requires air ports and possible windbox modification. Several air ports may be required to allow firing of different types of fuels. Larger forced draft fan power also may be needed, and an oxygen trim system should probably be installed.

Flue gas recirculation requires a larger forced draft fan and the associated duct work to recycle a portion of the flue gas. Windbox and burners may need to be modified to accommodate the additional gas flow. A control system to regulate the combustion oxygen and the amount of the flue gas recirculated would probably also be needed.

Low  $NO_x$  burner operation may require a larger forced draft fan if the burners have an increased pressure drop. Windbox modifications may also be required. An oxygen trim system is recommended to allow operation at the lowest possible excess air.

Ammonia injection requires injector ports, the injection system, and the ammonia handling and storage system. Ammonia injection may also require several different injection port locations and a control device to switch ports as load changes. An air compressor to supply a carrier gas for the ammonia would also be needed. Controls to regulate the flow of  $NH_3$  will also be required. Since the process is patented by Exxon, they will require a licensing fee. This fee was not included in the present analysis as that cost is a negotiable item and the information is not available.

#### 4.1.2 Cost Basis

Table 4-1 summarizes the simplified cost basis used in evaluating  $NO_x$  controls. Capital costs represent the initial investment for the control: equipment and installation costs. On an annualized basis, the initial investment can be levelized into capital recovery charges and combined with taxes and insurance to comprise annualized capital charges. Annualized capital charges plus annual operating costs give the total cost to control per year.

TABLE 4-1. COST BASIS FOR EVALUATING NO<sub>x</sub> CONTROLS

|                                    |
|------------------------------------|
| Capital Costs (Initial Investment) |
| Equipment Costs                    |
| Installation Costs, Indirect       |
| Engineering                        |
| Construction and Field Expense     |
| Construction Fees                  |
| Start-up                           |
| Performance Test                   |
| Installation Costs, Direct         |
| Contingencies                      |
| Annualized Costs                   |
| Capital Charges (Fixed Costs)      |
| Capital Recovery                   |
| Taxes                              |
| Insurance                          |
| Operating Costs                    |
| Utilities                          |
| Raw Materials                      |
| Operating Labor                    |
| Maintenance                        |
| Fuel Costs                         |

Since experience with industrial boiler NO<sub>x</sub> controls is very limited, a detailed breakdown of the costs into the various capital and operational cost components as illustrated in Table 4-1 was not always possible. The analysis relied heavily on estimates from equipment vendors and published data from utility boiler experience. Where information was lacking, engineering estimation rules as outlined in Reference 4-2 were used. Costs were collected from various sources and extrapolated to the boiler size under consideration. Using engineering judgement, a typical cost was estimated from these extrapolated values.

Following the guidelines of the EPA memo which described the suggested cost analysis approach used here (Reference 4-21), the



reliability of the cost estimates presented here is estimated to be no better than plus or minus 30 percent except for ammonia injection and low  $\text{NO}_x$  burners. Since these last two techniques represent untried technologies, the reliability of their costs is estimated to be plus 100 percent.

As discussed in Section 2, the limited control performance data does not allow one to determine the effect of different coal types upon  $\text{NO}_x$  emissions. Hence the control cost estimates presented here are not broken down by coal type.

In calculating the costs of control systems, several assumptions were made. The annualized capital charges, were taken to be 20 percent of the total installed cost of the combustion modification, and the annualized operating labor and maintenance costs were taken to be 5 percent of the total installed cost. Twenty percent was the factor used for annualized capital charges because it is common industrial practice to use 20 percent when presenting a first estimate of annualized capital charges. For example, see the EPA Standard Support and Environmental Impact Statement for Stationary Gas Turbines (Reference 4-3), the cost estimates for ammonia injection (References 4-4 and 4-5), and the utility industry price estimates for  $\text{NO}_x$  control given in Reference 4-6. This 20 percent includes four percent for G&A, taxes, and insurance and a capital recovery factor of 16 percent. The utility industry also used 5 percent annualized operating labor and maintenance cost for  $\text{NO}_x$  combustion modification techniques for utility boilers (Reference 4-6). Since there is no long term operating experience with combustion modifications for industrial boilers, it was decided to use five percent as a first estimate.

An industrial boiler is assumed to be 82 percent efficient without an air preheater or economizer and 84 percent efficient with one except for a pulverized coal-fired boiler which is assumed to be 87 percent efficient (References 4-7 and 4-8). To generate one kilogram of steam requires 0.00256 GJ (1100 Btu/lb) of heat. The load factors and fuel costs given by PEDCo (Reference 4-2) were used in the cost analysis used. PEDCo used load factors of 45 percent for boilers smaller than  $7 \times 10^3$  kg steam/hour ( $15 \times 10^3$  lb steam/hr) and 60 percent for the larger sizes. The fuel prices used are \$2.84/GJ for No. 2 oil, \$2.21/GJ for No. 6 oil,

\$1.85/GJ for natural gas, and \$1.10/GJ for low sulfur coal. The price of No. 6 oil is increased by 20 percent to \$2.65/GJ to account for the cost of heating the fuel when firing and keeping the storage tank warm. The fuel prices, as well as all other costs to be presented, are 1978 prices.

In the following discussion, costs to modify the boiler are given as a percentage of the boiler's installed cost, while the steam costs include the entire steam plant. The total steam plant costs more than that of the boiler alone because it includes additional equipment such as the smoke stack and water treatment system. The boiler and steam production costs used are from a report by PEDCo presented to the EPA-OAQPS (Reference 4-2). Except for adding an  $O_2$  trim system and ammonia injection, retrofit costs were assumed to be twice that of installing  $NO_x$  controls on a new unit as was found by one author for a small industrial boiler (Reference 4-9). However, this may be optimistic and retrofit control costs may actually be four times that for new designs. The factor of two assumed here is just for the purposes of a first estimate in control costs. It should be reiterated that the control costs presented in this section, as well as achievable  $NO_x$  control levels, are based on very limited data.

The cost estimates presented are only for reaching the moderate, intermediate, and stringent control levels discussed in Section 3. It is usually possible to achieve lower  $NO_x$  levels by extending the degree of application of the control technique but the control costs were estimated assuming that the indicated technique is used just to reach the indicated level of control. In many cases, using even lower excess air can increase efficiency, lower the required energy, and reduce the steam cost.

The cost data will be presented in tables in which the capital and annualized incremental costs and cost effectiveness of  $NO_x$  controls will be summarized (the limited available details are given in the Appendix). The costs are incremented from the costs of the basic uncontrolled systems. In the tables, the annualized incremental costs were calculated by the following formulas (units of mills/ $10^3$  kg steam).

Total Annual Cost = Annualized Fixed Costs Plus Operating Cost

Annualized Fixed Costs =

$$\frac{(\text{Total Installed Cost of Control})(0.2)(1000)}{(\text{Hours/yr})(\text{Load Factor})(\text{Boiler Capacity, } 10^3 \text{ kg steam/hr})}$$

of fly ash in the FGD sludge. SO<sub>2</sub> scrubbers which also function as particulate control devices may produce sludges containing 20 to 60 percent fly ash. Highly volatile trace elements present in coal such as mercury, and possibly selenium and arsenic, may be present in flue gas as vapors. Concentrations of these volatile elements in sludge depend primarily on their concentrations in the fuel and on the efficiency with which they are captured in the scrubber. Sludge concentrations of highly volatile trace elements are essentially independent of the efficiency of particulate removal prior to scrubbing.

The ranges of trace element concentrations in FGD waste solids are shown in Table 3-25. The data are based on tests of seven utility plants.<sup>2</sup>

No data for benzo(a)pyrene concentration in FGD sludges were found. In limited tests conducted in the Emissions Assessment Program,<sup>2,6</sup> a few POM compounds were found in scrubber ash from a wood-fired source. The concentration ranged between 1.9 ppm for pyrene, and 306 ppm for naphthalene.

### 3.3.3 Wastewater Treatment Process Sludges

The waste characteristics of water treatment process sludges generated at utility and industrial combustion plants are a function of the raw water quality, the degree of treatment required (i.e., clarification, filtration, ion exchange, etc.), and the treatment process employed. Table 3-26 summarizes the general characteristics of these wastes. The greatest quantities of solid waste at utility and industrial sites are produced by clarification with chemical coagulants and softening precipitation. No data on trace metals or BaP are available.

Figure 4-1. Estimated annualized control cost versus  $\text{NO}_x$  level for coal-fired boilers (costs are only first estimates).

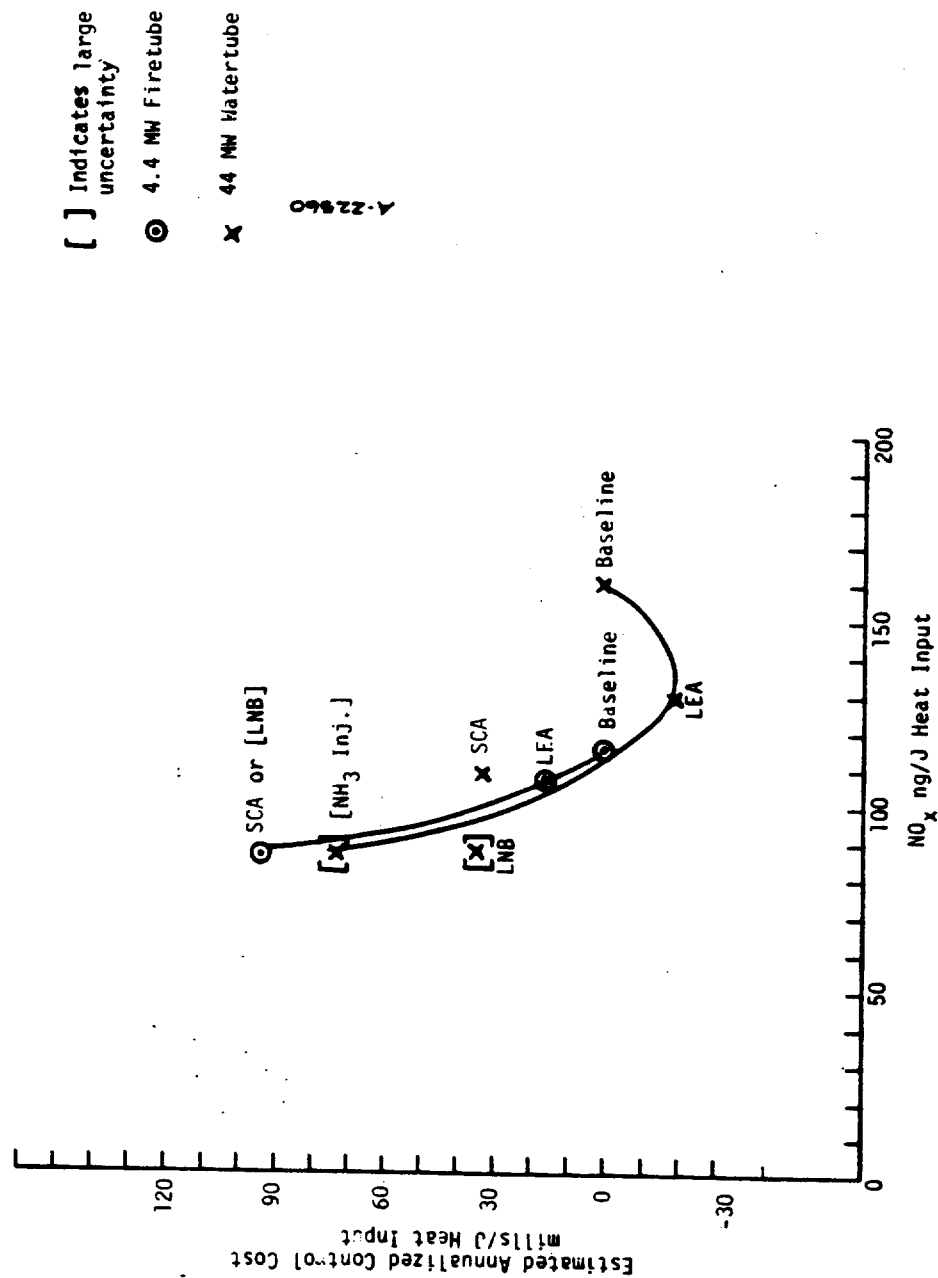


Figure 4-2. Estimated annualized control cost versus NO<sub>x</sub> emission level for residual oil-fired boilers (costs are only first estimates).

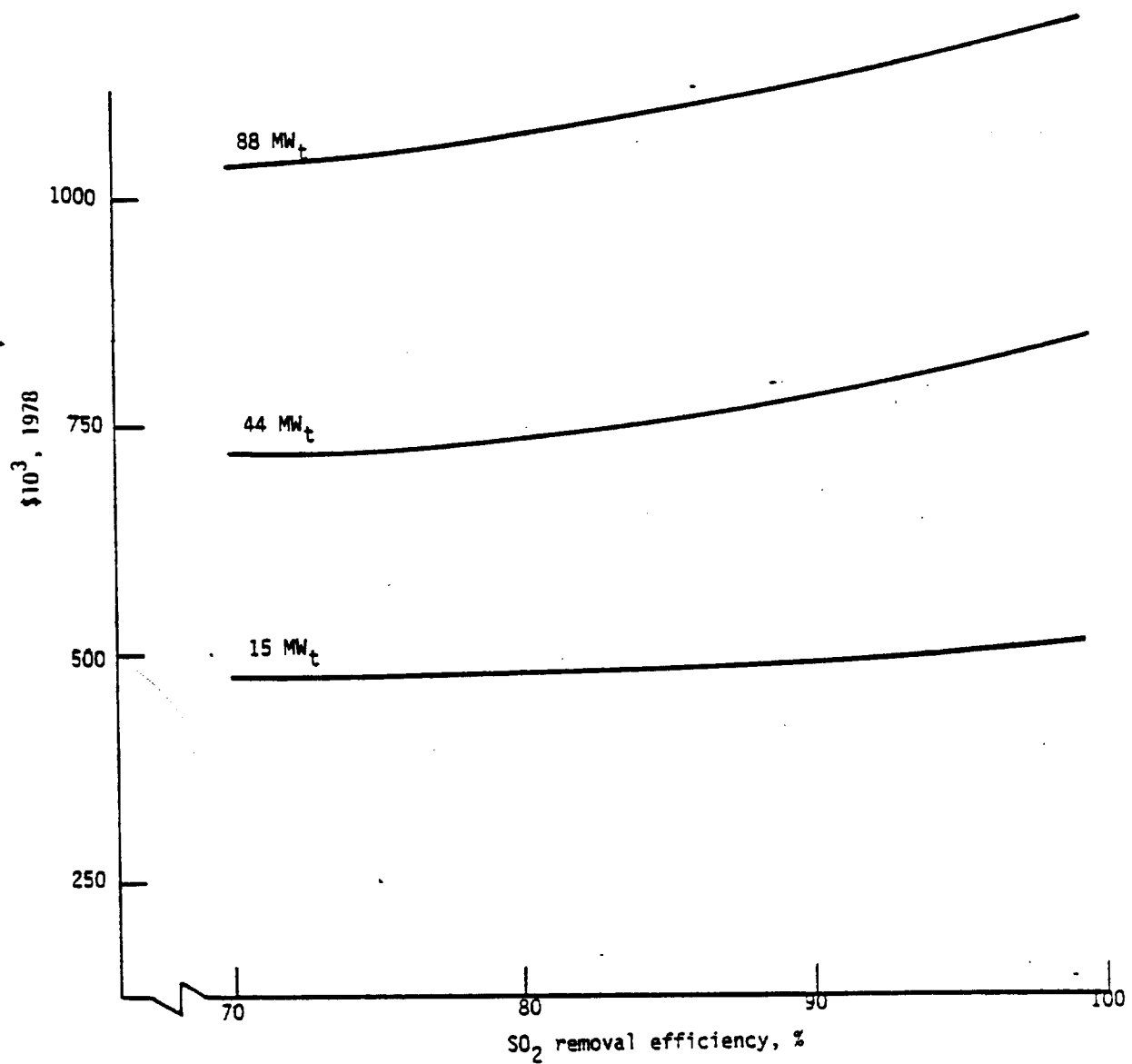


Figure B-17. Annualized costs for industrial dual alkali FGD system.

Note: Eastern coal 3.5% sulfur, 60% capacity factor.

TABLE 4-2. ESTIMATED COSTS OF CANDIDATE NO<sub>x</sub> CONTROL TECHNIQUES FOR  
NEW COAL-FIRED BOILERS

| System           |                            |                                                                                                                  |                               | Estimated Incremental Costs |                    |                       |                    |                |
|------------------|----------------------------|------------------------------------------------------------------------------------------------------------------|-------------------------------|-----------------------------|--------------------|-----------------------|--------------------|----------------|
| Standard Boilers |                            | Type and Level of Control                                                                                        | Control Effectiveness Percent | Capital Cost 103 \$         | Annualized Costs   |                       |                    |                |
| Type             | Heat Input MW (106 Btu/hr) |                                                                                                                  |                               |                             | Fixed Costs        | Operating Costs       | Total Costs        |                |
|                  |                            |                                                                                                                  |                               |                             | mills 103 kg steam | mills 103 kg steam    | mills 103 kg steam | mills GJ input |
| Pulverized Coal  | 59 (200)                   | No Controls<br>SIP Moderate<br>LEA Intermediate<br>SCA Stringent<br>LNB Stringent<br>Ammonia Injection Stringent | --                            | --                          | --                 | --                    | --                 |                |
|                  |                            |                                                                                                                  |                               | 27                          | -13 (-6)           | 0(0)                  | 0 <0> <sup>c</sup> |                |
|                  |                            |                                                                                                                  |                               | 47                          | 47 (21)            | 71 (32)               | 24 <25>            |                |
|                  |                            |                                                                                                                  |                               | [47] <sup>b</sup>           | [47 (21)]          | [71 (32)]             | [24 <25]           |                |
|                  |                            |                                                                                                                  |                               | [237]                       | [82]               | [205]                 | [70 <74]           |                |
|                  | 117 (400)                  |                                                                                                                  | --                            | --                          | --                 | --                    |                    |                |
|                  |                            |                                                                                                                  | 44                            | -13 (-6)                    | -2(-1)             | 0.6<0.7> <sup>c</sup> |                    |                |
|                  |                            |                                                                                                                  | 78                            | 46 (21)                     | 67 (30)            | 22 <24>               |                    |                |
|                  |                            |                                                                                                                  | [78]                          | [46 (21)]                   | [67 (30)]          | [22 <24>]             |                    |                |
|                  |                            |                                                                                                                  | [472]                         | [82]                        | [205]              | [70 <74>]             |                    |                |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.  
<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

Continued

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TABLE 4-2. Concluded

| System             |                                        |                                                                           |                               | Estimated Incremental Costs            |                                                             |                                                                 |                                                                                           |                                           |
|--------------------|----------------------------------------|---------------------------------------------------------------------------|-------------------------------|----------------------------------------|-------------------------------------------------------------|-----------------------------------------------------------------|-------------------------------------------------------------------------------------------|-------------------------------------------|
| Standard Boilers   |                                        | Type and Level of Control                                                 | Control Effectiveness Percent | Capital Cost 10 <sup>3</sup> \$        | Annualized Costs                                            |                                                                 |                                                                                           |                                           |
| Type               | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                                                           |                               |                                        | Fixed Costs<br><div>mills<br/>10<sup>3</sup> kg steam</div> | Operating Costs<br><div>mills<br/>10<sup>3</sup> kg steam</div> | Total Costs<br><div>mills<br/>10<sup>3</sup> kg steam</div> <div>mills<br/>GJ input</div> |                                           |
| Spreader Stoker    | 44 (150)                               | No Controls<br>SIP<br>Moderate<br>LEA<br>Intermediate<br>SCA<br>Stringent | --<br><br>1<br><br>20         | --<br><br>22<br><br>22                 | --<br><br>16 (7) <sup>a</sup><br><br>16 (7)                 | --<br><br>-5 (-2)<br><br>4 (2)                                  | --<br><br>11 (5)<br><br>20 (9)                                                            | --<br><br>3 <3> <sup>c</sup><br><br>6 <7> |
| Spreader Stoker    | 25 (85)                                | No Controls<br>SIP<br>SCA<br>Moderate<br>Ammonia Injection<br>Stringent   | --<br><br>20<br><br>55        | --<br><br>17<br><br>[102] <sup>b</sup> | --<br><br>22 (10)<br><br>[133 (60)]                         | --<br><br>5 (2)<br><br>[90 (40)]                                | --<br><br>27 (12)<br><br>[223 (100)]                                                      | --<br><br>8 <8><br><br>[ 71 <75>]         |
| Chain Grate Stoker | 22 (75)                                | No Controls<br>SIP<br>Intermediate<br>LEA<br>Stringent                    | --<br><br>10                  | --<br><br>17                           | --<br><br>26 (12)                                           | --<br><br>-10 (-4)                                              | --<br><br>16 (8)                                                                          | --<br><br>5 <5>                           |
| Underfeed Stoker   | 9 (30)                                 | No controls<br>SIP<br>Intermediate<br>LEA<br>Stringent                    | --<br><br>10                  | --<br><br>14                           | --<br><br>54 (24)                                           | --<br><br>-6 (-3)                                               | --<br><br>48 (21)                                                                         | --<br><br>15 <16>                         |

<sup>a</sup>Numbers in parentheses are mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicates units of mill/10<sup>6</sup> Btu heat input.

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TABLE 4-3. ESTIMATED COST-EFFECTIVENESS AND IMPACTS OF CANDIDATE NO<sub>x</sub> CONTROL TECHNIQUES FOR NEW COAL-FIRED BOILERS

| System           |                                        |                                | Impacts                                          |                                        |                       |                                      |                       |
|------------------|----------------------------------------|--------------------------------|--------------------------------------------------|----------------------------------------|-----------------------|--------------------------------------|-----------------------|
| Standard Boilers |                                        | Type and Level of Control      | Cost Effectiveness \$/kg NO <sub>x</sub> Reduced | Percent Increase in Capital Costs Over |                       | Percent Increase in Steam Costs Over |                       |
| Type             | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                |                                                  | Uncontrolled Boiler                    | SIP-Controlled Boiler | Uncontrolled Boiler                  | SIP-Controlled Boiler |
| Pulverized Coal  | 59 (200)                               | No Controls<br>SIP<br>Moderate | --                                               | --                                     | --                    | --                                   | --                    |
|                  |                                        | LEA<br>Intermediate            | 0                                                | 0.4                                    | --                    | 0                                    | 0                     |
|                  |                                        | SCA<br>Stringent               | 0.3                                              | 0.8                                    | 0.8                   | 0.6                                  | 0.6                   |
|                  |                                        | LNB<br>Stringent               | [0.3] <sup>c</sup>                               | [0.8]                                  | [0.8]                 | [0.6]                                | [0.6]                 |
|                  |                                        | Ammonia Injection<br>Stringent | [1.0]                                            | [4.0]                                  | [4.0]                 | [2.0]                                | [2.0]                 |
|                  |                                        |                                |                                                  |                                        |                       |                                      |                       |
|                  | 117 (400)                              | No Controls<br>SIP<br>Moderate | --                                               | --                                     | --                    | --                                   | --                    |
|                  |                                        | LEA<br>Intermediate            | 0                                                | 0.4                                    | --                    | 0                                    | 0                     |
|                  |                                        | SCA<br>Stringent               | 0.3                                              | 0.8                                    | 0.8                   | 0.6                                  | 0.6                   |
|                  |                                        | LNB<br>Stringent               | [0.3] <sup>c</sup>                               | [0.8]                                  | [0.8]                 | [0.6]                                | [0.6]                 |
|                  |                                        | Ammonia Injection<br>Stringent | [1.0]                                            | [4.0]                                  | [4.0]                 | [2.0]                                | [2.0]                 |
|                  |                                        |                                |                                                  |                                        |                       |                                      |                       |

<sup>a</sup>Cost of boiler only.  
<sup>b</sup>Cost includes entire steam plant.  
<sup>c</sup>Bracket indicates gross estimate.

Continued

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TABLE 4-3. Concluded

| System             |                                        | Impacts                                                                   |                                                  |                                        |                            |                                      |                            |
|--------------------|----------------------------------------|---------------------------------------------------------------------------|--------------------------------------------------|----------------------------------------|----------------------------|--------------------------------------|----------------------------|
| Standard Boilers   |                                        | Type and Level of Control                                                 | Cost Effectiveness \$/kg NO <sub>x</sub> Reduced | Percent Increase in Capital Costs Over |                            | Percent Increase in Steam Costs Over |                            |
| Type               | Heat Input MM (10 <sup>6</sup> Btu/hr) |                                                                           |                                                  | Uncontrolled Boiler                    | SIP-Controlled Boiler      | Uncontrolled Boiler                  | SIP-Controlled Boiler      |
| Spreader Stoker    | 44 (150)                               | No Controls<br>SIP<br>Moderate<br>LEA<br>Intermediate<br>SCA<br>Stringent | --<br><br>1.6<br><br>0.1                         | --<br><br>0.5<br><br>0.5               | --<br><br>0.5<br><br>0.5   | --<br><br>0.1<br><br>0.1             | --<br><br>0.1<br><br>0.1   |
| Spreader Stoker    | 25 (85)                                | No Controls<br>SIP<br>SCA<br>Moderate<br>Ammonia Injection<br>Stringent   | --<br><br>0.2<br><br>[0.5]                       | --<br><br>0.7<br><br>[5.0]             | --<br><br>0.7<br><br>[5.0] | --<br><br>0.2<br><br>[2.5]           | --<br><br>0.2<br><br>[2.5] |
| Chain Grate Stoker | 22 (75)                                | No Controls<br>SIP<br>Intermediate<br>LEA<br>Stringent                    | --<br><br>0.4                                    | --<br><br>1.2                          | --<br><br>1.2              | --<br><br>0.2                        | --<br><br>0.2              |
| Underfeed Stoker   | 9 (30)                                 | No Controls<br>SIP<br>Intermediate<br>LEA<br>Stringent                    | --<br><br>0.6                                    | --<br><br>1.5                          | --<br><br>1.5              | --<br><br>0.2                        | --<br><br>0.2              |

<sup>a</sup>Cost of boiler only.<sup>b</sup>Cost includes entire steam plant.<sup>c</sup>Bracket indicates gross estimate.

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TABLE 4-4. ESTIMATED COSTS OF CANDIDATE CONTROL TECHNIQUES  
FOR RETROFITTED COAL-FIRED BOILERS

| System           |                                        |                                |                               | Estimated Incremental Costs     |                                                             |                                                                 |                                                                                           |                    |
|------------------|----------------------------------------|--------------------------------|-------------------------------|---------------------------------|-------------------------------------------------------------|-----------------------------------------------------------------|-------------------------------------------------------------------------------------------|--------------------|
| Standard Boilers |                                        | Type and Level of Control      | Control Effectiveness Percent | Capital Cost 10 <sup>3</sup> \$ | Annualized Costs                                            |                                                                 |                                                                                           |                    |
| Type             | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                |                               |                                 | Fixed Costs<br><div>mills<br/>10<sup>3</sup> kg steam</div> | Operating Costs<br><div>mills<br/>10<sup>3</sup> kg steam</div> | Total Costs<br><div>mills<br/>10<sup>3</sup> kg steam</div> <div>mills<br/>GJ input</div> |                    |
| Pulverized Coal  | 59 (200)                               | No Controls<br>SIP<br>Moderate | --                            | --                              | --                                                          | --                                                              | --                                                                                        |                    |
|                  |                                        | LEA<br>Intermediate            | 10                            | 30                              | 16 (7) <sup>a</sup>                                         | -12 (-5)                                                        | 4 (2)                                                                                     | 1 <1> <sup>c</sup> |
|                  |                                        | SCA<br>Stringent               | 25                            | 70                              | 37 (17)                                                     | 59 (27)                                                         | 96 (44)                                                                                   | 33 <35>            |
|                  |                                        | LNB<br>Stringent               | 25                            | [70 <sup>b</sup> ]              | [35 (16)]                                                   | [60 (27)]                                                       | [95 (43)]                                                                                 | [32 <34>]          |
|                  |                                        | Ammonia Injection<br>Stringent | 25                            | [237]                           | [125 (57)]                                                  | [82 (37)]                                                       | [205 (93)]                                                                                | [70 <73>]          |
|                  | 117 (400)                              | No Controls<br>SIP<br>Moderate | --                            | --                              | --                                                          | --                                                              | --                                                                                        |                    |
|                  |                                        | LEA<br>Intermediate            | 10                            | 50                              | 13 (6) <sup>a</sup>                                         | -13 (-6)                                                        | 0 (0)                                                                                     | 0 <0> <sup>c</sup> |
|                  |                                        | SCA<br>Stringent               | 25                            | 118                             | 31 (14)                                                     | 57 (26)                                                         | 88 (40)                                                                                   | 29 <31>            |
|                  |                                        | LNB<br>Stringent               | 25                            | [118 <sup>b</sup> ]             | [31 (14)]                                                   | [57 (26)]                                                       | [88 (40)]                                                                                 | [29 <31>]          |
|                  |                                        | Ammonia Injection<br>Stringent | 25                            | [237]                           | [125 (57)]                                                  | [82 (37)]                                                       | [205 (93)]                                                                                | [70 <73>]          |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

Continued

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TABLE 4-4. Concluded

| System           |                            |                                                                           |                               | Estimated Incremental Costs            |                                             |                                          |                                      |                                           |
|------------------|----------------------------|---------------------------------------------------------------------------|-------------------------------|----------------------------------------|---------------------------------------------|------------------------------------------|--------------------------------------|-------------------------------------------|
| Standard Boilers |                            | Type and Level of Control                                                 | Control Effectiveness Percent | Capital Cost 103 \$                    | Annualized Costs                            |                                          |                                      | Total Costs                               |
| Type             | Heat Input MW (106 Btu/hr) |                                                                           |                               |                                        | Fixed Costs<br>mills<br>103 kg steam        | Operating Costs<br>mills<br>103 kg steam | mills<br>103 kg steam                |                                           |
| Spreader Stoker  | 44 (150)                   | No Controls<br>SIP<br>Moderate<br>LEA<br>Intermediate<br>SCA<br>Stringent | --<br><br>1<br><br>20         | --<br><br>25<br><br>25                 | --<br><br>18 (8) <sup>a</sup><br><br>18 (8) | --<br><br>-3 (-1)<br><br>5 (2)           | --<br><br>15 (7)<br><br>23 (10)      | --<br><br>5 <5> <sup>c</sup><br><br>7 <7> |
| Spreader Stoker  | 25 (85)                    | No Controls<br>SIP<br>Moderate<br>SCA<br>Ammonia Injection<br>Stringent   | --<br><br>20<br><br>55        | --<br><br>20<br><br>[100] <sup>b</sup> | --<br><br>26 (12)<br><br>[131 (59)]         | --<br><br>7 (3)<br><br>[88 (40)]         | --<br><br>33 (15)<br><br>[220 (100)] | --<br><br>11 <11><br><br>[70 <74>]        |
| Chain Grate      | 22 (75)                    | No Controls<br>SIP<br>Intermediate<br>LEA<br>Stringent                    | --<br><br>10                  | --<br><br>20                           | --<br><br>30 (14)                           | --<br><br>-10 (-4)                       | --<br><br>20 (10)                    | --<br><br>6 <6>                           |
| Underfeed Stoker | 9 (30)                     | No Controls<br>SIP<br>Intermediate<br>LEA<br>Stringent                    | --<br><br>15                  | --<br><br>14                           | --<br><br>54 (24)                           | --<br><br>-4 (-2)                        | --<br><br>50 (23)                    | --<br><br>16 <17>                         |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

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TABLE 4-5. ESTIMATED COST-EFFECTIVENESS AND IMPACTS OF CANDIDATE NO<sub>x</sub> CONTROL TECHNIQUES FOR RETROFITTED COAL-FIRED BOILERS

| System           |                            |                             | Impacts                                          |                                        |                       |                                      |                       |  |
|------------------|----------------------------|-----------------------------|--------------------------------------------------|----------------------------------------|-----------------------|--------------------------------------|-----------------------|--|
| Standard Boilers |                            | Type and Level of Control   | Cost Effectiveness \$/kg NO <sub>x</sub> Reduced | Percent Increase in Capital Costs Over |                       | Percent Increase in Steam Costs Over |                       |  |
| Type             | Heat Input MW (106 Btu/hr) |                             |                                                  | Uncontrolled Boiler                    | SIP-Controlled Boiler | Uncontrolled Boiler                  | SIP-Controlled Boiler |  |
| Pulverized Coal  | 59 (200)                   | LEA Intermediate            | 0.1                                              | 0.5                                    | 0.5                   | 0                                    | 0                     |  |
|                  |                            | SCA Stringent               | 0.5                                              | 1.2                                    | 1.2                   | 0.8                                  | 0.8                   |  |
|                  |                            | LNB Stringent               | [0.4] <sup>c</sup>                               | [1.2]                                  | [1.2]                 | [0.8]                                | [0.8]                 |  |
|                  |                            | Ammonia Injection Stringent | [1.0]                                            | [4.0]                                  | [4.0]                 | [2.0]                                | [2.0]                 |  |
|                  | 117 (400)                  | LEA Intermediate            | 0                                                | 0.5                                    | 0.5                   | 0                                    | 0                     |  |
|                  |                            | SCA Stringent               | 0.4                                              | 1.2                                    | 1.2                   | 0.8                                  | 0.8                   |  |
|                  |                            | LNB Stringent               | [0.4] <sup>c</sup>                               | [1.2]                                  | [1.2]                 | [0.8]                                | [0.8]                 |  |
|                  |                            | Ammonia Injection Stringent | [1.0]                                            | [4.0]                                  | [4.0]                 | [2.0]                                | [2.0]                 |  |

<sup>a</sup>Cost of boiler only.

<sup>b</sup>Cost includes entire steam plant.

<sup>c</sup>Bracket indicates gross estimate.

Continued

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TABLE 4-5. Concluded

| System             |                                        | Impacts                                                                           |                                                  |                                                    |                          |                                                  |                          |
|--------------------|----------------------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------|----------------------------------------------------|--------------------------|--------------------------------------------------|--------------------------|
| Standard Boilers   |                                        | Type and Level of Control                                                         | Cost Effectiveness \$/kg NO <sub>x</sub> Reduced | Percent Increase in Capital Cost <sup>a</sup> Over |                          | Percent Increase in Steam Cost <sup>b</sup> Over |                          |
| Type               | Heat Input MM (10 <sup>6</sup> Btu/hr) |                                                                                   |                                                  | Uncontrolled Boiler                                | SIP-Controlled Boiler    | Uncontrolled Boiler                              | SIP-Controlled Boiler    |
| Spreader Stoker    | 44 (150)                               | No Controls<br>SIP<br>Moderate<br><br>LEA<br>Intermediate<br><br>SCA<br>Stringent | --<br><br>2.4<br><br>0.2                         | --<br><br>0.6<br><br>0.6                           | --<br><br>0.6<br><br>0.6 | --<br><br>0.1<br><br>0.2                         | --<br><br>0.1<br><br>0.2 |
| Spreader Stoker    | 25 (85)                                | No Controls<br>SIP<br><br>SCA<br>Moderate<br><br>Amonia Injection<br>Stringent    | --<br><br>0.2<br><br>0.5 <sup>c</sup>            | --<br><br>1.0<br><br>5.0                           | --<br><br>1.0<br><br>5.0 | --<br><br>0.3<br><br>2.5                         | --<br><br>0.3<br><br>2.5 |
| Chain Grate Stoker | 22 (75)                                | No Controls<br>SIP<br>Intermediate<br><br>LEA<br>Stringent                        | --<br><br>0.5                                    | --<br><br>1.4                                      | --<br><br>1.4            | --<br><br>0.2                                    | --<br><br>0.2            |
| Underfeed Stoker   | 9 (30)                                 | No Controls<br>SIP<br>Intermediate<br><br>LEA<br>Stringent                        | --<br><br>0.7                                    | --<br><br>1.5                                      | --<br><br>1.5            | --<br><br>0.2                                    | --<br><br>0.2            |

<sup>a</sup>Cost of boiler only.<sup>b</sup>Cost includes entire steam plant.<sup>c</sup>Bracket indicates gross estimate.

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#### 4.2.1 New Facilities

For pulverized coal-fired boilers, controls are not needed to reach SIP or moderate levels (301 ng/J). To achieve intermediate levels (258 ng/J), low excess air can sometimes be used which should not raise the cost of generating steam. Staged combustion through overfire air operation may allow stringent control levels to be met and could increase steam cost by about 0.5 percent. Low  $\text{NO}_x$  burners or ammonia injection may be needed to reach stringent control levels. Since both techniques are only in the development stage, only rough cost estimates can be given. However, LNB will probably not cost any more than OFA (References 4-1, 4-16). Low  $\text{NO}_x$  burners will most likely have a smaller energy penalty than OFA. Furthermore, low  $\text{NO}_x$  burner windbox modification and any additional burner cost will probably be no more than installing OFA ports. Ammonia injection prices were based on a utility boiler report (References 4-4 and 4-5) and have been extrapolated to industrial boiler size. Because industrial boiler loads fluctuate more than those of utility boilers, the cost of an  $\text{NH}_3$  injection system per kilowatt should be higher for industrial boilers than utility boilers, which operate at more constant loads. Specifically, the ammonia injection system will probably have a higher unit cost since it may require several injection ports and a control system for switching between the ports. Using the utility boiler costs, ammonia injection is estimated to raise the price of steam by over 2 percent.

Large size spreader stokers need controls to reach an intermediate  $\text{NO}_x$  level (258 ng/J) and low excess air operation should be sufficient which would minimally affect the steam price. Overfire air can be used to achieve the even tighter stringent control levels (215 ng/J) which may raise the price of steam slightly. Stokers unlike pulverized coal units, normally have OFA ports as smoke control devices so there is no incremental charge for these ports and no additional fan power requirement. This assumes that the OFA ports need not be relocated for better  $\text{NO}_x$  control. Using more LEA than is needed to reach the  $\text{NO}_x$  control level can reduce the cost of steam. However, this can only be done where process operation limitations permit. The smaller size spreader stokers (<29 MW heat input) must meet more rigid control levels. To meet moderate levels (215 ng/J), OFA can be used which would raise

steam costs slightly as was the case for the larger size stokers. Ammonia injection should achieve stringent control levels (129 ng/J) but, using utility boiler price estimates to give a gross estimate, steam cost can increase by about 2.5 percent which is a very large increase when compared to the other control techniques. Based on the only two tests reported, chain grate stokers only need controls to meet stringent control levels and LEA is recommended. Underfeed stokers only need control to reach stringent levels and LEA is recommended. Low excess air operation would raise steam cost slightly, but using even lower excess air than is needed to reach the control level may lower the steam price, if process operation limitations will permit.

#### 4.2.2 Modified and Reconstructed Facilities

It is usually cheaper to modify a unit in the design phase than to retrofit after installation. Also, since retrofit costs are more site dependent than modifications to new units, retrofit cost estimates have a larger error than estimates for original equipment. Retrofitted controls would probably not be as efficient as original equipment. Therefore where OFA is used in Tables 4-4 and 4-5, the thermal efficiency is assumed to decrease by 0.25 percent. Ammonia injection costs are assumed to be the same for retrofitted units as for new ones. In general,  $\text{NO}_x$  control costs show the same trends for retrofitted as for new units.

#### 4.3 CONTROL COSTS FOR OIL-FIRED BOILERS

The estimated incremental cost of  $\text{NO}_x$  controls for new boilers firing residual oil and distillate oil are shown in Tables 4-6, 4-7, 4-8, and 4-9. Since residual oil-fired units require different control methods than distillate oil-fired boilers, they are listed separately. Although boiler costs are about the same for both oils, residual oil firing requires more fuel handling equipment which raises the cost of the steam plant. The prices listed in the tables are engineering estimates based on vendor quotes and published costs (References 4-9, 4-10, 4-11, 4-12, 4-14, and 4-17 through 4-20). Tables 4-10, 4-11, 4-12, and 4-13 list the estimated costs for retrofitted boilers. Again, using lower excess air than is required to meet a control level can minimize the cost impact where process operation permits. Figures 4-2 and 4-3 show plots of annualized estimated control costs for new oil-fired boilers.



TABLE 4-6. ESTIMATED COSTS OF CANDIDATE NO<sub>x</sub> CONTROL TECHNIQUES FOR  
NEW RESIDUAL OIL-FIRED BOILERS

| System           |                            |                                | Estimated Incremental Costs   |                    |                       |                       |                                            |                 |
|------------------|----------------------------|--------------------------------|-------------------------------|--------------------|-----------------------|-----------------------|--------------------------------------------|-----------------|
| Standard Boilers |                            | Type and Level of Control      | Control Effectiveness Percent | Capital Cost       | Annualized Costs      |                       |                                            |                 |
| Type             | Heat Input MW (106 Btu/hr) |                                |                               |                    | Fixed Costs           | Operating Costs       | Total Costs                                |                 |
|                  |                            |                                |                               |                    | mills<br>103 kg steam | mills<br>103 kg steam | mills<br>103 kg steam<br>Mills<br>GJ input |                 |
| Firetube         | 4.4 (15)                   | No Controls<br>SIP<br>Moderate | --                            | --                 | --                    | --                    |                                            |                 |
|                  |                            | LEA<br>Intermediate            | 5                             | 9                  | 91 (41) <sup>a</sup>  | -21 (-10)             | 70 (31)                                    | 22 < 24 > c     |
|                  |                            | SCA<br>Stringent               | 25                            | 19                 | 193 (88)              | 117 (53)              | 310 (141)                                  | 99 < 105 >      |
|                  |                            | LNB<br>Stringent               | 25                            | [ 19] <sup>b</sup> | [195 (88)]            | [ 120 (54) ]          | [ 310 (141) ]                              | [ 99 < 105 > ]  |
| Watertube        | 8.8 (30)                   | LEA<br>SIP<br>Moderate         | 20                            | 12                 | 45 (20)               | -68 (-31)             | -23 (-11)                                  | -7 < -8 >       |
|                  |                            | SCA<br>Intermediate            | 35                            | 22                 | 82 (37)               | 89 (40)               | 171 (78)                                   | 55 < 58 >       |
|                  |                            | LNB<br>Stringent               | 45                            | [ 22 ]             | [ 82 (37)]            | [ 89 (40) ]           | [ 171 (78) ]                               | [ 55 < 58 > ]   |
|                  |                            | Ammonia Injection<br>Stringent | 45                            | [ 72 ]             | [270 (122) ]          | [ 93 (42) ]           | [ 363 (165) ]                              | [ 117 < 123 > ] |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

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Continued

TABLE 4-6. Concluded

| System           |                                           |                                              | Estimated Incremental Costs   |                                    |                                                      |                                                          |                                                                               |
|------------------|-------------------------------------------|----------------------------------------------|-------------------------------|------------------------------------|------------------------------------------------------|----------------------------------------------------------|-------------------------------------------------------------------------------|
| Standard Boilers |                                           | Type and Level of Control                    | Control Effectiveness Percent | Capital Cost<br>10 <sup>3</sup> \$ | Annualized Costs                                     |                                                          |                                                                               |
| Type             | Heat Input<br>MW (10 <sup>6</sup> Btu/hr) |                                              |                               |                                    | Fixed Costs<br><br>mills<br>10 <sup>3</sup> kg steam | Operating Costs<br><br>mills<br>10 <sup>3</sup> kg steam | Total Costs<br><br>mills<br>10 <sup>3</sup> kg steam<br><br>Mills<br>GJ input |
| Watertube        | 44 (150)                                  | LEA                                          | 20                            | 17                                 | 12 (5)                                               | -75 (-34)                                                | -63 (-29)                                                                     |
|                  |                                           | SIP Moderate                                 |                               |                                    |                                                      |                                                          |                                                                               |
|                  |                                           | SCA Intermediate                             | 35                            | 32                                 | 23 (10)                                              | 80 (36)                                                  | 103 (46)                                                                      |
|                  |                                           | LNB Stringent<br>Ammonia Injection Stringent | 45<br>45                      | [32]<br>[182]                      | [ 23 (10)]<br>[133 (60)]                             | [80 (36)]<br>[90 (41)]                                   | [33 < 34>]<br>[72 < 75>]                                                      |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

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TABLE 4-7. ESTIMATED COST-EFFECTIVENESS AND IMPACTS OF CANDIDATE NO<sub>x</sub> CONTROL TECHNIQUES FOR NEW RESIDUAL OIL-FIRED BOILERS

| System           |                                        | Impacts                     |                                                  |                     |                       |                       |
|------------------|----------------------------------------|-----------------------------|--------------------------------------------------|---------------------|-----------------------|-----------------------|
| Standard Boilers |                                        | Type and Level of Control   | Cost Effectiveness \$/kg NO <sub>x</sub> Reduced | Percent Increase in |                       |                       |
| Type             | Heat Input MW (10 <sup>6</sup> Btu/hr) |                             |                                                  | Uncontrolled Boiler | SIP-Controlled Boiler | SIP-Controlled Boiler |
| Firetube         | 4.4 (15)                               | No Controls                 | --                                               | --                  | --                    | --                    |
|                  |                                        | SIP Moderate                |                                                  |                     |                       |                       |
|                  |                                        | LEA Intermediate            | 2.3                                              | 8.7                 | 8.7                   | 0.2                   |
|                  |                                        | SCA Stringent               | 3.2                                              | 21.0                | 21.0                  | 1.2                   |
|                  |                                        | LNB Stringent               | [3.2] <sup>c</sup>                               | [21.0]              | [21.0]                | [1.2]                 |
| Watertube        | 8.8 (30)                               | LEA SIP Moderate            | --                                               | 3.0                 | --                    | --                    |
|                  |                                        | SCA Intermediate            | 1.1                                              | 5.5                 | 2.5                   | 1.3                   |
|                  |                                        | LNB Stringent               | [0.7]                                            | [5.5]               | [2.5]                 | [1.3]                 |
|                  |                                        | Ammonia Injection Stringent | [1.6]                                            | [18.0]              | [18.0]                | [2.6]                 |

<sup>a</sup>Cost of boiler only.

<sup>b</sup>Cost includes entire steam plant.

<sup>c</sup>Bracket indicates gross estimate.

Continued

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TABLE 4-7. Concluded

| System           |                                        |                                | Impacts                                             |                       |                                                   |                       |
|------------------|----------------------------------------|--------------------------------|-----------------------------------------------------|-----------------------|---------------------------------------------------|-----------------------|
| Standard Boilers |                                        | Type and Level of Control      | Percent Increase in Capital Costs <sup>a</sup> Over |                       | Percent Increase in Steam Costs <sup>b</sup> Over |                       |
| Type             | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                | Uncontrolled Boiler                                 | SIP-Controlled Boiler | Uncontrolled Boiler                               | SIP-Controlled Boiler |
| Watertube        | 44 (150)                               | LEA<br>SIP<br>Moderate         | 1.9                                                 | --                    | -0.5                                              | --                    |
|                  |                                        | SCA<br>Intermediate            | 3.8                                                 | 1.9                   | 0.8                                               | 1.3                   |
|                  |                                        | LNB<br>Stringent               | [ 4.0 ]                                             | [ 2.0 ]               | [ 0.8 ]                                           | [ 1.3 ]               |
|                  |                                        | Ammonia Injection<br>Stringent | [ 22.5 ]                                            | [ 22.0 ]              | [ 2.0 ]                                           | [ 2.5 ]               |
|                  |                                        |                                |                                                     |                       |                                                   |                       |

<sup>a</sup>Cost of boiler only.<sup>b</sup>Cost includes entire steam plant.<sup>c</sup>Bracket indicates gross estimate.

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TABLE 4-8. ESTIMATED COSTS OF CANDIDATE NO. CONTROL TECHNIQUES FOR  
NEW DISTILLATE OIL-FIRED BOILERS<sup>a</sup>

| System                             |                            |                                   |                               | Estimated Incremental Costs |                       |                       |                       |                      |
|------------------------------------|----------------------------|-----------------------------------|-------------------------------|-----------------------------|-----------------------|-----------------------|-----------------------|----------------------|
| Standard Boilers                   |                            | Type and Level of Control         | Control Effectiveness Percent | Capital Cost 103 \$         | Annualized Costs      |                       |                       |                      |
| Type                               | Heat Input MW (106 Btu/hr) |                                   |                               |                             | Fixed Costs           | Operating Costs       | Total Costs           |                      |
|                                    |                            |                                   |                               |                             | mills<br>103 kg steam | mills<br>103 kg steam | mills<br>103 kg steam | mills<br>GJ input    |
| Firetube                           | 4.4 (15)                   | No Control<br>SIP<br>Moderate     | --                            | --                          | --                    | --                    | --                    |                      |
|                                    |                            | LEA<br>Intermediate               | 10                            | 9                           | 91 (41) <sup>a</sup>  | -26 (-12)             | 65 (29)               | 20 <21> <sup>c</sup> |
|                                    |                            | FGR<br>Stringent                  | 40                            | 19                          | 192 (87)              | 175 (80)              | 367 (167)             | 117 < 125>           |
|                                    |                            | LNB<br>Stringent                  | 40                            | [ 19] <sup>b</sup>          | [192 (87) ]           | [ 100 (45) ]          | [292 (132) ]          | [93 <99> ]           |
| Watertube without an Air Preheater | 29 (100)                   | No control<br>SIP<br>Intermediate | --                            | --                          | --                    | --                    | --                    |                      |
|                                    |                            | FGR<br>Stringent                  | 15                            | 26                          | 30 (13)               | 139 (63)              | 170 (77)              | 54 <57>              |
|                                    |                            | LNB<br>Stringent                  | 15                            | [ 26 ]                      | [ 30 (13) ]           | [ 86 (39) ]           | [115 (52) ]           | [ 37 <27> ]          |
|                                    |                            | SCA<br>Stringent                  | 15                            | 26                          | 30 (13)               | 86 (39)               | 116 (52)              | 36 <39>              |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicate units of mills/10<sup>6</sup> Btu heat input.

Continued T-1552

TABLE 4-8. Continued

| System                       |                            |                           |                               | Estimated Incremental Costs |                                                                 |                                                                     |                                                                 |                                        |
|------------------------------|----------------------------|---------------------------|-------------------------------|-----------------------------|-----------------------------------------------------------------|---------------------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------|
| Standard Boilers             |                            | Type and Level of Control | Control Effectiveness Percent | Capital Cost 103 \$         | Annualized Costs                                                |                                                                     |                                                                 |                                        |
| Type                         | Heat Input MW (106 Btu/hr) |                           |                               |                             | Fixed Costs<br><br>$\frac{\text{mills}}{10^3 \text{ kg steam}}$ | Operating Costs<br><br>$\frac{\text{mills}}{10^3 \text{ kg steam}}$ | Total Costs<br><br>$\frac{\text{mills}}{10^3 \text{ kg steam}}$ | $\frac{\text{mills}}{\text{GJ input}}$ |
| Watertube with Air Preheater | 29 (100)                   | No Controls<br>SIP        | --                            | --                          | --                                                              | --                                                                  | --                                                              |                                        |
|                              |                            | LEA<br>Moderate           | 5                             | 14                          | 16 (7) <sup>a</sup>                                             | -19 (-9)                                                            | -3 (-2)                                                         | -1 < -1 > <sup>c</sup>                 |
|                              |                            | RAP<br>Intermediate       | 30                            | 2                           | 2 (1)                                                           | 130 (59)                                                            | 132 (60)                                                        | 42 < 44 >                              |
|                              |                            | FGR<br>Intermediate       | 30                            | 26                          | 29 (13)                                                         | 135 (61)                                                            | 164 (74)                                                        | 54 < 57 >                              |
|                              |                            | LNB<br>Intermediate       | 30                            | [ 26] <sup>b</sup>          | [ 29 (13) ]                                                     | [ 90 (41) ]                                                         | [ 119 (54) ]                                                    | [ 38 < 40 > ]                          |
|                              |                            | SCA<br>Intermediate       | 30                            | 26                          | 29 (13)                                                         | 84 (38)                                                             | 113 (51)                                                        | 36 < 38 >                              |
|                              |                            | RAP & FGR<br>Stringent    | 55                            | 26                          | 29 (13)                                                         | 265 (120)                                                           | 294 (133)                                                       | 94 < 98 >                              |
|                              |                            | RAP & LNB<br>Stringent    | 55                            | [ 26 ]                      | [ 29 (13) ]                                                     | [ 215 (98) ]                                                        | [ 244 (111) ]                                                   | [ 78 < 82 > ]                          |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.<sup>b</sup>Bracket indicates gross estimate.<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

Continued

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TABLE 4-8. Concluded

| System                       |                            |                           | Estimated Incremental Costs   |                     |                       |                       |                       |                        |  |
|------------------------------|----------------------------|---------------------------|-------------------------------|---------------------|-----------------------|-----------------------|-----------------------|------------------------|--|
| Standard Boilers             |                            | Type and Level of Control | Control Effectiveness Percent | Capital Cost 103 \$ | Annualized Costs      |                       |                       |                        |  |
| Type                         | Heat Input MW (106 Btu/hr) |                           |                               |                     | Fixed Costs           | Operating Costs       |                       | Total Costs            |  |
|                              |                            |                           |                               |                     | mills<br>103 kg steam | mills<br>103 kg steam | mills<br>103 kg steam | mills<br>GJ input      |  |
| Watertube with Air Preheater | 44 (150)                   | No Controls SIP           | --                            | --                  | --                    | --                    | --                    |                        |  |
|                              |                            | LEA Moderate              | 5                             | 17                  | 12 (6) <sup>a</sup>   | -19 (-9)              | -7 (-3)               | -2 < -2 > <sup>c</sup> |  |
|                              |                            | RAP Intermediate          | 30                            | 2                   | 1 (1)                 | 128 (58)              | 130 (59)              | 42 < 44 >              |  |
|                              |                            | FGR Intermediate          | 30                            | 32                  | 23 (11)               | 133 (60)              | 156 (71)              | 51 < 54 >              |  |
|                              |                            | LNB Intermediate          | 30                            | [32] <sup>b</sup>   | [ 23 (11) ]           | [ 82 (37) ]           | [105 (48) ]           | [ 34 < 36 > ]          |  |
|                              |                            | SCA Intermediate          | 30                            | 32                  | 23 (11)               | 82 (37)               | 105 (48)              | 34 < 36 >              |  |
|                              |                            | RAP & FGR Stringent       | 55                            | 32                  | 23 (11)               | 260 (118)             | 284 (129)             | 93 < 98 >              |  |
|                              |                            | RAP & LNB Stringent       | 55                            | [32]                | [ 23 (11) ]           | [ 219 (100) ]         | [ 243 (116) ]         | [ 80 < 84 > ]          |  |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.<sup>b</sup>Bracket indicates gross estimate.<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

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TABLE 4-9. ESTIMATED COST-EFFECTIVENESS AND IMPACTS OF CANDIDATE NO<sub>x</sub> CONTROL TECHNIQUES FOR NEW DISTILLATE OIL-FIRED BOILERS

| System                                   |                                           |                                                                                               | Impacts                                          |                                        |                                   |                                      |                                 |
|------------------------------------------|-------------------------------------------|-----------------------------------------------------------------------------------------------|--------------------------------------------------|----------------------------------------|-----------------------------------|--------------------------------------|---------------------------------|
| Standard Boilers                         |                                           | Type and Level of Control                                                                     | Cost Effect-<br>\$/kg NO <sub>x</sub><br>Reduced | Percent Increase in Capital Costs Over |                                   | Percent Increase in Steam Costs Over |                                 |
| Type                                     | Heat Input<br>MM (10 <sup>6</sup> Btu/hr) |                                                                                               |                                                  | Uncontrolled<br>Boiler                 | SIP-Controlled<br>Boiler          | Uncontrolled<br>Boiler               | SIP-Controlled<br>Boiler        |
| Firetube                                 | 4.4 (15)                                  | No Control<br>SIP<br>Moderate<br>LEA<br>Intermediate<br>FGR<br>Stringent<br>LNB<br>Stringent  | --<br><br>2.3<br>4.1<br>[ 3.2] <sup>c</sup>      | --<br><br>9.0<br>21.0<br>[ 21.0 ]      | --<br><br>9.0<br>21.0<br>[ 21.0 ] | --<br><br>0.2<br>1.2<br>[ 1.0 ]      | --<br><br>0.2<br>1.2<br>[ 1.0 ] |
| Watertube<br>without an<br>Air Preheater | 29 (100)                                  | No Control<br>SIP<br>Intermediate<br>FGR<br>Stringent<br>LNB<br>Stringent<br>SCA<br>Stringent | --<br><br>4.4<br>[ 3.0 ]<br>3.0                  | --<br><br>8.0<br>[ 8.0 ]<br>8.0        | --<br><br>8.0<br>[ 8.0 ]<br>8.0   | --<br><br>1.8<br>[ 1.2 ]<br>1.2      | --<br><br>1.8<br>[ 1.2 ]<br>1.2 |

<sup>a</sup>Cost of boiler only.

<sup>b</sup>Cost includes entire steam plant.

<sup>c</sup>Bracket indicates gross estimate.

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TABLE 4-9. Continued

| System                       |                                         |                           | Impacts                                             |                       |                                                   |                       |
|------------------------------|-----------------------------------------|---------------------------|-----------------------------------------------------|-----------------------|---------------------------------------------------|-----------------------|
| Standard Boilers             |                                         | Type and Level of Control | Percent Increase in Capital Costs <sup>a</sup> Over |                       | Percent Increase in Steam Costs <sup>b</sup> Over |                       |
| Type                         | Heat Input, MM (10 <sup>6</sup> Btu/hr) |                           | Uncontrolled Boiler                                 | SIP-Controlled Boiler | Uncontrolled Boiler                               | SIP-Controlled Boiler |
| Watertube with Air Preheater | 29 (100)                                | No Controls<br>SIP        | --                                                  | --                    | --                                                | --                    |
|                              |                                         | LEA<br>Moderate           | 3.4                                                 | 3.4                   | 0                                                 | 0                     |
|                              |                                         | RAP<br>Intermediate       | 0                                                   | 0                     | 1.4                                               | 1.4                   |
|                              |                                         | FGR<br>Intermediate       | 7.0                                                 | 7.0                   | 1.7                                               | 1.7                   |
|                              |                                         | LNB<br>Intermediate       | [7.0]                                               | [7.0]                 | [1.2]                                             | [1.2]                 |
|                              |                                         | SCA<br>Intermediate       | 7.0                                                 | 7.0                   | 1.2                                               | 1.2                   |
|                              |                                         | RAP + FGR<br>Stringent    | 7.0                                                 | 7.0                   | 3.1                                               | 3.1                   |
|                              |                                         | RAP + LNB<br>Stringent    | [7.0]                                               | [7.0]                 | [2.6]                                             | [2.6]                 |
|                              |                                         |                           | [1.7]                                               |                       |                                                   |                       |

<sup>a</sup>Cost of boiler only.<sup>b</sup>Cost includes entire steam plant.<sup>c</sup>Bracket indicates gross estimate.

Continued

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TABLE 4-9. Concluded

| System                       |                               | Impacts                   |                                                                  |                                        |                       |                                      |                       |
|------------------------------|-------------------------------|---------------------------|------------------------------------------------------------------|----------------------------------------|-----------------------|--------------------------------------|-----------------------|
| Standard Boilers             |                               | Type and Level of Control | Cost Effectiveness<br>\$/kg NO <sub>x</sub> Reduced <sup>a</sup> | Percent Increase in Capital Costs Over |                       | Percent Increase in Steam Costs Over |                       |
| Type                         | Heat Input<br>MW (106 Btu/hr) |                           |                                                                  | Uncontrolled Boiler                    | SIP-Controlled Boiler | Uncontrolled Boiler                  | SIP-Controlled Boiler |
| Watertube with Air Preheater | 44 (150)                      | No Controls               | --                                                               | --                                     | --                    | --                                   | --                    |
|                              |                               | LEA                       |                                                                  | 3.4                                    | 3.4                   | 0                                    | 0                     |
|                              |                               | Moderate                  |                                                                  |                                        |                       |                                      |                       |
|                              |                               | RAP                       | 1.6                                                              | 0.1                                    | 0.1                   | 1.3                                  | 1.3                   |
|                              |                               | Intermediate              |                                                                  |                                        |                       |                                      |                       |
|                              |                               | FGR                       | 2.0                                                              | 5.0                                    | 5.0                   | 1.6                                  | 1.6                   |
|                              |                               | Intermediate              |                                                                  |                                        |                       |                                      |                       |
|                              |                               | LNB                       | [1.3] <sup>c</sup>                                               | [4.0]                                  | [4.0]                 | [1.1]                                | [1.1]                 |
|                              |                               | Intermediate              |                                                                  |                                        |                       |                                      |                       |
|                              |                               | SCA                       | 1.3                                                              | 4.0                                    | 4.0                   | 1.1                                  | 1.1                   |
|                              |                               | Intermediate              |                                                                  |                                        |                       |                                      |                       |
|                              |                               | RAP + FGR                 | 1.9                                                              | 4.0                                    | 4.0                   | 2.9                                  | 2.9                   |
|                              |                               | Stringent                 |                                                                  |                                        |                       |                                      |                       |
|                              |                               | RAP + LNB                 | [1.6]                                                            | [4.0]                                  | [4.0]                 | [2.4]                                | [2.4]                 |
|                              |                               | Stringent                 |                                                                  |                                        |                       |                                      |                       |

<sup>a</sup>Cost of boiler only.<sup>b</sup>Cost includes entire steam plant.<sup>c</sup>Bracket indicates gross estimate.

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TABLE 4-10. ESTIMATED COSTS OF CANDIDATE NO. 2 CONTROL TECHNIQUES FOR RETROFITTED RESIDUAL OIL-FIRED BOILERS

| System           |                                        |                                                                                                                 | Estimated Incremental Costs      |                                                 |                                                                     |                                                               |                                                                 |                                                                          |
|------------------|----------------------------------------|-----------------------------------------------------------------------------------------------------------------|----------------------------------|-------------------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------|-----------------------------------------------------------------|--------------------------------------------------------------------------|
| Standard Boilers |                                        | Type and Level of Control                                                                                       | Control Effectiveness Percent    | Capital Cost 10 <sup>3</sup> \$                 | Annualized Costs                                                    |                                                               |                                                                 | mills 60 input                                                           |
| Type             | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                                                                                                 |                                  |                                                 | Fixed Costs $\frac{\text{mills}}{10^3 \text{ kg steam}}$            | Operating Costs $\frac{\text{mills}}{10^3 \text{ kg steam}}$  | Total Costs $\frac{\text{mills}}{10^3 \text{ kg steam}}$        |                                                                          |
| Firetube         | 4.4 (15)                               | No Controls<br>SIP<br>Moderate<br><br>LEA<br>Intermediate<br><br>SCA<br>Stringent<br><br>LNB<br>Stringent       | --<br><br>5<br><br>25<br><br>25  | --<br><br>10<br><br>30<br><br>[30] <sup>b</sup> | --<br><br>102 (46) <sup>a</sup><br><br>304 (138)<br><br>[300 (136)] | --<br><br>-14 (-6)<br><br>170 (77)<br><br>[170 (77)]          | --<br><br>88 (40)<br><br>475 (216)<br><br>[475 (216)]           | --<br><br>28 < 30 > <sup>c</sup><br><br>152 < 161 ><br><br>[152 < 161 >] |
| Watertube        | 8.8 (30)                               | LEA<br>SIP<br>Moderate<br><br>SCA<br>Intermediate<br><br>LNB<br>Stringent<br><br>Ammonia Injection<br>Stringent | 20<br><br>35<br><br>45<br><br>45 | 14<br><br>34<br><br>[34]<br><br>[72]            | 52 (24)<br><br>127 (58)<br><br>[127 (58)]<br><br>[270 (122)]        | -66 (-30)<br><br>102 (46)<br><br>[102 (46)]<br><br>[ 93 (42)] | -14 (-6)<br><br>229 (104)<br><br>[229 (104)]<br><br>[363 (165)] | -4 < -5 ><br><br>74 < 78 ><br><br>[ 74 < 78 >]<br><br>[117 < 123 >]      |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.  
<sup>b</sup>Bracket indicates gross estimate.  
<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

TABLE 4-10. Concluded

| System           |                                        |                                                                                                                 |                               | Estimated Incremental Costs     |                                              |                                              |                                              |                                        |
|------------------|----------------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------|---------------------------------|----------------------------------------------|----------------------------------------------|----------------------------------------------|----------------------------------------|
| Standard Boilers |                                        | Type and Level of Control                                                                                       | Control Effectiveness Percent | Capital Cost 10 <sup>3</sup> \$ | Annualized Costs                             |                                              |                                              |                                        |
| Type             | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                                                                                                 |                               |                                 | Fixed Costs                                  | Operating Costs                              | Total Costs                                  |                                        |
|                  |                                        |                                                                                                                 |                               |                                 | $\frac{\text{mills}}{10^3 \text{ kg steam}}$ | $\frac{\text{mills}}{10^3 \text{ kg steam}}$ | $\frac{\text{mills}}{10^3 \text{ kg steam}}$ | $\frac{\text{mills}}{\text{GJ input}}$ |
| Watertube        | 44 (150)                               | LEA<br>SIP<br>Moderate<br><br>SCA<br>Intermediate<br><br>LNB<br>Stringent<br><br>Ammonia Injection<br>Stringent | 20                            | 20                              | 15 (7)                                       | -75 (-34)                                    | -60 (-27)                                    | -19 < -20 >                            |
|                  |                                        |                                                                                                                 |                               | 50                              | 37 (17)                                      | 103 (47)                                     | 140 (64)                                     | 45 < 48 >                              |
|                  |                                        |                                                                                                                 |                               | [ 50 ]                          | [ 37 (17) ]                                  | [ 103 (47) ]                                 | [ 140 (64) ]                                 | [ 45 < 48 > ]                          |
|                  |                                        |                                                                                                                 |                               | [ 180 ]                         | [ 170 (77) ]                                 | [ 90 (41) ]                                  | [ 250 (114) ]                                | [ 80 < 85 > ]                          |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

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TABLE 4-11. ESTIMATED COST EFFECTIVENESS AND IMPACTS OF CANDIDATE NO<sub>x</sub> CONTROL TECHNIQUES FOR RETROFITTED RESIDUAL OIL-FIRED BOILERS

| System           |                                        |                             | Impacts                                          |                                                     |                       |                                                   |                       |
|------------------|----------------------------------------|-----------------------------|--------------------------------------------------|-----------------------------------------------------|-----------------------|---------------------------------------------------|-----------------------|
| Standard Boilers |                                        | Type and Level of Control   | Cost Effectiveness \$/kg NO <sub>x</sub> Reduced | Percent Increase in Capital Costs <sup>a</sup> Over |                       | Percent Increase in Steam Costs <sup>b</sup> Over |                       |
| Type             | Heat Input MM (10 <sup>6</sup> Btu/hr) |                             |                                                  | Uncontrolled Boiler                                 | SIP-Controlled Boiler | Uncontrolled Boiler                               | SIP-Controlled Boiler |
| Firetube         | 4.4 (15)                               | No Controls                 | --                                               | --                                                  | --                    | --                                                | --                    |
|                  |                                        | SIP Moderate                |                                                  |                                                     |                       |                                                   |                       |
|                  |                                        | LEA Intermediate            | 4.0                                              | 12.5                                                | 12.5                  | 0.4                                               | 0.4                   |
|                  |                                        | SCA Stringent               | 5.2                                              | 27.5                                                | 27.5                  | 1.9                                               | 1.9                   |
|                  |                                        | LNB Stringent               | [ 5.2] <sup>c</sup>                              | [ 38.0 ]                                            | [ 38.0 ]              | [ 2.0 ]                                           | [ 2.0 ]               |
| Watertube        | 8.8 (30)                               | LEA SIP Moderate            |                                                  | 3.5                                                 | --                    | -0.1                                              | --                    |
|                  |                                        | SCA Intermediate            | 1.5                                              | 8.5                                                 | 5.0                   | 1.6                                               | 1.7                   |
|                  |                                        | LNB Stringent               | [ 0.9 ]                                          | [ 8.5 ]                                             | [ 5.0 ]               | [ 1.6 ]                                           | [ 1.7 ]               |
|                  |                                        | Ammonia Injection Stringent | [ 1.6 ]                                          | [ 18.0 ]                                            | [ 18.0 ]              | [ 2.5 ]                                           | [ 2.6 ]               |

<sup>a</sup>Cost of boiler only

<sup>b</sup>Cost includes entire steam plant.

<sup>c</sup>Bracket indicates gross estimate.

Continued

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TABLE 4-11. Concluded

| System           |                               |                                | Impacts                                       |                                        |                       |                                      |                       |
|------------------|-------------------------------|--------------------------------|-----------------------------------------------|----------------------------------------|-----------------------|--------------------------------------|-----------------------|
| Standard Boilers |                               | Type and Level of Control      | Cost Effect-<br>\$/kg NO <sub>x</sub> Reduced | Percent Increase in Capital Costs Over |                       | Percent Increase in Steam Costs Over |                       |
| Type             | Heat Input<br>MW (106 Btu/hr) |                                |                                               | Uncontrolled Boiler                    | SIP-Controlled Boiler | Uncontrolled Boiler                  | SIP-Controlled Boiler |
| Watertube        | 44 (150)                      | LEA<br>SIP<br>Moderate         |                                               | 2.5                                    | --                    | -0.5                                 | --                    |
|                  |                               | SCA<br>Intermediate            | 0.9                                           | 6.2                                    | 3.7                   | 1.1                                  | 1.6                   |
|                  |                               | LNB<br>Stringent               | [ 0.6 ]                                       | [ 6.2 ]                                | [ 3.7 ]               | [ 1.1 ]                              | [ 1.6 ]               |
|                  |                               | Ammonia Injection<br>Stringent | [ 1.1 ]                                       | [ 22.5 ]                               | [ 22.5 ]              | [ 1.9 ]                              | [ 2.5 ]               |

<sup>a</sup>Cost of boiler only<sup>b</sup>Cost includes entire steam plant.<sup>c</sup>Bracket indicates gross estimate.

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TABLE 4-12. ESTIMATED COSTS OF CANDIDATE NO. CONTROL TECHNIQUES FOR RETROFITTED DISTILLATE OIL-FIRED BOILERS

| System                             |                                        |                              | Estimated Incremental Costs   |                                 |                                            |                                                |                                            |
|------------------------------------|----------------------------------------|------------------------------|-------------------------------|---------------------------------|--------------------------------------------|------------------------------------------------|--------------------------------------------|
| Standard Boilers                   |                                        | Type and Level of Control    | Control Effectiveness Percent | Capital Cost 10 <sup>3</sup> \$ | Annualized Costs                           |                                                |                                            |
| Type                               | Heat Input MW (10 <sup>6</sup> Btu/hr) |                              |                               |                                 | Fixed Costs mills 10 <sup>3</sup> kg steam | Operating Costs mills 10 <sup>3</sup> kg steam | Total Costs mills 10 <sup>3</sup> kg steam |
| Firetube                           | 4.4 (15)                               | No Control SIP Moderate      | --                            | --                              | --                                         | --                                             | --                                         |
|                                    |                                        | LEA Intermediate             | 10                            | 10                              | 102 (46) <sup>a</sup>                      | -20 (-9)                                       | 82 (37)                                    |
|                                    |                                        | FGR Stringent                | 40                            | 30                              | 304 (138)                                  | 208 (94)                                       | 512 (230)                                  |
|                                    |                                        | LNB Stringent                | 40                            | [ 30 ] <sup>b</sup>             | [ 304 (138) ]                              | [ 156 (71) ]                                   | [ 460 (209) ]                              |
| Watertube without an Air Preheater | 29 (100)                               | No controls SIP Intermediate | --                            | --                              | --                                         | --                                             | --                                         |
|                                    |                                        | FGR Stringent                | 15                            | 40                              | 46 (21)                                    | 144 (65)                                       | 190 (86)                                   |
|                                    |                                        | LNB Stringent                | 15                            | [ 40 ]                          | [ 46 (21) ]                                | [ 92 (42) ]                                    | [ 140 (64) ]                               |
|                                    |                                        | OSC Stringent                | 15                            | 40                              | 46 (21)                                    | 92 (42)                                        | 138 (64)                                   |
|                                    |                                        |                              |                               |                                 |                                            |                                                |                                            |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

Continued

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TABLE 4-12. Continued

| System                          |                                        |                           | Estimated Incremental Costs   |                                 |                                              |                                              |                                              |                                        |
|---------------------------------|----------------------------------------|---------------------------|-------------------------------|---------------------------------|----------------------------------------------|----------------------------------------------|----------------------------------------------|----------------------------------------|
| Standard Boilers                |                                        | Type and Level of Control | Control Effectiveness Percent | Capital Cost 10 <sup>3</sup> \$ | Annualized Costs                             |                                              |                                              |                                        |
| Type                            | Heat Input MW (10 <sup>6</sup> Btu/hr) |                           |                               |                                 | Fixed Costs                                  | Operating Costs                              | Total Costs                                  |                                        |
|                                 |                                        |                           |                               |                                 | $\frac{\text{mills}}{10^3 \text{ kg steam}}$ | $\frac{\text{mills}}{10^3 \text{ kg steam}}$ | $\frac{\text{mills}}{10^3 \text{ kg steam}}$ | $\frac{\text{mills}}{\text{GJ input}}$ |
| Watertube with an Air Preheater | 29 (100)                               | No Control                | --                            | --                              | --                                           | --                                           | --                                           |                                        |
|                                 |                                        | SIP                       |                               |                                 |                                              |                                              |                                              |                                        |
|                                 |                                        | LEA                       | 5                             | 15                              | 17 (8) <sup>a</sup>                          | -17 (-8)                                     | 0                                            | 0                                      |
|                                 |                                        | Moderate                  |                               |                                 |                                              |                                              |                                              |                                        |
|                                 |                                        | RAP                       | 30                            | 2                               | 2 (1)                                        | 130 (59)                                     | 132 (60)                                     | 44 < 47 >                              |
|                                 |                                        | Intermediate              |                               |                                 |                                              |                                              |                                              |                                        |
|                                 |                                        | FGR                       | 30                            | 40                              | 45 (20)                                      | 139 (63)                                     | 185 (84)                                     | 63 < 66 >                              |
|                                 |                                        | Intermediate              |                               |                                 |                                              |                                              |                                              |                                        |
|                                 |                                        | LNB                       | 30                            | [ 40 ] <sup>b</sup>             | [ 45 (20) ]                                  | [ 90 (41) ]                                  | [ 135 (61) ]                                 | [ 46 < 48 > ]                          |
|                                 |                                        | Intermediate              |                               |                                 |                                              |                                              |                                              |                                        |
| SCA                             | 30                                     | 40                        | 45 (20)                       | 88 (40)                         | 135 (61)                                     | 46 < 48 >                                    |                                              |                                        |
| Intermediate                    |                                        |                           |                               |                                 |                                              |                                              |                                              |                                        |
| RAP + FGR                       | 55                                     | 40                        | 45 (20)                       | 269 (122)                       | 315 (143)                                    | 107 < 113 >                                  |                                              |                                        |
| Stringent                       |                                        |                           |                               |                                 |                                              |                                              |                                              |                                        |
| RAP + LNB                       | 55                                     | [ 40 ]                    | [ 45 (20) ]                   | [ 220 (100) ]                   | [ 265 (120) ]                                | [ 90 < 95 > ]                                |                                              |                                        |
| Stringent                       |                                        |                           |                               |                                 |                                              |                                              |                                              |                                        |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.  
<sup>b</sup>Bracket indicates gross estimate.  
<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

Continued

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TABLE 4-12. Concluded

| System                          |                            |                           | Estimated Incremental Costs   |                     |                       |                       |                                            |               |
|---------------------------------|----------------------------|---------------------------|-------------------------------|---------------------|-----------------------|-----------------------|--------------------------------------------|---------------|
| Standard Boilers                |                            | Type and Level of Control | Control Effectiveness Percent | Capital Cost 103 \$ | Annualized Costs      |                       |                                            |               |
| Type                            | Heat Input MW (106 Btu/hr) |                           |                               |                     | Fixed Costs           | Operating Costs       | Total Costs                                |               |
|                                 |                            |                           |                               |                     | mills<br>103 kg steam | mills<br>103 kg steam | mills<br>103 kg steam<br>mills<br>GJ input |               |
| Watertube with an Air Preheater | 44 (150)                   | No Control SIP            | --                            | --                  | --                    | --                    |                                            |               |
|                                 |                            | LEA Moderate              | 5                             | 19                  | 14 (6) <sup>a</sup>   | -18 (-8)              | -4 (-2)                                    | -1 < -1 >     |
|                                 |                            | RAP Intermediate          | 30                            | 2                   | 1 (1)                 | 130 (59)              | 132 (60)                                   | 44 < 47 >     |
|                                 |                            | FGR Intermediate          | 30                            | 62                  | 45 (20)               | 139 (63)              | 185 (84)                                   | 63 < 66 >     |
|                                 |                            | LNB Intermediate          | 30                            | [ 62 ] <sup>b</sup> | [ 45 (20) ]           | [ 90 (41) ]           | [ 135 (61) ]                               | [ 46 < 48 > ] |
|                                 |                            | SCA Intermediate          | 30                            | 62                  | 45 (20)               | 88 (40)               | 135 (61)                                   | 46 < 48 >     |
|                                 |                            | RAP + FGR Stringent       | 55                            | 62                  | 45 (20)               | 269 (122)             | 315 (143)                                  | 107 < 113 >   |
|                                 |                            | RAP + LNB Stringent       | 55                            | [ 62 ]              | [ 45 (20) ]           | [ 220 (100) ]         | [ 265 (120) ]                              | [ 90 < 95 > ] |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

TABLE 4-13. ESTIMATED COST EFFECTIVENESS AND IMPACTS OF CANDIDATE NO<sub>x</sub> CONTROL TECHNIQUES FOR RETROFITTED DISTILLATE OIL-FIRED BOILERS

| System                             |                                        |                                                                                                | Impacts                                              |                                            |                                            |                                         |                                         |
|------------------------------------|----------------------------------------|------------------------------------------------------------------------------------------------|------------------------------------------------------|--------------------------------------------|--------------------------------------------|-----------------------------------------|-----------------------------------------|
| Standard Boilers                   |                                        | Type and Level of Control                                                                      | Cost Effectiveness \$/kg NO <sub>x</sub> Reduced     | Percent Increase in Capital Costs Over     |                                            | Percent Increase in Steam Costs Over    |                                         |
| Type                               | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                                                                                |                                                      | Uncontrolled Boiler                        | SIP-Controlled Boiler                      | Uncontrolled Boiler                     | SIP-Controlled Boiler                   |
| Firetube                           | 4.4 (15)                               | No Control<br>SIP<br>Moderate<br>LEA<br>Intermediate<br>FGR<br>Stringent<br>LNB<br>Stringent   | --<br><br>4.3<br><br>6.0<br><br>[ 5.4 ] <sup>c</sup> | --<br><br>12.5<br><br>37.5<br><br>[ 37.5 ] | --<br><br>12.5<br><br>37.5<br><br>[ 37.5 ] | --<br><br>0.3<br><br>1.8<br><br>[ 1.6 ] | --<br><br>0.3<br><br>1.8<br><br>[ 1.6 ] |
| Watertube without an Air Preheater | 29 (100)                               | No Controls<br>SIP<br>Intermediate<br>FGR<br>Stringent<br>LNB<br>Stringent<br>SCA<br>Stringent | --<br><br>5.0<br><br>[ 3.6 ]<br><br>3.6              | --<br><br>13.0<br><br>[ 13.0 ]             | --<br><br>13.0<br><br>[ 13.0 ]             | --<br><br>2.0<br><br>[ 1.5 ]            | --<br><br>2.0<br><br>[ 1.5 ]            |

<sup>a</sup>Cost of boiler only  
<sup>b</sup>Cost includes entire steam plant.  
<sup>c</sup>Bracket indicates gross estimate.

Continued

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TABLE 4-13. Continued

| System                          |                            | Impacts                   |                                                  |                                                     |                       |                     |
|---------------------------------|----------------------------|---------------------------|--------------------------------------------------|-----------------------------------------------------|-----------------------|---------------------|
| Standard Boilers                |                            | Type and Level of Control | Cost Effectiveness \$/kg NO <sub>x</sub> Reduced | Percent Increase in Capital Costs <sup>a</sup> Over |                       |                     |
| Type                            | Heat Input MW (106 Btu/hr) |                           |                                                  | Uncontrolled Boiler                                 | SIP-Controlled Boiler | Uncontrolled Boiler |
| Watertube with an Air Preheater | 29 (100)                   | No Control                | --                                               | --                                                  | --                    | --                  |
|                                 |                            | SIP                       |                                                  |                                                     |                       |                     |
|                                 |                            | LEA                       | 0                                                | 4.0                                                 | 4.0                   | 0                   |
|                                 |                            | Moderate                  |                                                  |                                                     |                       |                     |
|                                 |                            | RAP                       | 1.7                                              | 0                                                   | 0                     | 1.4                 |
|                                 |                            | Intermediate              |                                                  |                                                     |                       |                     |
|                                 |                            | FGR                       | 2.4                                              | 11.0                                                | 11.0                  | 2.0                 |
|                                 |                            | Intermediate              |                                                  |                                                     |                       |                     |
|                                 |                            | LNB                       | [ 1.7 ] <sup>c</sup>                             | [ 11.0 ]                                            | [ 11.0 ]              | [ 1.4 ]             |
|                                 |                            | Intermediate              |                                                  |                                                     |                       |                     |
|                                 |                            | SCA                       | 1.7                                              | 11.0                                                | 11.0                  | 1.4                 |
|                                 |                            | Intermediate              |                                                  |                                                     |                       |                     |
|                                 |                            | RAP + FGR                 | 2.1                                              | 11.0                                                | 11.0                  | 3.4                 |
|                                 |                            | Stringent                 |                                                  |                                                     |                       |                     |
|                                 |                            | RAP + LNB                 | [ 1.8 ]                                          | [ 11.0 ]                                            | [ 11.0 ]              | [ 2.9 ]             |

<sup>a</sup>Cost of boiler only<sup>b</sup>Cost includes entire steam plant.<sup>c</sup>Bracket indicates gross estimate.

Continued

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TABLE 4-13. Concluded

| System                          |                                        |                               | Impacts                                          |                                                    |                       |                                                  |                       |
|---------------------------------|----------------------------------------|-------------------------------|--------------------------------------------------|----------------------------------------------------|-----------------------|--------------------------------------------------|-----------------------|
| Standard Boilers                |                                        | Type and Level of Control     | Cost Effectiveness \$/kg NO <sub>x</sub> Reduced | Percent Increase in Capital Cost <sup>a</sup> Over |                       | Percent Increase in Steam Cost <sup>b</sup> Over |                       |
| Type                            | Heat Input MM (10 <sup>6</sup> Btu/hr) |                               |                                                  | Uncontrolled Boiler                                | SIP-Controlled Boiler | Uncontrolled Boiler                              | SIP-Controlled Boiler |
| Watertube with an Air Preheater | 44 (150)                               | No Control SIP                | --                                               | --                                                 | --                    | --                                               | --                    |
|                                 |                                        | LEA Moderate                  | 0                                                | 4.0                                                | 4.0                   | 0                                                | 0                     |
|                                 |                                        | RAP Intermediate              | 1.7                                              | 0                                                  | 0                     | 1.4                                              | 1.4                   |
|                                 |                                        | FGR Intermediate              | 2.4                                              | 11.0                                               | 11.0                  | 2.0                                              | 2.0                   |
|                                 |                                        | LNB Intermediate              | [ 1.7] <sup>c</sup>                              | [ 11.0 ]                                           | [ 11.0 ]              | [ 1.4 ]                                          | [ 1.4 ]               |
|                                 |                                        | SCA Intermediate              | 1.7                                              | 11.0                                               | 11.0                  | 1.4                                              | 1.4                   |
|                                 |                                        | RAP + FGR Stringent RAP + LNB | 2.1                                              | 11.0                                               | 11.0                  | 3.4                                              | 3.4                   |
|                                 |                                        | Stringent                     | [ 1.8 ]                                          | [ 11.0 ]                                           | [ 11.0 ]              | [ 2.9 ]                                          | [ 2.9 ]               |

<sup>a</sup>Cost of boiler only<sup>b</sup>Cost includes entire steam plant.<sup>c</sup>Bracket indicates gross estimate.

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#### 4.3.1 New Facilities

For the typical residual oil-fired firetube boiler to achieve intermediate  $\text{NO}_x$  emission levels (108 ng/J) low excess air (LEA) is recommended. This control technique can raise the price of steam by about 0.2 percent. However, even lower excess air over that needed to achieve the emission level can lower the impact on steam cost. Staged combustion (SCA) or low  $\text{NO}_x$  burners (LNB) are recommended techniques for reaching stringent control levels (86 ng/J). Staged combustion may raise the price of steam by over 1 percent and as already noted, LNB should probably have a smaller effect on steam cost than SCA does. Recall that this is because LNB are expected to have a smaller incremental capital cost and also have a smaller energy impact. At present a true estimate of the cost of LNB can not be made and thus LNB are assumed to be priced the same as SCA operation.

For the typical watertube boiler firing residual oil, low excess air is recommended for reaching SIP or moderate control levels (129 ng/J); LEA has the additional benefit of lowering steam cost. Staged combustion can be used to meet intermediate control levels (108 ng/J) but it may raise the price of steam by over 1 percent. Recall that the effect of staged combustion (overfire air or sidefire air) on thermal efficiency depends on port location and the fuel being fired; thus the exact cost impact of the SCA technique will depend on the air port location and the fuel being fired. If only one type of fuel is fired, it would be possible to optimize the location of the air port and possibly decrease the effect on steam cost. Meeting stringent control levels requires either LNB or ammonia injection, both of which have already been described. Ammonia injection costs are based on extrapolated utility prices and low  $\text{NO}_x$  burner costs are assumed to be no more than SCA costs. Since both methods (LNB and  $\text{NH}_3$  injection) are in the development stage, the costs estimates may have large errors.

The recommended control methods for a firetube boiler firing distillate oil are LEA for intermediate levels and flue gas recirculation (FGR) or LNB for stringent levels. Increased fan power requirements for FGR makes it a costly technique for a typical distillate oil-fired firetube boiler. Although LNB are estimated to cost less than FGR, FGR is

presently available, while low  $\text{NO}_x$  burners are still in the development stage.

The larger watertube boilers firing distillate oil are divided between those with and without an air preheater because the units with air preheaters emit more  $\text{NO}_x$  (see Section 3). Economizers are recommended over air preheaters as a device for increasing thermal efficiency since they raise efficiency without raising  $\text{NO}_x$  emission levels. Watertube boilers without air preheaters can use FGR, LNB, or SCA to reach stringent control levels. Staged combustion is estimated to have a smaller effect on steam cost than FGR but to allow for fuel switching, SCA may require several air port locations, which may be impractical. Again LNB are estimated to cost no more than SCA and probably less.

Watertube boilers with air preheaters can use LEA to reach moderate control levels without raising steam costs. Achieving intermediate control levels would require RAP, FGR, LNB, or SCA. Low  $\text{NO}_x$  burners should have the least economic impact of these four methods. Reduced air preheat is the easiest to implement but the thermal efficiency gained by installing the air preheater is lost. Again SCA should have a smaller economic impact than FGR if the need for several air port locations to allow for fuel switching does not make SCA impractical. To reach stringent control levels, RAP + FGR or RAP + LNB can be used. The high costs of these methods strongly suggest that economizers be used whenever possible instead of air preheaters. Low  $\text{NO}_x$  burners can have a smaller economic impact than is noted in the table but RAP + LNB would still be a costly technique due to the loss in thermal efficiency with RAP operation. The use of LEA and LNB with an economizer instead of an air preheater may result in lower steam costs and lower  $\text{NO}_x$  emissions.

#### 4.3.2 Modified and Reconstructed Facilities

Firetube boilers are relatively more expensive on a percent basis to retrofit since their initial cost is not very high. For both residual and distillate oils, achieving stringent control levels can raise the steam costs by over 2 percent. The control costs are also high for firetube boilers because of the small base to spread modification costs over. It also costs more to retrofit watertube boilers than to include the emission control system in the original design.

#### 4.4 CONTROL COSTS FOR NATURAL GAS-FIRED BOILERS

The control costs for natural gas-fired boilers discussed in this section are also engineering estimates based on published costs and manufacturer estimates (References 4-9 through 4-12, 4-14, and 4-17 through 4-20). Since most of the control methods have already been discussed, they are only briefly covered here. In all cases, LEA operation is recommended to lower the cost impact. Tables 4-14, 4-15, 4-16, and 4-17 list cost estimates for new and retrofitted units.

##### 4.4.1 New Facilities

Firetube boilers firing natural gas meet all recommended  $\text{NO}_x$  emission levels without control systems. For watertube boilers again, economizers are recommended over air preheaters. Watertube boilers without air preheaters only need LEA operation to meet stringent  $\text{NO}_x$  control levels, possibly reducing steam costs slightly. Watertube boilers with air preheaters will require additional controls to meet all recommended emission levels.

Watertube boilers with air preheaters need RAP, FGR, SCA or LNB to meet SIP or moderate control levels (86 ng/J). Using RAP deletes the efficiency gained by the air preheaters, but RAP may still be less costly than FGR. Staged combustion or LNB should have smaller cost impacts than RAP or FGR but LNB are still being developed and SCA may be impractical because of fuel switching problems as was discussed earlier. Flue gas recirculation is not as effective for controlling  $\text{NO}_x$  emissions from residual oil-fired boilers and can limit the oils that can be fired when natural gas is not available. For achieving intermediate control levels, RAP + OFA/SFA can be used but it can raise steam prices by over 3 percent. The least expensive method for reaching stringent control levels is RAP + LNB. The system of RAP + FGR can also be used, which may raise the price of steam by over 4 percent. Alternatively, RAP +  $\text{NH}_3$  injection can be used, but it is the most costly of these controls and because of load fluctuations and possible  $\text{NH}_3$  emissions, it may prove impractical.

##### 4.4.2 Modified and Reconstructed Facilities

Reducing air preheat on an existing boiler equipped with an air preheater is less cost-effective than using an economizer instead of an air preheater on a new unit. The other control techniques are expected to

TABLE 5-13. COMPARISON OF CALCULATED SURFACE AREA REMOVAL TO  
MEASURED TRACE ELEMENT REMOVAL FOR ESP's

| Element        | Removal Efficiency, %  |                      |
|----------------|------------------------|----------------------|
|                | Plant A <sup>a</sup>   | Plant C <sup>b</sup> |
| Total particle | 99.3                   | 99.7                 |
| Surface area   | 94.47                  | 98.6                 |
| As             | 98.4                   | NR                   |
| Be             | NR <sup>c</sup>        | NR                   |
| Cd             | NR                     | 98.8                 |
| Cr             | 99.8                   | 99.8                 |
| Hg             | 60.0                   | NR                   |
| Mn             | 94.2-99.7 <sup>d</sup> | 100                  |
| Mo             | NR                     | NR                   |
| Ni             | 96.3                   | 99.7                 |
| Se             | 97.2                   | 94.3                 |
| V              | 95.9-94.7 <sup>d</sup> | 99.9                 |

<sup>a</sup>Data on plant given in Table 5-3. Reference 3.

<sup>b</sup>Data on plant given in Table 5-3. Reference 5.

<sup>c</sup>NR - Not reported.

<sup>d</sup>Different values are for different analytical techniques.



TABLE 4-14. Concluded

| System                          |                                        |                                           |                               | Estimated Incremental Costs     |                                                      |                                                          |                                   |             |
|---------------------------------|----------------------------------------|-------------------------------------------|-------------------------------|---------------------------------|------------------------------------------------------|----------------------------------------------------------|-----------------------------------|-------------|
| Standard Boilers                |                                        | Type and Level of Control                 | Control Effectiveness Percent | Capital Cost 10 <sup>3</sup> \$ | Annualized Costs                                     |                                                          |                                   | Total Costs |
| Type                            | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                           |                               |                                 | Fixed Costs<br><br>mills<br>10 <sup>3</sup> kg steam | Operating Costs<br><br>mills<br>10 <sup>3</sup> kg steam | mills<br>10 <sup>3</sup> kg steam |             |
| Watertube with an Air Preheater | 29 (100)                               | RAP + FGR Stringent                       | 60                            | 26                              | 29 (13) <sup>a</sup>                                 | 233 (106)                                                | 262 (119)                         | 89 <94 >    |
|                                 |                                        | RAP + LNB Stringent                       | 60                            | [26] <sup>b</sup>               | [29 (13)]                                            | [182 (82)]                                               | [210 (95)]                        | [71 <75>]   |
|                                 |                                        | RAP + NH <sub>3</sub> Injection Stringent | 60                            | [118]                           | [132 (60)]                                           | [201 (91)]                                               | [333 (151)]                       | [113 <118>] |
|                                 | 44 (150)                               | RAP<br>SIP<br>Moderate                    | 30                            | 2                               | 2 (1)                                                | 111 (51)                                                 | 113 (51)                          | 37 <39>     |
|                                 |                                        | FGR<br>SIP<br>Moderate                    | 30                            | 32                              | 23 (11)                                              | 117 (53)                                                 | 141 (64)                          | 46 <49>     |
|                                 |                                        | LNB<br>SIP<br>Moderate                    | 30                            | [32] <sup>b</sup>               | [23 (11)]                                            | [66 (30)]                                                | [89 (41)]                         | [29 <31>]   |
|                                 |                                        | RAP + OSC Intermediate                    | 45                            | 32                              | 23 (11)                                              | 179 (81)                                                 | 203 (92)                          | 67 <70>     |
|                                 | 44 (150)                               | RAP + FGR Stringent                       | 65                            | 32                              | 23 (11) <sup>a</sup>                                 | 229 (104)                                                | 252 (114)                         | 83 <87 >    |
|                                 |                                        | RAP + LNB Stringent                       | 65                            | [32] <sup>b</sup>               | [23 (11)]                                            | [179 (81)]                                               | [202 (92)]                        | [66 <70>]   |
|                                 |                                        | RAP + NH <sub>3</sub> Injection Stringent | 65                            | [182]                           | [133 (60)]                                           | [199 (90)]                                               | [332 (150)]                       | [109 <115>] |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup> <> indicates units of mills/10<sup>6</sup> Btu heat input.

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TABLE 4-15. ESTIMATED COST EFFECTIVENESS AND IMPACTS OF CANDIDATE NO<sub>x</sub> CONTROL TECHNIQUES FOR NEW NATURAL GAS-FIRED BOILERS

| System                             |                                        | Impacts                                                |                                                  |                     |                       |                       |
|------------------------------------|----------------------------------------|--------------------------------------------------------|--------------------------------------------------|---------------------|-----------------------|-----------------------|
| Standard Boilers                   |                                        | Type and Level of Control                              | Cost Effectiveness \$/kg NO <sub>x</sub> Reduced | Percent Increase in |                       |                       |
| Type                               | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                                        |                                                  | Uncontrolled Boiler | SIP-Controlled Boiler | SIP-Controlled Boiler |
| Firetube                           | 4.4 (15)                               | No Control<br>SIP<br>Stringent                         | --                                               | --                  | --                    | --                    |
| Watertube without an Air Preheater | 29 (100)                               | No Controls<br>SIP<br>Intermediate<br>LEA<br>Stringent | --                                               | --                  | --                    | --                    |
| Watertube with an Air Preheater    | 29 (100)                               |                                                        |                                                  |                     |                       |                       |
|                                    |                                        | RAP<br>SIP<br>Moderate                                 | 1.5                                              | 7                   | --                    | --                    |
|                                    |                                        | FGR<br>SIP<br>Moderate                                 | 2.0                                              | 7                   | --                    | --                    |
|                                    |                                        | SCA<br>SIP<br>Moderate                                 | 1.3                                              | 7                   | --                    | --                    |
|                                    |                                        | LNB<br>SIP<br>Moderate                                 | [1.3] <sup>c</sup>                               | [7] <sup>f</sup>    | --                    | --                    |
|                                    |                                        | RAP + SCA<br>Intermediate                              | 1.5                                              | 7                   | 3.4                   | 1.6                   |

<sup>a</sup>Cost of boiler only  
<sup>b</sup>Cost includes entire steam plant.  
<sup>c</sup>Bracket indicates gross estimate.

Continued

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TABLE 4-15. Continued

| System                          |                                           |                                           | Impacts                                        |                                        |                       |                                      |                       |
|---------------------------------|-------------------------------------------|-------------------------------------------|------------------------------------------------|----------------------------------------|-----------------------|--------------------------------------|-----------------------|
| Standard Boilers                |                                           | Type and Level of Control                 | Effectiveness<br>\$/kg NO <sub>x</sub> Reduced | Percent Increase in Capital Costs Over |                       | Percent Increase in Steam Costs Over |                       |
| Type                            | Heat Input<br>MM (10 <sup>6</sup> Btu/hr) |                                           |                                                | Uncontrolled Boiler                    | SIP-Controlled Boiler | Uncontrolled Boiler                  | SIP-Controlled Boiler |
| Watertube with an Air Preheater | 29 (100)                                  | RAP + FGR Stringent                       | 1.3                                            | 7                                      | 7                     | 4.2                                  | 2.4                   |
|                                 |                                           | RAP + LNB Stringent                       | [1.0] <sup>c</sup>                             | [7]                                    | [7]                   | [3.3]                                | [1.5]                 |
|                                 |                                           | RAP + NH <sub>3</sub> Injection Stringent | [1.6]                                          | [33]                                   | [33]                  | [5.3]                                | [3.5]                 |
| Watertube with an Air Preheater | 44 (150)                                  | RAP<br>SIP<br>Moderate                    | 1.1                                            | 7                                      | --                    | 1.8                                  | --                    |
|                                 |                                           | FGR<br>SIP<br>Moderate                    | 1.4                                            | 7                                      | --                    | 2.4                                  | --                    |
|                                 |                                           | LNB<br>SIP<br>Moderate                    | [0.9] <sup>c</sup>                             | [7] <sup>c</sup>                       | --                    | [1.5]                                | --                    |
|                                 |                                           | RAP + SCA Intermediate                    | 1.2                                            | 7                                      | 7                     | 3.4                                  | 1.6                   |

<sup>a</sup>Cost of boiler only<sup>b</sup>Cost includes entire steam plant.<sup>c</sup>Bracket indicates gross estimate.

Continued

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TABLE 4-15. Concluded

| System                          |                                           |                                           | Impacts                                             |                                                    |                       |                                                  |                       |
|---------------------------------|-------------------------------------------|-------------------------------------------|-----------------------------------------------------|----------------------------------------------------|-----------------------|--------------------------------------------------|-----------------------|
| Standard Boilers                |                                           | Type and Level of Control                 | Cost Effectiveness<br>\$/kg NO <sub>x</sub> Reduced | Percent Increase in Capital Cost <sup>a</sup> Over |                       | Percent Increase in Steam Cost <sup>b</sup> Over |                       |
| Type                            | Heat Input<br>MW (10 <sup>6</sup> Btu/hr) |                                           |                                                     | Uncontrolled Boiler                                | SIP-Controlled Boiler | Uncontrolled Boiler                              | SIP-Controlled Boiler |
| Watertube with an Air Preheater | 44 (150)                                  | RAP + FGR Stringent                       | 1.1                                                 | 7                                                  | 7                     | 4.2                                              | 2.4                   |
|                                 |                                           | RAP + LNB Stringent                       | [ 0.9 ] <sup>c</sup>                                | [ 7 ]                                              | [ 7 ]                 | [ 3.3 ]                                          | [ 1.5 ]               |
|                                 |                                           | RAP + NH <sub>3</sub> Injection Stringent | [ 1.4 ]                                             | [ 33 ]                                             | [ 33 ]                | [ 5.3 ]                                          | [ 3.5 ]               |

<sup>a</sup>Cost of boiler only  
<sup>b</sup>Cost includes entire steam plant.  
<sup>c</sup>Bracket indicates gross estimate.

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TABLE 4-16. ESTIMATED COSTS OF CANDIDATE NO<sub>x</sub> CONTROL TECHNIQUES FOR RETROFITTED NATURAL GAS BOILERS

| System                             |                            |                                                                                            |                               | Estimated Incremental Costs   |                                                       |                                                            |                                                               |                |
|------------------------------------|----------------------------|--------------------------------------------------------------------------------------------|-------------------------------|-------------------------------|-------------------------------------------------------|------------------------------------------------------------|---------------------------------------------------------------|----------------|
| Standard Boilers                   |                            | Type and Level of Control                                                                  | Control Effectiveness Percent | Capital Cost 103 \$           | Annualized Costs                                      |                                                            |                                                               |                |
| Type                               | Heat Input MM (106 Btu/hr) |                                                                                            |                               |                               | Fixed Costs                                           | Operating Costs                                            | Total Costs                                                   |                |
|                                    |                            |                                                                                            |                               |                               | mills 103 kg steam                                    | mills 103 kg steam                                         | mills 103 kg steam                                            | mills GJ Input |
| Firetube                           | 4.4 (15)                   | No Controls SIP Stringent                                                                  | --                            | --                            | --                                                    | --                                                         | --                                                            |                |
| Watertube without an Air Preheater | 29 (100)                   | No Controls SIP Intermediate LEA Stringent                                                 | --                            | 15                            | --                                                    | --                                                         | --                                                            |                |
| Watertube with an Air Preheater    | 29 (100)                   | RAP SIP Moderate FGR SIP Moderate SCA SIP Moderate LNB SIP Moderate RAP + SCA Intermediate | 25<br>25<br>25<br>25<br>40    | 2<br>40<br>40<br>[ 40 ]<br>40 | 2 (1)<br>45 (20)<br>45 (20)<br>[ 45 (20) ]<br>45 (20) | 113 (51)<br>125 (57)<br>74 (34)<br>[ 74 (34) ]<br>187 (85) | 115 (51)<br>170 (77)<br>120 (54)<br>[ 120 (54) ]<br>230 (104) |                |
|                                    |                            |                                                                                            |                               |                               |                                                       |                                                            |                                                               |                |
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<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

Continued T-1556

TABLE 4-16. Continued

| System                          |                            |                                           | Estimated Incremental Costs   |                     |                       |                       |                                            |                        |
|---------------------------------|----------------------------|-------------------------------------------|-------------------------------|---------------------|-----------------------|-----------------------|--------------------------------------------|------------------------|
| Standard Boilers                |                            | Type and Level of Control                 | Control Effectiveness Percent | Capital Cost 103 \$ | Annualized Costs      |                       |                                            |                        |
| Type                            | Heat Input MW (106 Btu/hr) |                                           |                               |                     | Fixed Costs           | Operating Costs       | Total Costs                                |                        |
|                                 |                            |                                           |                               |                     | mills<br>103 kg steam | mills<br>103 kg steam | mills<br>103 kg steam<br>mills<br>GJ input |                        |
| Watertube with an Air Preheater | 29 (100)                   | RAP + FGR Stringent                       | 60                            | 40                  | 45 (20) <sup>a</sup>  | 237 (108)             | 280 (128)                                  | 95 < 101> <sup>c</sup> |
|                                 |                            | RAP + LNB Stringent                       | 60                            | [ 40] <sup>b</sup>  | [ 45 (20) ]           | [ 185 (84) ]          | [ 230 (104) ]                              | [ 78 < 82> ]           |
|                                 |                            | RAP + NH <sub>3</sub> Injection Stringent | 60                            | [ 116 ]             | [ 130 (59) ]          | [ 201 (91) ]          | [ 330 (150) ]                              | [ 112 < 118> ]         |
|                                 | 44 (150)                   | RAP SIP Moderate                          | 30                            | 2                   | 2 (1)                 | 113 (51)              | 115 (51)                                   | 39 < 40 >              |
|                                 |                            | FGR SIP Moderate                          | 30                            | 62                  | 45 (20)               | 125 (57)              | 170 (77)                                   | 58 < 61 >              |
|                                 |                            | LNB SIP Moderate                          | 30                            | [ 62 ]              | [ 45 (20) ]           | [ 74 (34) ]           | [ 120 (54) ]                               | [ 41 < 43> ]           |
|                                 |                            | RAP + SCA Intermediate                    | 45                            | 62                  | 45 (20)               | 187 (85)              | 230 (104)                                  | 78 < 82 >              |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.<sup>b</sup>Bracket indicates gross estimate.<sup>c</sup>< > indicates units of mills/10<sup>6</sup> Btu heat input.

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TABLE 4-16. Concluded

| System                          |                                        |                                                                                         |                               | Estimated Incremental Costs                 |                                              |                                              |                                                                                        |                         |
|---------------------------------|----------------------------------------|-----------------------------------------------------------------------------------------|-------------------------------|---------------------------------------------|----------------------------------------------|----------------------------------------------|----------------------------------------------------------------------------------------|-------------------------|
| Standard Boilers                |                                        | Type and Level of Control                                                               | Control Effectiveness Percent | Capital Cost 10 <sup>3</sup> \$             | Annualized Costs                             |                                              |                                                                                        |                         |
| Type                            | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                                                                         |                               |                                             | Fixed Costs                                  | Operating Costs                              | Total Costs                                                                            |                         |
|                                 |                                        |                                                                                         |                               |                                             | $\frac{\text{mills}}{10^3 \text{ kg steam}}$ | $\frac{\text{mills}}{10^3 \text{ kg steam}}$ | $\frac{\text{mills}}{10^3 \text{ kg steam}}$<br>$\frac{\text{mills}}{\text{GJ input}}$ |                         |
| Watertube with an Air Preheater | 44 (150)                               | RAP + FGR Stringent<br>RAP + LNB Stringent<br>RAP + NH <sub>3</sub> Injection Stringent | 65<br><br>65<br><br>65        | 62<br><br>[ 62] <sup>b</sup><br><br>[ 182 ] | 45 (20) <sup>a</sup>                         | 237 (108)                                    | 280 (128)                                                                              | 95 < 101 > <sup>c</sup> |
|                                 |                                        |                                                                                         |                               |                                             | [ 45 (20) ]                                  | [ 185 (84) ]                                 | [ 230 (104) ]                                                                          | [ 78 < 82 > ]           |
|                                 |                                        |                                                                                         |                               |                                             | [ 130 (59) ]                                 | [ 201 (91) ]                                 | [ 330 (150) ]                                                                          | [ 112 < 118 > ]         |

<sup>a</sup>Numbers in parentheses are in units of mills/10<sup>3</sup> lb steam.

<sup>b</sup>Bracket indicates gross estimate.

<sup>c</sup><> indicates units of mills/10<sup>6</sup> Btu heat input.

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TABLE 4-17. ESTIMATED COST EFFECTIVENESS AND IMPACTS OF CANDIDATE NO<sub>x</sub> CONTROL TECHNIQUES FOR RETROFITTED NATURAL GAS-FIRED BOILERS

| System                             |                            |                                                                                                                                   | Cost Effectiveness  | Impacts                                |                       |                                      |                       |
|------------------------------------|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------|---------------------|----------------------------------------|-----------------------|--------------------------------------|-----------------------|
| Standard Boilers                   |                            | Type and Level of Control                                                                                                         |                     | Percent Increase in Capital Costs Over |                       | Percent Increase in Steam Costs Over |                       |
| Type                               | Heat Input MW (106 Btu/hr) |                                                                                                                                   |                     | Uncontrolled Boiler                    | SIP-Controlled Boiler | Uncontrolled Boiler                  | SIP-Controlled Boiler |
| Firetube                           | 4.4 (15)                   | No Controls<br>SIP<br>Stringent                                                                                                   | --                  | --                                     | --                    | --                                   |                       |
| Watertube without an Air Preheater | 29 (100)                   | No Controls<br>SIP<br>Intermediate<br>LEA<br>Stringent                                                                            | --                  | --                                     | --                    | --                                   |                       |
| Watertube with an Air Preheater    | 29 (100)                   | RAP<br>SIP<br>Moderate<br>FGR<br>SIP<br>Moderate<br>SCA<br>SIP<br>Moderate<br>LNB<br>SIP<br>Moderate<br>RAP + SCA<br>Intermediate | 1.5                 | 0                                      | --                    | --                                   |                       |
|                                    |                            |                                                                                                                                   | 2.3                 | 11                                     | --                    | --                                   |                       |
|                                    |                            |                                                                                                                                   | 1.6                 | 11                                     | --                    | --                                   |                       |
|                                    |                            |                                                                                                                                   | [ 1.6] <sup>c</sup> | [ 11 ]                                 | --                    | --                                   |                       |
|                                    |                            |                                                                                                                                   | 1.7                 | 11                                     | 11                    | 1.9                                  |                       |

<sup>a</sup>Cost of boiler only  
<sup>b</sup>Cost includes entire steam plant.  
<sup>c</sup>Bracket indicates gross estimate.

Continued

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TABLE 4-17. Continued

| System                          |                            |                                           | Cost Effectiveness | Impacts                                            |                       |                                                  |                       |
|---------------------------------|----------------------------|-------------------------------------------|--------------------|----------------------------------------------------|-----------------------|--------------------------------------------------|-----------------------|
| Standard Boilers                |                            | Type and Level of Control                 |                    | Percent Increase in Capital Cost <sup>a</sup> Over |                       | Percent Increase in Steam Cost <sup>b</sup> Over |                       |
| Type                            | Heat Input MW (106 Btu/hr) |                                           |                    | Uncontrolled Boiler                                | SIP-Controlled Boiler | Uncontrolled Boiler                              | SIP-Controlled Boiler |
| Watertube with an Air Preheater | 29 (100)                   | RAP + FGR Stringent                       | 1.4                | 7                                                  | 7                     | 4.5                                              | 2.7                   |
|                                 |                            | RAP + LNB Stringent                       | [1.1]              | [7]                                                | [7]                   | [3.7]                                            | [1.9]                 |
|                                 |                            | RAP + NH <sub>3</sub> Injection Stringent | [1.6]              | [33]                                               | [5.3]                 | [3.5]                                            |                       |
| Watertube with an Air Preheater | 44 (150)                   | RAP SIP Moderate                          | 1.1                | 0                                                  | --                    | 1.8                                              | --                    |
|                                 |                            | FGR SIP Moderate                          | 1.7                | 11                                                 | --                    | 2.7                                              | --                    |
|                                 |                            | LNB SIP Moderate                          | [1.2] <sup>c</sup> | [11]                                               | --                    | [1.9]                                            | --                    |
|                                 |                            | RAP + SCA Intermediate                    | 1.3                | 11                                                 | 11                    | 3.7                                              | 1.9                   |

<sup>a</sup>Cost of boiler only<sup>b</sup>Cost includes entire steam plant.<sup>c</sup>Bracket indicates gross estimate.

Continued

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TABLE 4-17. Concluded

| System                          |                                        |                                                                                         | Cost Effectiveness              | Impacts                                             |                       |                                                   |                           |
|---------------------------------|----------------------------------------|-----------------------------------------------------------------------------------------|---------------------------------|-----------------------------------------------------|-----------------------|---------------------------------------------------|---------------------------|
| Standard Boilers                |                                        |                                                                                         | \$ / kg NO <sub>x</sub> Reduced | Percent Increase in Capital Costs <sup>a</sup> Over |                       | Percent Increase in Steam Costs <sup>b</sup> Over |                           |
| Type                            | Heat Input MW (10 <sup>6</sup> Btu/hr) | Type and Level of Control                                                               |                                 | Uncontrolled Boiler                                 | SIP-Controlled Boiler | Uncontrolled Boiler                               | SIP-Controlled Boiler     |
| Watertube with an Air Preheater | 44 (150)                               | RAP + FGR Stringent<br>RAP + LNB Stringent<br>RAP + NH <sub>3</sub> Injection Stringent | 1.2<br>[ 1.1 ]<br>[ 1.4 ]       | 7<br>[ 7 ]<br>[ 33 ]                                | 7<br>[ 7 ]<br>[ 33 ]  | 4.5<br>[ 3.7 ]<br>[ 5.3 ]                         | 2.7<br>[ 1.9 ]<br>[ 3.5 ] |

<sup>a</sup>Cost of boiler only<sup>b</sup>Cost includes entire steam plant.<sup>c</sup>Bracket indicates gross estimate.

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give higher steam costs than RAP, as shown in Tables 4-16 and 4-17. The previous comments on control techniques for new units still apply here for retrofitted boilers.

#### 4.5 SUMMARY

The primary contributions of combustion modification  $\text{NO}_x$  controls to steam cost changes are the equipment modification costs and changes in thermal efficiency and fan power demand. For firetube boilers annualized equipment costs are usually higher than costs due to efficiency or fan power demand changes. For watertube boilers, the opposite is usually true. For both firetube and watertube boilers, all costs are important and any factors that can lower any of these costs will be beneficial. In many cases, using the lowest possible excess air will lower the cost impact. Of course, the boiler should be designed to give the highest possible thermal efficiency and lowest fan power requirements. Careful design can result in better fuel efficiency than was assumed in the calculations for flue gas recirculation and staged combustion.

Of the  $\text{NO}_x$  controls covered, low excess air is the method recommended to be first considered since it can reduce fuel costs. Low  $\text{NO}_x$  burners are a promising technique since they should allow both low  $\text{NO}_x$  and LEA operation, and thus save fuel while lowering  $\text{NO}_x$  emissions. Staged combustion is the next best method, unless fuel switching problems make it impractical, since the optimal air port location is fuel dependent. If SCA cannot be used, FGR is the next most cost-effective technique. Ammonia injection is the least cost effective technique and load changing may make it very impractical. Also, whenever possible, an economizer is preferred over an air preheater as a fuel saving device since it does not raise  $\text{NO}_x$  levels.

In summary, combustion modification  $\text{NO}_x$  controls, once proven and demonstrated, should be a cost effective means of control for industrial boilers raising steam costs up to only 1 to 2 percent in most cases. However, the initial investment required, especially for small boilers, may be a large fraction of the cost of the boiler itself, up to 25 percent when controls are installed on a new boiler and up to 50 percent when retrofitting the controls on an existing boiler. Factory installed controls on new boilers should prove more cost effective than retrofit controls.

#### REFERENCES FOR SECTION 4

- 4-1. Lim, K. J., et al., "Environmental Assessment of Utility Boiler Combustion Modification NO<sub>x</sub> Controls," Acurex Draft Report TR-78-105, under EPA Contract No. 68-02-2160, April 1978.
- 4-2. "Task 7 Summary Report - Technical and Economic Bases for Evaluation of Emission Reduction Technology," prepared by PEDCo in support of OAQPS work on NSPS for industrial boilers, June 29, 1978, as revised August 3, 1978. And revisions by Pratapas, J. Ma., EPA/EAB, letter to J. D. Mobley, EPA/IERL-RTP, September 26, 1978.
- 4-3. "Standards Support and Environmental Impact Statement Volume 1: Proposed Standards of Performance for Stationary Gas Turbines," EPA-450/2-77-017a, NTIS-PB 272 422/7BE, September 1977.
- 4-4. Wong-Woo, H, and A. Goodley, "Observation of Flue Gas Desulfurization and Denitrification in Japan", Report SS-78-004, California Air Resources Board, March 1978.
- 4-5. Varga, G. M., Exxon Research and Engineering Co., Linden, New Jersey, Telecommunication with H. Lips, December 19, 1978.
- 4-6. Krippene, B. C., "Conventional NO<sub>x</sub> Reduction Techniques for Oil and Gas-fired Boilers," presented at the NO<sub>x</sub> Control Technology Workshop sponsored by Southern California Edison Company, Electric Power Research Institute, South Coast (California) Air Quality Management District, and Ventura County (California) Air Pollution Control District, Asilomar, California, October 26-28, 1977.
- 4-7. Coffin, B. D., "Estimate the Cost of Your Next Coal-Fired Industrial Boiler Plant", Power Magazine, Volume 121, No. 10, pp. 28-29, October 1977.
- 4-8. Hunter, S. C., and H. J. Buening, "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers - Phase I and II (Data Supplement)," EPA-600/2-77-122, NTIS-PB 270 112/AS, June 1977.
- 4-9. Heap, M. P., et al., "Reduction of Nitrogen Oxide Emissions from Field Operating Package Boilers, Phase III," EPA-600/2-77-025, NTIS-PB 269 277, January 1977.
- 4-10. Schwieger, "Industrial Boilers - What's Happening Today," Power Magazine, Volume. 121, No. 2 pp. S.1-S.24, February 1977 and Volume 122, No. 2 pp. 2.1-S.24, February 1978.
- 4-11. Gregar, D., Babcock & Wilcox Co., San Francisco, Telecommunication with H. Lips, Acurex Corp., August 16, 1978.

- 4-12. Pater, E., Combustion Engineering, San Francisco, Telecommunication with H. Lips, Acurex Corp., August 16, 1978.
- 4-13. Coles, W. F., and J. T. Stewart, "Considerations When Converting Industrial Plants to Coal Firing," ASME 77-IPC-FA-1, 1977.
- 4-14. Schreiber, R. J. and Evans, R. M., "Survey of Methods of Measuring NO<sub>x</sub> from Stationary Sources", Acurex Report TM-78-216 to Energy and Environmental Analysis, Inc., Arlington, Va., May 1978.
- 4-15. Giammar, R. D. and R. B. Engdahl, "Technical, Economic and Environmental Aspects of Industrial Stoker - Fired Boilers," APCA Paper No. 78-28.2, presented at 71st Annual Meeting of the Air Pollution Control Association, Houston, Texas, June 25-30, 1978.
- 4-16. Goodnight, H., John Zink Co., Oklahoma, Telecommunication with R. Merrill, Acurex Corp., July 10, 1978.
- 4-17. Lindahl, G., Lindahl Engineering, San Francisco, Telecommunication with H. Lips, Acurex Corp., August 16, 1978.
- 4-18. Morton, B., E. Keeler Co., Williamsport, PA, Telecommunication with H. Lips, Acurex Corp., August 8, 1978.
- 4-19. Shiu, E., R. F. Mac Donald Co., Foster City, California, Telecommunication with H. Lips, Acurex Corp., August 16, 1978.
- 4-20. Cato, G. A., et al., "Reference Guideline for Industrial Boiler Manufacturers to Control Pollution with Combustion Modification," EPA-600/8-77-003b, NTIS-PB 276 715/OBE, November 1977.
- 4-21. Pratapas, J. M., EPA/SASD, RTP, NC, Letter to J. D. Mobley, EPA/UIPD, RTP, NC, "Industrial Boiler NSPS -- Economic Basis for Technical Assessment (Chapter 3.0)," September 26, 1978.

## SECTION 5

### ENERGY IMPACT

This section discusses the energy impact of combustion modification techniques for controlling  $\text{NO}_x$  emissions from industrial boilers. The amount and type of energy required to operate each of the candidate emission control systems of Section III are identified. Where possible, these values are compared to the quantities and types of energy required by a typical facility, without any  $\text{NO}_x$  emission control system and one controlled to comply with average state regulations. These State Implementation Plan (SIP) regulations have been discussed elsewhere (Reference 5-1) and are summarized in Table 5-1.

TABLE 5-1. AVERAGE STATE IMPLEMENTATION PLAN REQUIREMENTS (REFERENCE 5-1)

| Fuel | Level of Control, ng $\text{NO}_2/\text{J}$ (lb/10 <sup>6</sup> Btu) |
|------|----------------------------------------------------------------------|
| Coal | 301 (0.7)                                                            |
| Oil  | 129 (0.3)                                                            |
| Gas  | 86 (0.2)                                                             |

#### 5.1 INTRODUCTION

The largest potential energy impact of combustion modification  $\text{NO}_x$  control techniques is their effect upon boiler thermal efficiency. Another significant source of energy impact is the change in fan power caused by these control techniques. Boiler control systems installed for low  $\text{NO}_x$  operation also increase electricity and instrument air requirements, but the energy impact is usually minimal.

The changes in boiler efficiency discussed here are from actual tests on industrial size boilers as well as engineering estimates. These estimates were arrived at by extrapolating or interpolating results from tested boilers. Even for the boiler sizes where there were actual efficiency measurements, the scatter in the data still required that engineering judgment be used to estimate a typical value. Because only a few tests of short duration have been made, any long term effects have not been determined. Also, industrial boilers operate under fluctuating loads and small changes in boiler performance are not readily observable. Because an industrial boiler operates with little attention and loads fluctuate, fine tuning of the boiler is limited. This restricts operation efficiency and limits the effectiveness of  $\text{NO}_x$  control methods.

The following paragraphs present general comments on the energy impacts of candidate  $\text{NO}_x$  control systems:

- Low excess air (LEA);
- Staged combustion air (SCA)
  - Overfire air (OFA)
  - Sidefire air (SFA);
- Flue gas recirculation (FGR);
- Reduced air preheat (RAP);
- Low  $\text{NO}_x$  burners (LNB);
- Ammonia injection.

Sections 5.2, 5.3, and 5.4 further discuss the energy impacts on coal-, oil-, and gas-fired industrial boilers, respectively.

Operating a boiler under low excess air conditions decreases the total air flow through the boiler, and hence the sensible heat loss out the stack is minimized, increasing boiler thermal efficiency. When LEA is used alone, a smaller force draft fan could save additional energy, although this would only be a small savings. Low excess air operation would probably require an oxygen trim system, but that would consume only a minimal amount of energy. Thus, there is a large net gain in energy with low excess air operation.

Staged combustion via overfire air (OFA) or sidefire air (SFA) operation can increase the combustion air pressure drop because of additional duct work. Also, air flow would be increased if the amount of overfire air is greater than the reduction of air through the flame.

Therefore additional forced draft fan power is usually required with staged combustion. From utility boiler experience, energy losses of 0.1 percent of boiler heat input capacity are the maximum expected due to the larger forced draft fan (Reference 5-2). The effect on thermal efficiency depends on air port location and the amount of total air used with OFA or SFA operation. The air port must be located so that proper mixing of the unburned fuel and air can be achieved, maintaining combustion efficiency. If the amount of air through the OFA or SFA ports is no more than the decreased air through the flame, thermal efficiency, in theory, should not be hurt.

Flue gas recirculation (FGR) also requires more fan power. This increased fan power requirement is expected to be of the order of 0.25 percent of boiler heat input capacity, based on utility boiler experience (Reference 5-2). The 0.25 percent factor for industrial boilers is slightly higher than that for utility boilers, because of the former's proportionately more constrictive recirculation duct work. Flue gas recirculation may have a small effect on boiler thermal efficiency because FGR causes lower furnace temperatures which may decrease the amount of heat transferred to the water and steam.

Reduced air preheat (RAP) operation will usually lower the boiler's efficiency. Unless the boiler has an economizer with extra capacity, RAP operation will raise the flue gas temperature causing a greater loss of sensible heat from the boiler.

Low  $\text{NO}_x$  burners for industrial boilers are still in the development stage. Some low  $\text{NO}_x$  burners increase the pressure drop across the burner (References 5-3 through 5-6) and could require more fan power. In principle, low  $\text{NO}_x$  burners should not affect boiler thermal efficiency. A number will be given for energy use by LNB but that number is a very rough estimate.

Ammonia injection is another control technique under development. The process requires energy for the injectors and  $\text{NH}_3$  handling equipment. There is also a slight energy loss due to the carrier gas.

All the comments given here are for typical boilers controlled to meet representative  $\text{NO}_x$  emission levels. The actual energy impact depends on the particular boiler and quantity of control used. Because of this, the uncertainty in the energy impact listed in the following tables



is at least +50 percent. Also as already mentioned, the following discussions are based on very limited data. First, energy impacts for coal-fired units are discussed, then oil-fired and gas-fired boilers. The control methods and control levels were described in Section 3.

## 5.2 ENERGY IMPACT OF CONTROLS FOR COAL-FIRED BOILERS

Most coal-fired industrial boilers are either stoker-fired or pulverized coal-fired. Only the larger sized industrial boilers are pulverized coal-fired; the stoker size range covers all industrial boilers. The discussion that follows on pulverized coal units relies heavily on utility boiler experience (Reference 5-2). Most of the data on stokers were collected by KVB, Battelle, and Acurex under EPA sponsored programs (References 5-7 through 5-13). All comments are based on these references unless otherwise stated. Whenever possible, LEA should be combined with other control methods to reduce any energy increase. Table 5-2 summarizes the energy impact on coal-fired boilers.

### 5.2.1 New Facilities

The two main methods of firing pulverized coal are tangential and single wall-fired units. Based on the limited number of tests, these two firing types give about the same emission levels and are thus treated together, as discussed in Section 3. Without any controls, the average pulverized coal-fired units can meet State Implementation Plan (SIP) levels of 301 ng/J and moderate control levels of 301 ng/J. For a pulverized coal unit to meet intermediate control levels (258 ng/J), LEA was recommended since it may decrease coal consumption by 0.5 percent. Soot could increase slightly, requiring a little more use of soot blowers, but this would be a minimal effect. To meet stringent control levels, staged combustion with OFA, may be required. This can result in a small additional fan power requirement of 0.1 percent and a small drop in thermal efficiency of 0.25 percent. Low  $\text{NO}_x$  burners (LNB) or ammonia injection may also be used to reach stringent control levels. The energy consumption is unknown for both methods and with LEA operation, consumption might even decrease. Some types of low  $\text{NO}_x$  burners (References 5-3, 5-4, 5-5, and 5-6) could require more fan power which would increase energy use. For ammonia injection, energy requirements for the injectors and  $\text{NH}_3$  handling equipment would be minimal but the air compressor for

TABLE 5-2. ENERGY CONSUMPTION DUE TO NO<sub>x</sub> CONTROL TECHNIQUES FOR COAL-FIRED BOILERS

| System          |                                        |                                         |                               | Energy Consumption     |                                                               |                                                                      |                                                                      |
|-----------------|----------------------------------------|-----------------------------------------|-------------------------------|------------------------|---------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Standard Boiler |                                        | Type and Level of Controls <sup>a</sup> | Control Effectiveness Percent | Energy Types           | Energy Consumed by Control Device MW (10 <sup>6</sup> Btu/hr) | Percent Increase <sup>b</sup> in Energy Use Over Uncontrolled Boiler | Percent Change <sup>c</sup> in Energy Use Over SIP Controlled Boiler |
| Type            | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                         |                               |                        |                                                               |                                                                      |                                                                      |
| Pulverized Coal | 59 (200)                               | No Control Device SIP Moderate          | --                            | --                     | --                                                            | --                                                                   | --                                                                   |
|                 |                                        | Low Excess Air Intermediate             | --                            | --                     | --                                                            | --                                                                   | --                                                                   |
|                 |                                        | Overfire Air Stringent                  | 10                            | Coal                   | - 0.3 (- 1.0)                                                 | - 0.5                                                                | - 0.5                                                                |
|                 |                                        | Low NO <sub>x</sub> Burners Stringent   | 25                            | Electric or Steam Coal | 0.06 (0.2) }<br>0.15 (0.5) } <sup>d</sup>                     | 0.10 }<br>0.25 } <sup>d</sup>                                        | 0.10 }<br>0.25 } <sup>d</sup>                                        |
|                 |                                        | Ammonia Injection Stringent             | 25                            | Electric Coal          | 0.15 (0.5)                                                    | 0.25                                                                 | 0.25                                                                 |
| Pulverized Coal | 117 (400)                              | No Control Device SIP Moderate          | 25                            | Electric               | 0.3 (1.0)                                                     | 0.5                                                                  | 0.5                                                                  |
|                 |                                        | Low Excess Air Intermediate             | --                            | --                     | --                                                            | --                                                                   | --                                                                   |
|                 |                                        |                                         | 10                            | Coal                   | 0.6                                                           | - 0.5                                                                | - 0.5                                                                |

<sup>a</sup>Control levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1.

<sup>b</sup>Energy consumed by control device, MM) ÷ (Standard boiler heat input, MM) X 100

<sup>c</sup>(Energy consumed by control device, MM) - Energy consumed by SIP control device, MM) ÷ (Standard boiler heat input, MM) + energy consumed by SIP control device, MM) X 100

<sup>d</sup>Add figures for total energy consumption of control device

<sup>e</sup>Number is rough estimate

<sup>f</sup>Low excess air operation could lower energy impact

Continued

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TABLE 5-2. Continued

| System                      |                                        |                                           |                               | Energy Consumption     |                                                               |                                                          |                                                                      |
|-----------------------------|----------------------------------------|-------------------------------------------|-------------------------------|------------------------|---------------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------------------|
| Standard Boiler             |                                        | Type and Level of Controls                | Control Effectiveness Percent | Energy Types           | Energy Consumed by Control Device MW (10 <sup>6</sup> Btu/hr) | Percent Increased in Energy Use Over Uncontrolled Boiler | Percent Change <sup>c</sup> in Energy Use Over SIP Controlled Boiler |
| Type                        | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                           |                               |                        |                                                               |                                                          |                                                                      |
| Pulverized Coal (continued) | 117 (400)                              | Overfire Air Stringent                    | 25                            | Electric or Steam Coal | 0.1 (0.4) }<br>0.3 (1.0) } <sup>d</sup>                       | 0.10 }<br>0.25 } <sup>d</sup>                            | 0.10 }<br>0.25 } <sup>d</sup>                                        |
|                             |                                        | Low NO <sub>x</sub> Burners Stringent     | 25                            | Electric Coal          | 0.3 (1.0)e, f                                                 | 0.25                                                     | 0.25                                                                 |
|                             |                                        | Ammonia Injection Stringent               | 25                            | Electric               | 0.6 (2.0)e, f                                                 | 0.5                                                      | 0.5                                                                  |
| Spreader Stoker             | 44 (150)                               | No Control Device SIP Moderate            | --<br>--                      | --<br>--               | --<br>--                                                      | --<br>--                                                 | --<br>--                                                             |
|                             |                                        | Low Excess Air Intermediate               | 5                             | Coal                   | - 0.1 (- 0.4)                                                 | - 0.25                                                   | - 0.25                                                               |
|                             |                                        | Low Excess Air and Overfire Air Stringent | 20                            | Electric Coal          | None expected <sup>f</sup>                                    | --                                                       | --                                                                   |
|                             |                                        |                                           |                               |                        |                                                               |                                                          |                                                                      |

<sup>a</sup>Control levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1. T-1439

<sup>b</sup>(Energy consumed by control device, MW) ÷ (Standard boiler heat input, MW) X 100

<sup>c</sup>(Energy consumed by control device, MW) - Energy consumed by SIP control device, MW ÷ (Standard boiler heat input, MW + energy consumed by SIP control device, MW) X 100

<sup>d</sup>Add figures for total energy consumption of control device

<sup>e</sup>Number is rough estimate

<sup>f</sup>Low excess air operation could lower energy impact

Continued

TABLE 5-2. Concluded

| System             |                                        |                                                                                                            |                               | Energy Consumption                |                                                               |                                                         |                                                         |
|--------------------|----------------------------------------|------------------------------------------------------------------------------------------------------------|-------------------------------|-----------------------------------|---------------------------------------------------------------|---------------------------------------------------------|---------------------------------------------------------|
| Standard Boiler    |                                        | Type and Level of Controls                                                                                 | Control Effectiveness Percent | Energy Types                      | Energy Consumed by Control Device MW (10 <sup>6</sup> Btu/hr) | Percent Increase in Energy Use Over Uncontrolled Boiler | Percent Change in Energy Use Over SIP Controlled Boiler |
| Type               | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                                                                                            |                               |                                   |                                                               |                                                         |                                                         |
| Spreader Stoker    | 25 (85)                                | No Control Device SIP<br>Low Excess Air and Overfire Air Moderate                                          | --<br>20                      | --<br>Electric Coal               | --<br>None expected <sup>f</sup>                              | --<br>--                                                | --<br>--                                                |
| Chain Grate Stoker | 22 (75)                                | Ammonia Injection Intermediate Stringent<br>No Control Device SIP Intermediate<br>Low Excess Air Stringent | 35<br>55<br>--<br>--<br>8     | Electric Coal<br>--<br>--<br>Coal | 0.1 (0.4) <sup>f</sup><br>--<br>--<br>- 0.11 (-0.4)           | 0.5<br>--<br>--<br>-0.5                                 | 0.5<br>--<br>--<br>-0.5                                 |
| Underfeed Stoker   | 9 (30)                                 | No Control Device SIP Intermediate<br>Low Excess Air Stringent                                             | --<br>--<br>15                | --<br>--<br>Coal                  | --<br>--<br>- 0.04 (- 0.15)                                   | --<br>--<br>- 0.5                                       | --<br>--<br>- 0.5                                       |

<sup>a</sup>Control levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1.

<sup>b</sup>(Energy consumed by control device, MW) ÷ (Standard boiler heat input, MW) X 100

<sup>c</sup>(Energy consumed by control device, MW - Energy consumed by SIP control device, MW) ÷ (Standard boiler heat input, MW + energy consumed by SIP control device, MW) X 100

<sup>d</sup>Add figures for total energy consumption of control device

<sup>e</sup>Number is rough estimate

<sup>f</sup>Low excess air operation could lower energy impact

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the carrier gas could increase energy use by at least 0.25 percent (Reference 5-19).

Spreader stokers larger than 29 MW heat input require no controls to meet SIP or moderate control levels (301 ng/J). Only LEA operation is needed to meet intermediate levels of 258 ng/J, which could reduce coal consumption by 0.25 percent. Using even lower excess air than is required to meet the standard could lower fuel consumption even more. However, operational limitations may prevent such low excess air levels (see Section 3). Staged combustion air could be used to meet stringent control levels (215 ng/J). There is only a small fan power increase since stokers normally use some OFA as a smoke control method (baseline). Also thermal efficiency does not change; it could even increase by combining LEA with OFA. No controls are needed to meet SIP levels for spreader stokers less than 29 MW. But staged combustion is needed to meet moderate control levels (215 ng/J). Staged combustion would have the analogous energy impact on the smaller stokers as on the larger units. Ammonia injection is recommended to reach either intermediate (172 ng/J) or stringent (129 ng/J) control levels. This process has the same energy impact as for pulverized coal units.

Only two chain grate stoker tests have been reported, and based on that limited data, LEA control may be able to achieve the stringent control level (129 ng/J) with an energy savings of about 0.5 percent. The underfeed stokers tested needed no controls to meet SIP or intermediate control levels (172 ng/J). To reach stringent control levels, LEA operation is recommended, which could give an energy savings of at least 0.5 percent.

#### 5.2.2 Modified and Reconstructed Facilities

Existing units with retrofitted  $\text{NO}_x$  controls should have about the same energy impact as new units. Because of the windbox design, retrofitted OFA ports might have larger pressure drops and require more fan power. The efficiency for pulverized units using OFA ports, depends on location. Since it might not be possible to put the air ports in the optimal spot on a retrofitted boiler, efficiency might be lowered. Also, a new boiler might be designed to operate under a lower excess air level than an existing one. Thus the energy impacts on an existing unit may be greater than those on a new unit. Since the actual energy impact will

depend on the particular boiler being modified, the expected energy impact can not be quantified at this time.

### 5.3 ENERGY IMPACT OF CONTROLS FOR OIL-FIRED BOILERS

This discussion of the energy impact of combustion modifications for controlling  $\text{NO}_x$  emissions from oil-fired boilers is based on tests conducted by KVB and Ultrasystems (References 5-7, 5-8, 5-9, 5-14, 5-15, 5-17). As mentioned previously, these tests were all short term and the condition of the boiler was not always documented. Also the additional electricity and instrument air required to operate under low  $\text{NO}_x$  conditions are minimal, and these topics are not covered. Residual and distillate oil-fired boilers are discussed. The energy impacts on residual oil-fired boilers and distillate oil-fired boilers are summarized in Tables 5-3 and 5-4. Whenever possible, LEA operation should be used to increase boiler thermal efficiency and hence reduce energy consumption.

#### 5.3.1 New Units

Firetube boilers firing residual oil need no controls to meet SIP or moderate control levels (129 ng/J). Low excess air operation can be used to achieve intermediate control levels, resulting in an oil savings of about 0.5 percent. Low  $\text{NO}_x$  burners or staged combustion is recommended to reach the next control level, stringent (86 ng/J). Low  $\text{NO}_x$  burner might require more fan power but since LNB is still in the development stage, their effect on fan power requirement is unknown. Their effect on thermal efficiency is expected to be minimal. The thermal efficiency in staged combustion depends on both the air port location and the fuel being fired. Efficiency will not be affected if the air port is in the proper location for the fuel being fired. Since this will not always be the case, an efficiency loss of 0.5 percent is assumed. Also additional fan power equal to about 0.10 percent of boiler heat input, could be needed.

Low excess air operation is needed to reach SIP or moderate control levels (129 ng/J) for watertube boilers firing residual oil. This control technique could result in a fuel savings of 1 percent. To achieve an intermediate control level, staged combustion can be used. Efficiency can increase or decrease depending on type of fuel used and air port location. Thermal efficiency could be decreased by 0.5 percent, and fan requirements could be increased. Low  $\text{NO}_x$  burners or ammonia injection

TABLE 5-3. ENERGY CONSUMPTION FOR NO<sub>x</sub> CONTROL TECHNIQUES FOR RESIDUAL OIL-FIRED BOILERS

| System          |                                        |                                                           | Energy Consumption            |                             |                                                               |                                                                      |                                                                      |
|-----------------|----------------------------------------|-----------------------------------------------------------|-------------------------------|-----------------------------|---------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Standard Boiler |                                        | Type and Level of Controls <sup>a</sup>                   | Control Effectiveness Percent | Energy Types                | Energy Consumed by Control Device MW (10 <sup>6</sup> Btu/hr) | Percent Increase <sup>b</sup> in Energy Use Over Uncontrolled Boiler | Percent Change <sup>c</sup> in Energy Use Over SIP Controlled Boiler |
| Type            | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                                           |                               |                             |                                                               |                                                                      |                                                                      |
| Firetube        | 4.4 (15)                               | No Control Device SIP Moderate                            | --                            | --                          | --                                                            | --                                                                   | --                                                                   |
|                 |                                        | Low Excess Air Intermediate                               | --                            | --                          | --                                                            | --                                                                   | --                                                                   |
|                 |                                        | Low Excess Air and Overfire Air Stringent                 | 5                             | Oil                         | -0.02 (-0.075)                                                | -0.5                                                                 | -0.5                                                                 |
|                 |                                        | Low NO <sub>x</sub> Burners Stringent                     | 25                            | Oil, Electric               | 0.02 (0.07)<br>0.004 (0.015)                                  | 0.5 } <sup>d</sup><br>0.1 }                                          | 0.5 } <sup>d</sup><br>0.1 }                                          |
| Watertube       | 8.8 (30)                               | Low NO <sub>x</sub> Burners Stringent                     | 25                            | Oil, Electric               | 0.01 (0.04)                                                   | 0.25                                                                 | 0.25                                                                 |
|                 |                                        | Low Excess Air SIP Moderate                               | 20<br>20                      | Oil                         | -0.1 (-0.3)                                                   | -1.0                                                                 | --                                                                   |
|                 |                                        | Low Excess Air and Overfire or Side-fire Air Intermediate | 35                            | Oil<br>Electric<br>or Steam | 0.04 (0.15)<br>0.01 (0.03)                                    | 0.5 } <sup>d</sup><br>0.1 }                                          | 1.5 } <sup>d</sup><br>0.1 }                                          |

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aControl levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1.  
b(Energy consumed by control device, MW) ÷ (Standard boiler heat input, MW) X 100  
c(Energy consumed by control device, MW - Energy consumed by SIP control device, MW) ÷ (Standard boiler heat input, MW + energy consumed by SIP control device, MW) X 100  
dAdd figures for total energy consumption of control device  
eNumber is rough estimate  
fLow excess air operation could lower energy impact

Continued

TABLE 5-3. Concluded

| System                |                            |                                                           |                               | Energy Consumption       |                                                   |                                                         |                                                                      |
|-----------------------|----------------------------|-----------------------------------------------------------|-------------------------------|--------------------------|---------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------------------|
| Standard Boiler       |                            | Type and Level of Controls                                | Control Effectiveness Percent | Energy Types             | Energy Consumed by Control Device MW (106 Btu/hr) | Percent Increase in Energy Use Over Uncontrolled Boiler | Percent Change <sup>c</sup> in Energy Use Over SIP Controlled Boiler |
| Type                  | Heat Input MW (106 Btu/hr) |                                                           |                               |                          |                                                   |                                                         |                                                                      |
| Watertube (continued) | 8.8 (30)                   | Low NO <sub>x</sub> Burners Stringent                     | 45                            | Oil, Electric            | 0.02 (0.08)e,f                                    | 0.25                                                    | 1.25                                                                 |
|                       |                            | Ammonia Injection Stringent                               | 45                            | Oil, Electric            | 0.04 (0.15)f                                      | 0.5                                                     | 1.5                                                                  |
| Watertube             | 44 (150)                   | Low Excess Air SIP Moderate                               | 20<br>20                      | Oil                      | -0.4 (-1.5)                                       | -1.0                                                    | --                                                                   |
|                       |                            | Low Excess Air and Overfire or Side-fire Air Intermediate | 35                            | Oil<br>Electric or Steam | 0.04 (0.15)<br>0.01 (0.03) } <sup>d</sup>         | 0.5<br>0.1 } <sup>d</sup>                               | 1.5<br>0.1 } <sup>d</sup>                                            |
|                       |                            | Low NO <sub>x</sub> Burners Stringent                     | 45                            | Oil, Electric            | 0.1 (0.4)e,f                                      | 0.25                                                    | 1.25                                                                 |
|                       |                            | Ammonia Injection Stringent                               | 45                            | Oil, Electric            | 0.2 (0.8)f                                        | 0.5                                                     | 1.5                                                                  |

<sup>a</sup>Control levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1.

<sup>b</sup>(Energy consumed by control device, MW) ÷ (Standard boiler heat input, MW) x 100

<sup>c</sup>(Energy consumed by control device, MW - Energy consumed by SIP control device, MW) ÷ (Standard boiler heat input, MW + energy consumed by SIP control device, MW) x 100

<sup>d</sup>Add figures for total energy consumption of control device

<sup>e</sup>Number is rough estimate

<sup>f</sup>Low excess air operation could lower energy impact

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TABLE 5-4. ENERGY CONSUMPTION DUE TO NO<sub>x</sub> CONTROL TECHNIQUES FOR DISTILLATE OIL-FIRED BOILERS

| System                                |                                        |                                          | Energy Consumption            |                             |                                                               |                                                         |                                                         |
|---------------------------------------|----------------------------------------|------------------------------------------|-------------------------------|-----------------------------|---------------------------------------------------------------|---------------------------------------------------------|---------------------------------------------------------|
| Standard Boiler                       |                                        | Type and Level of Controls               | Control Effectiveness Percent | Energy Types                | Energy Consumed by Control Device MM (10 <sup>6</sup> Btu/hr) | Percent Increase in Energy Use Over Uncontrolled Boiler | Percent Change in Energy Use Over SIP Controlled Boiler |
| Type                                  | Heat Input MM (10 <sup>6</sup> Btu/hr) |                                          |                               |                             |                                                               |                                                         |                                                         |
| Firetube                              | 4.4 (15)                               | No Control Device<br>SIP<br>Moderate     | --                            | --                          | --                                                            | --                                                      | --                                                      |
|                                       |                                        | Low Excess Air<br>Intermediate           | --                            | --                          | --                                                            | --                                                      | --                                                      |
|                                       |                                        | Flue Gas<br>Recirculation<br>Stringent   | 10                            | Oil                         | -0.2 (-0.075)                                                 | -0.5                                                    | -0.5                                                    |
|                                       |                                        | Low NO <sub>x</sub> Burners<br>Stringent | 40                            | Oil<br>Electric             | 0.02 (0.075)<br>0.011 (0.04)                                  | 0.50<br>0.25                                            | 0.5<br>0.25 } <sup>d</sup>                              |
| Watertube<br>Without<br>Air Preheater | 29 (100)                               | No Control Device<br>SIP<br>Intermediate | 40                            | Oil, Electric               | None expected <sup>e,f</sup>                                  | --                                                      | --                                                      |
|                                       |                                        | Flue Gas<br>Recirculation<br>Stringent   | --                            | --                          | --                                                            | --                                                      | --                                                      |
|                                       |                                        |                                          | --                            | --                          | --                                                            | --                                                      | --                                                      |
|                                       |                                        |                                          | 15                            | Oil<br>Electric or<br>Steam | 0.14 (0.5)<br>0.07 (0.25)                                     | 0.5<br>0.25                                             | 0.5<br>0.25 } <sup>d</sup>                              |

aControl levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1. T-1441

b(Energy consumed by control device, MM) ÷ (Standard boiler heat input, MM) X 100

c(Energy consumed by control device, MM - Energy consumed by SIP control device, MM) ÷ (Standard boiler heat input, MM + energy consumed by SIP control device, MM) X 100

dAdd figures for total energy consumption of control device

eNumber is rough estimate

fLow excess air operation could lower energy impact

Continued

TABLE 5-4. Continued

| System                                      |                                        |                                                        |                               | Energy Consumption       |                                                               |                                                         |                                                         |
|---------------------------------------------|----------------------------------------|--------------------------------------------------------|-------------------------------|--------------------------|---------------------------------------------------------------|---------------------------------------------------------|---------------------------------------------------------|
| Standard Boiler                             |                                        | Type and Level of Controls                             | Control Effectiveness Percent | Energy Types             | Energy Consumed by Control Device MW (10 <sup>6</sup> Btu/hr) | Percent Increase in Energy Use Over Uncontrolled Boiler | Percent Change in Energy Use Over SIP Controlled Boiler |
| Type                                        | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                                        |                               |                          |                                                               |                                                         |                                                         |
| Watertube Without Air Preheater (continued) | 29 (100)                               | Low NO <sub>x</sub> Burners Stringent                  | 15                            | Electric, Oil            | None expected <sup>e,f</sup>                                  | --                                                      | --                                                      |
|                                             |                                        | Low Excess Air and Overfire or Side-fire Air Stringent | 15                            | Oil<br>Electric or Steam | 0.14 (0.5)<br>0.03 (0.1) } <sup>d</sup>                       | 0.5<br>0.1 } <sup>d</sup>                               | 0.5<br>0.1 } <sup>d</sup>                               |
| Watertube With Air Preheater                | 29 (100)                               | No Control Device SIP                                  | --                            | --                       | --                                                            | --                                                      | --                                                      |
|                                             |                                        | Low Excess Air Moderate                                | 5                             | Oil                      | -0.07 (-0.25)                                                 | -0.25                                                   | -0.25                                                   |
|                                             |                                        | Reduced Air Preheat Intermediate                       | 30                            | Oil                      | 0.44 (1.5) <sup>f</sup>                                       | 1.5                                                     | 1.5                                                     |
|                                             |                                        | Flue Gas Recirculation Intermediate                    | 30                            | Oil<br>Electric or Steam | 0.14 (0.5)<br>0.07 (0.25)                                     | 0.5<br>0.25 } <sup>d</sup>                              | 0.5<br>0.25 } <sup>d</sup>                              |
|                                             |                                        | Low NO <sub>x</sub> Burners Intermediate               | 30                            | Electric, Oil            | 0.07 (0.25) <sup>e,f</sup>                                    | 0.25                                                    | 0.25                                                    |

<sup>a</sup>Control levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1.

<sup>b</sup>(Energy consumed by control device, MW) ÷ (Standard boiler heat input, MW) X 100

<sup>c</sup>(Energy consumed by control device, MW - Energy consumed by SIP control device, MW) ÷ (Standard boiler heat input, MW + energy consumed by SIP control device, MW) X 100

<sup>d</sup>Add figures for total energy consumption of control device

<sup>e</sup>Number is rough estimate

<sup>f</sup>Low excess air operation could lower energy impact

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Continued

TABLE 5-4. Continued

| System                                   |                                        |                                                                | Energy Consumption            |                             |                                                               |                                                         |                                                         |
|------------------------------------------|----------------------------------------|----------------------------------------------------------------|-------------------------------|-----------------------------|---------------------------------------------------------------|---------------------------------------------------------|---------------------------------------------------------|
| Standard Boiler                          |                                        | Type and Level of Controls                                     | Control Effectiveness Percent | Energy Types                | Energy Consumed by Control Device MW (10 <sup>6</sup> Btu/hr) | Percent Increase in Energy Use Over Uncontrolled Boiler | Percent Change in Energy Use Over SIP Controlled Boiler |
| Type                                     | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                                                |                               |                             |                                                               |                                                         |                                                         |
| Watertube With Air Preheater (continued) | 29 (100)                               | Low Excess Air and Overfire or Side-fire Air Intermediate      | 30                            | Oil<br>Electric<br>or Steam | 0.14 (0.5)<br>0.03 (0.1)                                      | 0.5 } d<br>0.1 }                                        | 0.5 } d<br>0.1 }                                        |
|                                          |                                        | Reduced Air Pre-heat and Flue Gas Recirculation Stringent      | 55                            | Oil<br>Electric             | 0.6 (2.0)<br>0.07 (0.25)                                      | 2.0 } d<br>0.25 }                                       | 2.0 } d<br>0.25 }                                       |
|                                          |                                        | Reduced Air Pre-heat and Low NO <sub>x</sub> Burners Stringent | 55                            | Oil<br>Steam<br>or Electric | 0.44 (1.5) <sup>f</sup><br>0.07 (0.25) <sup>e</sup>           | 1.5<br>0.25                                             | 1.5<br>0.25                                             |
| Watertube With Air Preheater             | 44 (150)                               | No Control Device SIP                                          | --                            | --                          | --                                                            | --                                                      | --                                                      |
|                                          |                                        | Low Excess Air Moderate                                        | 5                             | Oil                         | -0.1 (-0.4)                                                   | -0.25                                                   | -0.25                                                   |
|                                          |                                        | Reduced Air Preheat Intermediate                               | 30                            | Oil                         | 0.7 (2.2) <sup>f</sup>                                        | 1.5                                                     | 1.5                                                     |

<sup>a</sup>Control levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1.

<sup>b</sup>(Energy consumed by control device, MW) ÷ (Standard boiler heat input, MW) X 100

<sup>c</sup>(Energy consumed by control device, MW - Energy consumed by SIP control device, MW) ÷ (Standard boiler heat input, MW + energy consumed by SIP control device, MW) X 100

<sup>d</sup>Add figures for total energy consumption of control device

<sup>e</sup>Number is rough estimate

<sup>f</sup>Low excess air operation could lower energy impact

Continued

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TABLE 5-4. Concluded

| System                                   |                                        |                                                                | Energy Consumption            |                       |                                                               |                                                                      |                                                                      |
|------------------------------------------|----------------------------------------|----------------------------------------------------------------|-------------------------------|-----------------------|---------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Standard Boiler                          |                                        | Type and Level of Controls <sup>a</sup>                        | Control Effectiveness Percent | Energy Types          | Energy Consumed by Control Device MW (10 <sup>6</sup> Btu/hr) | Percent Increase <sup>b</sup> in Energy Use Over Uncontrolled Boiler | Percent Change <sup>c</sup> in Energy Use Over SIP Controlled Boiler |
| Type                                     | Heat Input MW (10 <sup>6</sup> Btu/hr) |                                                                |                               |                       |                                                               |                                                                      |                                                                      |
| Watertube with Air Preheater (continued) | 44 (150)                               | Flue Gas Recirculation Intermediate                            | 30                            | Oil Electric or Steam | 0.22 (0.75)<br>0.1 (0.4)                                      | 0.5 }<br>0.25 }<br>d                                                 | 0.5 }<br>0.25 }<br>d                                                 |
|                                          |                                        | Low NO <sub>x</sub> Burners Intermediate                       | 30                            | Electric, Oil         | 0.1 (0.4) <sup>e,f</sup>                                      | 0.25                                                                 | 0.25                                                                 |
|                                          |                                        | Low Excess Air and Overfire or Side-fire Air Intermediate      | 30                            | Oil Electric or Steam | 0.22 (0.75)<br>0.04 (0.15)                                    | 0.5 }<br>0.1 }<br>d                                                  | 0.5 }<br>0.1 }<br>d                                                  |
|                                          |                                        | Reduced Air Pre-heat and Flue Gas Recirculation Stringent      | 55                            | Oil Electric          | 0.9 (3.0)<br>0.1 (0.4)                                        | 2.0 }<br>0.25 }<br>d                                                 | 2.0 }<br>0.25 }<br>d                                                 |
|                                          |                                        | Reduced Air Pre-heat and low NO <sub>x</sub> Burners Stringent | 55                            | Oil Steam or Electric | 0.44 (1.5) <sup>f</sup><br>0.1 (0.4) <sup>e</sup>             | 1.5<br>0.25                                                          | 1.5<br>0.25                                                          |

<sup>a</sup>Control levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1.

<sup>b</sup>(Energy consumed by control device, MW) ÷ (Standard boiler heat input, MW) x 100

<sup>c</sup>(Energy consumed by control device, MW - Energy consumed by SIP control device, MW) ÷ (Standard boiler heat input, MW + energy consumed by SIP control device, MW) x 100

<sup>d</sup>Add figures for total energy consumption of control device

<sup>e</sup>Number is rough estimate

<sup>f</sup>Low excess air operation could lower energy impact

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could be used to reach stringent control levels. Low  $\text{NO}_x$  burners will probably only have a small energy impact. Ammonia injection is also only in the development stage and will probably have a small energy impact of about 0.5 percent.

Firetube boilers firing distillate oil need no controls to reach SIP (129 ng/J) or moderate (86 ng/J) control levels. Low excess air operation can be used to reach intermediate control levels (65 ng/J), with a fuel savings of about 0.5 percent. Stringent control levels (43 ng/J) can be reached by using either flue gas recirculation or low  $\text{NO}_x$  burners. Flue gas recirculation tests showed small thermal efficiency changes in most cases, but some tests did show losses up to 1 percent. A 0.5 percent loss is assumed and an additional fan power requirement of 0.25 percent of boiler heat input could be required.

Watertube boilers equipped with air preheaters firing distillate oil emit more  $\text{NO}_x$  than those units without preheaters. Economizers can be used to reclaim sensible heat from the flue gas without increasing  $\text{NO}_x$  emissions, as discussed in Section 3. Thus economizers should be used instead of air preheaters whenever possible. Watertube boilers without air preheaters need no controls to reach SIP or intermediate control levels. Flue gas recirculation, low  $\text{NO}_x$  burners, or staged combustion can be used to reach stringent control levels. The energy impacts of FGR, LNB, and staged combustion discussed above apply here also.

Watertube boilers equipped with air preheaters firing distillate oil need no controls to meet SIP levels. To meet moderate control levels, LEA could save about 0.25 percent in energy use. Reduced air preheat, FGR, LNB, or staged combustion could be used to reach intermediate control levels. Except for reduced air preheat, the energy impact of these controls have already been described. Reduced air preheat could lower efficiency by 1.5 percent, which would offset the efficiency gained by installing the air preheater. To meet stringent control levels, RAP and FGR or RAP and LNB could be used. Unless LEA or addition of an economizer is used with these two methods to lower the energy impact, they will use a large amount of energy. Reduced air preheat and flue gas recirculation could decrease boiler efficiency by 2 percent and increase fan power use by 0.25 percent. Reduced air preheat and low  $\text{NO}_x$  burners might increase fuel use 1.5 percent and require more fan power. Again, the efficiency

gained by using the air preheater is lost, showing the advantage of an economizer instead of an air preheater.

### 5.3.2 Retrofitted Facilities

Retrofitted units have about the same energy impact as new units. Since staged combustion technique efficiency depends on air port location, it might not be possible when retrofitting to put the OFA or SFA ports in the optimal location. Since low  $\text{NO}_x$  burners change the flame shape, it might not be possible to retrofit these burners. Also, a new boiler could be designed to operate under a lower excess air level than an existing unit, especially, since burners have been developed that allow lower excess air operation (Reference 5-18).

## 5.4 ENERGY IMPACT OF CONTROLS FOR GAS-FIRED BOILERS

Data for the energy impact of combustion modifications for controlling  $\text{NO}_x$  emissions from natural gas-fired boilers were collected by KVB and Ultrasystems (References 5-7, 5-8, 5-9, and 5-14 through 5-17). Again, these were short term tests and the condition of the boiler was not always documented. Table 5-5 summarizes the energy impact on gas-fired industrial boilers. In all cases, LEA operation is recommended to minimize energy consumption.

### 5.4.1 New Facilities

A gas-fired firetube boiler should require no controls to meet SIP (86 ng/J) or stringent (43 ng/J) control levels. Again as in the oil-fired case, an economizer is recommended and for the same reasons: an economizer can save energy without increasing  $\text{NO}_x$  emissions. Watertube boilers without air preheaters need no controls to meet SIP or intermediate (65 ng/J) control levels. To meet stringent control levels, LEA could be used which would give about a 0.5 percent fuel savings.

For watertube boilers with air preheaters, controls are needed to meet SIP or moderate control levels. The recommended methods are RAP, FGR, staged combustion, and LNB. The energy impact of these controls have already been described. Fuel losses due to these techniques could be 2.0 percent for RAP, 0.5 percent for FGR, 0.5 percent for staged combustion, and negligible for LNB if they work as planned. It should be reiterated that low  $\text{NO}_x$  burners are in the development stage. The fuel loss for FGR and staged combustion would be less if the boiler is designed for and operated mainly on one type of fuel. As explained earlier, the

TABLE 5-5. ENERGY CONSUMPTION DUE TO NO<sub>x</sub> CONTROL TECHNIQUES FOR NATURAL GAS-FIRED BOILERS

| System                          |                                        |                                                                        | Energy Consumption            |                             |                                                               |                                                                      |                                                                      |
|---------------------------------|----------------------------------------|------------------------------------------------------------------------|-------------------------------|-----------------------------|---------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Standard Boiler                 |                                        | Type and Level of Controls                                             | Control Effectiveness Percent | Energy Types                | Energy Consumed by Control Device MM (10 <sup>6</sup> Btu/hr) | Percent Increase <sup>b</sup> in Energy Use Over Uncontrolled Boiler | Percent Change <sup>c</sup> in Energy Use Over SIP Controlled Boiler |
| Type                            | Heat Input MM (10 <sup>6</sup> Btu/hr) |                                                                        |                               |                             |                                                               |                                                                      |                                                                      |
| Firetube                        | 4.4 (15)                               | No Control Device<br>SIP<br>Stringent                                  | --<br>--                      | --<br>--                    | --<br>--                                                      | --<br>--                                                             | --<br>--                                                             |
| Watertube Without Air Preheater | 29 (100)                               | No Control Device<br>SIP<br>Intermediate                               | --<br>--                      | --<br>--                    | --<br>--                                                      | --<br>--                                                             | --<br>--                                                             |
|                                 |                                        | Low Excess Air<br>Stringent                                            | 5                             | Gas                         | -0.14 (-0.5)                                                  | -0.5                                                                 | -0.5                                                                 |
| Watertube With Air Preheater    | 29 (100)                               | Reduced Air Preheat<br>SIP<br>Moderate                                 | 25<br>25                      | Gas                         | 0.6 (2.0) <sup>f</sup>                                        | 2.0                                                                  | --                                                                   |
|                                 |                                        | Flue Gas<br>Recirculation<br>SIP<br>Moderate                           | 25<br>25                      | Gas<br>Electric<br>or Steam | 0.14 (0.5)<br>0.07 (0.25)                                     | 0.5<br>0.25 }<br>d                                                   | --                                                                   |
|                                 |                                        | Low Excess Air and<br>Overfire or Side-<br>fire Air<br>SIP<br>Moderate | 25<br>25                      | Gas<br>Electric<br>or Steam | 0.14 (0.5)<br>0.03 (0.1)                                      | 0.5<br>0.1 }<br>d                                                    | --<br>--                                                             |

<sup>a</sup>Control levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1.

<sup>b</sup>(Energy consumed by control device, MM) ÷ (Standard boiler heat input, MM) X 100

<sup>c</sup>(Energy consumed by control device, MM - Energy consumed by SIP control device, MM) ÷ (Standard boiler heat input, MM + energy consumed by SIP control device, MM) X 100

<sup>d</sup>Add figures for total energy consumption of control device

<sup>e</sup>Number is a rough estimate

<sup>f</sup>Low excess air operation could lower energy impact

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TABLE 5-5. Continued

| System                                   |                            |                                                               | Energy Consumption            |                       |                                                   |                                                         |                                                         |
|------------------------------------------|----------------------------|---------------------------------------------------------------|-------------------------------|-----------------------|---------------------------------------------------|---------------------------------------------------------|---------------------------------------------------------|
| Standard Boiler                          |                            | Type and Level of Controls                                    | Control Effectiveness Percent | Energy Types          | Energy Consumed by Control Device MW (106 Btu/hr) | Percent Increase in Energy Use Over Uncontrolled Boiler | Percent Change in Energy Use Over SIP Controlled Boiler |
| Type                                     | Heat Input MW (106 Btu/hr) |                                                               |                               |                       |                                                   |                                                         |                                                         |
| Watertube With Air Preheater (continued) | 29 (100)                   | Low NO <sub>x</sub> Burners SIP Moderate                      | 25<br>25                      | Gas, Electric         | 0.07 (0.25) <sup>e,f</sup>                        | 0.25                                                    | --                                                      |
|                                          |                            | Reduced Air Preheat and Overfire or Sidefire Air Intermediate | 40                            | Gas Electric or Steam | 0.7 (2.5)<br>0.03 (0.1)<br>d,f                    | 2.5<br>0.1<br>d                                         | 2.0<br>--                                               |
|                                          |                            | Reduced Air Preheat and Flue Gas Recirculation Stringent      | 60                            | Gas Electric          | 0.7 (2.5)<br>0.07 (0.25)<br>d,f                   | 2.5<br>0.25<br>d                                        | 2.0<br>0.15<br>d                                        |
|                                          |                            | Reduced Air Preheat and Low NO <sub>x</sub> Burners Stringent | 60                            | Gas Electric or Steam | 0.6 (2.0) <sup>f</sup><br>0.07 (0.25)             | 2.0<br>0.25                                             | 1.5<br>--                                               |
|                                          |                            | Reduced Air Preheat and Ammonia Injection Stringent           | 60                            | Gas Electric          | 0.6 (2.0) <sup>f</sup><br>0.14 (0.5)              | 2.0<br>0.5                                              | 1.5<br>--                                               |

<sup>a</sup>Control levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1.

<sup>b</sup>Energy consumed by control device, MW  $\div$  (Standard boiler heat input, MW) X 100

<sup>c</sup>Energy consumed by control device, MW - Energy consumed by SIP control device, MW  $\div$  (Standard boiler heat input, MW + energy consumed by SIP control device, MW) X 100

<sup>d</sup>Add figures for total energy consumption of control device

<sup>e</sup>Number is a rough estimate

<sup>f</sup>Low excess air operation could lower energy impact

Continued

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TABLE 4-37. BENZO(a)PYRENE EMISSION FACTORS FOR RESIDENTIAL COMBUSTION SOURCES

| Source Category                                      | No. of Tests | Emission Rate in pg/J |         |         | Reference No. |
|------------------------------------------------------|--------------|-----------------------|---------|---------|---------------|
|                                                      |              | Mean                  | Maximum | Minimum |               |
| Underfeed stoker - boiler - bituminous coal          | 3            | 32.8                  | 102     | 4.49    | 3             |
| Underfeed stoker - hot air furnace - bituminous coal | 2            | 28.9                  | 82.1    | 10.2    | 3             |
| Hand stoked - hot air furnace - bituminous coal      | 3            | 1640                  | 3,910   | 508     | 3             |
| All types - bituminous coal                          | 8            | 137                   | -       | -       | 3             |
| Stove - various coals <sup>a</sup>                   | 11           | 195                   | 14,800  | 27.4    | 3             |
| Fireplace - various woods <sup>b</sup>               | 12           | 108                   | 158     | <76.1   | 3             |
| Oil-fired - boiler <sup>c</sup>                      | 1            | <0.042                | -       | -       | 3             |
| Oil-fired - hot air furnace <sup>c</sup>             | 2            | <0.064                | -       | -       | 3             |
| Oil-fired - all types                                | 3            | <0.054                | -       | -       | 3             |
| All types - bituminous coal <sup>d</sup>             | 2            | 100                   | -       | -       | 8             |
| Fireplace - wood <sup>e,b</sup>                      | 3            | 95.1                  | 108     | <88     | 9             |
| Stove - wood <sup>e,b</sup>                          | 5            | 494                   | 735     | 69.7    | 9             |

<sup>a</sup>Emission rates are based on heating value of bituminous coal (25,586 J/g).

<sup>b</sup>Emission rates are based on a heating value for wood of 15,775 J/g. This value is an average of seasoned and green oak and pine woods as received.

<sup>c</sup>Emission rates are based on tests of a cast-iron sectional boiler fired with No. 2 distillate oil and two hot air furnaces (one fired with distillate oil No. 1 and the other with distillate oil No. 2).

<sup>d</sup>Includes steam or hot-water boilers, warm-air furnaces, and domestic heating stoves. The reported value includes benzo(e)pyrene and perylenes.

<sup>e</sup>BaP values include benzo(e)pyrene and perylenes. Assume an average heating value for wood of 15,775 J/g, based on averaged seasoned and green oak and pine woods.

TABLE 5-5. Concluded

| System                                   |                            |                                                               | Energy Consumption            |                       |                                                    |                                                          |
|------------------------------------------|----------------------------|---------------------------------------------------------------|-------------------------------|-----------------------|----------------------------------------------------|----------------------------------------------------------|
| Standard Boiler                          |                            | Type and Level of Control <sup>a</sup>                        | Control Effectiveness Percent | Energy Types          | Energy Consumed by Control Device MW (106 Btu/hr)  | Percent Increased in Energy Use Over Uncontrolled Boiler |
| Type                                     | Heat Input MW (106 Btu/hr) |                                                               |                               |                       |                                                    |                                                          |
| Watertube With Air Preheater (continued) | 44 (150)                   | Reduced Air Preheat and Low NO <sub>x</sub> Burners Stringent | 65                            | Gas Electric or Steam | 0.6 (2.0) <sup>f</sup><br>0.1 (0.4) <sup>e,f</sup> | 2.0<br>0.25                                              |
|                                          |                            | Reduced Air Preheat and Ammonia Injection Stringent           |                               |                       |                                                    |                                                          |
|                                          |                            |                                                               | 65                            | Gas Electric          | 0.6 (2.0) <sup>f</sup><br>0.2 (0.8)                | 2.0<br>0.5                                               |
|                                          |                            |                                                               |                               |                       |                                                    | 1.5<br>--                                                |

<sup>a</sup>Control levels moderate, intermediate, and stringent are discussed in Section 3. State Implementation Plan (SIP) control levels are given in Table 5-1.

<sup>b</sup>(Energy consumed by control device, MW) ÷ (Standard boiler heat input, MW) X 100

<sup>c</sup>(Energy consumed by control device, MW - Energy consumed by SIP control device, MW) ÷ (Standard boiler heat input, MW + energy consumed by SIP control device, MW) X 100

<sup>d</sup>Add figures for total energy consumption of control device

<sup>e</sup>Number is a rough estimate

<sup>f</sup>Low excess air operation could lower energy impact

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Logical organization refers to the way information is attached to the various character fields present in each document summary on the computer file. Thoughtful additions to the character fields can increase the usefulness of the Catalog System. For instance, the keyword field could be used for accession numbers, document descriptors, program goal descriptors, etc., as well as topical descriptors. A special application would be to use one keyword as a flag for a group of related documents. For example, including the keyword "CCEA" for every document produced under the CCEA contract, it would be simple to create a listing of all the CCEA contract documents. The abstract field of the computer file can theoretically contain any kind of information, (e.g., legibility of the document). It is recommended that such options be considered for implementation prior to future indexing efforts.

are used with LEA and only one type of fuel is burned. For boilers that burn several fuels, several air ports would be needed and these ports may not always be in just the right location. Except for increased fan power use, it might be possible to design boilers so that FGR would not decrease thermal efficiency significantly. In some tests this was not always the case. Low  $\text{NO}_x$  burners should not decrease thermal efficiency and might even allow lower excess air operation which could increase thermal efficiency. Low  $\text{NO}_x$  burners are the most promising new technology. Ignoring  $\text{NH}_3$  and carrier gas, ammonia injection appears to have only a minor energy impact though for raw material consumption, operational, and environmental reasons it might not be desirable. For new distillate oil- and gas-fired boilers, economizers are recommended over air preheaters as energy saving devices.

In summary, combustion modification  $\text{NO}_x$  controls for new industrial boilers should only have a minor energy impact. In fact, with proper boiler design and control implementation, it might even be possible in some cases to significantly lower  $\text{NO}_x$  emissions and use less energy.

## REFERENCES FOR SECTION 5

- 5-1 Broz, L, Acurex Corporation, C. Sedman, EPA/OAQPS, and J.D. Mobley, EPA/IERL, letter to Industrial Boiler Contractors, August 29, 1978.
- 5-2 Lim, K.J., et al., "Environmental Assessment of Utility Boiler Combustion Modification NO<sub>x</sub> Controls," Acurex Draft Report TR-78-105, Under EPA Contract No. 68-02-2160, April 1978.
- 5-3 Unpublished data supplied by N. Kido, Japan National Research Institute for Pollution and Resources, August 1978.
- 5-4 Ando, J., et al., "Nitrogen Oxide Abatement Technology in Japan - 1973," EPA-R2-73-284, NTIS-PB 222 335, June 1974.
- 5-5 Ando, J., et al., "NO<sub>x</sub> Abatement for Stationary Sources in Japan," EPA-600/7-77-103b, NTIS-PB 276 948/AS, September 1977.
- 5-6 Goodnight, H. John Zink Co., Oklahoma, Telcommunication with R. Merrill, Acurex Corp., July 10, 1978.
- 5-7 Cato, C.A., et al., "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers - Phase I," EPA-600/2-74-078a, NTIS-PB 238 920/AS, October 1974.
- 5-8 Cato, C.A., et al., "Field Testing: Application of Combustion Modification to Control Pollutant Emissions from Industrial Boilers - Phase 2," EPA-600/2-76-086a, NTIS-PB 253 500/AS, April 1976.
- 5-9 Hunter, S.C., and H.J. Buening, "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers - Phases I and II (Data Supplement)," EPA-600/2-77-122, NTIS-PB 270 112/AS, June 1977.
- 5-10 Giammar, R.D. and R.B. Engdahl, "Technical, Economic and Environmental Aspects of Industrial Stoker-Fuel Boilers," APCA Paper No. 78-28.2, presented at 71st Annual Meeting of the Air Pollution Control Association, Houston, Texas, June 25-30, 1978.
- 5-11 Unpublished data supplied by E. B. Higginbotham, Acurex Corporation, Mountain View, California, September 1978.
- 5-12 Gabrielson, J. E., et al., "Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement-Site A," EPA-600/7-78-136a, NTIS-PB 295 172/AS, July 1978.
- 5-13 Maloney, K. L., et al., "Low-sulfur Western Coal Use in Existing Small and Intermediate Size Boilers, EPA 600/7-78-153a, NTIS-PB 287 937/AS, July 1978.

- 5-14 Carter, W.A., et al., "Emissions Reduction on Two Industrial Boilers with Major Combustion Modifications," EPA 600/7-78-099a, NTIS-PB 283 109, June 1978.
- 5-15 Cichanowicz, J.E., et al., "Pollution Control Techniques for Package Boilers. Phase I, Hardware Modifications and Alternate Fuels," Draft Report, EPA Contract 68-02-1498, November 1976.
- 5-16 Muzio, L.J., et al., "Package Boiler Flame Modification for Reducing Nitric Oxide Emissions - Phase II of III," EPA-R2-73-292-B, NTIS-PB 236 752, June 1974.
- 5-17 Heap, M.P., et al., "Reduction of Nitrogen Oxide Emissions from Field Operating Package Boilers, Phase III," EPA-600/2-77-025, NTIS-PB 269 277, January 1977.
- 5-18 Schwieger, R., "Industrial Boilers -- What's Happening Today," Power, Volume 121, No. 2, pp. S.1-S.24, February 1977.
- 5-19 Castaldini, C., et al., "Technical Assessment of Exxon's Thermal De NO<sub>x</sub> Process," Acurex Final Report 79-301, EPA Contract 68-02-2611, April 1979.

## SECTION 6

### ENVIRONMENTAL IMPACTS OF CANDIDATES FOR BEST EMISSION CONTROL SYSTEMS

Modification of the combustion process for  $\text{NO}_x$  control can alter the emission rates of other pollutants. These changes, referred to as incremental emissions, could lead to adverse environmental effects. Therefore, a key consideration of all  $\text{NO}_x$  control development programs must be the effects on emission levels of the criteria pollutants: carbon monoxide (CO), unburned hydrocarbons (UHC), particulate, and sulfur oxides ( $\text{SO}_x$ ), and the  $\text{SO}_2/\text{SO}_3$  ratio. Also of concern in recent control development programs are the noncriteria pollutants, trace metals and organics.

This section presents the expected effect of combustion modification  $\text{NO}_x$  controls on the criteria and noncriteria pollutants. These postulations are further supported by a review of the possible formation mechanisms for each pollutant. However, data are insufficient to completely describe the effect of the  $\text{NO}_x$  control and the resulting incremental emissions. The data that are available are presented as a function of boiler and fuel type.

#### 6.1 IDENTIFICATION OF THE MAJOR ENVIRONMENTAL CONCERNS

The candidate best  $\text{NO}_x$  control system for each fuel category was presented in Tables 3-7, 3-8, 3-10, 3-11, and 3-12. Table 6-1 presents the expected effect each modification will have on incremental emissions. A review of Table 6-1 shows that:

- Increased CO and vapor phase hydrocarbon emissions are of major concern only when excess air levels are lowered
- Sulfate emission levels are expected to decrease or remain unchanged with all controls except staged combustion and

TABLE 6-1. POSTULATED EFFECT OF COMBUSTION MODIFICATIONS ON INCREMENTAL EMISSIONS FROM INDUSTRIAL BOILERS.

| Combustion Modification     | Resulting Combustion Conditions                                                                                                                                                                   | CO                 | Vapor Phase HC     | Sulfate                                                                                                | Organics                                                          |
|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|--------------------|--------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------|
| Low excess air              | Reduced local O <sub>2</sub> concentration; decreased gas velocities; increased furnace residence time                                                                                            | Increased          | Increased          | Decreased overall because of lowered O <sub>2</sub> availability                                       | Possibly increased                                                |
| Staged combustion           | Reduced local O <sub>2</sub> concentration; reduced peak flame temperature; increased convection zone temperature; delayed flame zone mixing                                                      | Possibly increased | Possibly increased | Possibly decreased because of decreased convection zone catalysis (less volatile metal redistribution) | Possibly increased                                                |
| Flue gas recirculation      | Reduced local O <sub>2</sub> concentration; reduced peak flame temperature; reduced furnace residence time; increased gas velocities; more turbulent flame; increased convective zone temperature | Possibly increased | Possibly increased | Possibly decreased                                                                                     | Possibly increased                                                |
| Reduced air preheat         | Reduced peak flame temperature; decreased gas velocities; increased furnace residence times; increased local O <sub>2</sub> concentration                                                         | No effect          | No effect          | Possibly decreased                                                                                     | Possibly increased                                                |
| Ammonia injection           | Increased local NH <sub>3</sub> concentration                                                                                                                                                     | No effect          | No effect          | Possibly increased through near plume solution catalysis                                               | Decreased with decreased particle emissions; no effect otherwise  |
| Low NO <sub>x</sub> burners | Delayed fuel-air mixing; off-stoichiometric combustion                                                                                                                                            | Possibly increased | Possibly increased | Possibly decreased because of less potential for SO <sub>2</sub> oxidation                             | Possibly increased due to greater carbonaceous particle formation |

Continued



TABLE 6-1. (Concluded)

| Combustion Modification   | Particulate                                                     |                                                                                                                                                | Trace Metals                                                                                                 |                                                                                                 |
|---------------------------|-----------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
|                           | Size Distribution                                               | Mass Emissions                                                                                                                                 | Segregating                                                                                                  | Nonsegregating                                                                                  |
| Low excess air            | Possible trend to larger sizes                                  | Possibly decreased because of increased bottom and ash fallout and internal deposition                                                         | Unknown effect: possible increase due to increased volatility but possible decrease with internal deposition | Possibly reduced because of reduced mineral particle emissions and internal particle deposition |
| Staged combustion         | Possible trend to larger sizes                                  | Unknown effect: possible increase due to soot formation; possible decrease due to larger particles and convection zone deposition and slagging | Possibly decreased because of decreased repartitioning to small particles                                    | Possibly reduced due to larger particles (more carbon) and convection zone slagging             |
| Flue gas recirculation    | Probably no effect                                              | Possibly increased due to increased velocities and possibility of soot formation                                                               | Possibly decreased because of decreased repartitioning to small particles                                    | Possibly increased with increased particle emissions                                            |
| Reduced air preheat       | Probably no effect                                              | Possibly increased due to less bottom slagging                                                                                                 | Possibly reduced because of less concentration in small particles                                            | Possibly increased with increased particle emissions                                            |
| Reduced load              | Probably no effect                                              | Probably no net effect                                                                                                                         | Possibly reduced because of less concentration in small particles                                            | Probably no effect                                                                              |
| Ammonia injection         | Trend to smaller particles ( $\text{NH}_4\text{HSO}_4$ aerosol) | Possibly decreased with ESPs because of conditioning; increased otherwise                                                                      | Possibly increased because larger fraction of small particles                                                | Decreased with decreased particle emissions; no effect otherwise                                |
| Low $\text{NO}_x$ burners | Trend to larger particles                                       | Possibly increased because of greater soot formation                                                                                           | Possibly decreased because of overall trend to larger particles more easily controlled                       | Possibly decreased because larger particles more easily controlled                              |

ammonia injection (which alters the form of  $\text{SO}_3$  to  $\text{NH}_3\text{HSO}_4$ )

- Changes in emitted particle size distribution are expected only when operating with low excess air, staged combustion or low  $\text{NO}_x$  burners. In these instances the production of larger particles is expected.
- Increased particulate mass emissions are of potential concern when flue gas recirculation, staged combustion, or low  $\text{NO}_x$  burners are used
- Condensible organic emissions are likely to increase with all combustion  $\text{NO}_x$  controls except ammonia injection
- Decreased segregating trace metal emissions are possible when using staged combustion, flue gas recirculation, or ammonia injection. Segregating species are those that are partitioned to various particle sizes.
- Nonsegregating trace metal emissions are only of potential concern when implementing flue gas recirculation and reduced air preheat

The following subsection discusses the formation mechanism for each pollutant as a function of the combustion conditions.

Obviously care must be taken when quantifying impacts of  $\text{NO}_x$  controls. A careful balance between reduced  $\text{NO}_x$  and increased incremental emissions must be maintained to minimize the total impact on ambient environmental goals.

## 6.2 FORMATION MECHANISMS OF MAJOR POLLUTANTS

Since incremental emissions are sensitive to the same combustion conditions as  $\text{NO}_x$ , an understanding of the formation mechanisms of these incremental pollutants will permit a better appreciation of how  $\text{NO}_x$  control conditions affect these combustion generated pollutants. Such knowledge can aid in the interpretation of the limited field test data available and provide informed speculation on how  $\text{NO}_x$  controls act. Subsection 6.2.1 reviews the formation mechanism of the criteria pollutants: carbon monoxide, unburned hydrocarbons, particulate, and sulfur oxides. (Nitrogen oxides formation has already been discussed in Section 2.) Subsection 6.2.2 discusses the formation mechanisms of the noncriteria pollutants: trace metals and organics.

## 6.2.1 Criteria Pollutants -- Formation Mechanisms

### Carbon Monoxides

The presence of CO in the exhaust gases of combustion systems results principally from incomplete fuel combustion. Several conditions can result in incomplete combustion. These include:

- Insufficient oxygen availability
- Poor fuel/air mixing
- Cold wall flame quenching
- Reduced combustion temperature
- Decreased combustion gas residence time
- Load reduction (reduced efficiency)

Since various combustion modifications for NO<sub>x</sub> reduction can produce one or more of the above conditions, the possibility of increased CO emissions is a concern for environmental, energy and operational reasons. Flue gas CO emission concentrations in excess of 2000 ppm can severely damage equipment from explosions in flue gas exit passages (Reference 6-1).

### Unburned Hydrocarbons

Unburned hydrocarbon emissions can include essentially all vapor phase organic compounds emitted from a combustion source. These are primarily emissions of aliphatic, oxygenated, and low molecular weight aromatic compounds which exist in the vapor phase at flue gas temperatures. These emissions include all alkanes, alkenes, aldehydes, carboxylic acids, and substituted benzenes (e.g., benzene, toluene, xylene, ethyl benzene, etc.) (References 6-2 and 6-3). Condensed phase organic compounds are presently noncriteria pollutants and are discussed in Section 6.3.

Like CO, UHC occur due to incomplete combustion. Therefore, any combustion modification which reduces the combustion efficiency will most likely increase the concentrations of vapor phase hydrocarbons. These pollutants are of environmental concern because of their role in the atmospheric reactions which lead to photochemical smog (Reference 6-1).

### Total Particulate

Gas-fired combustion equipment produces negligible amounts of particulate matter. The quantity of emissions increases when distillate oil and residual oil are used and the greatest quantity is emitted when coal is the primary fuel (Reference 6-4).

Particulate emissions from oil-fired units can be composed of soot (condensed organic matter) and ash (incombustible mineral matter). Coal particulate emissions are largely ash, and occasionally contain some unburned carbonaceous residue (Reference 6-1). The composition of the particulate generated in the combustor can affect mass emissions. This is due primarily to the relationship between composition and particle size, and the particulate control device employed for particle removal. In addition, some trace element emissions depend on the particle size distribution. Finally, polycyclic organic matter (POM) emissions from combustion sources occur largely as solid phase carbonaceous residue. High particulate emissions, especially from coal-fired boilers, may increase the possibility of high POM emissions (Reference 6-1). (The formation mechanisms and emissions of trace elements and POM are discussed in later sections.)

The formation of particulates in a combustion source is closely related to combustion aerodynamics, the mechanisms of fuel/air mixing, and the effects of these factors on combustion gas temperature-time history. The optimum conditions for reducing particulate formation (intense, high temperature flames as produced in high turbulence and rapid fuel/air mixing) are not the conditions for suppressing  $\text{NO}_x$  formation. Therefore, most attempts to design low- $\text{NO}_x$  combustors have been compromised by the need to limit the formation of particulates (Reference 6-1).

Particulate emissions are subdivided into expected particle size distribution and particulate mass emissions. When  $\text{NO}_x$  controls are applied to reduce combustion efficiency, condensible organic matter (soot) increases. If the combustion modification results in a reducing atmosphere rather than an oxidizing atmosphere, ash emissions may decrease due to increased slag formation and internal deposition of ash ("bottom ash").

Particle size distribution can affect the emissions of trace metals. Some trace metals segregate to the smaller particle sizes. If combustion modifications reduce particle sizes, segregating trace metals emissions will increase. Since small particulate remains suspended for larger periods of time, it can penetrate the body's respiratory system more easily, and remain in the lungs for longer periods of time.

Therefore, greater adverse health effects are possible. The more complete the combustion, the smaller the particle size distribution. Therefore, loss of combustion efficiency can result in increased mass emissions from the boiler and increased particle size (Reference 6-1). Larger particles are more easily removed by pollution control devices. Boilers equipped with these devices may reduce mass emissions from the stack when combustion efficiency is reduced.

### Sulfates

Ambient sulfate levels are of increasing concern in regions with large numbers of combustion sources firing sulfur-bearing coal and oil. Although the direct health effects of high ambient sulfate levels are currently unclear (Reference 6-5), high sulfate aerosol concentrations decrease visibility and aggravate acid precipitation.

Ambient sulfates are generally comprised of directly emitted sulfates (primary sulfates) and those derived from the atmospheric oxidation of sulfur dioxide,  $\text{SO}_2$ , (secondary sulfates). Sulfur dioxide is emitted when sulfur is contained in the fuel. Up to 98 percent of all sulfur entering the boiler may be discharged as  $\text{SO}_2$ . The primary concern for incremental emissions, then, is to control the ratio of primary sulfate to  $\text{SO}_2$  ( $\text{SO}_4/\text{SO}_2$ ). The sulfate present may exist as either sulfuric acid ( $\text{H}_2\text{SO}_4$ ) or as metal or ammonium sulfates.

The precise mechanisms for the formation of sulfates are not completely understood. However, two processes contribute to final flue gas sulfate levels. The first is homogeneous  $\text{SO}_2$  oxidation in the flame through the reaction:



where M is a third body molecule. Although  $\text{SO}_2$  is the thermodynamically favored product at high temperatures, it is currently thought that some  $\text{SO}_3$  is formed through Equation (6-1). Subsequent rapid gas quenching then freezes the system into a nonequilibrium state. Any  $\text{SO}_3$  formed through this reaction will, at reduced temperatures, combine with available water vapor to form sulfuric acid. This sulfuric acid will then adsorb onto available particulate matter or, in the absence of sufficient particulate matter, condense as an acid mist.

The second important sulfate formation mechanism is catalyzed heterogeneous  $\text{SO}_2$  oxidation in postcombustion regions by flue gas particulate and internal boiler deposits. Several potential oxidation catalysts exist in suspended and deposited flue gas particulate, including vanadium, nickel, iron, manganese oxides, and carbon (soot).

Based on the above, it is possible to speculate how  $\text{NO}_x$  controls might affect primary sulfate production. Reduced oxygen availability should definitely decrease primary sulfate emissions. Thus,  $\text{NO}_x$  controls which decrease local oxygen availability should lower sulfate emission levels. It is difficult to identify the effects of combustor temperature time history on sulfate production. This is because not much is known about in situ catalytic mechanisms and their relative importance to homogeneous  $\text{SO}_2$  oxidation. Since trace metals present in the gas stream catalytically oxidize  $\text{SO}_2$  to  $\text{SO}_3$ , combustion conditions which facilitate volatilization-condensation and partitioning of these metals, such as high peak flame temperatures, should promote  $\text{SO}_2$  conversion. Conversely, combustion controls which lower peak flame temperature should decrease sulfate production.

#### 6.2.2 Noncriteria Pollutants -- Formation Mechanisms

##### Organics

Organics are those species not included in the criteria pollutant class of unburned vapor phase hydrocarbons. The remaining organic emissions are composed largely of compounds emitted from combustion sources in a condensed phase. These compounds can almost exclusively be classed into a group known variously as polycyclic organic matter (POM) or polynuclear aromatic hydrocarbons (PNA or PAH). The following discussion treats POM emissions from stationary combustion sources and the effects of  $\text{NO}_x$  controls on these emissions.

Although polycyclic organic matter can conceivably be formed in the combustion of any hydrocarbon fuel, it is considered more of a problem when associated with soot (carbonaceous particulate) emissions from coal- and oil-fired combustion equipment. Polycyclic organic matter are especially prevalent in the emissions from coal burning, because a large fraction of the volatile matter in coal (coal tar) preexists as POM.

Although the formation of POM in flames is complex and variable, it is possible to form a relatively clear picture of the overall reaction.

In a reducing atmosphere at temperatures around 2,000K (conditions common in the center of flames), radical species of the form,  $\text{HC}=\text{CH}$  and  $\text{RCH}=\text{CH}$ , can rapidly combine and form large polynuclear aromatic molecules through radical chain propagation (References 6-3, 6-6). As combustion gas cools and chain propagation is quenched, a variety of POM species can remain when combustion is incomplete. Upon further cooling, these species condense and are emitted largely as soot or high carbon content particulate.

POM emissions have significant environmental impact because several species are highly carcinogenic (Reference 6-3). The fact that they generally exist as fine particulate makes them an even more serious health hazard.

It is important to again note that although POM formation is possible during methane combustion, the formation of these large aromatic molecules is facilitated by the presence of higher molecular weight radicals. Thus, POM production is of only minor concern in gas-fired systems, of some concern in oil-fired systems, and of greatest concern in coal-fired equipment. Whatever the combustion source, POM emissions should increase under conditions of poor combustion efficiency. Since  $\text{NO}_x$  combustion controls can lead to inefficient combustion and soot formation if not carefully applied (especially low excess air and staged combustion), implementation of these controls can lead to increased POM formation.

A few comments are in order here concerning an extremely toxic subclass of polynuclear aromatic hydrocarbons, the polychlorinated and polybrominated biphenyls (PCBs and PBBs). A theoretical assessment of PCB formation in combustion sources (Reference 6-7) concluded that, although PCB formation is thermodynamically possible during coal and residual oil (fuels which contain some chlorine) combustion, it is unlikely due to short reaction residence times and low chlorine concentrations. If PCBs are formed, they would be expected to occur under conditions which promote POM emissions. However, PCBs have never been verified in conventional combustion source emissions.

#### Trace Elements

Emissions of trace metals are a concern for combustion sources firing coal and residual oil. They are a lesser problem in sources firing

distillate fuels since trace metal concentrations in distillate oils are generally much lower than those in residual oils. Trace metals from stationary sources are emitted to the atmosphere with the flue gas either as a vapor or condensed on particulate. The quantity of any given metal emitted, in general, depends on:

- Its concentration in the fuel
- The combustion conditions in the boiler
- The type of particulate control device used, and its collection efficiency as a function of particle size
- The physical and chemical properties of the element itself

It has become widely recognized that some trace metals concentrate in certain waste particle streams from a boiler (bottom ash, collector ash, flue gas particulate), while others do not (References 6-8 through 6-14). The most logical explanation for this segregation involves a volatilization-condensation mechanism (Reference 6-8). Certain metals have boiling points sufficiently high that they are not volatilized in the combustion zone. Instead, they form a melt of relatively uniform concentration, which becomes both bottom ash or slag, and flyash. Thus, these elements, termed Class I, remain in a condensed phase throughout the boiler and show little partitioning with particle size. By contrast, other metals have boiling points below peak combustion temperatures, so they are volatilized in the combustion zone and do not become incorporated in the slag. As combustion gases cool by traveling through the boiler, these elements, termed Class II, either form condensation nuclei or condense onto other available solid surfaces (predominantly preexisting Class I ash particles). Since the available surface area to mass ratio increases as particle size decreases, these elements concentrate in small particles. Finally, metals such as Mercury (Hg) and to some extent Selenium (Se), remain vaporized through the stack and are emitted as flue gas vapor components. These are referred to as Class III metals.

By understanding trace metal partitioning and concentration in fine particulate, it is possible to postulate the effects of  $\text{NO}_x$  combustion controls on incremental trace metal emissions. Several  $\text{NO}_x$  controls for boilers reduce peak flame temperatures (staged combustion, flue gas recirculation, reduced air preheat, load reduction, and water injection). The volatilization-condensation theory predicts that if the combustion



temperature is reduced, less Class II metals will initially volatilize, hence less will be available for subsequent condensation. Under these conditions (lowered flame temperature), it is expected that less Class II metal (the segregating trace metals) will be redistributed to small particulate. Therefore, in boilers with particulate controls, lowered volatile metal emissions should result due to improved particulate removal. Flue gas emissions of class I metals (the nonsegregating trace metals) should remain relatively unchanged.

Lowered local  $O_2$  concentrations are also expected to affect segregating metal emissions from boilers with particle controls. Lowered  $O_2$  availability decreases the possibility of volatile metal oxidation to less volatile oxides. Under these conditions Class II metals should remain in the vapor phase into the cooler sections of the boiler. More redistribution to small particles should occur and emissions should increase. Again, class I metals should be unaffected. This behavior is expected when low excess air is implemented. Other combustion  $NO_x$  controls which decrease local  $O_2$  concentrations (Staged Combustion and flue gas recirculation) also reduce peak flame temperature. For these, the effect of lowered combustion temperature is expected to predominate.

The effect of  $NO_x$  combustion controls on segregating metal emissions from combustion sources without particle collection devices should be marginal at best. Particle redistribution will not affect mass emissions because all particulate produced is emitted from these sources. However, since trace metal condensation on internal boiler surfaces undoubtedly occurs, conditions which decrease the extent of Class II metal volatilization (lowered peak flame temperature) should cause a slight decrease in segregating metal emissions. Conversely, conditions which increase metal volatility (low local  $O_2$  concentrations) should cause slight increases in volatile metal emissions (Reference 6-1).

### 6.3 ENVIRONMENTAL IMPACTS OF $NO_x$ CONTROLS FOR COAL-FIRED BOILERS

Coal-fired industrial boilers have been grouped into four equipment categories as follows:

- Field erected, pulverized coal.
- Field erected, stoker, spreader stoker
- Field erected, stoker, chain grate stoker
- Packaged, stoker, underfeed stoker

The recommended  $\text{NO}_x$  control levels for the various fuels for industrial boilers were presented in Table 3-6. These recommendations, coupled with the  $\text{NO}_x$  control techniques discussed in Section II, provided the data for Tables 3-7 and 3-8, which showed the best control method to reach a given standard. However, the incremental impact of each suggested control must be known before the control is implemented on a widespread basis.

Table 6-2 presents incremental emission data from recently completed field test programs (References 6-15 and 6-19 through 6-21). Included in this test series were stoker type industrial boilers, as presented in Table 6-3. The information from these tables is presented graphically in Figures 6-1 and 6-2.

All tests used low excess air for  $\text{NO}_x$  control except test series H, which included one overfire air test and test N which included one high excess air test. In nearly all cases, CO emissions increased slightly, as predicted. Unburned vapor phase hydrocarbon emissions fluctuated between increases and decreases.

All comparative particulate tests show a decrease in particulate emissions following a particulate control device. Reduced excess air was expected to increase particle size. This would make the particles easier to collect in particulate control devices. Since all boilers in the comparative tests were equipped with dust control devices, it appears that the predicted effect is correct. Reduced excess air was expected to increase mass emissions of particulates.

The particle size distribution of the ash emitted from a boiler will also increase with low excess and overfire air  $\text{NO}_x$  control. This is due to a slight decrease in combustion efficiency. Table 6-4 presents test data collected downstream of a dust collection device during a recent field test program (Reference 6-16). Though other tests were conducted, these data were the only comparative test data identified. A clear shift to larger particle size is noted. These data, coupled with the results from Figures 6-1 and 6-2, further suggest improved dust removal device efficiency and reduced particulate mass emissions from the stack.

Data collected during a coal-fired boiler test program (Reference 6-16) are in accordance with the trace metal partitioning theory discussed in Section 6-3. Figure 6-3 illustrates the partitioning of low-volatility iron, moderately volatile cobalt, and highly volatile copper.

TABLE 6-2. INCREMENTAL EMISSIONS FROM PULVERIZED COAL-FIRED INDUSTRIAL BOILERS  
(References 6-15 and 6-20)

| Boiler Test Series | System<br>Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Boiler Type           | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |                               |
|--------------------|----------------------------------------------------------------|-----------------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------|-------------------------------|
|                    |                                                                |                       |                                                     | ng/J                      | Incremental Change, ng/J | Pollutant                       | ng/J Incremental Change, ng/J |
| A                  | 116/145 (400)/(500)                                            | Watertube Single Wall | Baseline (8.6)                                      | 216                       | --                       | CO                              | 29                            |
|                    | 133/145 (390)/(500)                                            | Watertube Single Wall | Low Excess Air (8.1)                                | 212                       | -4                       | UHC                             | --                            |
|                    |                                                                |                       |                                                     |                           |                          | SO <sub>3</sub>                 | --                            |
|                    |                                                                |                       |                                                     |                           |                          | PART                            | 1140                          |
|                    |                                                                |                       |                                                     |                           |                          | CO                              | 47                            |
|                    |                                                                |                       |                                                     |                           |                          | UHC                             | --                            |
|                    |                                                                |                       |                                                     |                           |                          | SO <sub>3</sub>                 | --                            |
|                    |                                                                |                       |                                                     |                           |                          | PART                            | --                            |
|                    |                                                                |                       |                                                     |                           |                          |                                 | +18                           |
| B                  | 38/75 (129)/(260)                                              | Watertube Single Wall | Baseline (7.4)                                      | 563                       | --                       | CO                              | 0                             |
|                    | 38/75 (130)/(260)                                              | Watertube Single Wall | Low Excess Air (6.6)                                | 529                       | -34                      | UHC                             | --                            |
|                    |                                                                |                       |                                                     |                           |                          | SO <sub>3</sub>                 | --                            |
|                    |                                                                |                       |                                                     |                           |                          | PART                            | 2288                          |
|                    |                                                                |                       |                                                     |                           |                          | CO                              | 0                             |
|                    |                                                                |                       |                                                     |                           |                          | UHC                             | --                            |
|                    |                                                                |                       |                                                     |                           |                          | SO <sub>3</sub>                 | --                            |
|                    |                                                                |                       |                                                     |                           |                          | PART                            | --                            |
|                    |                                                                |                       |                                                     |                           |                          |                                 | 0                             |
| C                  | 53/65 (180)/(220)                                              | Watertube Tangential  | Baseline (5.3)                                      | 234                       | --                       | CO                              | 0                             |
|                    | 53/65 (180)/(220)                                              | Watertube Tangential  | Low Excess Air (4.5)                                | 222                       | -12                      | UHC                             | 4                             |
|                    |                                                                |                       |                                                     |                           |                          | SO <sub>3</sub>                 | 5                             |
|                    |                                                                |                       |                                                     |                           |                          | PART                            | 511                           |
|                    |                                                                |                       |                                                     |                           |                          | CO                              | --                            |
|                    |                                                                |                       |                                                     |                           |                          | UHC                             | 1                             |
|                    |                                                                |                       |                                                     |                           |                          | SO <sub>3</sub>                 | --                            |
|                    |                                                                |                       |                                                     |                           |                          | PART                            | --                            |
|                    |                                                                |                       |                                                     |                           |                          |                                 | --                            |
|                    |                                                                |                       |                                                     |                           |                          |                                 | -3                            |
|                    |                                                                |                       |                                                     |                           |                          |                                 | --                            |
|                    |                                                                |                       |                                                     |                           |                          |                                 | --                            |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-2. Concluded

| Boiler Test Series | System                                               |                       | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |                               |
|--------------------|------------------------------------------------------|-----------------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------|-------------------------------|
|                    | Actual/Design Heat Input MM (10 <sup>6</sup> Btu/hr) | Boiler Type           |                                                     | ng/J                      | Incremental Change, ng/J | Pollutant                       | ng/J Incremental Change, ng/J |
| D                  | 76/93 (260)/(320)                                    | Watertube Tangential  | Baseline (5.8)                                      | 296                       | --                       | CO                              | 0                             |
|                    |                                                      |                       |                                                     |                           |                          | UHC                             | 2                             |
|                    |                                                      |                       |                                                     |                           |                          | SO <sub>3</sub>                 | 9                             |
|                    |                                                      |                       |                                                     |                           |                          | PART                            | 834                           |
|                    | 76/93 (261)/(320)                                    | Watertube Tangential  | Low Excess Air (4.8)                                | 303                       | +7                       | CO                              | 0                             |
|                    |                                                      |                       |                                                     |                           |                          | UHC                             | 1                             |
|                    |                                                      |                       |                                                     |                           |                          | SO <sub>3</sub>                 | --                            |
|                    |                                                      |                       |                                                     |                           |                          | PART                            | --                            |
| E                  | 38/67.2 (130)/(230)                                  | Watertube Single Wall | Baseline (4.5)                                      | 201                       | --                       | CO                              | 11                            |
|                    |                                                      |                       |                                                     |                           |                          | UHC                             | 90                            |
|                    |                                                      |                       |                                                     |                           |                          | SO <sub>3</sub>                 | 4.7                           |
|                    |                                                      |                       |                                                     |                           |                          | PART                            | --                            |
|                    | 38/67.2 (130)/(230)                                  | Watertube Single Wall | Low Excess Air (3.4)                                | 152                       | -49                      | CO                              | 12                            |
|                    |                                                      |                       |                                                     |                           |                          | UHC                             | 5.4                           |
|                    |                                                      |                       |                                                     |                           |                          | SO <sub>3</sub>                 | 2.2                           |
|                    |                                                      |                       |                                                     |                           |                          | PART                            | 2895                          |
| F                  | 32.8/46.7 (112)/(160)                                | Watertube Single Wall | Baseline (5.1)                                      | 174                       | --                       | CO                              | 23.2                          |
|                    |                                                      |                       |                                                     |                           |                          | UHC                             | 10                            |
|                    |                                                      |                       |                                                     |                           |                          | SO <sub>3</sub>                 | 21.7                          |
|                    |                                                      |                       |                                                     |                           |                          | PART                            | 1194                          |
|                    | 33.1/46.7 (113)/(160)                                | Watertube Single Wall | Low Excess Air (3.4)                                | 136                       | -38                      | CO                              | 4.2                           |
|                    |                                                      |                       |                                                     |                           |                          | UHC                             | 14                            |
|                    |                                                      |                       |                                                     |                           |                          | SO <sub>3</sub>                 | 0                             |
|                    |                                                      |                       |                                                     |                           |                          | PART                            | 995                           |

<sup>a</sup>No data available on noncriteria emissions

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TABLE 6-3. INCREMENTAL EMISSIONS FROM STOKER COAL-FIRED INDUSTRIAL BOILERS  
(References 6-15 and 6-20)

| Boiler Test Series | System                                   |                           | NO <sub>x</sub> Emissions                           |      | Criteria Emissions <sup>a</sup> |                 |
|--------------------|------------------------------------------|---------------------------|-----------------------------------------------------|------|---------------------------------|-----------------|
|                    | Actual/Design Heat Input MW (106 Btu/hr) | Boiler Type               | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J | Incremental Change, ng/J        | Pollutant       |
| G                  | 30/62 (103)/(210)                        | Watertube Chain Grate     | Baseline (9.5)                                      | 100  | --                              | CO              |
|                    |                                          |                           |                                                     |      |                                 | UHC             |
|                    |                                          |                           |                                                     |      |                                 | SO <sub>3</sub> |
|                    |                                          |                           |                                                     |      |                                 | PART            |
|                    | 30/62 (100)/(210)                        | Watertube Chain Grate     | Low Excess Air (9.0)                                | 75   | -25                             | CO              |
|                    |                                          |                           |                                                     |      |                                 | UHC             |
|                    |                                          |                           |                                                     |      |                                 | SO <sub>3</sub> |
|                    |                                          |                           |                                                     |      |                                 | PART            |
|                    | 30/62 (105)/(20)                         | Watertube Chain Grate     | Low Excess Air (8.7)                                | 77   | -23                             | CO              |
|                    |                                          |                           |                                                     |      |                                 | UHC             |
|                    |                                          |                           |                                                     |      |                                 | SO <sub>3</sub> |
|                    |                                          |                           |                                                     |      |                                 | PART            |
| H                  | 24/36 (81)/(125)                         | Watertube Spreader Stoker | Baseline (6.2)                                      | 196  | --                              | CO              |
|                    |                                          |                           |                                                     |      |                                 | UHC             |
|                    |                                          |                           |                                                     |      |                                 | SO <sub>3</sub> |
|                    |                                          |                           |                                                     |      |                                 | PART            |
|                    | 24/36 (81)/(125)                         | Watertube Spreader Stoker | Overfire Air (6.1)                                  | 145  | -51                             | CO              |
|                    |                                          |                           |                                                     |      |                                 | UHC             |
|                    |                                          |                           |                                                     |      |                                 | SO <sub>3</sub> |
|                    |                                          |                           |                                                     |      |                                 | PART            |
|                    | 24/36 (82)/(120)                         | Watertube Spreader Stoker | Low Excess Air (4.7)                                | 142  | -54                             | CO              |
|                    |                                          |                           |                                                     |      |                                 | UHC             |
|                    |                                          |                           |                                                     |      |                                 | SO <sub>3</sub> |
|                    |                                          |                           |                                                     |      |                                 | PART            |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-3. Continued

| Boiler Test Series | System                                               |                            | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |                               |
|--------------------|------------------------------------------------------|----------------------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------|-------------------------------|
|                    | Actual/Design Heat Input MM (10 <sup>6</sup> Btu/hr) | Boiler Type                |                                                     | ng/J                      | Incremental Change, ng/J | Pollutant                       | ng/J Incremental Change, ng/J |
| I                  | 14/17 (48)/(60)                                      | Watertube Underfeed Stoker | Baseline (6.6)                                      | 163                       | --                       | CO                              | 0                             |
|                    |                                                      |                            |                                                     |                           |                          | UHC                             | --                            |
|                    |                                                      |                            |                                                     |                           |                          | SO <sub>2</sub>                 | 23                            |
|                    |                                                      |                            |                                                     |                           |                          | PART                            | --                            |
|                    | 13/17 (44)/(60)                                      | Watertube Underfeed Stoker | Low Excess Air (4.9)                                | 115                       | -48                      | CO                              | 0                             |
|                    |                                                      |                            |                                                     |                           |                          | UHC                             | --                            |
|                    |                                                      |                            |                                                     |                           |                          | SO <sub>2</sub>                 | --                            |
|                    |                                                      |                            |                                                     |                           |                          | PART                            | --                            |
|                    | 13/17 (45)/(60)                                      | Watertube Underfeed Stoker | Baseline (9.8)                                      | 137                       | --                       | CO                              | 0                             |
|                    |                                                      |                            |                                                     |                           |                          | UHC                             | --                            |
|                    |                                                      |                            |                                                     |                           |                          | SO <sub>2</sub>                 | --                            |
|                    |                                                      |                            |                                                     |                           |                          | PART                            | 1647                          |
|                    | 13/17 (45)/(60)                                      | Watertube Underfeed Stoker | Low Excess Air (7.0)                                | 123                       | -14                      | CO                              | 119                           |
|                    |                                                      |                            |                                                     |                           |                          | UHC                             | --                            |
|                    |                                                      |                            |                                                     |                           |                          | SO <sub>2</sub>                 | --                            |
|                    |                                                      |                            |                                                     |                           |                          | PART                            | +119                          |
| J                  | 32/39 (109)/(135)                                    | Watertube Spreader Stoker  | Baseline (7.0)                                      | 226                       | --                       | CO                              | 10                            |
|                    |                                                      |                            |                                                     |                           |                          | UHC                             | 5                             |
|                    |                                                      |                            |                                                     |                           |                          | SO <sub>2</sub>                 | 15                            |
|                    |                                                      |                            |                                                     |                           |                          | PART                            | 1587                          |
|                    | 33/39 (112)/(135)                                    | Watertube Spreader Stoker  | Low Excess Air (4.9)                                | 205                       | -21                      | CO                              | 47                            |
|                    |                                                      |                            |                                                     |                           |                          | UHC                             | 2                             |
|                    |                                                      |                            |                                                     |                           |                          | SO <sub>2</sub>                 | --                            |
|                    |                                                      |                            |                                                     |                           |                          | PART                            | +37                           |
| K                  | 12/15 (40)/(50)                                      | Watertube Spreader Stoker  | Baseline (8.0)                                      | 284                       | --                       | CO                              | 9                             |
|                    |                                                      |                            |                                                     |                           |                          | UHC                             | 2                             |
|                    |                                                      |                            |                                                     |                           |                          | SO <sub>2</sub>                 | 15                            |
|                    |                                                      |                            |                                                     |                           |                          | PART                            | --                            |
|                    | 12/15 (40)/(50)                                      | Watertube Spreader Stoker  | Low Excess Air (5.8)                                | 202                       | -82                      | CO                              | 7                             |
|                    |                                                      |                            |                                                     |                           |                          | UHC                             | 4                             |
|                    |                                                      |                            |                                                     |                           |                          | SO <sub>2</sub>                 | --                            |
|                    |                                                      |                            |                                                     |                           |                          | PART                            | -219                          |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-3. Continued

| Boiler Test Series | System<br>Actual/Design Heat Input<br>MW (106 Btu/hr) | NO <sub>x</sub> Control<br>(Excess O <sub>2</sub> , %) | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |                          |
|--------------------|-------------------------------------------------------|--------------------------------------------------------|---------------------------|--------------------------|---------------------------------|--------------------------|
|                    |                                                       |                                                        | ng/J                      | Incremental Change, ng/J | Pollutant                       | Incremental Change, ng/J |
| L                  | 18/22<br>(60)/(75)<br>Watertube Spreader Stoker       | Baseline<br>(7.8)<br><br>Low Excess Air<br>(5.9)       | 284                       | --                       | CO                              | 34                       |
|                    |                                                       |                                                        |                           |                          | UHC                             | 2                        |
|                    |                                                       |                                                        |                           |                          | SO <sub>3</sub>                 | 28                       |
|                    |                                                       |                                                        |                           |                          | PART                            | 140                      |
|                    | 18/22<br>(62)/(75)<br>Watertube Spreader Stoker       | Low Excess Air<br>(5.9)                                | 237                       | -47                      | CO                              | 22                       |
|                    |                                                       |                                                        |                           |                          | UHC                             | 4                        |
|                    |                                                       |                                                        |                           |                          | SO <sub>3</sub>                 | --                       |
|                    |                                                       |                                                        |                           |                          | PART                            | 123                      |
| M                  | 35/44<br>(119)/(150)<br>Watertube Spreader Stoker     | Baseline<br>(10.2)<br><br>Low Excess Air<br>(8.9)      | 338                       | --                       | CO                              | 0                        |
|                    |                                                       |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                       |                                                        |                           |                          | SO <sub>3</sub>                 | 36                       |
|                    |                                                       |                                                        |                           |                          | PART                            | 1649                     |
|                    | 36/44<br>(120)/(150)<br>Watertube Spreader            | Low Excess Air<br>(8.9)                                | 228                       | -50                      | CO                              | 0                        |
|                    |                                                       |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                       |                                                        |                           |                          | SO <sub>3</sub>                 | --                       |
|                    |                                                       |                                                        |                           |                          | PART                            | --                       |
| N                  | 47/67<br>(160)/(120)<br>Watertube Spreader Stoker     | Baseline<br>(10.8)<br><br>Low Excess Air<br>(8.9)      | 334                       | --                       | CO                              | 0                        |
|                    |                                                       |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                       |                                                        |                           |                          | SO <sub>3</sub>                 | 4                        |
|                    |                                                       |                                                        |                           |                          | PART                            | 361                      |
|                    | 44/67<br>(150)/(230)<br>Watertube Spreader Stoker     | Low Excess Air<br>(8.9)                                | 220                       | -114                     | CO                              | 0                        |
|                    |                                                       |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                       |                                                        |                           |                          | SO <sub>3</sub>                 | --                       |
|                    |                                                       |                                                        |                           |                          | PART                            | --                       |
|                    | 42/67<br>(143)/(230)<br>Watertube Spreader Stoker     | High Excess Air (HEA)<br>(12.6)                        | 241                       | -93                      | CO                              | 0                        |
|                    |                                                       |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                       |                                                        |                           |                          | SO <sub>3</sub>                 | 13                       |
|                    |                                                       |                                                        |                           |                          | PART                            | 317                      |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-3. Continued

| Boiler Test Series | System<br>Actual/Design Heat Input<br>MW (10 <sup>6</sup> Btu/hr) | NO <sub>x</sub> Control<br>(Excess O <sub>2</sub> , %) | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |                          |
|--------------------|-------------------------------------------------------------------|--------------------------------------------------------|---------------------------|--------------------------|---------------------------------|--------------------------|
|                    |                                                                   |                                                        | ng/J                      | Incremental Change, ng/J | Pollutant                       | Incremental Change, ng/J |
| P                  | 17.6/29.3<br>(60)/(100)                                           | Baseline<br>Montana Coal<br>(10.9)                     | 312                       | --                       | CO                              | 205                      |
|                    |                                                                   |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                                   |                                                        |                           |                          | SO <sub>3</sub>                 | 10                       |
|                    |                                                                   |                                                        |                           |                          | PART                            | 447                      |
|                    | 17.6/29.3<br>(60)/(100)                                           | Low Excess Air<br>Montana Coal<br>(6.5)                | 206                       | -106                     | CO                              | 17                       |
|                    |                                                                   |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                                   |                                                        |                           |                          | SO <sub>3</sub>                 | --                       |
|                    |                                                                   |                                                        |                           |                          | PART                            | 388                      |
|                    | 17.6/29.3<br>(60)/(100)                                           | Baseline<br>Illinois Coal<br>(10.0)                    | 289                       | --                       | CO                              | 18                       |
|                    |                                                                   |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                                   |                                                        |                           |                          | SO <sub>3</sub>                 | 9                        |
|                    |                                                                   |                                                        |                           |                          | PART                            | 674                      |
|                    | 17.6/29.3<br>(60)/(100)                                           | Low Excess Air<br>Illinois Coal<br>(7.8)               | 258                       | -31                      | CO                              | 0                        |
|                    |                                                                   |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                                   |                                                        |                           |                          | SO <sub>3</sub>                 | --                       |
|                    |                                                                   |                                                        |                           |                          | PART                            | 455                      |
| Q                  | 43.2/46.9<br>(83)/(160)                                           | Baseline<br>Montana Coal<br>(8.6)                      | 326                       | --                       | CO                              | 53                       |
|                    |                                                                   |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                                   |                                                        |                           |                          | SO <sub>3</sub>                 | 14                       |
|                    |                                                                   |                                                        |                           |                          | PART                            | --                       |
|                    | 23.1/46.9<br>(79)/(160)                                           | Low Excess Air<br>Montana Coal<br>(7.7)                | 183                       | -53                      | CO                              | 48                       |
|                    |                                                                   |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                                   |                                                        |                           |                          | SO <sub>3</sub>                 | --                       |
|                    |                                                                   |                                                        |                           |                          | PART                            | 5803                     |
|                    | 31.5/46.9<br>(107)/(160)                                          | Baseline<br>Illinois Coal<br>(8.6)                     | 287                       | --                       | CO                              | 17                       |
|                    |                                                                   |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                                   |                                                        |                           |                          | SO <sub>3</sub>                 | --                       |
|                    |                                                                   |                                                        |                           |                          | PART                            | --                       |
|                    | 32.2/46.9<br>(110)/(160)                                          | Low Excess Air<br>Illinois Coal<br>(6.6)               | 241                       | -46                      | CO                              | 33                       |
|                    |                                                                   |                                                        |                           |                          | UHC                             | --                       |
|                    |                                                                   |                                                        |                           |                          | SO <sub>3</sub>                 | --                       |
|                    |                                                                   |                                                        |                           |                          | PART                            | 234                      |

aCyclone outlet only

Continued

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TABLE 6-3. Concluded

| Boiler Test Series | Actual/Design Heat Input MM (10 <sup>6</sup> Btu/hr) | System Boiler Type               | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |                          |
|--------------------|------------------------------------------------------|----------------------------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------|--------------------------|
|                    |                                                      |                                  |                                                     | ng/J                      | Incremental Change, ng/J | Pollutant                       | Incremental Change, ng/J |
| R                  | 13.4/23.4 (45.7/(80))                                | Watertube Spreader Stoker        | Baseline 2/3 Illinois, 1/3 Montana Coal (9.4)       | 207                       | --                       | CO                              | 61                       |
|                    |                                                      |                                  |                                                     |                           |                          | UHC                             | --                       |
|                    |                                                      |                                  |                                                     |                           |                          | SO <sub>3</sub>                 | 133                      |
|                    |                                                      |                                  |                                                     |                           |                          | PART                            | 1209                     |
|                    | 13.4/23.4 (45.9/(80))                                | Watertube Spreader Stoker        | Low Excess 2/3 Illinois, 1/3 Montana Coal (8.0)     | 239                       | +32                      | CO                              | 33                       |
|                    |                                                      |                                  |                                                     |                           |                          | UHC                             | --                       |
|                    |                                                      |                                  |                                                     |                           |                          | SO <sub>3</sub>                 | 44                       |
|                    |                                                      |                                  |                                                     |                           |                          | PART                            | 987                      |
| S                  | 5.0/13.2 (17.0/(45))                                 | Watertube Vibrating Grate Stoker | Baseline Western Coal (9.8)                         | 199                       | --                       | CO                              | 18                       |
|                    |                                                      |                                  |                                                     |                           |                          | UHC                             | --                       |
|                    |                                                      |                                  |                                                     |                           |                          | SO <sub>3</sub>                 | --                       |
|                    |                                                      |                                  |                                                     |                           |                          | PART                            | --                       |
|                    | 5.0/13.2 (17.0/(45))                                 | Watertube Vibrating Grate Stoker | Low Excess Western Coal (7.3)                       | 152                       | -47                      | CO                              | 8                        |
|                    |                                                      |                                  |                                                     |                           |                          | UHC                             | --                       |
|                    |                                                      |                                  |                                                     |                           |                          | SO <sub>3</sub>                 | --                       |
|                    |                                                      |                                  |                                                     |                           |                          | PART                            | --                       |

<sup>a</sup>No data available on noncriteria emissions

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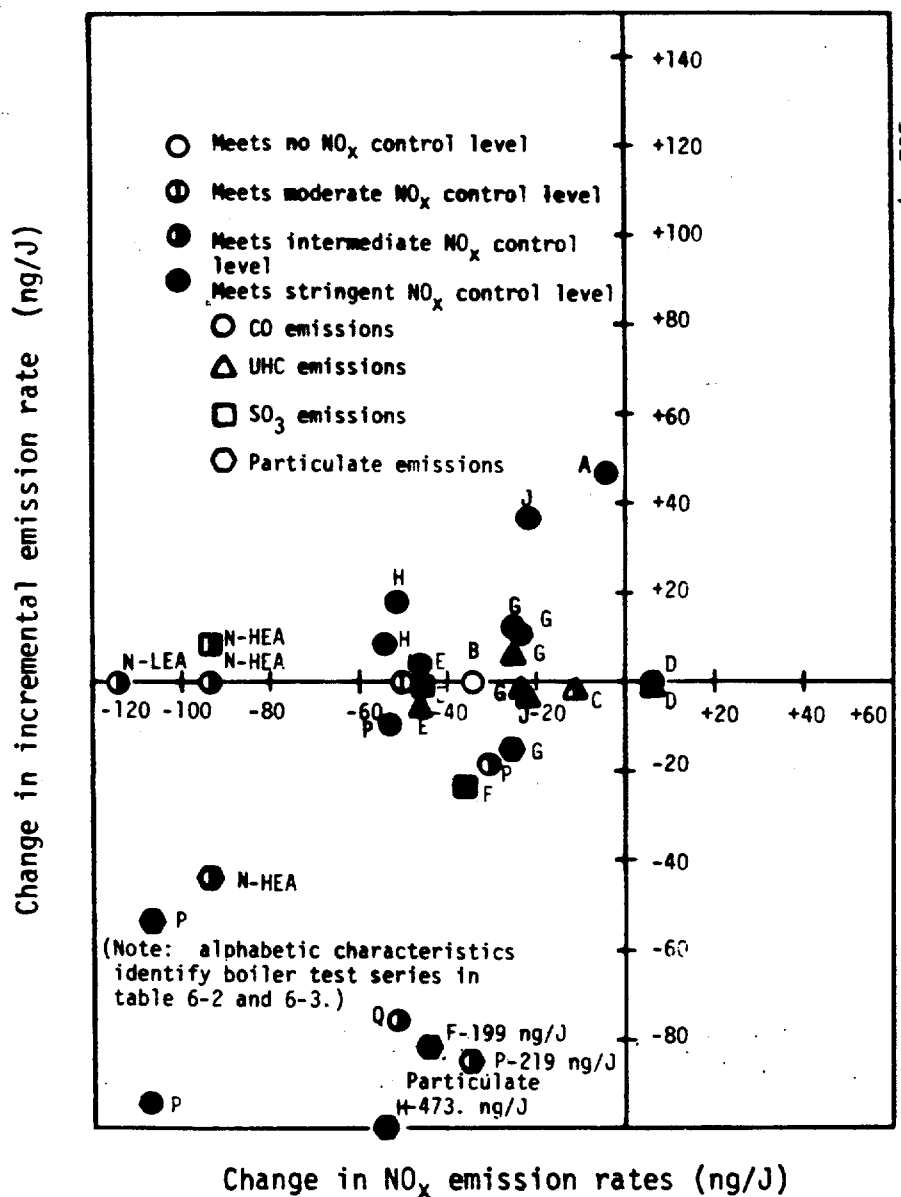


Figure 6-1. Change in incremental emissions from coal-fired industrial boilers >29 MW ( $100 \times 10^6$  Btu/hr).

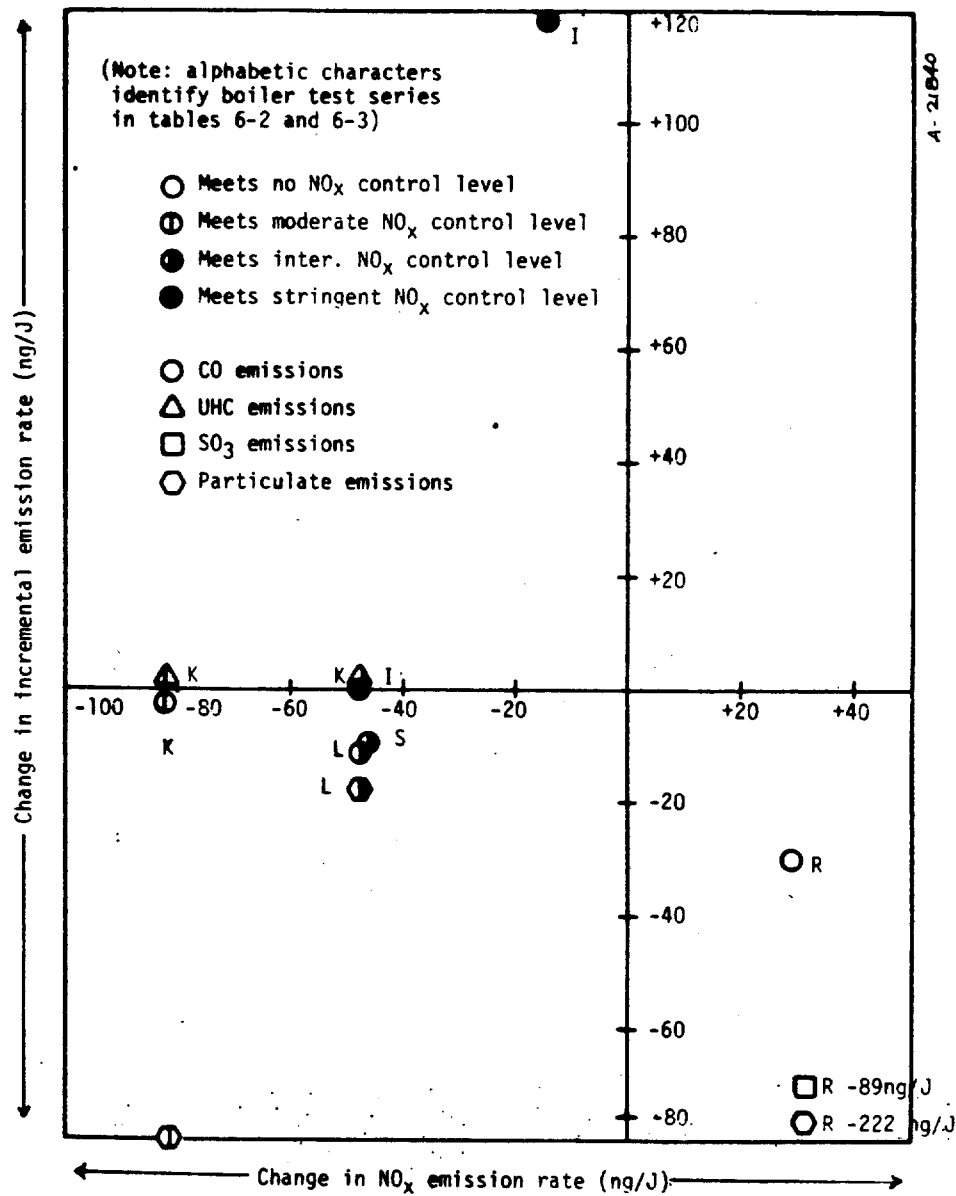


Figure 6-2. Change in incremental emissions from coal-fired industrial boilers <29 MW (100 x 10<sup>6</sup> Btu/hr).

TABLE 6-4. EFFECT OF OVERFIRE AIR NO<sub>x</sub> CONTROL ON PARTICLE SIZE DISTRIBUTION<sup>a</sup>  
FOR A COAL-FIRED CHAIN GRATE STOKER (Reference 6-16)

| Fuel Burner Type | Test Load GJ hr <sup>-1</sup> | NO <sub>x</sub> ng/J | Impact Flow cm <sup>3</sup> s <sup>-1</sup> | D <sub>50</sub> Cycl. μm | Actual D <sub>50</sub> of Stage No. b |      |      |      |      | Cyclone mg | Cyclone, Stage and Filter Catch |       |       |       |       | Total Catch mg | Comments                    |
|------------------|-------------------------------|----------------------|---------------------------------------------|--------------------------|---------------------------------------|------|------|------|------|------------|---------------------------------|-------|-------|-------|-------|----------------|-----------------------------|
|                  |                               |                      |                                             |                          | Actual D <sub>50</sub> of Stage No. b |      |      |      |      |            | Stage No.                       |       |       |       |       |                |                             |
|                  |                               |                      |                                             |                          | 1 μm                                  | 2 μm | 3 μm | 4 μm | 5 μm |            | 1 mg                            | 2 mg  | 3 mg  | 4 mg  | 5 mg  |                |                             |
| Coal Grate       | 112                           | 85.5                 | 24.6                                        | 15.6                     | 3.5                                   | 2.1  | 1.4  | 0.70 | 0.35 | 10.39      | 1.056                           | 0.780 | 0.660 | 0.340 | 0.600 | 0.572          | Baseline no soot            |
| Coal Grate       | 103                           | --                   | 23.6                                        | 15.1                     | 3.5                                   | 2.1  | 1.4  | 0.71 | 0.35 | 10.82      | 0.200                           | 0.276 | 0.472 | 2.10  | 3.26  | 1.29           | Low NO <sub>x</sub> no soot |

<sup>a</sup>particle size distribution determined by use of a Brink model "B" cascade impactor  
<sup>b</sup>D<sub>50</sub> identifies the size fraction in microns. Particulates with an aerodynamic diameter greater than the D<sub>50</sub> cut point will be captured. Increasing stage number corresponds to decreasing particle size.

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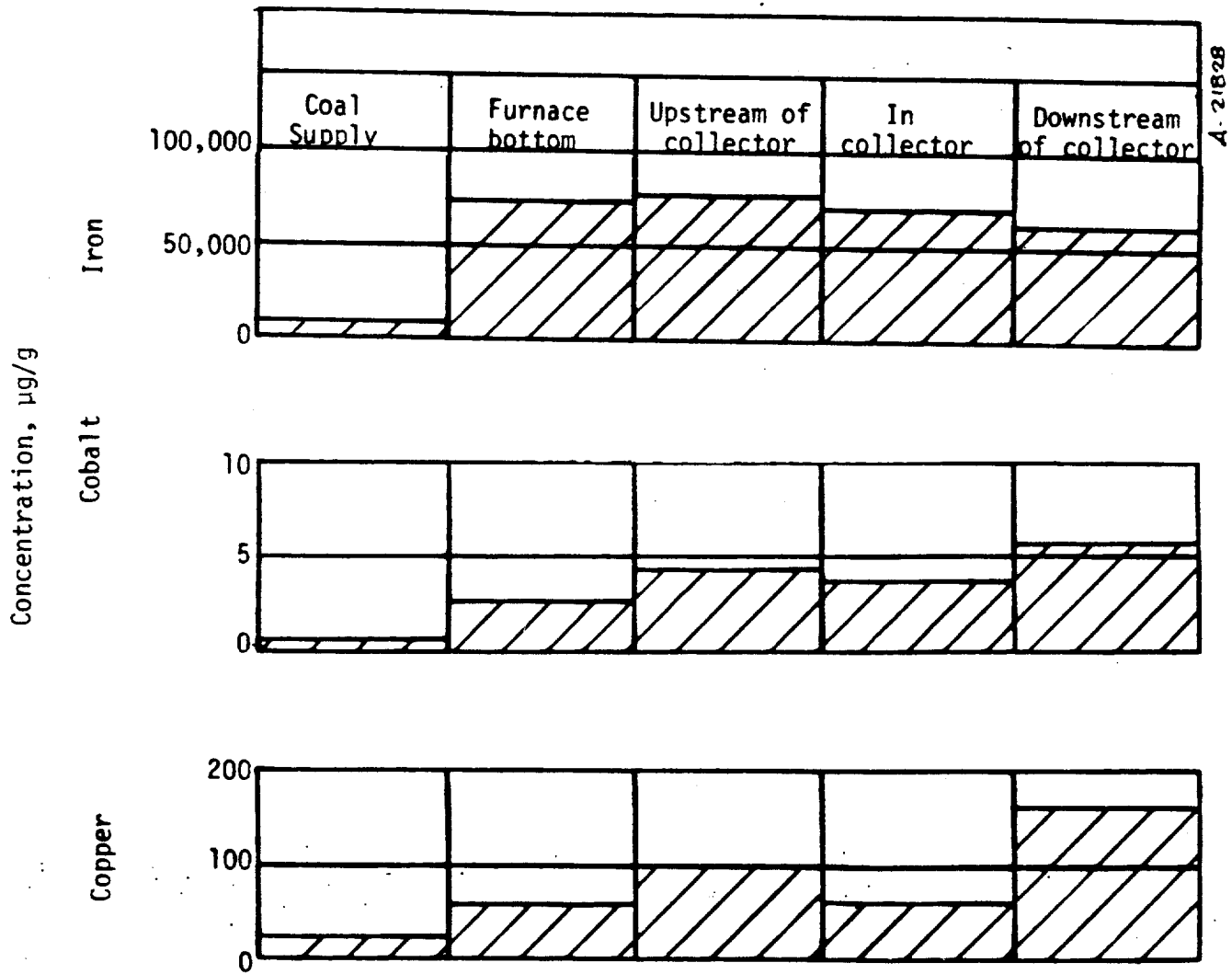


Figure 6-3. Partitioning of elements based on effluent location for a coal-fired industrial boiler (Reference 6-16).

Test data collected during the same test program (Reference 6-16) support the trace metal segregation theory as discussed in Section 6.3. As shown in Figure 6-4, the concentration of the volatile element antimony increased as the particle size decreased. The concentration of less volatile manganese remains relatively evenly distributed between particulate fractions.

The data presented above, indicate that  $\text{NO}_x$  control techniques which alter the overall boiler temperature profile, or change the particulate mass emissions or particle size distribution can affect the concentration of trace metals emitted from the collector.

Tests for polycyclic organic matter (POM) have been conducted (Reference 6-16). The data from a stoker coal-fired boiler (chain grate) is presented in Table 6-5. The data are incomplete due to the lack of sufficient gas stream samples for analyses. Though organic species are present, their general trend as a function of  $\text{NO}_x$  control is not known.

EPA-sponsored tests of two industrial spreader stokers indicate only a possible slight increase in organic emissions under low- $\text{NO}_x$  firing conditions (LEA, OFA) as compared to those under baseline conditions (References 6-22 and 6-23).

The above emission data was presented for combustion modifications only. Low  $\text{NO}_x$  burners and ammonia injection, considered to be advanced control methods, are still in the development stages. Actual incremental emission data are not available.

#### 6.4 ENVIRONMENTAL IMPACTS OF $\text{NO}_x$ CONTROLS FOR RESIDUAL OIL-FIRED BOILERS

Oil-fired industrial boilers fall into two major equipment categories. These are packaged watertube and firetube boilers. The recommended  $\text{NO}_x$  control levels for industrial boilers firing residual oil fuel are presented in Table 3-6. The recommended  $\text{NO}_x$  control techniques from Section III are low excess air, staged combustion, low  $\text{NO}_x$  burners and ammonia injection.

Table 6-6 presents incremental emission data collected during two recent test programs (References 6-15 and 6-17). This information is presented graphically in Figures 6-5 through 6-8.

Figure 6-5 presents all changes in low excess air incremental emission data as a function of changes in  $\text{NO}_x$  emission levels. All low  $\text{NO}_x$  control conditions that meet any of the recommended control levels results in an increase in CO emissions. Generally, the more the  $\text{NO}_x$  emissions are reduced, the higher the CO emission rate. As with coal fired boilers, hydrocarbon levels remain relatively unchanged.

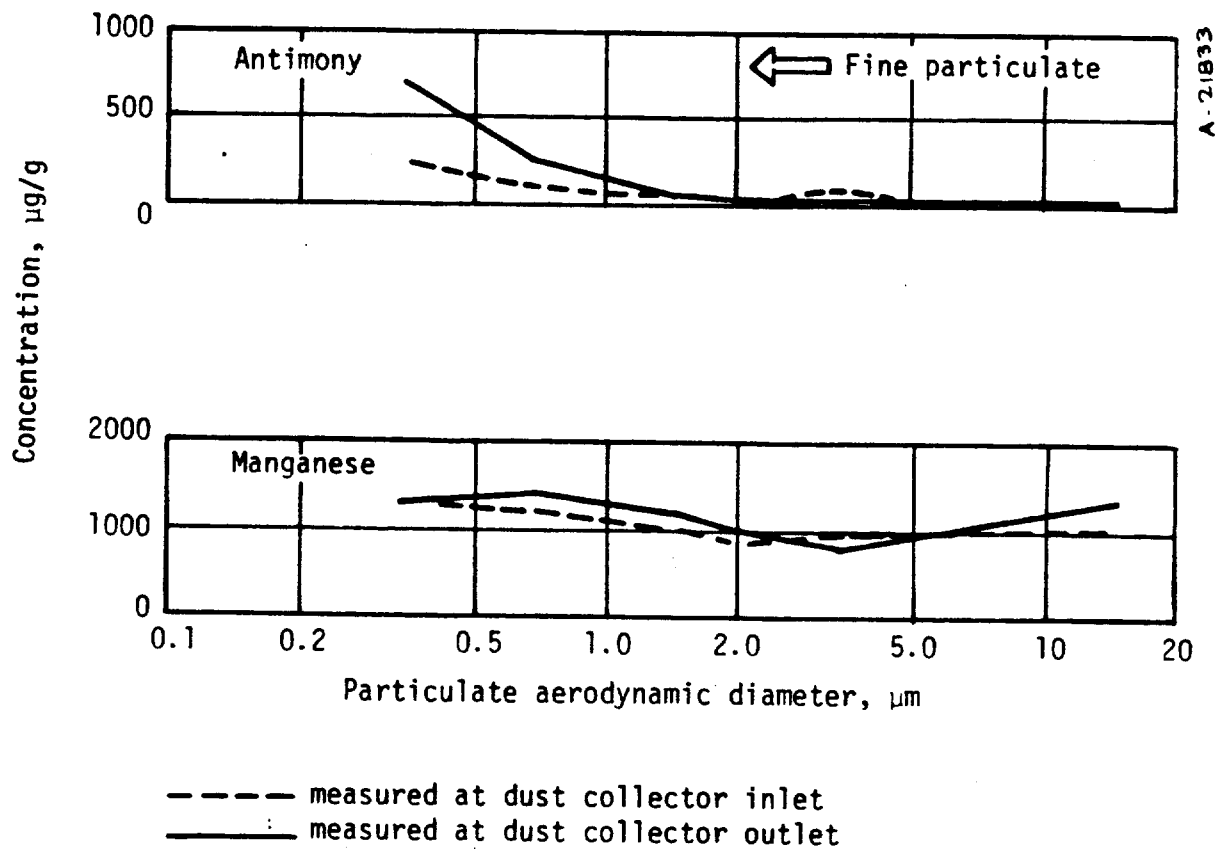


Figure 6-4. Trace element concentration in fine particulate (Reference 6-16).

TABLE 6-5. EMISSION RATES OF POLYCYCLIC ORGANIC MATTER (POM) FROM A COAL-FIRED CHAIN-GRATE STOKER BOILER (Reference 6-16)

| Run No. | POM                            | In Coal       |     | In Hopper Ash |      | In Stack Gases      |               |
|---------|--------------------------------|---------------|-----|---------------|------|---------------------|---------------|
|         |                                | g             | %   | g             | %    | Particulate g       | Vapor %       |
| 9       | 7,12 Dimethylbenz(a)anthracene | None detected |     | None detected |      | Insufficient sample | None detected |
| 10      |                                | None detected |     | 2.26          | --   | Insufficient sample | Trace         |
| 11      |                                | None detected |     | 1.39          | --   | Insufficient sample | None detected |
| 9       | Benzo(a)pyrene                 | 109           | 100 | 37            | 34   | Insufficient sample | None detected |
| 10      |                                | 245           | 100 | 92.6          | 38   | Insufficient sample | None detected |
| 11      |                                | 18.8          | 100 | 651           | 3462 | Insufficient sample | None detected |
| 9       | 3 Methylcholanthrene           | None detected |     | None detected |      | Insufficient sample | None detected |
| 10      |                                | None detected |     | None detected |      | Insufficient sample | None detected |
| 11      |                                | None detected |     | None detected |      | Insufficient sample | None detected |
| 9       | Dibenz(a,h)anthracene          | 610           | 100 | None detected |      | Insufficient sample | None detected |
| 10      |                                | 822           | 100 | None detected |      | Insufficient sample | None detected |
| 11      |                                | 673           | 100 | None detected |      | Insufficient sample | None detected |



TABLE 6-6. INCREMENTAL EMISSIONS FROM RESIDUAL OIL-FIRED BOILERS  
(REFERENCE 6-15)

| Boiler Test Series | System                                               |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup>       |      |                          |
|--------------------|------------------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------------|------|--------------------------|
|                    | Actual/Design Heat Input MM (10 <sup>6</sup> Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                             | ng/J | Incremental Change, ng/J |
| A                  | 35/44<br>(120)/(150)                                 | Watertube   | Baseline<br>(5.0)                                   | 165                       | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 0    | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | 7    | --                       |
|                    | 35/44<br>(120)/(150)                                 | Watertube   | Low Excess Air<br>(3.1)                             | 138                       | -27                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | 0    | 0                        |
| B                  | 8.4/20<br>(27)/(68)                                  | Watertube   | Baseline<br>(5.3)                                   | 115                       | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 0    | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    | 8.1/20<br>(27)/(68)                                  | Watertube   | Low Excess Air<br>(4.9)                             | 101                       | -14                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 140  | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | 10   | +10                      |
| C                  | 18/23<br>(61)/(79)                                   | Watertube   | Baseline<br>(3.3)                                   | 148                       | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | 0    | --                       |
|                    | 19/23<br>(64)/(79)                                   | Watertube   | Low Excess Air<br>(2.7)                             | 143                       | -5                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 2    | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | 780  | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | 70   | +70                      |
|                    |                                                      |             |                                                     |                           |                          |                                       | 2    | 0                        |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-6. Continued

| Boiler Test Series | System                                               |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |      |                          |
|--------------------|------------------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------|------|--------------------------|
|                    | Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                       | ng/J | Incremental Change, ng/J |
| D                  | 9.3/12 (32)/(40)                                     | Watertube   | Baseline (4.3)                                      | 109                       | --                       | CO                              | 0    | --                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 3    | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | 12   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | 62   | --                       |
| E                  | 9.3/12 (32)/(40)                                     | Watertube   | Low Excess Air (4.0)                                | 98                        | -11                      | CO                              | 9    | +9                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | -3                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | 41   | -21                      |
|                    | 10/13 (36)/(45)                                      | Watertube   | Baseline (3.0)                                      | 183                       | --                       | CO                              | 0    | --                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | 2    | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | 46   | --                       |
|                    | 11/13 (37)/(45)                                      | Watertube   | Low Excess Air (1.6)                                | 136                       | -47                      | CO                              | 41   | +41                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 5    | +5                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | --   | --                       |
|                    | 10/13 (36)/(45)                                      | Watertube   | Overfire Air (2.9)                                  | 97                        | -86                      | CO                              | 19   | +19                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 4    | 4                        |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | 59   | +13                      |
|                    | 10/13 (36)/(45)                                      | Watertube   | Overfire Air (3.0)                                  | 90                        | -93                      | CO                              | 31   | +31                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | 0                        |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | --   | --                       |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-6. Continued

| Boiler Test Series | System                                               |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup>       |                      |                          |
|--------------------|------------------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------------|----------------------|--------------------------|
|                    | Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                             | ng/J                 | Incremental Change, ng/J |
| F                  | 4.1/5.1 (14)/(17)                                    | Watertube   | Baseline (3.1)                                      | 95                        | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 0<br>0<br>--<br>13   | --<br>--<br>--<br>--     |
|                    | 4.1/5.1 (14)/(17)                                    | Watertube   | Low Excess Air (0.9)                                | 70                        | -25                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 34<br>--<br>--<br>-- | +34<br>--<br>--<br>--    |
|                    | 4.1/5.1 (14)/(17)                                    | Watertube   | Overfire Air (2.4)                                  | 61                        | -34                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 53<br>1<br>--<br>--  | +53<br>+1<br>--<br>--    |
|                    | 3.9/5.1 (14)/(17)                                    | Watertube   | Overfire Air (3.25)                                 | 102                       | +7                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 0<br>0<br>--<br>--   | 0<br>0<br>--<br>--       |
|                    | 4.1/5.1 (14)/(17)                                    | Watertube   | Overfire Air (3.1)                                  | 75                        | -20                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 0<br>3<br>--<br>12   | 0<br>3<br>--<br>-2       |
|                    | 4.1/5.1 (14)/(17)                                    | Watertube   | Baseline (2.9)                                      | 91                        | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 0<br>0<br>2<br>13    | --<br>--<br>--<br>--     |
|                    | 4.1/5.1 (14)/(17)                                    | Watertube   | Low Excess Air (2.25)                               | 77                        | -14                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 48<br>0<br>--<br>--  | +48<br>0<br>--<br>--     |
|                    |                                                      |             |                                                     |                           |                          |                                       |                      |                          |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-6. Continued

| Boiler Test Series | System                                               |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |      |                          |
|--------------------|------------------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------|------|--------------------------|
|                    | Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                       | ng/J | Incremental Change, ng/J |
| F (Cont.)          | 4.1/5.1 (14)/(17)                                    | Watertube   | Overfire Air (3.0)                                  | 84                        | -7                       | CO                              | 27   | +27                      |
|                    | 4.1/5.1 (14)/(17)                                    | Watertube   | Overfire Air (2.9)                                  | 73                        | -18                      | UHC                             | 13   | +13                      |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | CO                              | 10   | +10                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | 0                        |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | --   | --                       |
| G                  | 4.0/5.1 (14)/(17)                                    | Watertube   | Baseline (3.0)                                      | 122                       | --                       | CO                              | 1    | --                       |
|                    | 4.1/5.1 (14)/(17)                                    | Watertube   | Low Excess Air (1.0)                                | 84                        | -38                      | UHC                             | 2    | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | 4    | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | 36   | --                       |
|                    |                                                      |             |                                                     |                           |                          | CO                              | 62   | +61                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 4    | +2                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | 3    | -1                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | 26   | -10                      |
|                    | 4.0/5.1 (14)/(17)                                    | Watertube   | Overfire Air (3.1)                                  | 85                        | -37                      | CO                              | 8    | +7                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 1    | -1                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | 3    | -1                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | 32   | -4                       |
| H                  | 11/13 (38)/(45)                                      | Watertube   | Baseline (2.9)                                      | 146                       | --                       | CO                              | 8    | --                       |
|                    | 11/13 (39)/(45)                                      | Watertube   | Low Excess Air (1.6)                                | 107                       | -39                      | UHC                             | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | 22   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | 66   | --                       |
|                    |                                                      |             |                                                     |                           |                          | CO                              | 21   | +13                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | 10   | -12                      |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | 44   | -22                      |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-6. Concluded

| Boiler Test Series | System                                   |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup>       |                        |                          |
|--------------------|------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------------|------------------------|--------------------------|
|                    | Actual/Design Heat Input MW (106 Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                             | ng/J                   | Incremental Change, ng/J |
| H (Cont.)          | 11/13 (37)/(45)                          | Watertube   | Overfire Air (3.0)                                  | 86                        | -60                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 10<br>--<br>--<br>--   | +2<br>--<br>--<br>--     |
| I                  | 5.4/7.3 (18)/(30)                        | Watertube   | Baseline (9.3)                                      | 184                       | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | <10<br>--<br>--<br>--  | --<br>--<br>--<br>--     |
|                    | 5.4/7.3 (8)/(30)                         | Watertube   | Low Excess Air (7.6)                                | 174                       | -10                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | <10<br>--<br>--<br>--  | 0<br>--<br>--<br>--      |
|                    | 5.4/7.3 (18)/(30)                        | Watertube   | Low Excess Air (5.5)                                | 156                       | -28                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | <10<br>--<br>--<br>--  | 0<br>--<br>--<br>--      |
|                    | 5.5/7.3 (19)/(30)                        | Watertube   | Low Excess Air (4.5)                                | 127                       | -57                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | <10<br>--<br>--<br>--  | 0<br>--<br>--<br>--      |
|                    | 5.5/7.3 (19)/(30)                        | Watertube   | Low Excess Air (4.3)                                | 140                       | -44                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | <10<br>--<br>--<br>--  | 0<br>--<br>--<br>--      |
|                    | 5.5/7.3 (19)/(30)                        | Watertube   | Low Excess Air (4.2)                                | 94                        | -90                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 1232<br>--<br>--<br>-- | +1232<br>--<br>--<br>--  |
|                    | 5.4/7.3 (19)/(30)                        | Watertube   | Low Excess Air (3.6)                                | 113                       | -71                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 103<br>--<br>--<br>--  | +103<br>--<br>--<br>--   |

<sup>a</sup>No data available on noncriteria emissions

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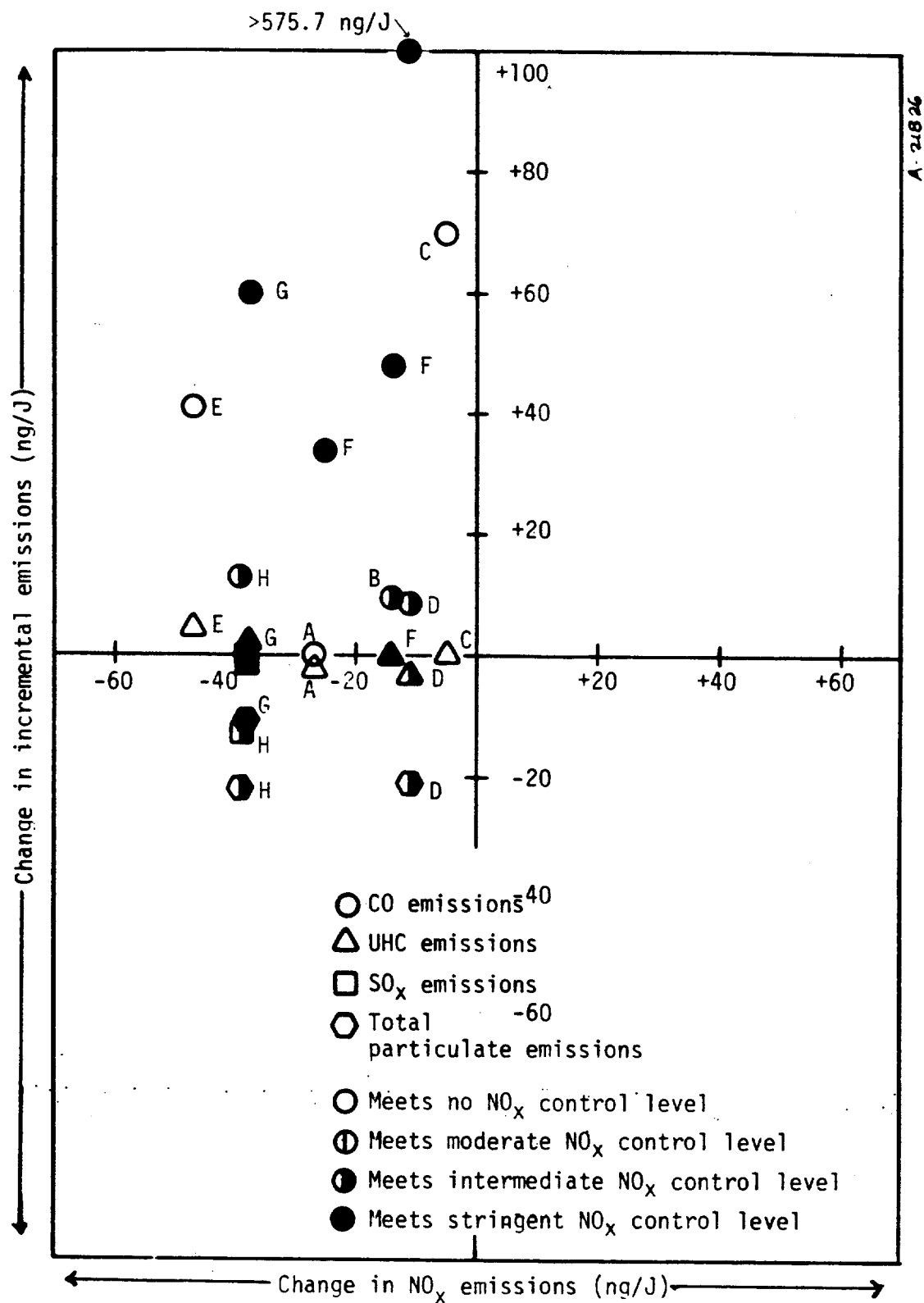


Figure 6-5. Change in incremental emissions with low excess air NO<sub>x</sub> control for residual oil-fired watertube industrial boilers (References 6-15 and 6-17).

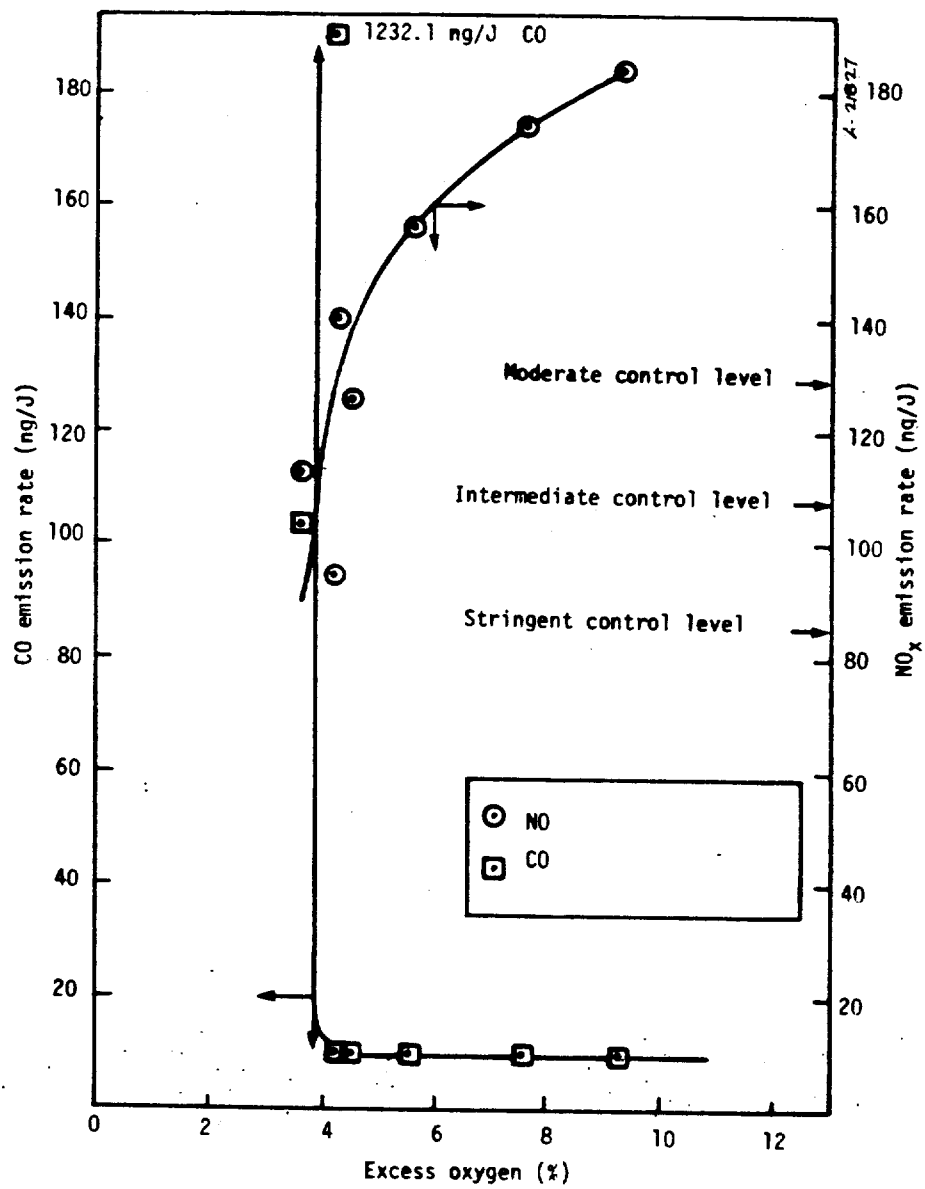


Figure 6-6. Changes in CO and NO<sub>x</sub> emissions with reduced excess oxygen for a residual oil-fired watertube industrial boiler (Reference 6-17).

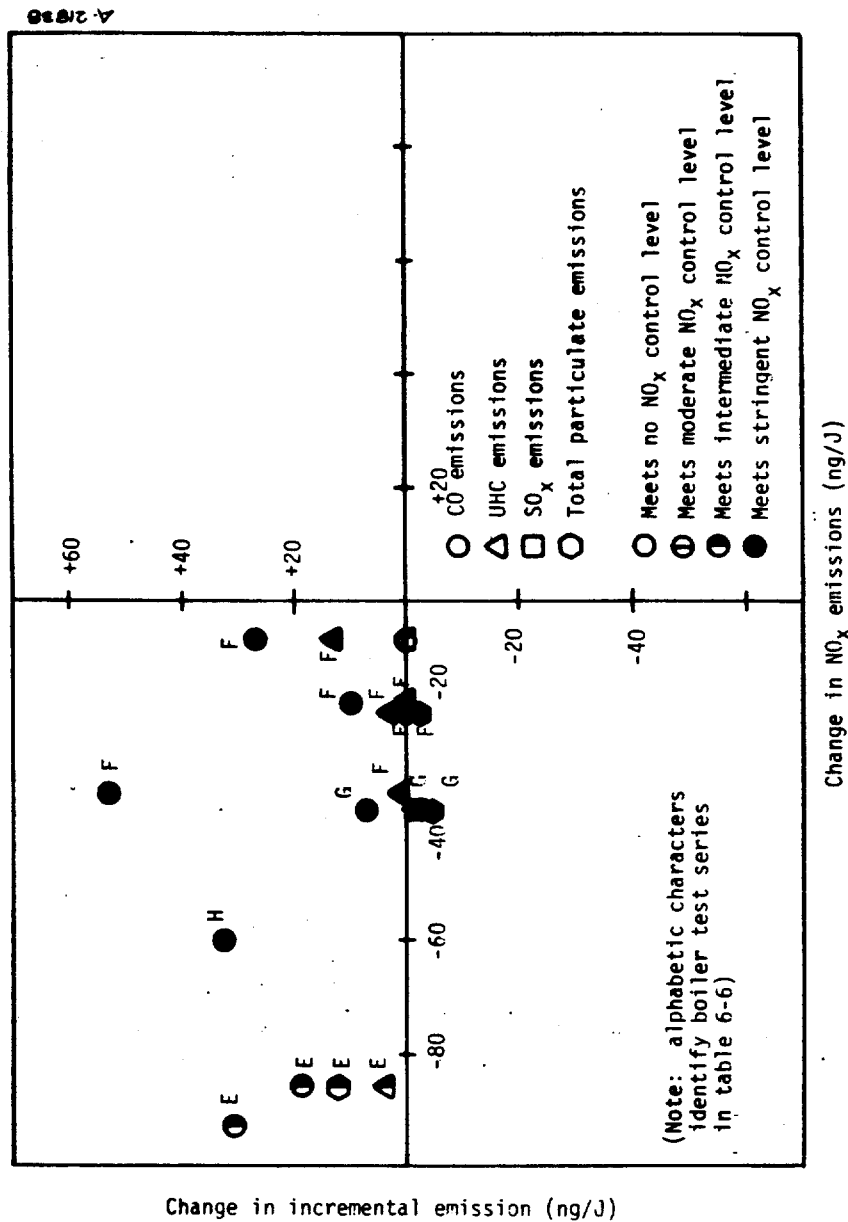


Figure 6-7. Change in incremental emissions with overfire air  $\text{NO}_x$  control for residual oil-fired watertube industrial boilers (References 6-15 and 6-17).



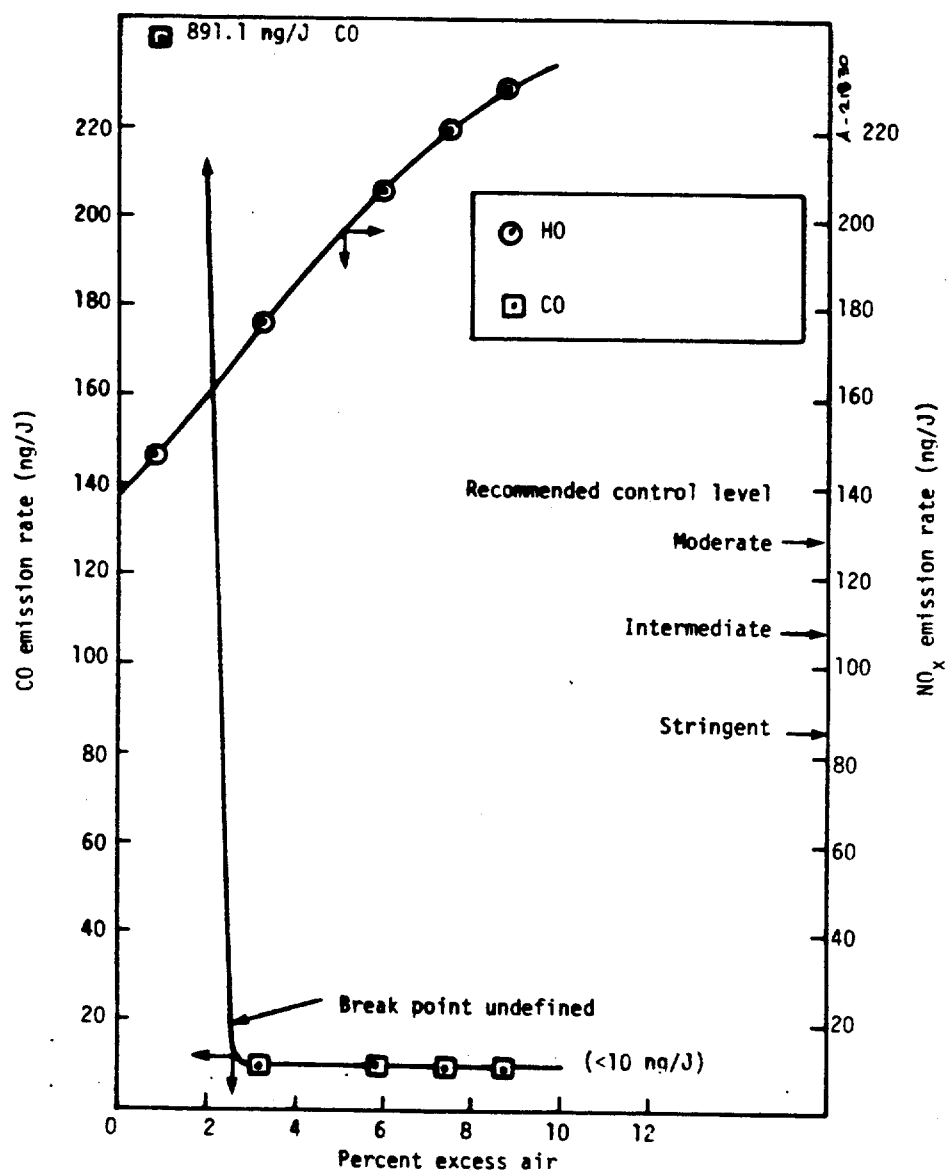


Figure 6-8. Change in CO and NO<sub>x</sub> emissions with decreasing excess oxygen for a residual oil-fired firetube industrial boiler (Reference 6-17).

A trend for sulfate emissions similar to that of coal-fired boilers is not apparent for residual oil-fired boilers. However, a test from Series H was conducted with an excess oxygen content of 1.6 percent, and tests from Series G with 1.55 percent and 1.0 percent excess  $O_2$  levels. Though marginally conclusive, the higher  $O_2$  level test does have the highest  $SO_3$  oxidation level.

Finally, as was true with the coal-fired boilers, Figure 6-5 shows that particulate emissions for boilers with dust control devices are reduced with low excess air firing. This is most likely due to increased particle size resulting from reduced combustion completeness, making the particles easier to catch.

Test data collected on a watertube boiler (Reference 6-17) over a range of excess oxygen levels is presented in Figure 6-6. This figure shows the reductions in  $NO_x$  with decreasing excess oxygen levels. Complete combustion occurs until the oxygen level is reduced to approximately 4.25 percent. The emission rate of CO then climbs sharply. The data presented in Figure 6-5 show a significantly more scattered relationship between CO and  $NO_x$  emissions than Figure 6-6 suggests. However, it is reasonable to conclude that each boiler has similar emission characteristics, but fuel/air mixing, fuel nitrogen concentrations, flame temperatures, and many other variables, are responsible for the data scatter.

The effect of overfire air on  $NO_x$  control is shown in Figure 6-7. The emission rate of CO is generally increased with increasing reductions in  $NO_x$  emission rates. The emission rates of UHC remain the same or are increased only slightly.

Overfire air (staged combustion) reduces the excess oxygen available for reaction in the primary combustion zone of the boiler. Since less oxygen is available for reaction under these conditions, a reduction in sulfate emissions in the primary zone could be expected. Addition of secondary combustion air may quench the reaction, resulting in reduced overall  $SO_3$ . Figure 6-7 shows decreases in sulfate emissions on both tests conducted. (The potential for trace metal catalytic oxidation will be discussed later in this section.)

Finally, the trend established in Figures 6-1 and 6-5 of reduced particulate emissions, has one exception, test condition E. The boiler

located at this test site does not have a dust control device. Since reduced combustion efficiency results in increased particulate size and emission rate, this facility would be expected to have increased particulate emissions without dust control devices. Again, sufficient data is not available to establish overall particulate removal efficiencies.

A second series of tests conducted at various excess oxygen contents was reported in Reference 6-17. These data were collected on a firetube boiler and illustrate the relationship between  $\text{NO}_x$  and CO emission rates as a function of excess oxygen concentrations. As in Figure 6-6, a distinct increase in CO emissions is noted as excess oxygen reaches the lower practical operating limit. Unfortunately, this lower limit is not clearly defined. It is seen that CO emissions drastically increase before the  $\text{NO}_x$  emission rate reaches even the moderate control level.

A set of size distribution tests were conducted during the field test series reported in Reference 6-16. It was found that the combustion of oil fuel produced a larger proportion of particulates having an aerodynamic diameter less than 3 micrometers than did coal fuel. A comparison of Table 6-4 for coal and Table 6-7 for residual oil shows this trend.

Other data collected during various low  $\text{NO}_x$  control conditions were reported in References 6-15 and 6-18. The data are presented in Figures 6-9 through 6-11. Though test number 132 does not follow the trend, generally an increase in particle size as excess air levels are decreased can be seen. The remaining combustion modifications and combinations of modifications also indicate an increased particle size but the degree of change is mixed.

A recently completed field test program on an oil-fired industrial boiler (Reference 6-18) is the only source of organic emission data identified. The organic species proved very difficult to identify, with most sample quantities insufficient to allow for analysis.

No polychlorinated biphenyls (PCB) were identified during the oil tests. The concentration of polycyclic organic matter (POM) contained in the various sample train fractions is shown in Table 6-8. The most complete analysis was obtained from the organic absorbent (XAD-2) resin.

TABLE 6-7. EFFECT OF OVERFIRE AIR NO<sub>x</sub> CONTROL ON PARTICLE SIZE DISTRIBUTION<sup>a</sup> FOR A RESIDUAL OIL-FIRED WATERTUBE BOILER (Reference 6-16)

| Fuel Burner Type | Test Load GJ hr <sup>-1</sup> | NO <sub>x</sub> ng/J | Impact Flow cm <sup>3</sup> s <sup>-1</sup> | D <sub>50</sub> Cycl. μm | Actual D <sub>50</sub> of Stage No.b |      |      |      |      |                                 | Cyclone mg | Cyclone, Stage and Filter Catch |       |       |       |           | Total Catch mg | Comments            |
|------------------|-------------------------------|----------------------|---------------------------------------------|--------------------------|--------------------------------------|------|------|------|------|---------------------------------|------------|---------------------------------|-------|-------|-------|-----------|----------------|---------------------|
|                  |                               |                      |                                             |                          | Actual D <sub>50</sub> of Stage No.b |      |      |      |      | Cyclone, Stage and Filter Catch |            |                                 |       |       |       |           |                |                     |
|                  |                               |                      |                                             |                          | Actual D <sub>50</sub> of Stage No.b |      |      |      |      | Cyclone, Stage and Filter Catch |            |                                 |       |       |       |           |                |                     |
|                  |                               |                      |                                             |                          | 1 μm                                 | 2 μm | 3 μm | 4 μm | 5 μm | 1 mg                            |            | 2 mg                            | 3 mg  | 4 mg  | 5 mg  | Filter mg |                |                     |
| No. 6 Steam      | 34                            | 111                  | 22.6                                        | --                       | 3.62                                 | 2.17 | 1.45 | 0.72 | 0.36 | None                            | 2.812      | 1.616                           | 0.668 | 0.456 | 0.312 | 2.700     | 8.564          | Baseline            |
| No. 6 Steam      | 34                            | 97.6                 | 22.7                                        | --                       | 3.61                                 | 2.17 | 1.44 | 0.72 | 0.36 | None                            | 3.112      | 1.372                           | 0.596 | 0.332 | 0.196 | 2.344     | 7.952          | Low NO <sub>x</sub> |

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<sup>a</sup>Particle size distribution determined by use of a Brink model "B" cascade impactor. <sup>b</sup>D<sub>50</sub> identifies the size fraction in micrometers. Particulates with an aerodynamic diameter greater than the D<sub>50</sub> cut point will be captured. Increasing stage number corresponds to decreasing particle size.

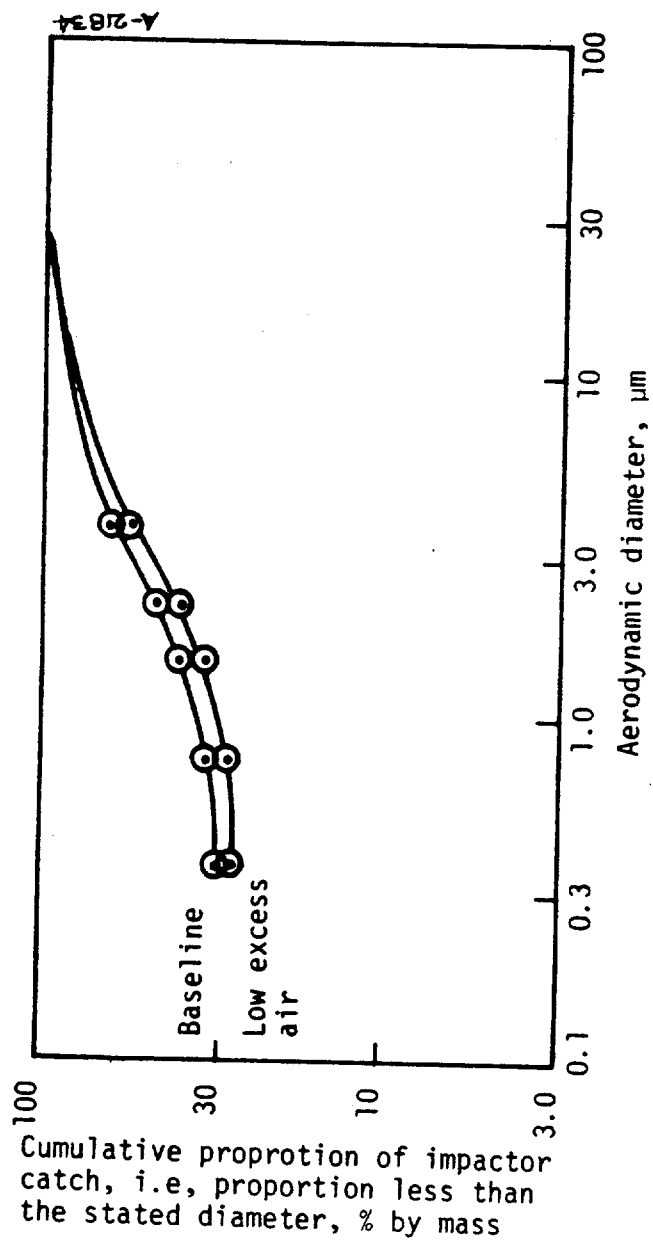


Figure 6-9. Effect of low excess air  $\text{NO}_x$  control on particle size distribution for a residual oil-fired watertube industrial boiler. (Reference 6-15)

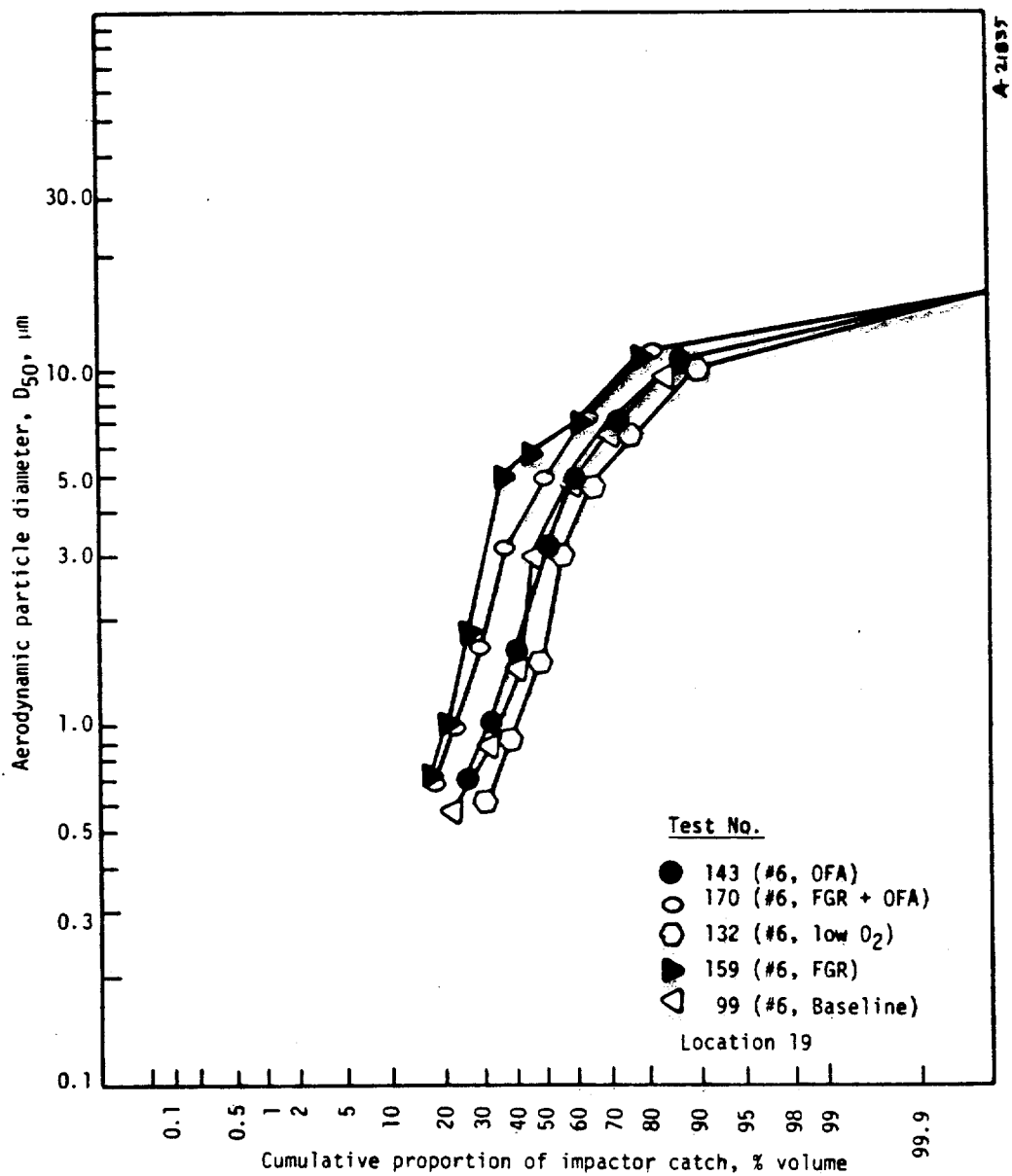


Figure 6-10. Effect of  $\text{NO}_x$  controls on particle size distribution for a residual oil-fired watertube industrial boiler. (Reference 6-18)

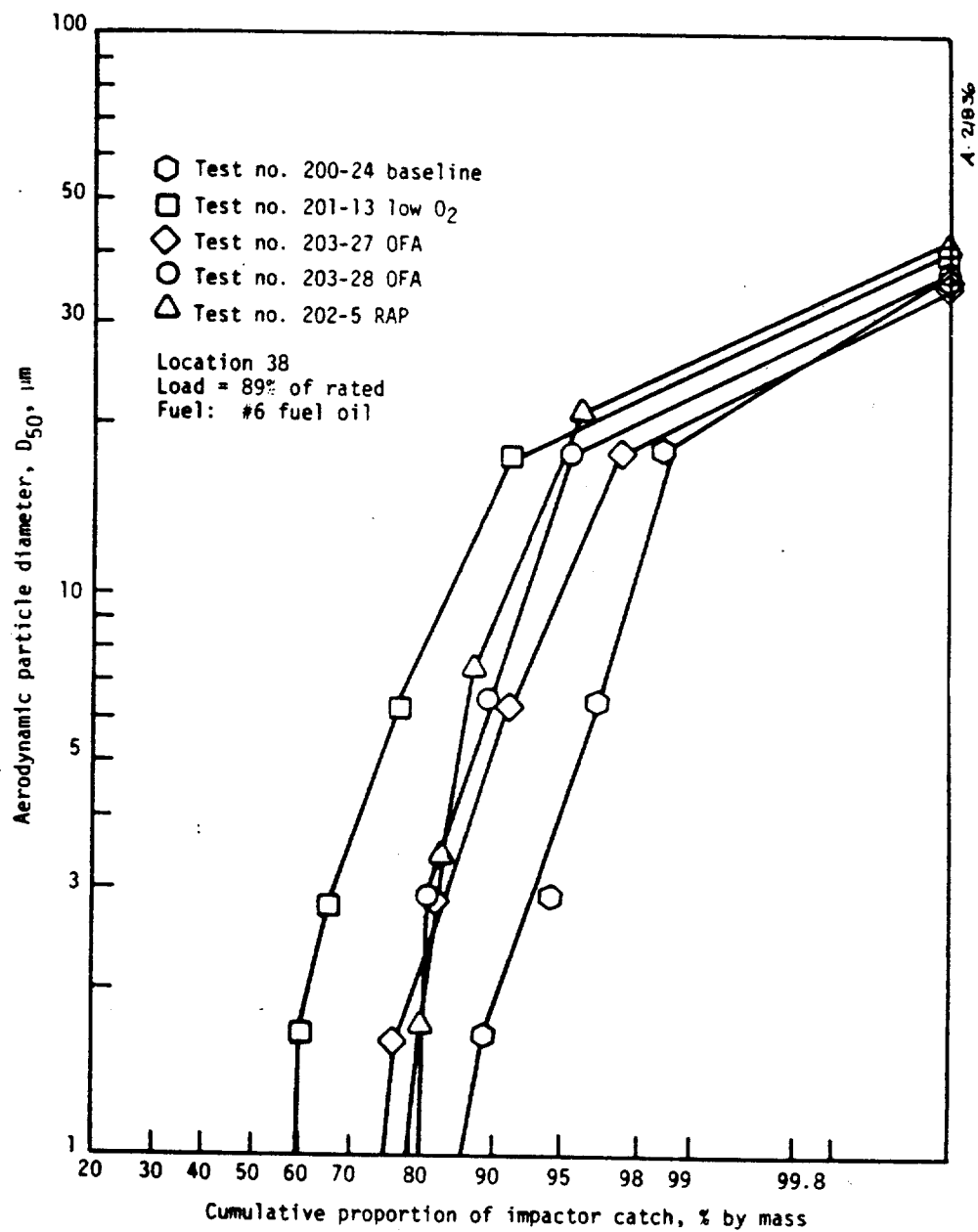


Figure 6-11. Effect of NO<sub>x</sub> controls on particle size distribution for a residual oil-fired watertube industrial boiler. (Reference 6-18)

TABLE 6-8. EFFECT OF COMBINED LOW EXCESS AIR, STAGED COMBUSTION, AND FLUE GAS RECIRCULATION ON POLYCYCLIC ORGANIC MATTER (POM) EMISSIONS FROM A RESIDUAL OIL-FIRED INDUSTRIAL BOILER (Reference 6-18)

| Sample Train Fraction | Polycyclic Organic Matter (POM) |                   |                       |                   |                       |                   |
|-----------------------|---------------------------------|-------------------|-----------------------|-------------------|-----------------------|-------------------|
|                       | Test Number*                    |                   |                       |                   |                       |                   |
|                       | 2-Baseline                      |                   | 3-Low NO <sub>x</sub> |                   | 4-Low NO <sub>x</sub> |                   |
|                       | µg/g                            | µg/m <sup>3</sup> | µg/g                  | µg/m <sup>3</sup> | µg/g                  | µg/m <sup>3</sup> |
| 10 µm solids          | IS <sup>+</sup>                 | --                | 1                     | 0.1               | IS                    | --                |
| 3 µm solids           | IS                              | --                | IS                    | --                | IS                    | --                |
| 1 µm solids           | IS                              | --                | IS                    | --                | IS                    | --                |
| Filters               | IS                              | --                | IS                    | --                | IS                    | --                |
| Solids section wash   | NR <sup>0</sup>                 | --                | NR                    | --                | NR                    | --                |
| XAD-2 resin           | 0.005                           | 0.04              | 0.0008                | 0.006             | <0.1                  | <0.8              |
| Organic module rinse  | IS                              | --                | 1.45                  | 50                | IS                    | --                |
| Condensate            | <0.001                          | <0.24             | 0.002                 | 0.5               | NR                    | --                |
| Impinger 1-3          | --                              | --                | --                    | --                | --                    | --                |

\*Test 1 results were obtained using a fuel with a different analysis.

<sup>+</sup>Insufficient sample.

<sup>0</sup>Not recorded.



The results of these tests are presented in Table 6-9. The results show a significant reduction in POM in the XAD-2 resin for the low NO<sub>x</sub> test compared to that for baseline conditions. The test results are definitely not in line with the expected trends. However, without complete analysis of all fractions, a conclusion concerning the total gas stream cannot be made.

Trace element emission data are also limited. The same study which provided the POM data, above, provided the trace element data reported below (Reference 6-18). A combination of reduced excess air staged combustion and flue gas recirculation resulted in an increase in particulate emissions of from 30 to 60 percent over baseline conditions. Tables 6-10 through 6-12 present the results of the element partitioning study as a result of the increased particulate loading. Comparison of test 3 (low NO<sub>x</sub>) with test 2 (baseline) indicates that calcium, chromium, iron, manganese, titanium and zinc were increased by 10 to 90 percent in the solid particulate less than 3 micrometers. These same elements, plus barium, cobalt, and copper were increased by over 20% in the total amount of solid particulate collected.

Comparison of the concentration of arsenic, cobalt, copper, iron, manganese, nickel, vanadium, zinc, chloride and sulfates at each size fraction shows a clear shift in concentration towards the smaller particle sizes during low NO<sub>x</sub> operation. The remaining species were not present in sufficient quantities to allow an assessment.

It appears that, for this particular boiler, an increase in trace metal emissions, in proportion to increased particulate, occurs with increased NO<sub>x</sub> control. A shift towards increased trace metal concentration in smaller particulate can also be seen.

The NO<sub>x</sub> control data, unfortunately, is still very limited, presenting information only on a combination of control technologies, and only for one boiler. More data must be collected before firm conclusions can be presented.

The above emission data were presented for combustion modifications only. Low NO<sub>x</sub> burners and ammonia injection, considered to be advanced control method, are still in the development stages. Actual incremental emission data are not available.

TABLE 6-9. EFFECT OF NO<sub>x</sub> CONTROL ON POLYCYCLIC ORGANIC MATTER (POM)  
EMISSIONS FROM A RESIDUAL OIL-FIRED BOILER: XAD-2 RESIN  
TEST ONLY<sup>a</sup> (Reference 6-18)

| POM Component <sup>b</sup> | Baseline                |                                   | Low NO <sub>x</sub>     |                                   |
|----------------------------|-------------------------|-----------------------------------|-------------------------|-----------------------------------|
|                            | ng POM<br>g Particulate | ng POM<br>m <sup>3</sup> Flue gas | ng POM<br>g Particulate | ng POM<br>m <sup>3</sup> Flue gas |
| Anthracene                 | 3.2                     | 24                                | 0.45                    | 3.4                               |
| Phenanthrene               | --                      | --                                | 0.02                    | 0.1                               |
| Methyl Anthracenes         | 0.2                     | 1.6                               | 0.12                    | 0.9                               |
| Fluoranthene               | 1.2                     | 9.0                               | 0.13                    | 0.9                               |
| Pyrene                     | 0.05                    | 0.4                               | 0.05                    | 0.4                               |
| Benzo(c)phenanthrene       | 0.002                   | 0.02                              | --                      | --                                |
| Chrysene                   | 0.03                    | 0.19                              | 0.004                   | 0.03                              |
| Benzo Fluoranthenes        | 0.007                   | 0.05                              | 0.007                   | 0.05                              |
| Benz(a)pyrene              | 0.004                   | 0.032                             | --                      | --                                |
| Benz(e)pyrene              | 0.004                   | 0.032                             | --                      | --                                |
| Total POM                  | 4.74                    | 35.5                              | 0.78                    | 5.8                               |

<sup>a</sup>Low NO<sub>x</sub> condition: combined low excess air, staged combustion,  
and flue gas recirculation.

<sup>b</sup>Analysis by gas chromatograph -- mass spectrometry.

TABLE 6-10. EFFECT OF COMBINED LOW EXCESS AIR, STAGED COMBUSTION,  
AND FLUE GAS RECIRCULATION ON TRACE SPECIES EMISSIONS  
FROM A RESIDUAL OIL-FIRED INDUSTRIAL BOILER  
(Reference 6-18)

| Total Emission Concentrations by<br>Atomic Absorption, $\mu\text{g}/\text{m}^3$ |             |                     |                     |
|---------------------------------------------------------------------------------|-------------|---------------------|---------------------|
| Test                                                                            | 2           | 3 <sup>a</sup>      | 4 <sup>a</sup>      |
| Condition                                                                       | Baseline    | Low NO <sub>x</sub> | Low NO <sub>x</sub> |
| Antimony                                                                        | < 380       | < 540               | < 350               |
| Arsenic                                                                         | 6.5 < 15    | 59 < 64             | 55                  |
| Barium                                                                          | 95 < 210    | 640 < 740           | 800 < 850           |
| Beryllium                                                                       | < 6         | < 8.9               | < 6                 |
| Cadmium                                                                         | 13          | 4.8 < 12            | 1.1 < 6             |
| Calcium                                                                         | 650         | 2000                | 440 < 460           |
| Chromium                                                                        | 750         | 740                 | 530                 |
| Cobalt                                                                          | 65 < 130    | 79 < 150            | 18 < 85             |
| Copper                                                                          | 32          | 39 < 44             | 95                  |
| Iron                                                                            | 4300        | 4700                | 3100                |
| Lead                                                                            | 45 < 70     | 9.9 < 21            | < 15                |
| Manganese                                                                       | 70          | 99                  | 65                  |
| Mercury                                                                         | < 1.9       | 0.06 < 21           | 2                   |
| Nickel                                                                          | 1300 < 1400 | 1600                | 2200                |
| Selenium                                                                        | < 12        | 9.9 < 290           | < 11                |
| Tellurium                                                                       | < 300       | < 450               | < 290               |
| Tin                                                                             | < 750       | < 1000              | < 700               |
| Titanium                                                                        | 70 < 1600   | 120 < 2500          | 20 < 100            |
| Vanadium                                                                        | 3200 < 3400 | 3400 < 3600         | 2400                |
| Zinc                                                                            | 370         | 810                 | 3300                |
| Chloride                                                                        | 12000       | 3500                | 6000                |
| Fluoride                                                                        | 170 < 180   | 54 < 79             | 24 < 33             |
| Nitrates                                                                        | 130         | 110 < 120           | 85                  |
| Sulfates                                                                        | 18000       | 18000               | 21000               |

<sup>a</sup>

Tests 3 and 4 are duplicate runs.

| Total Emission Concentrations by Spark Source<br>Mass Spectrometry, $\mu\text{g}/\text{m}^3$ |                     |
|----------------------------------------------------------------------------------------------|---------------------|
| 2                                                                                            | 3                   |
| Baseline                                                                                     | Low NO <sub>x</sub> |
| 11                                                                                           | 160                 |
| 6.5                                                                                          | 6 < 12              |
| MC                                                                                           | 640                 |
| 0.055 < 3                                                                                    | 0.3 < 2             |
| 7.5 < 13                                                                                     | 0.09 < 5            |
| 2000 < MC                                                                                    | 67 < MC             |
| 960                                                                                          | 500                 |
| 8 < MC                                                                                       | 94                  |
| 49                                                                                           | 130                 |
| 1300 < MC                                                                                    | 1100                |
| 52 < 67                                                                                      | 54                  |
| 69                                                                                           | 64                  |
| NR                                                                                           | NR                  |
| 180 < MC                                                                                     | 240 < MC            |
| 2 < 5                                                                                        | 100 < 110           |
| 0.04 < 3                                                                                     | 0.2 < 3             |
| 0.4 < 8                                                                                      | 12                  |
| 53                                                                                           | 580                 |
| 8 < MC                                                                                       | 9 < MC              |
| MC                                                                                           | 680                 |
| 4.3                                                                                          | 2100                |
| 23                                                                                           | 170                 |
| --                                                                                           | --                  |
| --                                                                                           | --                  |

TABLE 6-11. TRACE SPECIES EMISSIONS FROM A RESIDUAL OIL-FIRED INDUSTRIAL BOILER  
UNDER BASELINE CONDITIONS (TEST 2) (REFERENCE 6-18)

| Sample Type   | Nozzle, Probe,<br>10 µm Cyclone<br>Solids |                   | 3 µm Cyclone<br>Solids |                   | 1 µm Cyclone<br>Solids |                   | Filters |                   | Solid<br>Section<br>Wash |                   |
|---------------|-------------------------------------------|-------------------|------------------------|-------------------|------------------------|-------------------|---------|-------------------|--------------------------|-------------------|
|               | µg/g                                      | µg/m <sup>3</sup> | µg/g                   | µg/m <sup>3</sup> | µg/g                   | µg/m <sup>3</sup> | µg/g    | µg/m <sup>3</sup> | µg/ml                    | µg/m <sup>3</sup> |
| Sample Number | 566                                       | 1.6620 g          | 716                    | 0.4443 g          | 720                    | 0.2196 g          | 538     | 0.4157 g          | 19-2A                    | 160° ml           |
| Units         |                                           |                   |                        |                   |                        |                   |         |                   |                          |                   |
| Antimony      | < 38                                      | < 3.2             | < 210                  | < 4.7             | < 250                  | < 2.7             | < 500   | < 10              | < 0.5                    | < 40              |
| Arsenic       | < 1.5                                     | < 0.13            | 33                     | 0.73              | < 10                   | < 0.11            | 200     | 4.2               | 0.019                    | 1.4               |
| Barium        | 38                                        | 3.2               | 460                    | 10                | 6000                   | 66                | 800     | 17                | < 0.1                    | < 8               |
| Beryllium     | < 0.8                                     | < 0.065           | < 4.2                  | < 0.093           | < 5                    | < 0.055           | < 10    | < 0.2             | < 0.005                  | < 0.4             |
| Calcium       | 0.8                                       | 0.065             | < 4.2                  | < 0.093           | < 5                    | < 0.055           | < 10    | < 0.2             | 0.005                    | 0.4               |
| Calcium       | 1900                                      | 160               | 1900                   | 42                | 3500                   | 38                | 4800    | 100               | 0.49                     | 39                |
| Chromium      | 72                                        | 6                 | 140                    | 3.1               | 310                    | 3.4               | 240     | 5                 | 0.09                     | 7.2               |
| Cobalt        | 120                                       | 10                | 310                    | 6.7               | 940                    | 10                | 1600    | 33                | < 0.2                    | < 16              |
| Copper        | 46                                        | 3.8               | 50                     | 1.1               | 100                    | 1.1               | 460     | 9.6               | 0.06                     | 4.8               |
| Iron          | 5400                                      | 450               | 7200                   | 160               | 37000                  | 350               | 21000   | 440               | 2.6                      | 210               |
| Lead          | 150                                       | 13                | < 20                   | < 0.44            | < 25                   | < 0.27            | 1000    | 21                | 0.14                     | 11                |
| Manganese     | 51                                        | 4.3               | 75                     | 1.7               | 210                    | 2.3               | 250     | 5.2               | 0.17                     | 14                |
| Mercury       | < 0.03                                    | < 0.0025          | < 0.17                 | < 0.0038          | < 0.3                  | < 0.0022          | < 0.4   | < 0.008           | < 0.005                  | < 0.4             |
| Nickel        | 1900                                      | 160               | 2200                   | 49                | 9000                   | 99                | 30000   | 620               | 0.77                     | 62                |
| Selenium      | < 1.5                                     | < 0.13            | < 8                    | 0.18              | < 10                   | < 0.11            | < 20    | < 0.42            | < 0.01                   | 0.8               |
| Tellurium     | < 38                                      | < 3.2             | < 210                  | < 4.7             | < 250                  | < 2.7             | < 500   | < 10              | < 0.3                    | < 24              |
| Tin           | < 76                                      | < 6.3             | < 420                  | < 9.3             | < 500                  | < 5.5             | < 1000  | < 21              | < 1                      | < 80              |
| Titanium      | < 460                                     | < 38              | < 1200                 | < 27              | 2500                   | 27                | < 3000  | < 62              | < 1                      | < 80              |
| Vanadium      | 6300                                      | 520               | 10000                  | 220               | 43000                  | 470               | 89000   | 1800              | 2.5                      | 200               |
| Zinc          | 400                                       | 33                | 400                    | 8.9               | 1300                   | 14                | 4900    | 100               | 1.7                      | 140               |
| Chloride      | 279                                       | 23                | NES                    | NES               | NES                    | NES               | 11600   | 240               | 2.1                      | 170               |
| Fluoride      | 205                                       | 17                | 134                    | 3                 | 909                    | 10                | < 2     | < 0.04            | < 0.1                    | < 8               |
| Nitrates      | 113                                       | 9.4               | NES                    | NES               | NES                    | NES               | 39.5    | 0.82              | 0.24                     | 19                |
| Sulfates      | 14200                                     | 1200              | NES                    | NES               | NES                    | NES               | 457000  | 9500              | 7.0                      | 560               |

TABLE 6-12. TRACE SPECIES EMISSIONS FROM A RESIDUAL OIL-FIRED INDUSTRIAL BOILER  
UNDER LOW NO<sub>x</sub> CONDITIONS (TEST 3)<sup>a</sup> (REFERENCE 6-18)

| Sample Type | Sample Number | Sample Weight/Vol. | Nozzle, Probe,<br>10 µm Cyclone<br>Solids |                   | 3 µm Cyclone<br>Solids |                   | 1 µm Cyclone<br>Solids |                   | Filters |                   | Solid<br>Section<br>Wash |                   |
|-------------|---------------|--------------------|-------------------------------------------|-------------------|------------------------|-------------------|------------------------|-------------------|---------|-------------------|--------------------------|-------------------|
|             |               |                    | µg/g                                      | µg/m <sup>3</sup> | µg/g                   | µg/m <sup>3</sup> | µg/g                   | µg/m <sup>3</sup> | µg/g    | µg/m <sup>3</sup> | µg/ml                    | µg/m <sup>3</sup> |
| Units       |               |                    |                                           |                   |                        |                   |                        |                   |         |                   |                          |                   |
| Antimony    | 722           | 2.4163 g           | < 50                                      | < 6               | < 2500                 | < 130             | < 830                  | < 9               | < 170   | < 8               | < 0.5                    | < 46              |
| Arsenic     |               |                    | 4                                         | 0.5               | < 100                  | < 5               | < 33                   | < 0.4             | 33      | 1.6               | 0.01                     | 0.5               |
| Barium      |               |                    | 480                                       | 57                | < 1000                 | < 53              | < 330                  | < 4               | 730     | 36                | < 0.1                    | < 9               |
| Beryllium   |               |                    | < 1                                       | < 0.12            | < 50                   | < 3               | < 17                   | < 0.2             | < 3.3   | < 0.2             | < 0.005                  | < 0.5             |
| Cadmium     |               |                    | < 1                                       | < 0.12            | < 50                   | < 3               | < 17                   | < 0.2             | < 3.3   | < 0.2             | < 0.005                  | < 0.5             |
| Calcium     |               |                    | 1900                                      | 230               | 3500                   | 120               | 3000                   | 31                | 3100    | 150               | 15                       | 1400              |
| Chromium    |               |                    | 69                                        | 8                 | 950                    | 50                | 300                    | 3.1               | 180     | 8.9               | 0                        | 0                 |
| Cobalt      |               |                    | 104                                       | 12                | 450                    | 24                | 300                    | 3.1               | 807     | 40                | < 0.2                    | < 18              |
| Copper      |               |                    | 43                                        | 5                 | < 50                   | < 3               | < 150                  | < 2               | 200     | 9.9               | 0.11                     | 10                |
| Iron        |               |                    | 5200                                      | 620               | 4400                   | 230               | 6500                   | 68                | 20000   | 1000              | 1.8                      | 160               |
| Lead        |               |                    | NES                                       | --                | NES                    | --                | NES                    | --                | NES     | --                | 0.11                     | 10                |
| Manganese   |               |                    | 49                                        | 6                 | 200                    | 11                | 117                    | 1.2               | 160     | 7.9               | 0.16                     | 15                |
| Mercury     |               |                    | 0.5                                       | 0.06              | < 2                    | < 0.1             | < 0.67                 | < 0.007           | < 0.13  | < 0.006           | < 0.005                  | < 0.5             |
| Nickel      |               |                    | 970                                       | 120               | 1700                   | 90                | 3000                   | 31                | 13000   | 640               | 0.5                      | 46                |
| Selenium    |               |                    | < 2                                       | 0.24              | < 5000                 | < 270             | < 33                   | < 0.4             | < 6.7   | < 0.3             | 0.04                     | 3.6               |
| Tellurium   |               |                    | < 50                                      | 6                 | < 2500                 | < 130             | < 830                  | < 9               | < 170   | < 8               | < 0.3                    | < 27              |
| Tin         |               |                    | < 100                                     | 12                | < 5000                 | < 270             | < 1700                 | < 18              | < 330   | < 16              | < 1                      | < 91              |
| Titanium    |               |                    | 600                                       | 72                | < 15000                | < 800             | 5000                   | 52                | < 1000  | < 49              | < 1                      | < 91              |
| Vanadium    |               |                    | 5400                                      | 650               | 7000                   | 370               | 14000                  | 150               | 43000   | 2100              | 1.4                      | 130               |
| Zinc        |               |                    | 281                                       | 34                | 250                    | 13                | 350                    | 3.7               | 3000    | 150               | 0.49                     | 45                |
| Chloride    |               |                    | < 30                                      | < 4               | < 97                   | < 5               | NES                    | --                | 1700    | 84                | < 0.5                    | < 46              |
| Fluoride    |               |                    | 34                                        | 6.5               | NES                    | --                | NES                    | --                | < 1     | < 0.05            | < 0.1                    | < 9               |
| Nitrates    |               |                    | 43                                        | 5.1               | 67                     | 3.6               | NES                    | --                | 46      | 2.3               | 0.26                     | 24                |
| Sulfates    |               |                    | 8910                                      | 1100              | 14000                  | 740               | NES                    | --                | 170000  | 8400              | 12                       | 1100              |

<sup>a</sup>Low NO<sub>x</sub> condition: combined low excess air, staged combustion, and flue gas recirculation.

Due to the comparative high cost of this technique, the ammonia injection process will probably not be feasible on small size boilers such as firetubes and package watertubes unless stringent emission levels are required. In addition, since these industrial units are generally not base loaded, that is they do not operate at a steady continuous load, the variable heat input will cause significant flue gas temperature fluctuations which will reduce the performance of the control technique.

#### 6.5 ENVIRONMENTAL IMPACTS OF NO<sub>x</sub> CONTROLS FOR DISTILLATE OIL AND NATURAL GAS-FIRED BOILERS.

Distillate oil and natural gas-fired industrial boilers are generally packaged firetube boilers. The recommended NO<sub>x</sub> control techniques are presented in Table 3-10 for distillate oil and Table 3-11 for natural gas. The recommended emission levels for both fuels are presented in Table 3-6.

Table 6-13 presents the incremental emission data available for distillate oil-fired boilers. Table 6-14 presents the incremental emission data available for natural gas-fired boilers.

Figure 6-12 presents the data for CO emissions with the various types of NO<sub>x</sub> control techniques for distillate oil fuels. Carbon monoxide emissions increase in all cases where NO<sub>x</sub> reductions occurred. Flue gas recirculation resulted in the largest decrease in NO<sub>x</sub> emission rate and met the stringent control level in both cases. All other control types met the intermediate control level, with CO emissions varying from no change to substantial increase. Low excess air resulted in the largest increases.

Figure 6-13 presents the incremental emission data for unburned vapor phase hydrocarbons from distillate oil-fired boilers. Generally there appears to be no change with NO<sub>x</sub> emission reduction.

Data on the emissions for natural gas-fired boilers are presented in Figure 6-14. Low excess air NO<sub>x</sub> control results in the largest incremental increases in CO emissions. However, the NO<sub>x</sub> emissions are generally reduced to only moderate or intermediate levels. The best control technique for reaching the required NO<sub>x</sub> levels without severe incremental emission impact is flue gas recirculation. All other control techniques are mixed in their ability to control NO<sub>x</sub> and their effects on other emissions. Figure 6-15 presents additional CO emission data as a

TABLE 6-13. INCREMENTAL EMISSIONS FROM DISTILLATE OIL-FIRED INDUSTRIAL BOILERS

| Boiler Test Series | System                                               |             | NO <sub>x</sub> Emissions                           |      | Criteria Emissions <sup>a</sup> |                 |      |
|--------------------|------------------------------------------------------|-------------|-----------------------------------------------------|------|---------------------------------|-----------------|------|
|                    | Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J | Incremental Change, ng/J        | Pollutant       | ng/J |
| A                  | 6.9/9.3 (23)/(33)                                    | Watertube   | Baseline (5.9)                                      | 66   | --                              | CO              | 0    |
|                    |                                                      |             |                                                     |      | --                              | UHC             | --   |
|                    | 7.0/9.3 (24)/(33)                                    | Watertube   | Low Excess Air (2.8)                                | 57   | -9                              | SO <sub>2</sub> | 7    |
|                    |                                                      |             |                                                     |      |                                 | PART            | 20   |
| B                  | 26/32 (89)/(110)                                     | Watertube   | Baseline (5.7)                                      | 115  | --                              | CO              | 0    |
|                    |                                                      |             |                                                     |      |                                 | UHC             | --   |
|                    | 26/32 (89)/(110)                                     | Watertube   | Low Excess Air (3.8)                                | --   | --                              | SO <sub>2</sub> | 8    |
|                    |                                                      |             |                                                     |      |                                 | PART            | 10   |
| C                  | 2.0/2.9 (7)/(10)                                     | Firtube     | Baseline (7.2)                                      | 121  | --                              | CO              | 0    |
|                    |                                                      |             |                                                     |      |                                 | UHC             | 24   |
|                    | 1.5/2.9 (5)/(10)                                     | Firtube     | Low Excess Air (3.6)                                | 85   | -36                             | SO <sub>2</sub> | 1    |
|                    |                                                      |             |                                                     |      |                                 | PART            | 23   |
| D                  | 4.1/5.1 (14)/(18)                                    | Watertube   | Baseline (3.6)                                      | 37   | --                              | CO              | 0    |
|                    |                                                      |             |                                                     |      |                                 | UHC             | 5    |
|                    |                                                      |             |                                                     |      |                                 | SO <sub>2</sub> | --   |
|                    |                                                      |             |                                                     |      |                                 | PART            | --   |
|                    |                                                      |             |                                                     |      |                                 | CO              | 17   |
|                    |                                                      |             |                                                     |      |                                 | UHC             | --   |
|                    |                                                      |             |                                                     |      |                                 | SO <sub>2</sub> | 6    |
|                    |                                                      |             |                                                     |      |                                 | PART            | 17   |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-13. Continued

| Boiler Test Series | System                                   |             | NO <sub>x</sub> Emissions                           |      | Criteria Emissions       |                                      |                       |                          |
|--------------------|------------------------------------------|-------------|-----------------------------------------------------|------|--------------------------|--------------------------------------|-----------------------|--------------------------|
|                    | Actual/Design Heat Input MM (106 Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J | Incremental Change, ng/J | Pollutant                            | ng/J                  | Incremental Change, ng/J |
| D<br>(Cont.)       | 4.1/5.1<br>(14)/(18)                     | Watertube   | Low Excess Air<br>(2.6)                             | 34   | -3                       | CO<br>UHC<br>SO <sub>2</sub><br>PART | 158<br>--<br>--<br>-- | +141<br>--<br>--<br>--   |
|                    | 4.1/5.1<br>(14)/(18)                     | Watertube   | Baseline<br>(30)                                    | 54   | --                       | CO<br>UHC<br>SO <sub>2</sub><br>PART | 0<br>1<br>--<br>--    | --<br>--<br>--<br>--     |
|                    | 4.1/5.1<br>(14)/(18)                     | Watertube   | High Excess Air (HEA)<br>(4.3)                      | 55   | +1                       | CO<br>UHC<br>SO <sub>2</sub><br>PART | 0<br>3<br>6<br>8      | 0<br>+2<br>--<br>--      |
|                    | 4.1/5.1<br>(14)/(18)                     | Watertube   | Low Excess Air<br>(1.6)                             | 44   | -10                      | CO<br>UHC<br>SO <sub>2</sub><br>PART | 60<br>2<br>--<br>--   | +60<br>+1<br>--<br>--    |
|                    | 3.5/5.1<br>(12)/(18)                     | Watertube   | Baseline<br>(4.3)                                   | 47   | --                       | CO<br>UHC<br>SO <sub>2</sub><br>PART | 0<br>--<br>--<br>9    | --<br>--<br>--<br>--     |
|                    | 3.5/5.1<br>(12)/(18)                     | Watertube   | Low Excess Air<br>(3.7)                             | 46   | -1                       | CO<br>UHC<br>SO <sub>2</sub><br>PART | 0<br>--<br>--<br>--   | 0<br>--<br>--<br>--      |
| E                  | 4.6/5.3<br>(16)/(20)                     | Firetube    | Baseline<br>(5.8)                                   | 126  | --                       | CO<br>UHC<br>SO <sub>2</sub><br>PART | 0<br>6<br>4<br>14     | --<br>--<br>--<br>--     |
|                    | 4.1/5.8<br>(14)/(20)                     | Firetube    | Low Excess Air<br>(2.7)                             | 76   | -50                      | CO<br>UHC<br>SO <sub>2</sub><br>PART | 0<br>17<br>--<br>--   | 0<br>+11<br>--<br>--     |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-13. Continued

| Boiler Test Series | System                                               |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |      |                          |
|--------------------|------------------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------|------|--------------------------|
|                    | Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                       | ng/J | Incremental Change, ng/J |
| F                  | 4.2/5.1 (14)/(18)                                    | Watertube   | Baseline (31)                                       | 66                        | --                       | CO                              | 3    | --                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 1    | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>2</sub>                 | 1    | --                       |
|                    |                                                      |             |                                                     |                           |                          | PART                            | 25   | --                       |
|                    |                                                      | Watertube   | Low Excess Air (1.2)                                | 55                        | -11                      | CO                              | 62   | +59                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 1    | 0                        |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>2</sub>                 | 3    | +2                       |
|                    |                                                      |             |                                                     |                           |                          | PART                            | 15   | -10                      |
|                    |                                                      | Watertube   | Flue Gas Recirculation (0.85) (28.4 % FGR)          | 17                        | -49                      | CO                              | 7    | +4                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 1    | +0                       |
| SO <sub>2</sub>    | 5                                                    |             |                                                     |                           |                          | +4                              |      |                          |
| PART               | 5                                                    |             |                                                     |                           |                          | -20                             |      |                          |
| G                  | 4.3/5.1 (15)/(18)                                    | Watertube   | Flue Gas Recirculation (0.7) (27.9 % FGR)           | 19                        | -47                      | CO                              | 24   | +21                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 1    | 0                        |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>2</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | PART                            | --   | --                       |
|                    |                                                      | Watertube   | Overfire Air (3.1)                                  | 54                        | -12                      | CO                              | 12   | +9                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 1    | 0                        |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>2</sub>                 | 1    | 0                        |
|                    |                                                      |             |                                                     |                           |                          | PART                            | 12   | -13                      |
|                    |                                                      | Watertube   | Overfire Air (3.2)                                  | 55                        | -11                      | CO                              | 8    | 5                        |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | -1                       |
| SO <sub>2</sub>    | --                                                   |             |                                                     |                           |                          | --                              |      |                          |
| PART               | --                                                   |             |                                                     |                           |                          | --                              |      |                          |
| G                  | 5.0/8.4 (17)/(28)                                    | Watertube   | Baseline (5.3)                                      | 51                        | --                       | CO                              | 31   | --                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>2</sub>                 | 12   | --                       |
|                    |                                                      |             |                                                     |                           |                          | PART                            | 13   | --                       |
|                    |                                                      | Watertube   | Low Excess Air (4.7)                                | 47                        | -4                       | CO                              | 51   | +20                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>2</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | PART                            | --   | --                       |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-13. Concluded

| Boiler Test Series | System                                               |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |      |                          |
|--------------------|------------------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------|------|--------------------------|
|                    | Actual/Design Heat Input MM (10 <sup>6</sup> Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                       | ng/J | Incremental Change, ng/J |
| H                  | 20/58 (68)/(200)                                     | Watertube   | Baseline (4.4)                                      | 58                        | --                       | CO                              | 0    | --                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | PART                            | 12   | --                       |
|                    |                                                      | Watertube   | Overfire Air (5.4)                                  | 55                        | -3                       | CO                              | 0    | 0                        |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | 0                        |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | PART                            | --   | --                       |

<sup>a</sup>No data available on noncriteria emissions

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TABLE 6-14. INCREMENTAL EMISSIONS FROM NATURAL GAS-FIRED INDUSTRIAL BOILERS

| Boiler Test Series | System                                               |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup>       |      |                          |
|--------------------|------------------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------------|------|--------------------------|
|                    | Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                             | ng/J | Incremental Change, ng/J |
| A                  | 4.9/8.4 (17)/(27)                                    | Watertube   | Baseline (2.2)                                      | 40                        | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 21   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    | 7.3/8.4 (24)/(21)                                    | Watertube   | Low Excess Air (0.9)                                | 38                        | -2                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 152  | +131                     |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
| B                  | 32/46 (10)/(157)                                     | Watertube   | Baseline (5.3)                                      | 79                        | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 0    | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | 22   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    | 35/46 (120)/(157)                                    | Watertube   | Low Excess Air (3.2)                                | 82                        | +3                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 3    | +3                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | 12   | -13                      |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    | 35/46 (120)/(157)                                    | Watertube   | Reduced Air Preheat (5.2)                           | 81                        | +2                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 0    | 0                        |
|                    |                                                      |             |                                                     |                           |                          |                                       | 12   | -10                      |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
| C                  | 8.4/20 (27)/(70)                                     | Watertube   | Baseline (5.7)                                      | 108                       | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 0    | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | 0    | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    | 8.4/20 (27)/(70)                                     | Watertube   | Low Excess Air (3.7)                                | 85                        | -23                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 4    | +4                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | 0    | 0                        |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    | 8.4/20 (27)/(70)                                     | Watertube   | Reduced Air Preheat (5.6)                           | 100                       | -8                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 0    | 0                        |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          |                                       | --   | --                       |

<sup>a</sup>No data available on noncriteria emissions

Continued

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|                      |    |                      |    |                      |     |
|----------------------|----|----------------------|----|----------------------|-----|
| GREENHOUSE EFFECT    | 1  | IGNITION DELAY       | 1  | JET AIRCRAFT         | 1   |
| GRID-CONNECTED       | 1  | ILLINOIS             | 11 | JET ENGINE           | 4   |
| GROUNDWATER          | 2  | ILLINOIS BASIN       | 1  | JET FUELED COMBUSTOR | 1   |
| GROUNDWTR TRANSPORT  | 11 | IMMATURE IN STAR     | 1  | KAIPAROWITS          | 1   |
| GROWTH               | 3  | IMPACT CRITERIA      | 1  | KANSAS               | 1   |
| GUIDELINES           | 2  | IMPINGER             | 1  | KENTUCKY             | 5   |
| GUIDELINES MANUAL    | 1  | INCINERATOR          | 14 | KEROSENE             | 2   |
| GYPSUM               | 1  | INDAN                | 1  | KILN BURNER          | 2   |
| HALOGEN              | 1  | INDENE               | 1  | KINETIC ENERGY       | 1   |
| HAMSTER              | 1  | INDEX TEST           | 1  | KINETICS             | 8   |
| HANDBOOK             | 2  | INDICATOR ORGANISM   | 2  | KPCP                 | 1   |
| HAZARDOUS WASTE      | 8  | INDUSTRIAL BOILER    | 89 | KUREHA WET PROCESS   | 1   |
| HEALTH EFFECTS       | 16 | INDUSTRIAL EXPOSURE  | 1  | LABORATORY           | 196 |
| HEALTH RISK          | 2  | INDUSTRIAL PROCESS   | 9  | LAKE MICHIGAN        | 1   |
| HEALTH STANDARDS     | 1  | INDUSTRIAL WASTE     | 6  | LAKE POWELL          | 1   |
| HEALTH-WELFARE       | 17 | INDUSTRY             | 1  | LAND                 | 46  |
| HEART DISEASE        | 1  | INDUSTRY SURVEY      | 1  | LAND MANAGEMENT      | 2   |
| HEAT BUDGET          | 1  | INHALATION           | 2  | LANDFILL             | 8   |
| HEAT GENERATION      | 1  | INLET AIR            | 2  | LARVAL FISH          | 1   |
| HEAT LOSS            | 3  | INLET TEMPERATURE    | 1  | LAS                  | 1   |
| HEAT RECOVERY        | 4  | INDORGANIC COMPOUNDS | 4  | LATENT HEAT          | 2   |
| HEAT TRANSFER        | 5  | INORGANIC SULFATE    | 1  | LD-50                | 3   |
| HEMATOPOIETIC        | 1  | INSECTICIDE          | 4  | LEACHATE             | 24  |
| HGMS                 | 1  | INSPECTION           | 2  | LEAD                 | 20  |
| HIGH SULFUR FUEL     | 1  | INSTALLATION         | 3  | LEAD SMELTER         | 1   |
| HIGH TEMPERATURE     | 3  | INSTRUMENTATION      | 37 | LEGISLATIVE CONCERN  | 1   |
| HOGGED-FUEL          | 2  | INTEGRATED ENERGY SY | 1  | LEUKEMOGENESIS       | 1   |
| HORIZONTAL TRANSPORT | 1  | INTERMEDIATE BOILER  | 1  | LEVEL I              | 7   |
| HP-25                | 1  | INTERNAL COMBUSTION  | 1  | LEVEL II             | 4   |
| HP-65                | 1  | ION CHROMATOGRAPHY   | 1  | LIGNITE              | 7   |
| HUMAN                | 1  | ION EXCHANGE         | 1  | LIME STORAGE         | 1   |
| HYDRAULICS           | 58 | IOWA                 | 1  | LIME-LIMESTONE       | 38  |
| HYDROCARBONS         | 1  | IRON                 | 2  | LIME-SODA            | 1   |
| HYDROGEN CYANIDE     | 57 | IRON-O-PHENANTHROLIN | 6  | LIMESTONE QUARRY     | 1   |
| HYDROLOGY            | 1  | IRON-STEEL           | 1  | LIMESTONE SLURRY     | 1   |
| HYDROMETEOR          | 1  | IRRADIATION          | 1  | LIMITING TEMPERATURE | 1   |
| HYDROPEROXIDE        | 1  | ISOKINETICS          | 1  | LINEAR RELATIONSHIP  | 1   |
| HYGAS                | 1  | ISOPLETH             | 1  | LIQUID EFFLUENT      | 42  |
| H2S                  | 2  | ISOTOPE DILUTION     | 1  | LIQUID RECYCLE       | 1   |
| H2SO4                | 3  | J-33 TURBOJET        | 1  | LIQUID TREATMENT     | 24  |
| H2O                  | 1  | JAPAN                | 1  | LITERATURE REVIEW    | 30  |
| ICE DEPOSITION       | 1  |                      | 2  | LITHIUM              | 1   |

TABLE 6-14. Continued

| Boiler Test Series | System                                   |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup>       |                      |                          |
|--------------------|------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------------|----------------------|--------------------------|
|                    | Actual/Design Heat Input MW (106 Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                             | ng/J                 | Incremental Change, ng/J |
| F                  | 12/13 (40)/(45)                          | Watertube   | Baseline (1.9)                                      | 112                       | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 0<br>2<br>--<br>--   | --<br>--<br>--<br>--     |
|                    | 12/13 (40)/(45)                          | Watertube   | Low Excess Air (1.35)                               | 93                        | -19                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 279<br>0<br>--<br>-- | -279<br>-2<br>--<br>--   |
|                    | 12/13 (40)/(45)                          | Watertube   | Reduced Air Preheat                                 | 120                       | +8                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 9<br>2<br>--<br>--   | +9<br>0<br>--<br>--      |
|                    | 10/13 (35)/(45)                          | Watertube   | Reduced Air Preheat                                 | 63                        | -49                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 9<br>0<br>--<br>--   | +9<br>-2<br>--<br>--     |
|                    | 11/13 (35)/(45)                          | Watertube   | Overfire Air (3.4)                                  | 82                        | -30                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 6<br>0<br>--<br>--   | +6<br>--<br>--<br>--     |
|                    | 11/13 (14)/(18)                          | Watertube   | Overfire Air                                        | 52                        | -60                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 11<br>--<br>--<br>-- | +11<br>--<br>--<br>--    |
| 6                  | 4.1/5.1 (14)/(18)                        | Watertube   | Baseline (3.2)                                      | 30                        | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 3<br>1<br>--<br>--   | --<br>--<br>--<br>--     |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-14. Continued

| Boiler Test Series | System                                               |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |      |                          |
|--------------------|------------------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------|------|--------------------------|
|                    | Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                       | ng/J | Incremental Change, ng/J |
| G (Cont.)          | 4.1/5.1 (14)/(18)                                    | Watertube   | Low Excess Air (2.0)                                | 29                        | -1                       | CO                              | 25   | +22                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | --   | --                       |
|                    | 4.1/5.1 (14)/(18)                                    | Watertube   | Flue Gas Recirculation (2.9)                        | 19                        | -11                      | CO                              | 0    | -3                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | -1                       |
|                    | 3.9/5.1 (13)/(18)                                    | Watertube   | Flue Gas Recirculation (2.75)                       | 8                         | -22                      | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | CO                              | 37   | +34                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 13   | +12                      |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | --   | --                       |
|                    | 4.2/5.1 (14)/(18)                                    | Watertube   | Overfire Air (2.8)                                  | 39                        | +9                       | CO                              | 0    | -3                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | -1                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | --   | --                       |
|                    | 4.0/5.1 (14)/(18)                                    | Watertube   | Overfire Air (2.4)                                  | 27                        | -3                       | CO                              | 3    | 0                        |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | -1                       |
| H                  |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | --   | --                       |
|                    | 12/13 (40)/(45)                                      | Watertube   | Baseline (1.6)                                      | 82                        | --                       | CO                              | 43   | --                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | --   | --                       |
|                    | 11/13 (40)/(45)                                      | Watertube   | Low Excess Air (1.25)                               | 71                        | -11                      | CO                              | 619  | 576                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub>                 | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | Part.                           | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | CO                              | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | --   | --                       |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-14. Continued

| Boiler Test Series | System                                               |                    |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup>       |                      |                          |
|--------------------|------------------------------------------------------|--------------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------------|----------------------|--------------------------|
|                    | Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Boiler Type        | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                             | ng/J                 | Incremental Change, ng/J |
| H<br>(Cont.)       | 11/13<br>(40)/(45)                                   | Watertube          | Overfire Air<br>(2.25)                              | 57                        | -25                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 38<br>--<br>--<br>-- | -5<br>--<br>--<br>--     |
|                    | 12/13<br>(40)/(45)                                   | Watertube<br>(2.2) | Reduced Air Preheat                                 | 62                        | -20                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 3<br>--<br>--<br>--  | -40<br>--1<br>--<br>--   |
|                    | 12/13<br>(40)/(45)                                   | Watertube          | Overfire Air<br>(2.25)                              | 53                        | -29                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 85<br>--<br>--<br>-- | -42<br>--<br>--<br>--    |
|                    |                                                      |                    |                                                     |                           |                          |                                       |                      |                          |
| I                  | 4.2/5.1<br>(14)/(18)                                 | Watertube          | Baseline<br>(3.0)                                   | 49                        | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 1<br>1<br>--<br>--   | --<br>--<br>--<br>--     |
|                    | 4.1/5.1<br>(14)/(18)                                 | Watertube          | Flue Gas Recirculation<br>(3.2)<br>(20.3% FGR)      | 12                        | -37                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 6<br>1<br>--<br>--   | +5<br>0<br>--<br>--      |
|                    | 4.4/5.1<br>(14)/(18)                                 | Watertube          | Flue Gas Recirculation<br>(2.5)<br>(19.9% FGR)      | 11                        | -38                      | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 5<br>0<br>--<br>--   | +4<br>-1<br>--<br>--     |
|                    | 4.0/5.1<br>(14)/(18)                                 | Watertube          | Baseline<br>(3.2)                                   | 46                        | --                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 6<br>1<br>--<br>--   | --<br>--<br>--<br>--     |

<sup>a</sup>No data available on noncriteria emissions

Continued

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TABLE 6-14. Continued

| Boiler Test Series | System                                               |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup> |      |                          |
|--------------------|------------------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------|------|--------------------------|
|                    | Actual/Design Heat Input MM (10 <sup>6</sup> Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                       | ng/J | Incremental Change, ng/J |
| I (Cont.)          | 4.0/5.1 (14)/(18)                                    | Watertube   | Low Excess Air (1.1)                                | 44                        | -2                       | CO                              | 208  | +302                     |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | -1                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub> Part.           | --   | --                       |
|                    | 4.2/5.1 (14)/(18)                                    | Watertube   | Overfire Air (2.8)                                  | 25                        | --                       | CO                              | 91   | +85                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | 0                        |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub> Part.           | --   | --                       |
|                    | 4.0/5.1 (14)/(18)                                    | Watertube   | Flue Gas Recirculation (3.3)                        | 13                        | -33                      | CO                              | 5    | -1                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | 0    | 0                        |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub> Part.           | 2    | --                       |
| J                  | 2.5/3.5 (8.5)/(12)                                   | Firetube    | Baseline (7.1)                                      | 87                        | --                       | CO                              | 19   | --                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub> Part.           | --   | --                       |
|                    | 2.2/3.5 (7.5)/(12)                                   | Firetube    | Low Excess Air (6.6)                                | 90                        | +3                       | UHC                             | 50   | +31                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub> Part.           | --   | --                       |
|                    | 2.3/3.5 (2.5)/(12)                                   | Firetube    | High Excess Air (7.8)                               | 90                        | +3                       | CO                              | 55   | +36                      |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub> Part.           | --   | --                       |
| K                  | 5.8/7.3 (20)/(25)                                    | Watertube   | Baseline (10.3)                                     | 64                        | --                       | CO                              | 25   | --                       |
|                    |                                                      |             |                                                     |                           |                          | UHC                             | --   | --                       |
|                    |                                                      |             |                                                     |                           |                          | SO <sub>3</sub> Part.           | --   | --                       |

No data available on noncriteria emissions

Continued

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TABLE 6-14. Concluded

| Boiler Test Series | System                                               |             |                                                     | NO <sub>x</sub> Emissions |                          | Criteria Emissions <sup>a</sup>       |      |                          |
|--------------------|------------------------------------------------------|-------------|-----------------------------------------------------|---------------------------|--------------------------|---------------------------------------|------|--------------------------|
|                    | Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Boiler Type | NO <sub>x</sub> Control (Excess O <sub>2</sub> , %) | ng/J                      | Incremental Change, ng/J | Pollutant                             | ng/J | Incremental Change, ng/J |
| K (Cont.)          | 5.8/7.3 (20)/(25)                                    | Watertube   | Low Excess Air                                      | 67                        | +3                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 27   | +2<br>--<br>--<br>--     |
|                    | 5.7/7.3 (20)/(25)                                    | Watertube   | Low Excess Air                                      | 68                        | +4                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 31   | +6<br>--<br>--<br>--     |
|                    | 5.7/7.3 (20)/(25)                                    | Watertube   | Low Excess Air (6.1)                                | 65                        | +1                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 36   | +11<br>--<br>--<br>--    |
|                    | 5.6/7.3 (20)/(25)                                    | Watertube   | Low Excess Air (5.0)                                | 59                        | -5                       | CO<br>UHC<br>SO <sub>3</sub><br>Part. | 883  | +858<br>--<br>--<br>--   |

<sup>a</sup>No data available on noncriteria emissions

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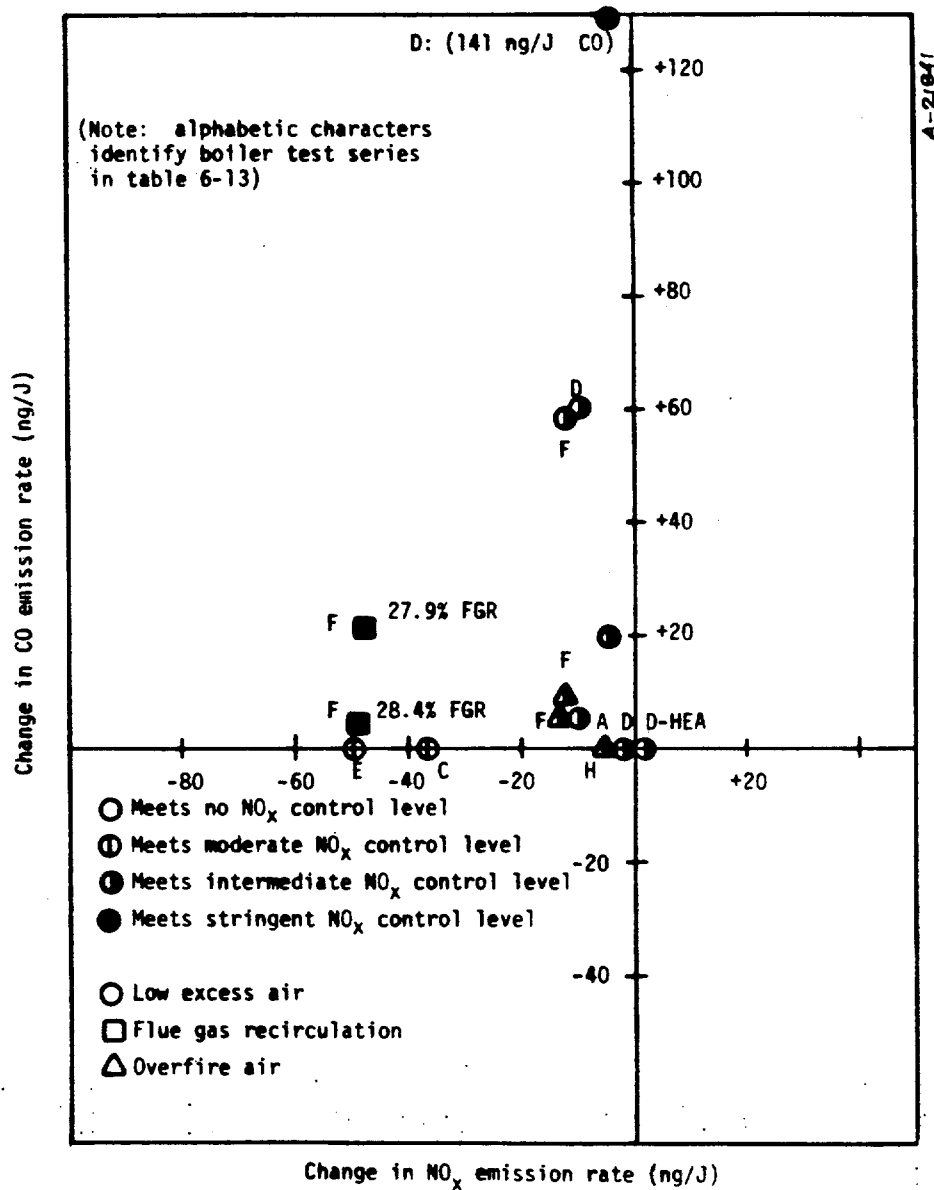


Figure 6-12. Change in CO emission rate with NO<sub>x</sub> control for distillate oil-fired industrial boilers (References 6-15 and 6-17).

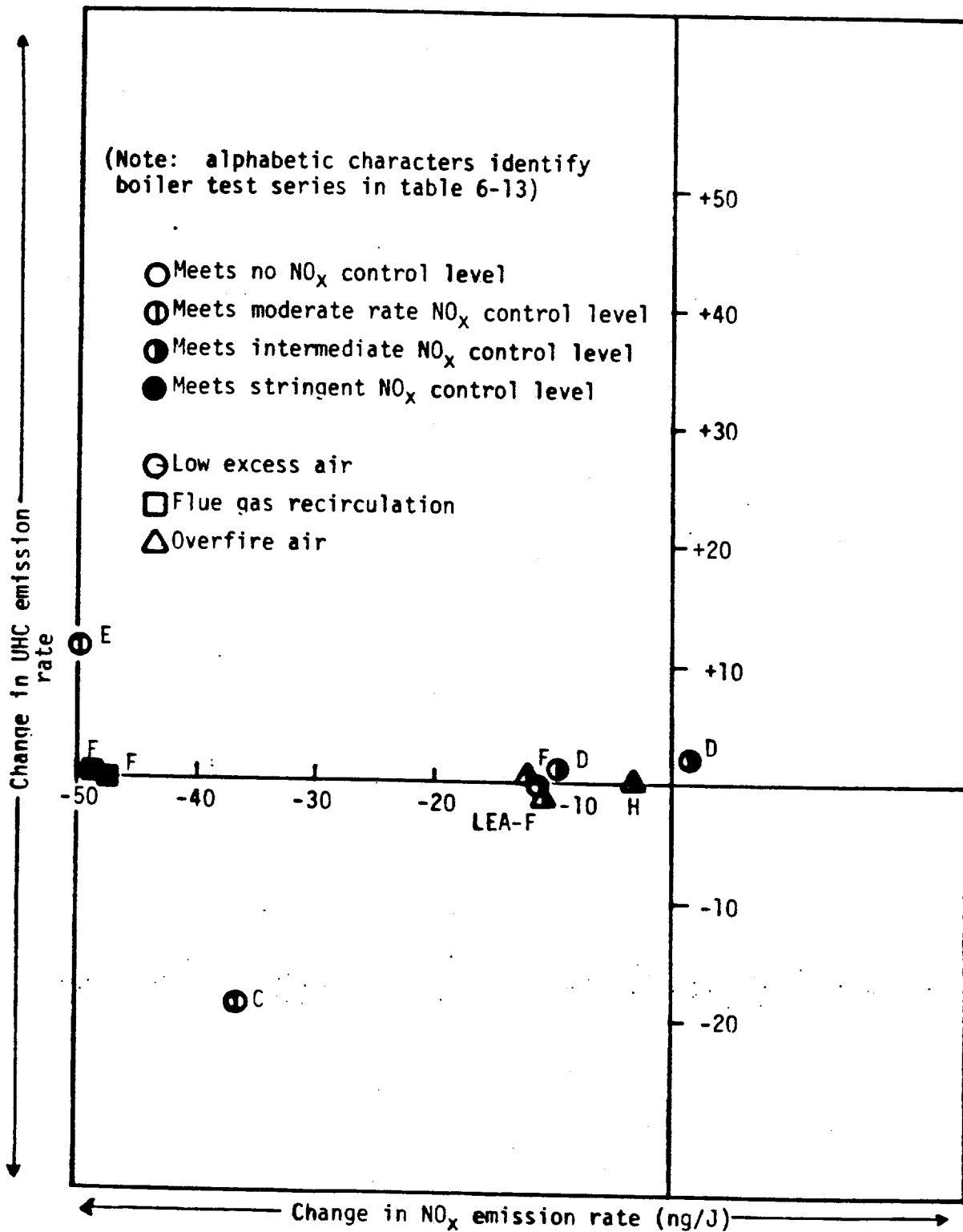


Figure 6-13. Change in UHC emission rate with  $\text{NO}_x$  control for distillate oil-fired industrial boilers (Reference 6-15 and 6-17).

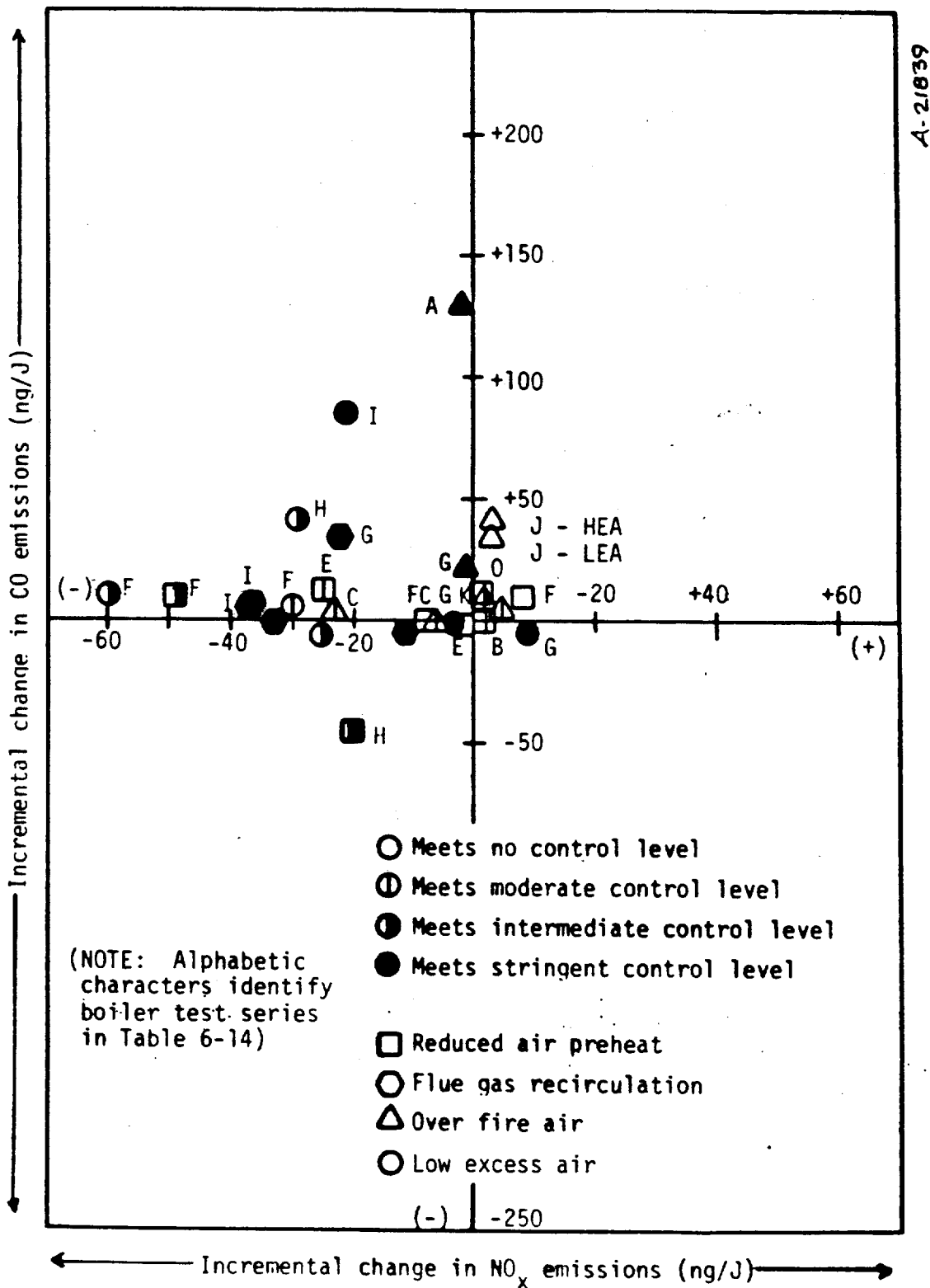


Figure 6-14. Change in CO emissions with NO<sub>x</sub> control for a gas-fired industrial boiler (Reference 6-17).

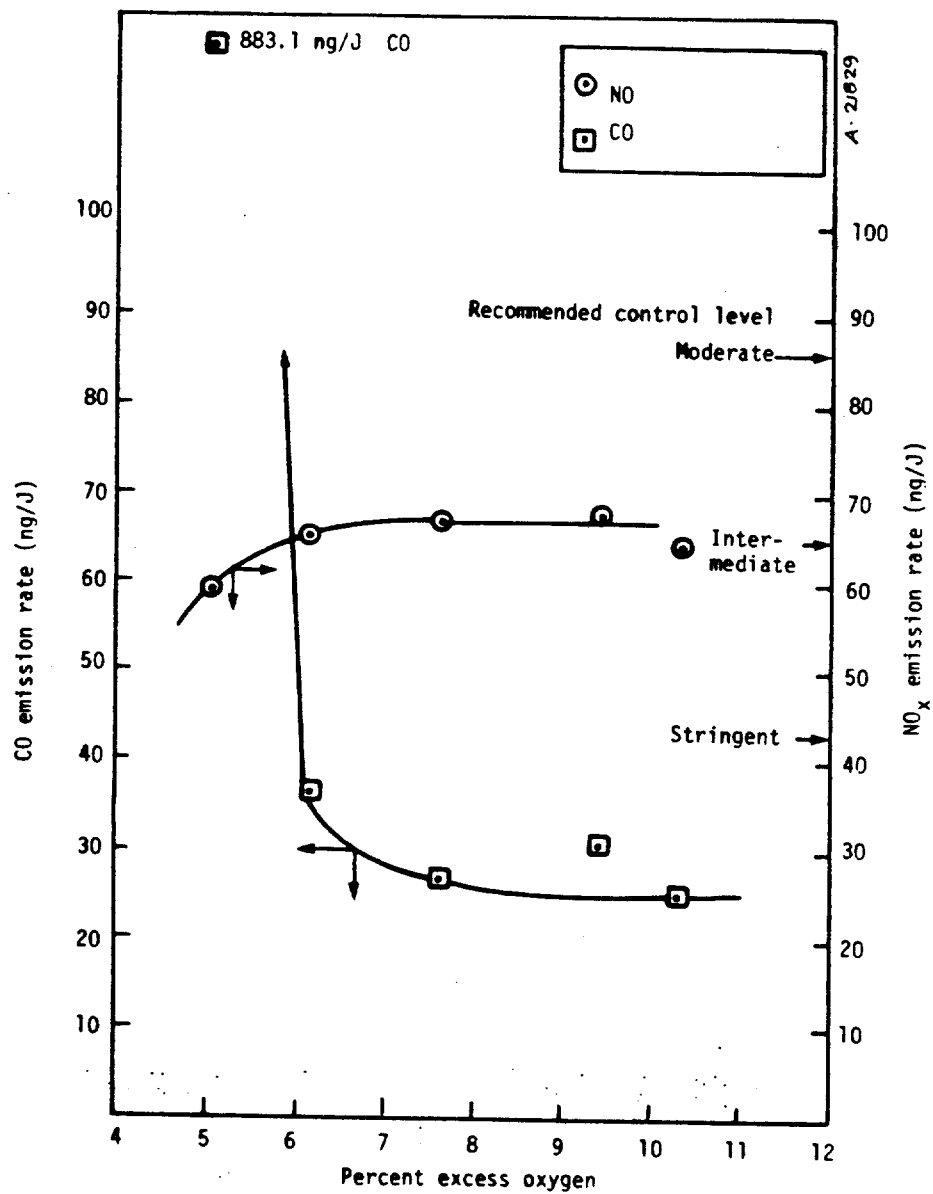


Figure 6-15. Changes in CO and NO<sub>x</sub> emissions with reduced excess oxygen for a gas-fired watertube industrial boiler (Reference 6-17).

function of low excess air levels. As with coal and residual oil, a point is reached where CO emissions begin to increase rapidly. It is readily apparent that, with this technique, a small incremental decrease in  $\text{NO}_x$  results in a large change in CO emissions at the lower excess oxygen levels.

Figure 6-16 presents the emission rates of unburned hydrocarbons. The quantity of data is very limited. Generally, however, very slight changes are noted with the various  $\text{NO}_x$  control techniques.

Particulate emissions from natural gas-fired boilers were reported as typically 1.72 to 3.01 ng/J (0.004 to 0.007 lb/10<sup>6</sup> Btu) in Reference 6-19. The reporting of particulate emissions during later test work with various  $\text{NO}_x$  techniques were omitted due to the low emission rates. Distillate oil-fired boilers emitted 8.6 to 17.2 ng/J (0.02 to 0.04 lbs/MBtu) in the same test series. Particulate emissions data (Table 6-13) are plotted in Figure 6-17. Once again, as noted with coal- and residual oil-firing, particulate emissions decrease with  $\text{NO}_x$  control. Since each of the boilers tested is equipped with a dust control device, this could indicate an increase in particle size under low  $\text{NO}_x$  conditions and improved dust control device efficiency. Table 6-15 confirms the shift to larger particles with 82.0 percent greater than 1.3 micrometers under baseline conditions and 94.5 percent greater than 1.3 micrometers under low  $\text{NO}_x$  conditions.

Emissions of sulfates, trace elements, and organics have generally not been measured during  $\text{NO}_x$  testing programs on units firing distillate oil or natural gas. This is due to the low concentrations of these components in the fuel. Therefore, no incremental emission data is available for presentation.

As with coal and residual oil fuels, low  $\text{NO}_x$  burners and ammonia injection are still in the development stages for natural gas application. Actual incremental emission data are not available.

## 6.6 OTHER POLLUTION SOURCES

The above discussions have centered around the impact of  $\text{NO}_x$  controls on the products of combustion. Generally, the pollutants are emitted from the stack as air pollutants. The decreased particulate emissions from the stack under low  $\text{NO}_x$  conditions are assumed to result from particulate collection by dust control devices. This increases the

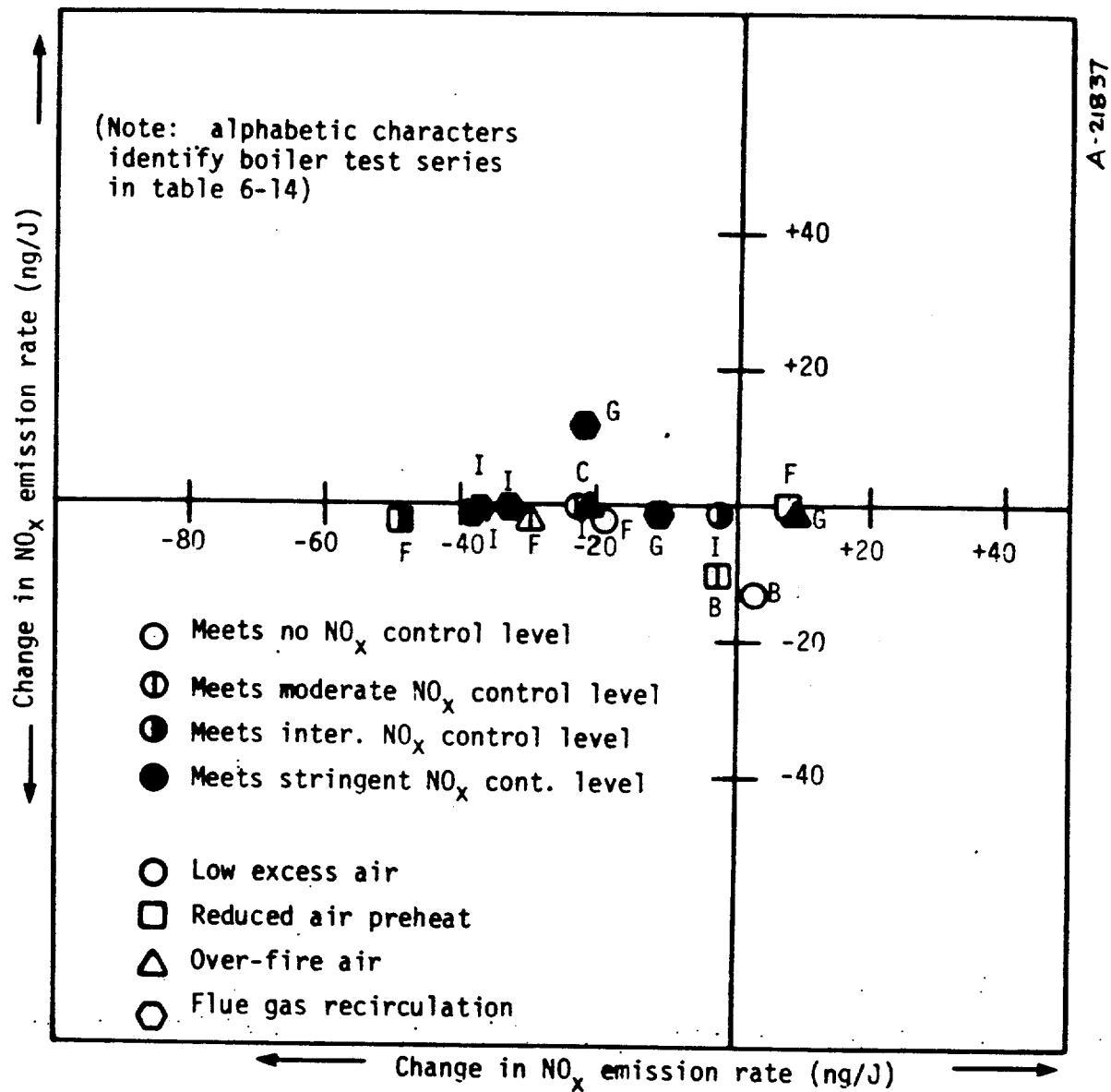


Figure 6-16. Change in unburned hydrocarbon emissions with NO<sub>x</sub> control for gas-fired industrial boilers (References 6-15 and 6-17).

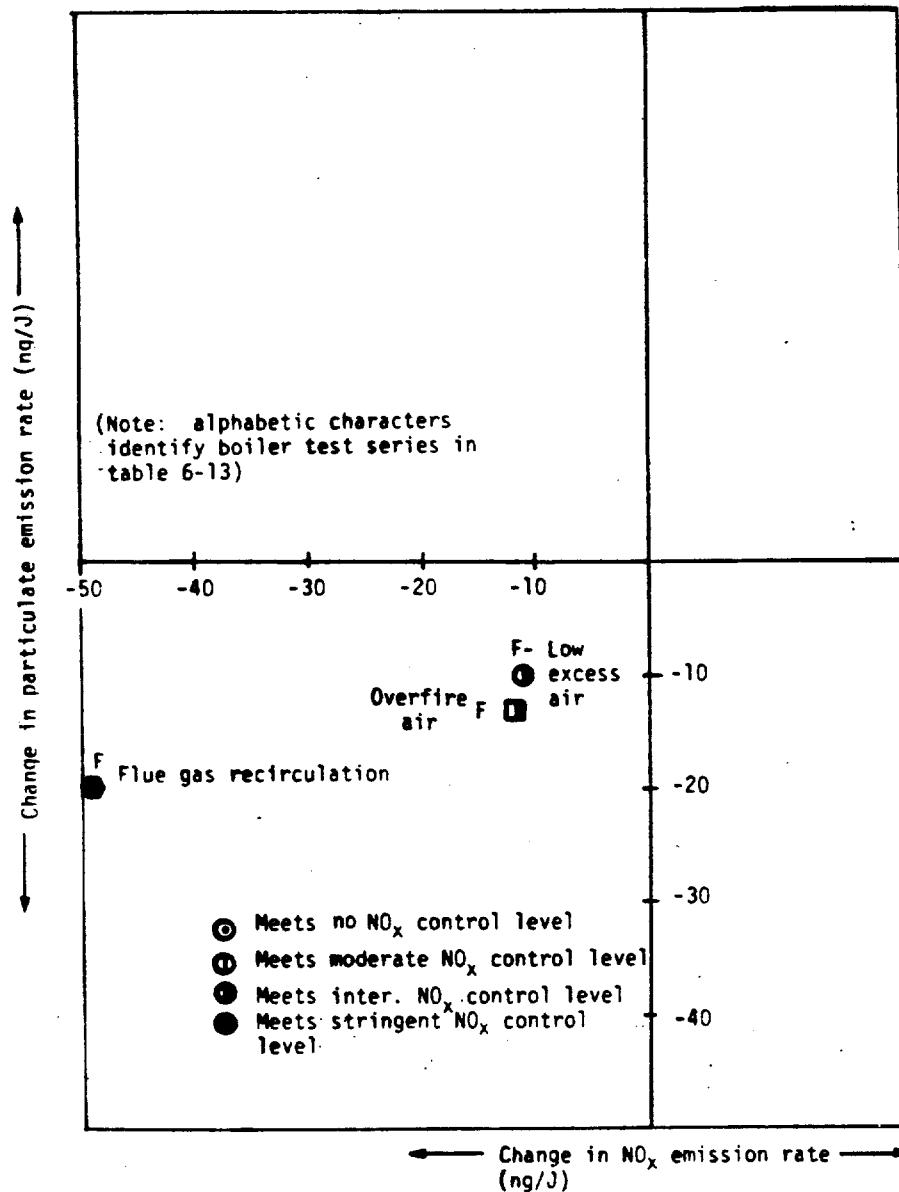


Figure 6-17. Change in particulate emissions with  $\text{NO}_x$  control for a distillate oil-fired watertube industrial boiler (Reference 6-15).



TABLE 6-15. EFFECT OF OVERFIRE AIR NO. CONTROL ON PARTICLE SIZE DISTRIBUTION FOR A DISTILLATE OIL-FIRED WATERTUBE INDUSTRIAL BOILER (Reference 6-16)

| Fuel Burner Type | Test Load<br>GJ hr <sup>-1</sup> | NO <sub>x</sub><br>ng/J | Impact Flow<br>cm <sup>3</sup> s <sup>-1</sup> | D <sub>50</sub> Cycl.<br>μm | Actual D <sub>50</sub> of Stage No. b |         |         |         |         |                   | Cyclone<br>mg | Cyclone, Stage and Filter Catch |         |         |         |         |              | Comments            |
|------------------|----------------------------------|-------------------------|------------------------------------------------|-----------------------------|---------------------------------------|---------|---------|---------|---------|-------------------|---------------|---------------------------------|---------|---------|---------|---------|--------------|---------------------|
|                  |                                  |                         |                                                |                             | Actual D <sub>50</sub> of Stage No. b |         |         |         |         | Total Catch<br>mg |               |                                 |         |         |         |         |              |                     |
|                  |                                  |                         |                                                |                             | Stage No.                             |         |         |         |         |                   |               |                                 |         |         |         |         |              |                     |
|                  |                                  |                         |                                                |                             | 1<br>μm                               | 2<br>μm | 3<br>μm | 4<br>μm | 5<br>μm |                   |               | 1<br>mg                         | 2<br>mg | 3<br>mg | 4<br>mg | 5<br>mg | Filter<br>mg |                     |
| No. 2 Steam      | 58                               | 49.4                    | 28.3                                           | --                          | 3.2                                   | 1.9     | 1.3     | 0.64    | 0.32    | None              | 96.9          | 7.55                            | 0.408   | 0.756   | 0.008   | 0.368   | 105.6        | Lower Load          |
| No. 2 Steam      | 65                               | --                      | 28.3                                           | --                          | 3.2                                   | 1.9     | 1.3     | 0.64    | 0.32    | None              | 5.60          | 0.148                           | 0.064   | 1.032   | 0.024   | 0.192   | 7.06         | Low NO <sub>x</sub> |
| No. 2 Steam      | 65                               | --                      | 28.3                                           | --                          | 3.2                                   | 1.9     | 1.3     | 0.64    | 0.32    | None              | 10.6          | 3.57                            | 0.788   | 0.62    | 0.034   | 0.20    | 15.842       | Baseline            |

aParticle size distribution determined by use of a Brink model "B" cascade impactor  
bD<sub>50</sub> identifies the size fraction in micrometers. Particulates with an aerodynamic diameter greater than the D<sub>50</sub> cut point will be captured. Increasing stage number corresponds to decreasing particle size.

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quantity of solid waste to be discharged from the system. The incremental increase in solid pollutants is expected to be small when compared to the total dust emissions from the system. No continuous sources of water are involved with the  $\text{NO}_x$  control techniques. Increased deposits within the boiler not removed as slag may require increased washing of internal surfaces. In addition, dust or slag removal devices which utilize sluicing as the transport mechanism for ash disposal may be increased slightly. However, information is not available to determine if the overall pollutant burden (leachate concentration, chemical oxygen demand, suspended solids content, etc.) would be impacted.

Pollution increases due to thermal and electrical discharge are not expected to increase. Noise pollution would be affected by any increase in operating equipment (such as fans for flue gas recirculation). However, it is not expected that the incremental increase will be measurable when compared to the overall plant noise level.

#### 6.7 SUMMARY

Tables 6-16 through 6-19 compare the recommended  $\text{NO}_x$  control techniques, the levels of control achievable, and the resulting incremental changes in other pollutant emissions. Where actual data are not available, a postulated effect is presented.

Carbon monoxide levels generally increase with  $\text{NO}_x$  control, although this can be minimized if not eliminated with judicious application of the control. Actual test data shows unburned hydrocarbon emissions to be decreased more often than increased, though the data are variable. Sulfate emissions decrease with decreasing oxygen content; particulate emissions decrease due to an (assumed) increase in particulate control device collection efficiency. The best  $\text{NO}_x$  control device for industrial boilers firing coal appear to be low excess air and staged combustion (overfire air), but information is too limited to be conclusive.

Low excess air and staged combustion (overfire air) appears to have little effect on incremental emissions from residual oil-fired boilers. For distillate oil- and natural gas-fired boilers, flue gas recirculation, staged combustion, and reduced air preheat appear to be the best methods available.

Incremental emissions are potentially increased by  $\text{NO}_x$  controls. More data are needed to quantify the incremental emissions for each control technique and to determine if any significant environmental impact may result.

TABLE 6-16. POSTULATED EFFECT OF CANDIDATE NO<sub>x</sub> CONTROL SYSTEMS ON INCREMENTAL EMISSIONS FROM COAL-FIRED INDUSTRIAL BOILERS

| Boiler                     | NO <sub>x</sub> Control Technique | Level of Control | Change in Incremental Emissions |      |                 |             |
|----------------------------|-----------------------------------|------------------|---------------------------------|------|-----------------|-------------|
|                            |                                   |                  | CO                              | UHC  | SO <sub>3</sub> | Particulate |
| Coal-Fired Boiler ≥ 29 MW  | Low Excess Air                    | Moderate         | +                               | -    | (-)             | (-)a        |
|                            |                                   | Intermediate     | +                               | -    | -               | -           |
|                            |                                   | Stringent        | +                               | v    | -               | -           |
|                            | Overfire Air                      | Intermediate     | +                               | (+)  | (-)             | (-)a        |
|                            |                                   | Stringent        | +                               | +    | -               | (-)a        |
| Coal-Fired Boilers < 29 MW | Low NO <sub>x</sub> Burners       | Stringent        | (+)                             | (+)  | (-)             | (-)a        |
|                            | Ammonia Injection <sup>b</sup>    | Stringent        | (NE)                            | (NE) | (+)             | (NE)        |
|                            | Low Excess Air                    | Intermediate     | -                               | +    | (-)             | -           |
|                            |                                   | Stringent        | v                               | (+)  | (-)             | (-)a        |

( ) No data available  
 - Some decrease  
 + Some increase  
 v Variable results  
 NE No effect

<sup>a</sup>Assuming dust control devices are utilized, otherwise (+)  
<sup>b</sup>Ammonia injection may cause ammonia and byproduct emissions

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TABLE 6-17. POSTULATED EFFECT OF CANDIDATE NO<sub>x</sub> CONTROL SYSTEMS ON INCREMENTAL EMISSIONS FROM RESIDUAL OIL-FIRED INDUSTRIAL BOILERS

| NO <sub>x</sub> Control Technique | Level of Control | Change in Incremental Emissions |      |                 |                  |
|-----------------------------------|------------------|---------------------------------|------|-----------------|------------------|
|                                   |                  | CO                              | UHC  | SO <sub>3</sub> | Particulate      |
| Low Excess Air                    | Moderate         | +                               | (+)  | (-)             | -                |
|                                   | Intermediate     | +                               | v    | -               | -                |
|                                   | Stringent        | ++                              | v    | -               | -                |
| Overfire Air                      | Moderate         | (+)                             | (+)  | (-)             | (-) <sup>a</sup> |
|                                   | Intermediate     | +                               | +    | (-)             | -                |
|                                   | Stringent        | +                               | +    | -               | -                |
| Low NO <sub>x</sub> Burners       | Intermediate     | (+)                             | (+)  | (-)             | (-) <sup>a</sup> |
|                                   | Stringent        | (+)                             | (+)  | (-)             | (-) <sup>a</sup> |
| Ammonia Injection                 | Stringent        | (NE)                            | (NE) | (+)             | (NE)             |

( ) No data available

- Some decrease

+ Some increase

++ Significant increase

<sup>a</sup> Assuming dust control devices are utilized. Otherwise (+)

v Variable results

NE No Effect

TABLE 6-18. POSTULATED EFFECT OF CANDIDATE NO<sub>x</sub> CONTROL SYSTEMS ON INCREMENTAL EMISSIONS FROM DISTILLATE OIL-FIRED INDUSTRIAL BOILERS

| NO <sub>x</sub> Control Technique | Level of Control | Change in Incremental Emissions |      |                 |             |
|-----------------------------------|------------------|---------------------------------|------|-----------------|-------------|
|                                   |                  | CO                              | UHC  | SO <sub>3</sub> | Particulate |
| Low Excess Air                    | Moderate         | (+)                             | (+)  | (-)             | (-)         |
|                                   | Intermediate     | ++                              | -    | (-)             | (-)a        |
|                                   | Stringent        | (++)                            | (+)  | (-)             | (-)a        |
| Flue Gas Recirculation            | Moderate         | (+)                             | (+)  | (-)             | (-)a        |
|                                   | Intermediate     | (+)                             | (+)  | (-)             | (-)a        |
|                                   | Stringent        | +                               | +    | (-)             | (-)a        |
| Overfire Air                      | Moderate         | (+)                             | (+)  | (-)             | (-)a        |
|                                   | Intermediate     | +                               | +    | (-)             | -           |
|                                   | Stringent        | +                               | +    | -               | -           |
| Reduced Air Preheat               | Intermediate     | (NE)                            | (NE) | (-)             | (+)         |
|                                   | Stringent        | (NE)                            | (NE) | (-)             | (+)         |
| Low NO <sub>x</sub> Burners       | Stringent        | (+)                             | (+)  | (-)             | (-)a        |

( ) No data available

- Some decrease

+ Some increase

++ Significant increase

a Assuming dust control devices are utilized. Otherwise (+)

NE No Effect

TABLE 6-19. POSTULATED EFFECT OF CANDIDATE NO<sub>x</sub> CONTROL SYSTEMS ON INCREMENTAL EMISSIONS FROM GAS-FIRED INDUSTRIAL BOILERS

| NO <sub>x</sub> Control Technique | Level of Control | Change in Incremental Emissions <sup>a</sup> |     |
|-----------------------------------|------------------|----------------------------------------------|-----|
|                                   |                  | CO                                           | UHC |
| Low Excess Air                    | Moderate         | +                                            | (+) |
|                                   | Intermediate     | +                                            | -   |
|                                   | Stringent        | +                                            | (+) |
| Flue Gas Recirculation            | Moderate         | (+)                                          | (+) |
|                                   | Intermediate     | (+)                                          | (+) |
|                                   | Stringent        | -                                            | (+) |
| Overfire Air                      | Moderate         | +                                            | (+) |
|                                   | Intermediate     | +                                            | (+) |
|                                   | Stringent        | -                                            | -   |
| Reduced Air Preheat               | Moderate         | +                                            | -   |
|                                   | Intermediate     | +                                            | (+) |
|                                   | Stringent        | +                                            | (+) |
| Low NO <sub>x</sub> Burners       | Stringent        | (+)                                          | (+) |

( ) No data available

- Some decrease

+ Some increase

++ Significant increase

<sup>a</sup> SO<sub>3</sub> and particulate not present in natural gas combustion products

## REFERENCES FOR SECTION 6

- 6-1. Mason, H. B. et al., "Preliminary Environmental Assessment of Combustion Modification Techniques, Volume II, Technical Results," EPA-600/7-77-119b, NTIS-PB 276 681/AS, October 1977.
- 6-2. Vapor Phase Organic Pollutants -- Volatile Hydrocarbons and Oxidation Products, National Academy of Sciences, Washington, 1976.
- 6-3. Particulate Polycyclic Organic Matter, National Academy of Sciences, Washington, 1972.
- 6-4. Surprenant, N., et al., "Preliminary Emissions Assessment of Conventional Stationary Combustion Systems," EPA-600/7-76-046a, NTIS-PB 251 612/8BA, January 1976.
- 6-5. Richards, J., and R. Gerstle, "Stationary Source Control Aspects of Ambient Sulfates: A Data Base Assessment," PEDCo Final Report, EPA Contract No. 68-02-1321, Task 34, PEDCo Environmental, Cincinnati, OH, February 1976.
- 6-6. Bittner, J. D., et al., "The Formation of Soot and Polycyclic Aromatic Hydrocarbons in Combustion Systems," in Proceedings of the Stationary Source Combustion Symposium, Vol. 1, EPA-600/2-76-152a, NTIS-PB 256 320/AS, June 1976.
- 6-7. Knierien, H., Jr., "A Theoretical Study of PCB Emissions from Stationary Sources," EPA-600/7-76-028, NTIS-PB 262 850/AS, September 1976.
- 6-8. Klein, D. H., et al., "Pathways of Thirty-Seven Trace Elements through Coal-Fired Powerplant," Environmental Science and Technology, Vol. 9, No. 10, pp 973-979, October 1975.
- 6-9. Davison, R. L., et al., "Trace Elements in Flyash," Environmental Science and Technology, Vol. 8, No. 13, pp. 1107-1113, December 1974.
- 6-10. Kaakinen, J. W., et al., "Trace Element Behavior in Coal-Fired Powerplant," Environmental Science and Technology, Vol. 9, No. 9 pp. 862-869, September 1975.
- 6-11. Cato, G. A., and R. A. Venezia, "Trace Metal and Organic Emissions of Industrial Boilers," Paper 76-27.8, 69th Annual APCA Meeting, June 1976.
- 6-12. "Coal-Fired Powerplant Trace Element Study, Vol. I, A Three Station Comparison," Radian Corp. report for EPA Region VIII, NTIS-PB 257 293/18E, September 1975.

- 6-13. Gladney, E. S., et al., "Composition and Size Distributions of Atmospheric Particulate Matter in Boston Area," Environmental Science and Technology, Vol. 8, No. 6, p. 551, June 1974.
- 6-14. Ensor, D. S., et al., "Elemental Analysis of Flyash from Combustion of a Low Sulfur Coal," Paper 75-33.7, 68th Annual APCA Meeting, June 1975.
- 6-15. "Cato, G. A., et al., "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers -- Phase II," EPA-600/2-76-086a, NTIS-PB 253 500/AS, April 1976.
- 6-16. Cato, G. A., "Field Testing: Trace Element and Organic Emissions from Industrial Boilers," EPA-600/2-76-086b, NTIS-PB 261 263/AS, October 1976.
- 6-17. Heap, M. P., et al., "Reduction of Nitrogen Oxide Emissions from Package Boilers," EPA-600/2-77-025, NTIS-PB 269 277, January 1977.
- 6-18. Carter, W. A., et al., "Emission Reduction on Two Industrial Boilers with Major Combustion Modifications," EPA-600/7-78-099a, NTIS-PB 263 109, June 1978.
- 6-19. Cato, G. A., et al., "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers -- Phase I," EPA-650/2-74-078a, NTIS-PB 238 920/AS, October 1974.
- 6-20. Maloney, K. L., et al., "Low Sulfur Western Coal Use in Existing Small and Intermediate Size Boilers," EPA-600/7-78-153a, NTIS-PB 287 937/AS, July 1978.
- 6-21. Gabrielson, J. E., et al., "Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement -- Site A," EPA-600/7-78-136a, NTIS-PB 285 972/AS, July 1978/
- 6-22. Goldberg, P.M., and E. B. Higginbotham, "Field Testing of an Industrial Stoker Coal-Fired Boiler -- Effects of Combustion Modification NO<sub>x</sub> Control on Emissions -- Site A," Acurex Report TR-79-25/EE, EPA Contract No. 68-02-2160, Acurex Corp., Mountain View, CA, August 1979.
- 6-23. Lips, H. I., and E. B. Higginbotham, "Field Testing of an Industrial Stoker Coal-Fired Boiler -- Effects of Combustion Modification NO<sub>x</sub> Control on Emissions -- Site B," Acurex Report TR-79-18/EE, EPA Contract No. 68-02-2160, Acurex Corp., Mountain View, CA August 1979.



## SECTION 7

### EMISSION SOURCE TEST DATA

This section contains the experimental data recorded on tests of various NO<sub>x</sub> emission controls conducted on industrial boilers. Data selection and test methods are summarized. These data (References 7-1 through 7-9) were used to generate the baseline and controlled NO<sub>x</sub> emission levels presented in the preceding sections of this report.

#### 7.1 CRITERIA FOR SELECTION

A brief description of the data selection procedure follows in Section 7.1.1. Section 7.1.2 summarizes the test methods used.

##### 7.1.1 Data Selection

Where possible, the data selected from published tests had to meet certain prescribed criteria to be included in the NO<sub>x</sub> control technology assessment. These criteria included:

- Well planned and controlled experimental conditions in which only the parameter under investigation was allowed to vary. All other important parameters were held as constant as practically possible.
- Characterization and documentation of all major parameters and conditions during the test, such as fuel analysis, and boiler and burner design and operating variables.
- Representative boilers with representative baseline emissions. In some cases, however, very limited data did not permit a determination of representativeness. These cases have been noted in the text of this report.
- Reasonableness of the data. In some cases extreme values are given, as these were the only data available. These values are generally noted and this section contains, in addition to the

parameters associated with these data, other data which support more moderate values, if available.

- Reliability and reproducibility of the data. In many cases, because of the very limited number of tests run, reproducibility could not be confirmed.

In the following data tables in this Section, a few selected test points may involve unacceptable operating conditions, as defined by:

- CO emissions >400 ppm @ 3 percent O<sub>2</sub>
- Bacharach smoke spot no. > 4
- Opacity >20 percent

Those controlled test points with high CO and/or smoke emissions are indicated with an asterisk (\*) in the data tables. However, it should be pointed out that in most cases, these "special" test points already had baseline NO<sub>x</sub> emission levels meeting or exceeding the suggested moderate control level (and in some cases even the stringent control level), all under acceptable operating conditions. And therefore it is not unexpected that further application of combustion modifications may lead to unacceptable operating conditions. Thus these data points are included here, in order for the data base to be complete and to project ranges of extreme control, as observed by field investigators.

#### 7.1.2 Test Methods

The two major investigative groups, KVB and Ultrasystems, used both wet chemical and instrumental methods. For instance, one group (KVB) used EPA Method 5 for particulate matter and EPA Method 9 for opacity. For sulfur oxides they used the Shell-Emeryville wet chemical procedure and for the remaining gases they used instruments obtained from a variety of manufacturers. The other group, Ultrasystems, principally used instrumentation to measure concentration. Selection of the methods used by both companies were primarily based on:

- Portability. All boilers investigated were in the field;
- Cost. Despite their high initial cost, most instruments if properly calibrated and maintained are more cost-effective than the wet analytical methods they replace;
- Reliability. Properly calibrated and maintained instruments are generally far more reliable than the wet methods they replace.

Table 7-1 lists the types of monitors employed by the two principal groups of investigators and their operating principles. A brief synopsis of the errors associated with the measurement of each of the pollutants follows. Only those for NO/NO<sub>x</sub> are presented. The reader is referred to Reference 7-4 for a complete discussion of the methods employed.

Nitrogen oxides concentrations were measured by a Thermo Electron model 10A analyzer. The functional basis of the instrument is the chemiluminescent reaction of NO and O<sub>3</sub> to form NO<sub>2</sub> in an excited state. When excited NO<sub>2</sub> molecules revert to their ground state, light emission results. The resulting chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier tube. The output of the photomultiplier is electronically processed so it is linearly proportional to the NO concentration.

Because the analyzer is sensitive only to NO, total NO<sub>x</sub> is determined by reducing any NO<sub>2</sub> in the sample to NO. Reduction is thermal, the gas being passed through a thermally insulated resistance-heated stainless steel coil. NO<sub>2</sub> can be obtained by taking the difference in readings with and without the converter in operation, and assuming that  $NO + NO_2 = NO_x$ .

The specifications of the instrument are presented below:

|                           |                                                                         |
|---------------------------|-------------------------------------------------------------------------|
| Accuracy                  | 1% of full scale                                                        |
| Span stability            | ± 1% of full scale in 24 hours                                          |
| Zero stability            | ± 1 ppm in 24 hours                                                     |
| Power requirements        | 115 ± 10V, 60 Hz, 1000 watts                                            |
| Response                  | 90% of full scale in 1 second (NO <sub>x</sub> mode), 0.7 sec (NO mode) |
| Output                    | 4 - 20 ma                                                               |
| Sensitivity               | 0.5 ppm                                                                 |
| Linearity                 | ± 1% of full scale                                                      |
| Vacuum detector operation |                                                                         |
| Range                     | 2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm full scale                |

Other criteria pollutants are listed in Table 7-1 along with the instrument or test method used. The reader is referred to Section 6 for a listing of the criteria pollutant emission data associated with NO<sub>x</sub>.

TABLE 7-1. EMISSION MEASUREMENT INSTRUMENTATION

| Emission                    | Symbol                             | KVB (References 7-4 and 7-5)        |                                                            | Ultrasystems (Reference 7-2) |                                         |
|-----------------------------|------------------------------------|-------------------------------------|------------------------------------------------------------|------------------------------|-----------------------------------------|
|                             |                                    | Measurement Method                  | Equipment Manufacturer and Model Number                    | Measurement Method           | Equipment Manufacturer and Model Number |
| Nitric oxide                | NO                                 | Chemiluminescent                    | Thermo Electron 10A                                        | Chemiluminescent             | Thermo-Electronic                       |
| Oxides of nitrogen          | NO <sub>x</sub>                    | Chemiluminescent                    | Thermo Electron 10A                                        | Chemiluminescent             | Thermo-Electronic                       |
| Carbon monoxide             | CO                                 | Spectrometer                        | Beckman 865                                                | Spectrometer                 | MSA LIRA-303                            |
| Carbon dioxide              | CO <sub>2</sub>                    | Spectrometer                        | Beckman 864                                                | --                           | --                                      |
| Oxygen                      | O <sub>2</sub>                     | Polarographic                       | Teledyne 325A                                              | Polarographic                | Theta Sensor                            |
| Hydrocarbons                | HC                                 | Flame ionization                    | Beckman 402                                                | --                           | --                                      |
| Sulfur dioxide and trioxide | SO <sub>2</sub><br>SO <sub>3</sub> | Absorption/<br>titration            | KVB Equipment Company                                      | Electrochemical              | Theta Sensor                            |
| Total particulate matter    | PM                                 | EPA Method 5                        | Joy Manufacturing Company                                  | --                           | --                                      |
| Particulate size            | --                                 | Visual counting<br>Cascade Impactor | Millipore Corporation <sup>a</sup> XI50<br>Monsanto-Brinkb | --                           | --                                      |
| Smoke spot                  | K                                  | Reflectance<br>Photometric          | Research Appliance Company<br>G2R-100                      | Visual                       | Bacharach                               |
| Opacity                     | --                                 | EPA Method 9                        | --                                                         | --                           | --                                      |

<sup>a</sup> Reference 7-4.<sup>b</sup> References 7-3, 7-5.<sup>c</sup> Backup measurements made with Theta Sensor US-6000 analyzer.<sup>d</sup> Backup measurements made with Teledyne 320AX.<sup>e</sup> SO<sub>2</sub> only.

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controls, and to References 7-2 and 7-4 for a discussion of the instruments and/or techniques employed.

## 7.2 EMISSION SOURCE TEST DATA FOR COAL-FIRED BOILERS

Coal-fired industrial boilers have been tested during several EPA sponsored field investigations (References 7-4, 7-5 and 7-7 through 7-9). These include six pulverized coal-fired units, one cyclone, twelve spreader stokers, two underfeed stokers, two chain grate stokers and a vibrating grate stoker. Tables 7-2 through 7-4 present the results of  $\text{NO}_x$  emission controls as applied to pulverized coal and cyclone boilers; Tables 7-5 through 7-8 present the results for various stokers.

The measurement of nitrogen oxides and the errors associated with these measurements have been described in Section 7.1. The direct experimental readings were in parts per million. These were corrected to the nominal 3 percent oxygen level and further corrected for water. The results were then converted into an input specific value,  $\text{ng/J}$  or  $\text{lb}/10^6 \text{ Btu}$  by:

- Knowing the higher heating value (HHV) of the fuel and the amount of fuel consumed in a given period of time, or
- Knowing the size of the boiler (the number of pounds of steam produced in a given period of time and the exact relationship between this with the HHV of the fuel, i.e., boiler efficiency).

As fuel consumption was not well documented, the unit conversion constants used by the investigators (References 7-4 and 7-5) were based on (b) from which they obtained a constant for each type of fuel for the conversion.

## 7.3 EMISSION SOURCE TEST DATA FOR OIL-FIRED INDUSTRIAL BOILERS

Tables 7-9 through 7-15 summarize the results of various  $\text{NO}_x$  emission controls as applied to a series of boilers burning residual oil. The data were obtained from a large number of tests run on industrial boilers under various EPA programs (References 7-1 through 7-6). The criteria used for selecting these data are listed in Section 7.1.

Residual oils employed in these tests consisted of No. 5 and No. 6 fuel oil and two others, NSF oil and PS 300 oil, which both qualify on the basis of viscosity as No. 5 oils. In addition to the effects of low excess air on boilers burning residual oil, Table 7-9 shows the effects of two differing No. 6 oils on the  $\text{NO}_x$  emissions of a watertube industrial

TABLE 7-2. NO<sub>x</sub> EMISSION TEST DATA FROM PULVERIZED COAL-FIRED INDUSTRIAL BOILERS WITH LOW EXCESS AIR (LEA)

| Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Control Method | Fuel Characteristics        |      |      |       | Number of Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> ng NO <sub>2</sub> /J (10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> ng NO <sub>2</sub> /J (10 <sup>6</sup> Btu) |      |                          | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification        | Remarks           | Reference |
|------------------------------------------------------|----------------|-----------------------------|------|------|-------|------------------------------|---------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|------|--------------------------|------------------------------------------------|-------------------------|------------------------------|-------------------|-----------|
|                                                      |                | Heat Value                  | % N  | % S  | % Ash |                              |                                                                                             | Low                                                                                           | High | Average                  |                                                |                         |                              |                   |           |
| 53.5/65.9 (182)/(225)                                | LEA 5.3-4.5    | 26.57 <sup>f</sup> (11,430) | 1.40 | 4.20 | 9.36  | 1                            | 234 (0.544)                                                                                 | --                                                                                            | --   | 222 (0.517)              | 5                                              | Intermediate            | # 12-24, 19, 17 <sup>h</sup> | --                | 7-1       |
| 76.2/91.8 (260)/(320)                                | LEA 5.8-4.8    | 25.94 (11,160)              | 1.34 | 2.74 | 11.58 | 1                            | 296 (0.688)                                                                                 | --                                                                                            | --   | 303 (0.704)              | -2                                             | --                      | # 12-20, 1, 17               | --                | 7-1       |
| 38.1/76.2 (130)/(260)                                | LEA 7.4-6.6    | 27.58 (11,063)              | 0.83 | 1.15 | 10.5  | 1                            | 563 (1.31)                                                                                  | --                                                                                            | --   | 529 <sup>g</sup> (1.23)  | 6                                              | --                      | # 31-7, SM, 17               | --                | 7-1       |
| 117/147 (400)/(500)                                  | LEA 8.6-8.1    | 28.59 (12,300)              | 1.50 | 1.36 | 14.48 | 1                            | 216 (0.502)                                                                                 | --                                                                                            | --   | 212 (0.493)              | 2                                              | Stringent               | # 13-2, SM, 17               | Multifuel Furnace | 7-1       |
| 38.0/67.2 (130)/(230)                                | LEA 4.5-3.4    | 21.70 (9,336)               | 0.73 | 0.81 | 10.04 | 1                            | 201 <sup>i</sup> (0.467)                                                                    | --                                                                                            | --   | 152 <sup>i</sup> (0.353) | 25                                             | Stringent               | Alma #3, SM, 17              | --                | 7-7       |
| 38.0/67.2 (130)/(230)                                | LEA 6.1-4.0    | 25.04 (10,776)              | 1.09 | 3.68 | 14.49 | 1                            | 244 <sup>i</sup> (0.567)                                                                    | --                                                                                            | --   | 197 <sup>i</sup> (0.458) | 19                                             | Stringent               | Alma #3, SM, 17              | --                | 7-7       |
| 32.8/46.7 (112)/(160)                                | LEA 5.1-3.4    | 24.9 (10,741)               | 0.93 | 0.32 | 6.89  | 1                            | 174 <sup>i</sup> (0.401)                                                                    | --                                                                                            | --   | 136 <sup>i</sup> (0.316) | 22                                             | Stringent               | Frement #6 SM, 17            | --                | 7-7       |
| 93.8/117 (320)/(400)                                 | LEA 3.4-3.1    | 30.66 (13,190)              | 1.55 | 2.92 | 7.78  | 1                            | 494 (1.15)                                                                                  | --                                                                                            | --   | 470 (1.09)               | 5                                              | --                      | #20-42, Cy, 17               | --                | 7-1       |

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<sup>a</sup> All reported tests were short-term (3 hr).  
<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
<sup>c</sup> Based on average of all tests.  
<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.  
<sup>e</sup> Excess oxygen, S, first value is high excess air (baseline) condition, second value is low excess air condition.  
<sup>f</sup> MJ/kg (Btu/lb) as received.  
<sup>g</sup> 1, tangential; SM, single wall; Cy, cyclone.  
<sup>h</sup> 1, water tube.  
<sup>i</sup> Estimate only. NO<sub>x</sub> values assume NO<sub>2</sub> is 5% of total (only NO was measured).  
<sup>j</sup> May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

TABLE 7-3. NO<sub>x</sub> EMISSION TEST DATA FROM PULVERIZED COAL-FIRED INDUSTRIAL BOILERS WITH BURNERS-OUT-OF-SERVICE (BOOS)

| Actual/Design Heat Input<br>MB (10 <sup>6</sup> Btu/hr) | Control Method     | Fuel Characteristics |        |        |          | Number of Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                            | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported <sup>d</sup> | Boiler Identification | Remarks                                                                  | Reference |
|---------------------------------------------------------|--------------------|----------------------|--------|--------|----------|------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|----------------------------|------------------------------------------------|--------------------------------------|-----------------------|--------------------------------------------------------------------------|-----------|
|                                                         |                    | Heat Value           | S<br>N | S<br>S | S<br>Ash |                              |                                                                                                                    | Low                                                                                                                  | High | Average                    |                                                |                                      |                       |                                                                          |           |
| 18.8/76.2<br>(64)/(260)                                 | BOOS, <sup>e</sup> | 27.587<br>(11.863)   | 0.83   | 1.15   | 10.5     | 1                            | 618<br>(1.44)                                                                                                      | --                                                                                                                   | --   | 378 <sup>g</sup><br>(0.88) | 39                                             | --                                   | 8 31-7, SM, 9<br>WT   | Only 32% NO <sub>x</sub> reduction when compared to baseline at 50% load | 7-1       |
| 38.1/67.2<br>(130)/(230)                                | BOOS, <sup>f</sup> | 25.04<br>(10.776)    | 1.09   | 3.68   | 14.49    | 1                            | 197<br>(0.458)                                                                                                     | --                                                                                                                   | --   | 144<br>(0.135)             | 27                                             | Stringent                            | Alma #3<br>SM, WT     | 4% excess O <sub>2</sub>                                                 | 7-7       |

<sup>a</sup> All reported tests were short-term (3 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.

<sup>e</sup> Burner pattern 2 X 2, top row firing air only.

<sup>f</sup> Burner pattern 2 X 2, top row firing air only.

<sup>g</sup> SM, single wall.

<sup>h</sup> WT, water tube.

<sup>i</sup> Burner pattern 2 X 2, top right firing air only.

<sup>j</sup> Estimate only. NO<sub>x</sub> values assume NO<sub>2</sub> is 5% of total (only NO was measured).

\* May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

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TABLE 7-4. NO<sub>x</sub> EMISSION TEST DATA FROM PULVERIZED COAL-FIRED INDUSTRIAL BOILERS WITH LOAD REDUCTION (LR)

| Actual/Design<br>Heat Input<br>MW (10 <sup>6</sup> Btu/hr) | Control<br>Method | Fuel Characteristics           |        |        |          | Number of<br>Tests <sup>c</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                             | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported <sup>d</sup> | Boiler<br>Identification | Remarks                             | Reference |
|------------------------------------------------------------|-------------------|--------------------------------|--------|--------|----------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|-----------------------------|------------------------------------------------------|--------------------------------------------|--------------------------|-------------------------------------|-----------|
|                                                            |                   | Heat<br>Value                  | %<br>H | %<br>S | %<br>Ash |                                 |                                                                                                                    | Low                                                                                                                  | High | Average                     |                                                      |                                            |                          |                                     |           |
| --/(93.8<br>--/(320))                                      | LRF<br>94-62      | 25.94 <sup>f</sup><br>(11,160) | 1.34   | 2.74   | 11.58    | 1                               | 209<br>(0.486)                                                                                                     | --                                                                                                                   | --   | 144<br>(0.335)              | 31                                                   | Stringent                                  | # 12-20,<br>19, WT       | 4% excess O <sub>2</sub>            | 7-1       |
| --/(147<br>--/(500))                                       | LR<br>92-64       | 28.59<br>(12,300)              | 1.50   | 1.36   | 14.48    | 1                               | 233<br>(0.541)                                                                                                     | --                                                                                                                   | --   | 197 <sup>g</sup><br>(0.458) | 15                                                   | Stringent                                  | # 13-2,<br>SW, WT        | 9% excess O <sub>2</sub>            | 7-1       |
| --/(76.2<br>--/(260))                                      | LR<br>50-25.4     | 27.58<br>(11,863)              | 0.83   | 1.15   | 10.5     | 1                               | 592<br>(1.38)                                                                                                      | --                                                                                                                   | --   | 618<br>(1.44)               | -4                                                   | --                                         | # 31-7,<br>SW, WT        | 7% excess O <sub>2</sub>            | 7-1       |
| --/(117<br>--/(400))                                       | LR<br>100-60      | 30.66<br>(13,190)              | 1.55   | 2.92   | 7.78     | 1                               | 489<br>(1.14)                                                                                                      | --                                                                                                                   | --   | 489<br>(1.07)               | 6                                                    | --                                         | # 20-42, WT              | Cyclone<br>3% excess O <sub>2</sub> | 7-1       |
| --/(672<br>--/(230))                                       | LR<br>87-57       | 25.04<br>(10,776)              | 1.09   | 3.68   | 14.49    | 1                               | 246 <sup>h</sup><br>(0.573)                                                                                        | --                                                                                                                   | --   | 197 <sup>i</sup><br>(0.448) | 20                                                   | Stringent                                  | Alma #3<br>SW, WT        | 4% excess O <sub>2</sub>            | 7-7       |
| --/(672<br>--/(230))                                       | LR<br>74-41       | 21.70<br>(9,336)               | 0.73   | 0.81   | 10.04    | 1                               | 283 <sup>j</sup><br>(0.658)                                                                                        | --                                                                                                                   | --   | 157 <sup>k</sup><br>(0.365) | 45                                                   | Stringent                                  | Alma #3<br>SW, WT        | 5% excess O <sub>2</sub>            | 7-7       |
| --/(46.9<br>--/(160))                                      | LRF<br>83-41      | 25.3<br>(10,889)               | 1.25   | 1.48   | 9.19     | 1                               | 264 <sup>l</sup><br>(0.613)                                                                                        | --                                                                                                                   | --   | 184 <sup>m</sup><br>(0.428) | 30                                                   | Stringent                                  | Frontier #6<br>SW, WT    | 5.4% excess O <sub>2</sub>          | 7-7       |
| --/(46.9<br>--/(160))                                      | LR<br>72-44       | 24.9<br>(10,741)               | 0.93   | 0.32   | 6.89     | 1                               | 155 <sup>n</sup><br>(0.360)                                                                                        | --                                                                                                                   | --   | 158 <sup>o</sup><br>(0.367) | -2                                                   | Stringent                                  | Frontier #6<br>SW, WT    | 4.2% excess O <sub>2</sub>          | 7-7       |

<sup>a</sup> All reported tests were short-term (<3 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on 100% of all tests.

<sup>d</sup> Moderate, intermediate or stringent level is discussed in Section 3.

<sup>e</sup> Percent rated load, first value is high load (baseline), second value is low load.

<sup>f</sup> MJ/kg (Btu/lb) as received.

<sup>g</sup> SW, single wall.

<sup>h</sup> WT, water tube.

<sup>i</sup> Estimate only, NO<sub>x</sub> values assume NO<sub>2</sub> is 5% of total (only NO was measured).

<sup>j</sup> May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

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TABLE 7-5. NO<sub>x</sub> EMISSION TEST DATA FROM COAL-FIRED INDUSTRIAL STOKERS WITH LOW EXCESS AIR (LEA)

| Actual/Design Heat Input (10 <sup>6</sup> Btu/hr) | Control Method           | Fuel Characteristics        |      |      |       | Number of Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                          | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification | Remarks  | Reference |
|---------------------------------------------------|--------------------------|-----------------------------|------|------|-------|------------------------------|-------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|------|--------------------------|------------------------------------------------|-------------------------|-----------------------|----------|-----------|
|                                                   |                          | Heat Value                  | S    | S    | Ash   |                              |                                                                                           | Low                                                                                         | High | Average                  |                                                |                         |                       |          |           |
| 32.2/39.6 (110)/(135)                             | LEA <sup>d</sup> 6.5-5.3 | 29.50 <sup>f</sup> (12,690) | 1.40 | 2.94 | 4.77  | 1                            | 235 (0.547)                                                                               | --                                                                                          | --   | 216 (0.502)              | 8                                              | Intermediate            | # 11-1, SS9           |          | 7-1       |
| 22/39.6 (75)/(135)                                | LEA 9.0-6.5              | 29.50 (12,690)              | 1.40 | 2.94 | 4.77  | 1                            | 263 (0.612)                                                                               | --                                                                                          | --   | 219 (0.510)              | 17                                             | Intermediate            | # 11-1, SS            | Low Load | 7-1       |
| 35.2/44.0 (120)/(150)                             | LEA 10.3-8.9             | 30.47 (13,110)              | 1.33 | 1.58 | 7.99  | 1                            | 336 (0.781)                                                                               | --                                                                                          | --   | 287 (0.668)              | 15                                             | Moderate                | # 14-1, SS            |          | 7-1       |
| 44.2/58.6 (151)/(200)                             | LEA 10.6-8.9             | 30.96 (13,320)              | 1.80 | 0.86 | 10.36 | 1                            | 330 (0.767)                                                                               | --                                                                                          | --   | 219 (0.509)              | 34                                             | Intermediate            | # 14-4, SS            |          | 7-1       |
| 11.7/14.6 (40)/(50)                               | LEA 8.0-5.8              | 31.96 (13,750)              | 1.45 | 0.76 | 6.75  | 1                            | 284 (0.640)                                                                               | --                                                                                          | --   | 202 (0.469)              | 29                                             | Moderate                | # 21-2, SS            |          | 7-1       |
| 17.9/22 (61)/(71)                                 | LEA 7.8-5.5              | 32.08 (13,800)              | 1.43 | 1.55 | 6.94  | 1                            | 283 (0.658)                                                                               | --                                                                                          | --   | 219 (0.509)              | 22                                             | --                      | # 21-3, SS            |          | 7-1       |
| 24.0/36.6 (82)/(125)                              | LEA 6.2-4.7              | 30.06 (12,293)              | 1.46 | 1.16 | 9.71  | 1                            | 196 (0.456)                                                                               | --                                                                                          | --   | 142 <sup>h</sup> (0.330) | 28                                             | Stringent               | # 30-8, SS            |          | 7-1       |
| 51.9/87.9 (177)/(300)                             | LEA 4.3-2.7              | 25.35 (10,365)              | 1.01 | 1.05 | 7.00  | 1                            | 239 <sup>h</sup> (0.556)                                                                  | --                                                                                          | --   | 180 <sup>h</sup> (0.419) | 25                                             | Stringent               | Site A, SS            |          | 7-8       |
| 59.8/87.9 (204)/(300)                             | LEA 5.2-3.4              | 25.89 (10,588)              | --   | --   | 5.21  | 1                            | 293 <sup>h</sup> (0.681)                                                                  | --                                                                                          | --   | 215 <sup>h</sup> (0.500) | 27                                             | Stringent               | Site A, SS            |          | 7-8       |
| 52.7/58.6 (180)/(200)                             | LEA 7.0-3.2              | 31.31 (13,469)              | 1.38 | 0.81 | 7.48  | 1                            | 208 <sup>h</sup> (0.036)                                                                  | --                                                                                          | --   | 131 <sup>h</sup> (0.305) | 37                                             | Stringent               | Site B, SS            |          | 7-9       |
| 17.6/29.3 (60)/(100)                              | LEA 10.9-6.5             | 20.2 (8,704)                | 0.78 | 0.73 | 8.29  | 1                            | 312 <sup>h</sup> (0.776)                                                                  | --                                                                                          | --   | 208 <sup>h</sup> (0.479) | 34                                             | Stringent               | UM-Madison # 2, SS    |          | 7-7       |

<sup>a</sup> All reported tests were short-term (K3 hr).  
<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
<sup>c</sup> Based on average of all tests.  
<sup>d</sup> Moderate, intermediate or stringent level discussed in Section 3.  
<sup>e</sup> Excess oxygen (%); first value is high excess air (baseline) condition, second value is low excess air condition.  
<sup>f</sup> MJ/kg (Btu/lb) as received.  
<sup>g</sup> SS, Spreader stoker; US, Underfeed stoker; GS, chain grate stoker; VS, vibrating grate stoker.  
<sup>h</sup> Estimate only. NO<sub>x</sub> values assume NO<sub>2</sub> is 5% of total (only NO was measured).  
<sup>i</sup> May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

Continued

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TABLE 7-5. Concluded

| Actual/Design<br>Heat Input<br>MM (10 <sup>6</sup> Btu/hr) | Control<br>Method | Fuel Characteristics          |        |        |          | Number of<br>Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>ng NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>ng NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                              | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported <sup>d</sup> | Boiler<br>Identification          | Reference |
|------------------------------------------------------------|-------------------|-------------------------------|--------|--------|----------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|------------------------------|------------------------------------------------------|--------------------------------------------|-----------------------------------|-----------|
|                                                            |                   | Heat<br>Value                 | %<br>N | %<br>S | %<br>Ash |                                 |                                                                                                                    | Low                                                                                                                  | High | Average                      |                                                      |                                            |                                   |           |
| 17.6/29.3<br>(60)/(100)                                    | LEA<br>10.0-7.8   | 27.9 <sup>f</sup><br>(12,006) | 1.30   | 3.07   | 9.60     | 1                               | 289 <sup>h</sup><br>(0.672)                                                                                        | --                                                                                                                   | --   | 259 <sup>h</sup><br>(0.600)  | 11                                                   | Intermediate                               | UM-Hudson<br># 2, SS <sup>g</sup> | 7-7       |
| 23.7/46.9<br>(81)/(160)                                    | LEA<br>8.6-7.7    | 19.5 <sup>f</sup><br>(8,408)  | 0.68   | 1.15   | 9.12     | 1                               | 238 <sup>h</sup><br>(0.549)                                                                                        | --                                                                                                                   | --   | 183 <sup>h</sup><br>(0.428)  | 22                                                   | Stringent                                  | Willmar #3<br>SS                  | 7-7       |
| 31.6/46.9<br>(108)/(160)                                   | LEA<br>8.6-6.6    | 28.9<br>(12,448)              | 1.37   | 2.28   | 7.76     | 1                               | 287 <sup>h</sup><br>(0.667)                                                                                        | --                                                                                                                   | --   | 241 <sup>h</sup><br>(0.560)  | 16                                                   | Intermediate                               | Willmar #3<br>SS                  | 7-7       |
| 13.5/23.4<br>(46)/(80)                                     | LEA<br>9.4-8.0    | 25.2<br>(10,842)              | 0.48   | 1.59   | 7.68     | 1                               | 207 <sup>h</sup><br>(0.481)                                                                                        | --                                                                                                                   | --   | 239 <sup>h</sup><br>(0.546)  | -13                                                  | --                                         | Fairmont #3<br>SS                 | 7-7       |
| 13.2/17.6<br>(45)/(60)                                     | LEA<br>6.6-4.9    | 26.99<br>(11,610)             | 1.40   | 0.86   | 9.51     | 1                               | 163<br>(0.379)                                                                                                     | --                                                                                                                   | --   | 117<br>(0.272)               | 28                                                   | Stringent                                  | # 15-32-10,<br>UPS                | 7-1       |
| 13.5/17.6<br>(46)/(60)                                     | LEA<br>9.8-8.0    | 26.99<br>(11,610)             | 1.40   | 0.86   | 9.51     | 1                               | 136<br>(0.317)                                                                                                     | --                                                                                                                   | --   | 161<br>(0.375)               | -18                                                  | Intermediate                               | # 15-32-13,<br>UPS                | 7-1       |
| 31.4/63.0<br>(107)/(215)                                   | LEA<br>9.5-8.2    | 27.60<br>(11,873)             | 0.94   | 3.05   | 13.7     | 1                               | 100<br>(0.233)                                                                                                     | --                                                                                                                   | --   | 96.5 <sup>h</sup><br>(0.225) | 4                                                    | Stringent                                  | # 35-6, CGS                       | 7-1       |
| 5.0/13.2<br>(17)/(45)                                      | LEA<br>9.8-7.3    | 24.1<br>(10,378)              | 0.91   | 0.83   | 3.92     | 1                               | 123 <sup>h</sup><br>(0.290)                                                                                        | --                                                                                                                   | --   | 115 <sup>h</sup><br>(0.267)  | 6                                                    | Intermediate                               | UM Stout<br># 2, WGS              | 7-7       |

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- <sup>a</sup> All reported tests were short-term (<3 hr).
- <sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.
- <sup>c</sup> Based on average of all tests.
- <sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.
- <sup>e</sup> Excess oxygen, %; first value is high excess air (baseline) condition, second value is low excess air condition.
- <sup>f</sup> MJ/kg (Btu/lb) as received.
- <sup>g</sup> SS, spreader stoker; UPS, underfeed stoker; CGS, chain grate stoker; WGS, vibrating grate stoker.
- <sup>h</sup> Estimate only; NO<sub>x</sub> values assume NO<sub>2</sub> is 58 of total (only NO was measured).
- <sup>i</sup> May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

TABLE 7-6. NO<sub>x</sub> EMISSION TEST DATA FROM COAL-FIRED INDUSTRIAL STOKERS WITH OVERFIRE AIR (OFA)

| Actual/Design Heat Input Mw (10 <sup>6</sup> Btu/hr) | Control Method | Fuel Characteristics |      |      |       | Number of Tests <sup>c</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> ng NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> ng NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |             |                           | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification   | Remarks                                         | Reference |
|------------------------------------------------------|----------------|----------------------|------|------|-------|------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|-------------|---------------------------|------------------------------------------------|-------------------------|-------------------------|-------------------------------------------------|-----------|
|                                                      |                | Heat Value           | % H  | % S  | % Ash |                              |                                                                                                                 | Low                                                                                                               | High        | Average                   |                                                |                         |                         |                                                 |           |
| 24/36.6 (82)/(125)                                   | OFA            | 30,060 (12,293)      | 1.46 | 1.16 | 9.71  | 2                            | 196 <sup>a</sup> (0.455)                                                                                        | 180 (0.419)                                                                                                       | 195 (0.443) | 188 <sup>a</sup> (0.44%)  | 4                                              | Stringent               | # 30-B, SS <sup>f</sup> | All tests conducted at 6% excess O <sub>2</sub> | 7-1       |
| 24/36.6 (82)/(125)                                   | OFA            | 30,060 (12,293)      | 1.46 | 1.16 | 9.71  | 1                            | 196 <sup>a</sup> (0.455)                                                                                        | --                                                                                                                | --          | 145 <sup>a</sup> (0.337)  | 26                                             | Stringent               | # 30-B, SS              | OFA ports plus redundant gas jets               | 7-1       |
| 30.5/63.0 (104)/(215)                                | OFA            | 27,600 (11,073)      | 0.94 | 3.05 | 13.7  | 2                            | 100 <sup>a</sup> (0.233)                                                                                        | 91.6 (0.213)                                                                                                      | 101 (0.24%) | 96.5 <sup>a</sup> (0.225) | 4                                              | Stringent               | # 35-6, CES             | 9% excess O <sub>2</sub>                        | 7-1       |
| 28/63.0 (95)/(215)                                   | OFA            | 27,600 (11,073)      | 0.94 | 3.05 | 13.7  | 2                            | 89.8 <sup>a</sup> (0.209)                                                                                       | 96.5 (0.225)                                                                                                      | 106 (0.247) | 101 <sup>a</sup> (0.235)  | -13                                            | Stringent               | # 35-6, CES             | 10% excess O <sub>2</sub>                       | 7-1       |
| 44.0/58.6 (150)/(200)                                | OFA            | 30,960 (13,320)      | 1.80 | 0.86 | 10.36 | 4                            | 330 (0.767)                                                                                                     | 177 (0.411)                                                                                                       | 234 (0.544) | 215 (0.499)               | 35                                             | Stringent               | # 14-4, SS              | 11% excess O <sub>2</sub>                       | 7-1       |
| 66.2/87.9 (226)/(300)                                | OFA            | 23,920 (10,209)      | 0.95 | 0.36 | 7.88  | 1                            | 254 (0.591)                                                                                                     | --                                                                                                                | --          | 227 (0.528)               | 10                                             | Stringent               | Site A, SS              | 6% excess O <sub>2</sub>                        | 7-8       |
| 30.8/46.9 (106)/(160)                                | OFA            | 19.5 (8,408)         | 0.68 | 1.15 | 9.12  | 1                            | 2369 (0.549)                                                                                                    | --                                                                                                                | --          | 2339 (0.542)              | 1                                              | Intermediate            | William #3 SS           | 9% excess O <sub>2</sub>                        | 7-7       |

<sup>a</sup> All reported tests were short-term (30 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.

<sup>e</sup> MJ/kg (Btu/lb) as received.

<sup>f</sup> SS, spreader stoker; UFS, underfeed stoker; CES, chain grate stoker; VES, vibrating grate stoker.

<sup>g</sup> Estimate only. NO<sub>x</sub> values assume NO<sub>2</sub> is 5% of total (only NO was measured).

<sup>h</sup> May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

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TABLE 7-7. NO<sub>x</sub> EMISSION TEST DATA FROM COAL-FIRED INDUSTRIAL STOKERS WITH LOAD REDUCTION (LR)

| Actual/Design<br>Heat Input<br>MB (10 <sup>6</sup> Btu/hr) | Control<br>Method         | Fuel Characteristics           |        |        |          | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                             | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported | Boiler<br>Identification | Remarks                             | Reference |
|------------------------------------------------------------|---------------------------|--------------------------------|--------|--------|----------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|-----------------------------|------------------------------------------------------|-------------------------------|--------------------------|-------------------------------------|-----------|
|                                                            |                           | Heat<br>Value                  | %<br>N | %<br>S | %<br>Ash |                                                                                                                    | Low                                                                                                                  | High | Average                     |                                                      |                               |                          |                                     |           |
| --/44.0<br>--/(150)                                        | LR <sup>e</sup><br>100-80 | 30.47 <sup>f</sup><br>(11,110) | 1.33   | 1.58   | 7.99     | 346<br>(0.806)                                                                                                     | --                                                                                                                   | --   | 338<br>(0.786)              | 2                                                    | --                            | # 14-1, SS               | 9.5 % excess O <sub>2</sub>         | 7-1       |
| --/58.6<br>--/(200)                                        | LR<br>100-80              | 30.96<br>(11,320)              | 1.80   | 0.86   | 10.36    | 365<br>(0.850)                                                                                                     | --                                                                                                                   | --   | 331<br>(0.770)              | 9                                                    | --                            | # 14-4, SS               | 10.8 % excess O <sub>2</sub>        | 7-1       |
| --/58.6<br>--/(200)                                        | LR<br>76-50               | 30.96<br>(11,320)              | 1.80   | 0.86   | 10.36    | 386<br>(0.897)                                                                                                     | --                                                                                                                   | --   | 282<br>(0.655)              | 27                                                   | Moderate                      | # 14-4, SS               | 13% excess O <sub>2</sub>           | 7-1       |
| --/36.6<br>--/(125)                                        | LR<br>65.6-38.4           | 30.06<br>(12,293)              | 1.46   | 1.16   | 9.71     | 196<br>(0.455)                                                                                                     | --                                                                                                                   | --   | 119<br>(0.277)              | 39                                                   | Stringent                     | # 30-8, SS               | 6.2-7.4%<br>excess O <sub>2</sub>   | 7-1       |
| --/29.3<br>--/(100)                                        | LR<br>90-60               | 20.2<br>(8,704)                | 0.78   | 0.73   | 8.29     | 274 <sup>h</sup><br>(0.636)                                                                                        | --                                                                                                                   | --   | 215 <sup>h</sup><br>(0.509) | 20                                                   | Intermediate                  | US-Medium<br># 2, SS     | 7.75-7.9%<br>excess O <sub>2</sub>  | 7-7       |
| --/29.3<br>--/(100)                                        | LR<br>90-60               | 27.9<br>(12,006)               | 1.30   | 3.07   | 9.60     | 325 <sup>h</sup><br>(0.756)                                                                                        | --                                                                                                                   | --   | 288 <sup>h</sup><br>(0.673) | 11                                                   | Moderate                      | US-Medium<br># 2, SS     | 10.0-10.3%<br>excess O <sub>2</sub> | 7-7       |
| --/87.9<br>--/(300)                                        | LR<br>77-59               | 24.5<br>(10,547)               | 1.01   | 1.05   | 6.09     | 213 <sup>h</sup><br>(0.498)                                                                                        | --                                                                                                                   | --   | 229 <sup>h</sup><br>(6.533) | 29                                                   | Moderate                      | Site A, SS               | 5.1-5.2%<br>excess O <sub>2</sub>   | 7-8       |
| --/46.9<br>--/(160)                                        | LR<br>70-47.6             | 28.9<br>(12,448)               | 1.37   | 2.28   | 7.76     | 331 <sup>h</sup><br>(0.769)                                                                                        | --                                                                                                                   | --   | 219 <sup>h</sup><br>(0.509) | 34                                                   | Intermediate                  | William #3<br>SS         | 8.4% excess O <sub>2</sub>          | 7-7       |
| --/46.9<br>--/(160)                                        | LR<br>67-49               | 19.5<br>(8,408)                | 0.68   | 1.15   | 9.12     | 234 <sup>h</sup><br>(0.543)                                                                                        | --                                                                                                                   | --   | 183 <sup>h</sup><br>(0.426) | 22                                                   | Stringent                     | William #3<br>SS         | 7.8% excess O <sub>2</sub>          | 7-7       |
| --/23.4<br>--/(80)                                         | LR<br>73.5-61             | 28.8<br>(12,441)               | 1.35   | 2.51   | 8.24     | 201 <sup>h</sup><br>(0.468)                                                                                        | --                                                                                                                   | --   | 171 <sup>h</sup><br>(0.397) | 15                                                   | Intermediate                  | Fairmont #3<br>SS        | 8.1% excess O <sub>2</sub>          | 7-7       |
| --/23.4<br>--/(80)                                         | LR<br>76-57.5             | 25.2<br>(10,842)               | 0.48   | 1.59   | 7.68     | 227 <sup>h</sup><br>(0.529)                                                                                        | --                                                                                                                   | --   | 239 <sup>h</sup><br>(0.556) | -5                                                   | --                            | Fairmont #3<br>SS        | 8.0% excess O <sub>2</sub>          | 7-7       |
| --/4.0<br>--/(13.5)                                        | LR<br>64.4-42.3           | 24.5<br>(10,515)               | 0.81   | 0.61   | 5.14     | 181 <sup>h</sup><br>(0.421)                                                                                        | --                                                                                                                   | --   | 128 <sup>h</sup><br>(0.299) | 29                                                   | Stringent                     | St. Johns #2<br>SS       | 15.2% excess O <sub>2</sub>         | 7-7       |

<sup>a</sup> All reported tests were short-term (<3 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.

<sup>e</sup> Percent load; first value is high load (baseline), second value is low load.

<sup>f</sup> MJ/kg (Btu/lb) as received.

<sup>g</sup> SS, spreader stoker; UFS, underfeed stoker; GDS, chain grate stoker; VGS, vibrating grate stoker.

<sup>h</sup> Estimate only; NO<sub>x</sub> values assume NO<sub>2</sub> is 5% of total (only NO was measured).

Continued

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TABLE 7-7. Concluded

| Actual Design<br>Load (lbm/hr) | Control<br>Method | Fuel Characteristics          |        |        |          | Number of<br>Tests <sup>a</sup> | Baseline $MO_2$ Emission <sup>b</sup><br>ng $MO_2$ /J (1b $MO_2$ /10 <sup>6</sup> Btu) | Controlled $MO_2$ Emission <sup>b</sup><br>ng $MO_2$ /J (1b $MO_2$ /10 <sup>6</sup> Btu) |                              |                              | Percent<br>$MO_2$<br>Reduction <sup>c</sup> | Control<br>Level<br>Support Load <sup>d</sup> | Roller<br>Identification  | Remarks                                                                      | Reference |
|--------------------------------|-------------------|-------------------------------|--------|--------|----------|---------------------------------|----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|------------------------------|------------------------------|---------------------------------------------|-----------------------------------------------|---------------------------|------------------------------------------------------------------------------|-----------|
|                                |                   | Heat<br>Value                 | %<br>H | %<br>S | %<br>Ash |                                 |                                                                                        | Low                                                                                      | High                         | Average                      |                                             |                                               |                           |                                                                              |           |
| -74.0<br>-113.5                | LR<br>62-43.5     | 30.5 <sup>f</sup><br>(13,123) | 0.95   | 0.58   | 5.29     | 1                               | 285 <sup>h</sup><br>(0.617)                                                            | --                                                                                       | --                           | 186 <sup>h</sup><br>(0.455)  | 26                                          | Moderate                                      | St. Johns # 2<br>SSO      | 15.5% excess $O_2$                                                           | 7-7       |
| -17.6<br>-160                  | LR<br>100-78      | 26.99<br>(11,610)             | 1.40   | 0.86   | 9.51     | 1                               | 195<br>(0.453)                                                                         | --                                                                                       | --                           | 181<br>(0.421)               | 7                                           | Moderate                                      | # 15-12-10, UFS           | 6% excess $O_2$                                                              | 7-1       |
| -17.6<br>-160                  | LR<br>78-53       | 26.99<br>(11,610)             | 1.40   | 0.86   | 9.51     | 1                               | 181<br>(0.421)                                                                         | --                                                                                       | --                           | 114 <sup>g</sup><br>(0.264)  | 37                                          | Stringent                                     | # 15-12-13, UFS           | 10.5% excess $O_2$                                                           | 7-1       |
| -63.0<br>-1715                 | LR<br>56-44       | 27.60<br>(11,873)             | 0.94   | 3.05   | 13.7     | 1                               | 94.7<br>(0.220)                                                                        | --                                                                                       | --                           | 79.4 <sup>g</sup><br>(0.185) | 16                                          | Stringent                                     | # 35-6, CGS               | 8.3% excess $O_2$                                                            | 7-1       |
| -63.0<br>-1715                 | LR<br>49-32       | 27.60<br>(11,873)             | 0.94   | 3.05   | 13.7     | 1                               | 94.1<br>(0.219)                                                                        | --                                                                                       | --                           | 118<br>(0.274)               | -25                                         | Stringent                                     | # 35-6, CGS               | 11% excess $O_2$                                                             | 7-1       |
| -17.6<br>-160                  | LR<br>58-25       | 21.5<br>(9,276)               | 1.10   | 0.72   | 5.1      | 2                               | 187 <sup>h</sup><br>(0.435)                                                            | 94.5 <sup>h</sup><br>(0.220)                                                             | 97.1 <sup>h</sup><br>(0.226) | 95.4 <sup>h</sup><br>(0.223) | 49                                          | Stringent                                     | IM-Fau Claire<br># 1, CGS | 10.8% excess $O_2$                                                           | 7-7       |
| -17.6<br>-160                  | LR<br>45-25       | 28.8<br>(12,182)              | 1.24   | 2.79   | 8.03     | 2                               | 184 <sup>h</sup><br>(0.428)                                                            | 128 <sup>h</sup><br>(0.299)                                                              | 147 <sup>h</sup><br>(0.343)  | 134 <sup>h</sup><br>(0.321)  | 25                                          | Intermediate                                  | IM-Fau Claire<br># 1, CGS | Baseline load at<br>10.9% excess $O_2$<br>Reduced load at<br>8% excess $O_2$ | 7-7       |
| -13.2<br>-145                  | LR<br>67-26       | 23.6<br>(10,142)              | 0.91   | 0.83   | 3.92     | 1                               | 101 <sup>h</sup><br>(0.235)                                                            | --                                                                                       | --                           | 126 <sup>h</sup><br>(0.293)  | -25                                         | Stringent                                     | IM-Stout # 2<br>VCS       | 7.8-7.9% excess $O_2$                                                        | 7-7       |
| -13.2<br>-145                  | LR<br>67-44       | 28.0<br>(12,023)              | 1.28   | 2.81   | 7.25     | 1                               | 120 <sup>h</sup><br>(0.279)                                                            | --                                                                                       | --                           | 120 <sup>h</sup><br>(0.279)  | 0                                           | Stringent                                     | IM-Stout # 2<br>VCS       | 8.2% excess $O_2$                                                            | 7-7       |

<sup>a</sup> All reported tests were short-term (C3 hr).<sup>b</sup>  $MO_2$  emissions determined by chemiluminescence in all cases.<sup>c</sup> Based on average of all tests.<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.<sup>e</sup> Percent load; first value is high load (baseline), second value is low load.<sup>f</sup> MJ/kg (Btu/lb) as received.<sup>g</sup> SS, spreader stoker; UFS, underfeed stoker; CGS, chain grate stoker; VCS, vibrating grate stoker.<sup>h</sup> Estimate only;  $MO_2$  values assume  $MO_2$  is 5% of total (only  $MO_2$  was measured).<sup>i</sup> May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

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TABLE 7-8. NO<sub>x</sub> EMISSION TEST DATA FROM COAL-FIRED INDUSTRIAL STOKERS WITH REDUCED AIR PREHEAT (RAP)

| Actual/Design<br>Net Input<br>MW (10 <sup>6</sup> Btu/hr) | Control<br>Method               | Fuel Characteristics           |        |        |          |          | Number of<br>Tests <sup>c</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                             | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported | Boiler<br>Identification | Remarks                  |
|-----------------------------------------------------------|---------------------------------|--------------------------------|--------|--------|----------|----------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|-----------------------------|------------------------------------------------------|-------------------------------|--------------------------|--------------------------|
|                                                           |                                 | Heat<br>Value                  | S<br>H | S<br>S | S<br>Ash | S<br>Ash |                                 |                                                                                                                    | Low                                                                                                                  | High | Average                     |                                                      |                               |                          |                          |
| 24/36.6<br>(82.5)/(125)                                   | RAP <sup>e</sup><br>366.5-354.3 | 30.06 <sup>f</sup><br>(12.233) | 1.46   | 1.16   | 9.71     | 9.71     | 1                               | 196<br>(0.466)                                                                                                     | --                                                                                                                   | --   | 162 <sup>g</sup><br>(0.377) | 17                                                   | Stringent                     | # 30-8, SS9              | 0% excess O <sub>2</sub> |
| 24.2/36.6<br>(82.5)/(125)                                 | RAP<br>369.4-355.4              | 30.06<br>(12.233)              | 1.46   | 1.16   | 9.71     | 9.71     | 1                               | 132<br>(0.307)                                                                                                     | --                                                                                                                   | --   | 134 <sup>g</sup><br>(0.311) | -2                                                   | Stringent                     | # 30-8, SS               | 5% excess O <sub>2</sub> |

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- a All reported tests were short-term (3 hr).  
b NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
c Based on average of all tests.  
d Moderate, intermediate or stringent levels discussed in Section 3.  
e First value, temperature (K) of baseline combustion air; second value, temperature (K) of RAP combustion air.  
f MJ/kg (Btu/lb) as received.  
g SS, spreader stoker.  
h May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

TABLE 7-9. NO<sub>x</sub> EMISSION TEST DATA FROM RESIDUAL OIL-FIRED INDUSTRIAL BOILERS WITH LOW EXCESS AIR (LEA)

| Actual/Design<br>Heat Input<br>MW (10 <sup>6</sup> Btu/hr) | Control<br>Method           | Fuel Characteristics           |        |        |          | Number of<br>Tests <sup>c</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |                |                              | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported | Boiler<br>Identification | Remarks                  | Reference |
|------------------------------------------------------------|-----------------------------|--------------------------------|--------|--------|----------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|----------------|------------------------------|------------------------------------------------------|-------------------------------|--------------------------|--------------------------|-----------|
|                                                            |                             | Heat<br>Value                  | X<br>H | X<br>S | X<br>Ash |                                 |                                                                                                                    | Low                                                                                                                  | High           | Average                      |                                                      |                               |                          |                          |           |
| 2.0/2.1<br>(6.7)/(7)                                       | LEA <sup>a</sup><br>5.4-3.9 | 42.49 <sup>f</sup><br>(18,280) | 0.27   | 1.85   | 0.038    | 1                               | 170<br>(0.395)                                                                                                     | --                                                                                                                   | --             | 143<br>(0.333)               | 16                                                   | --                            | # 23-1, FTG              | No. 6 oil                | 7-1       |
| 3.2/3.1<br>(10.9)/(10.5)                                   | LEA<br>3.2-1.9              | 43.61<br>(18,760)              | 0.20   | 1.30   | 0.26     | 1                               | 104<br>(0.243)                                                                                                     | --                                                                                                                   | --             | 99.3 <sup>g</sup><br>(0.231) | 5                                                    | Intermediate                  | # 24-TV, FT              | No. 5 oil                | 7-1       |
| 5.1/5.3<br>(17.4)/(18)                                     | LEA<br>7.2-3.7              | 42.31<br>(18,200)              | 0.10   | 1.46   | 0.007    | 2                               | 95.4<br>(0.222)                                                                                                    | 88.1<br>(0.205)                                                                                                      | 105<br>(0.244) | 96.5<br>(0.224)              | -1                                                   | Intermediate                  | # 26-1, FT               | No. 5 oil                | 7-1       |
| 3.5/3.2<br>(11.9)/(11)                                     | LEA<br>4.1-3.7              | 42.31<br>(18,200)              | 0.10   | 1.46   | 0.007    | 1                               | 106<br>(0.245)                                                                                                     | --                                                                                                                   | --             | 106 <sup>g</sup><br>(0.245)  | 0                                                    | Intermediate                  | # 26-2, FT               | No. 5 oil                | 7-1       |
| 1.6/3.5<br>(5.5)/(12)                                      | LEA<br>6.1-2.0              | --                             | --     | --     | --       | 1                               | 117<br>(0.273)                                                                                                     | --                                                                                                                   | --             | 95.9<br>(0.223)              | 18                                                   | Intermediate                  | # ECCC, FT               | No. 5 oil                | 7-2       |
| 2.3/3.5<br>(7.9)/(12)                                      | LEA<br>5.9-3.2              | --                             | --     | --     | --       | 1                               | 116<br>(0.270)                                                                                                     | --                                                                                                                   | --             | 99.3<br>(0.231)              | 14                                                   | Intermediate                  | # ECCC, FT               | No. 5 oil<br>Higher load | 7-2       |
| 4.2/5.1<br>(14.2)/(17.5)                                   | LEA<br>4.0-2.2              | 42.49<br>(18,280)              | 0.44   | 2.80   | 0.044    | 2                               | 195<br>(0.454)                                                                                                     | 155<br>(0.360)                                                                                                       | 160<br>(0.373) | 158<br>(0.367)               | 19                                                   | --                            | # 19-1, WT               | No. 6 oil                | 7-1       |
| 4.1/5.1<br>(14.1)/(17.5)                                   | LEA<br>3.1-0.9              | 45.01<br>(19,365)              | 0.14   | 0.37   | 0.009    | 1                               | 94.8<br>(0.220)                                                                                                    | --                                                                                                                   | --             | 69.6 <sup>g</sup><br>(0.162) | 27                                                   | Stringent                     | # 19-1, WT               | Different<br>No. 6 oil   | 7-1       |
| 15/23<br>(51)/(80)                                         | LEA<br>5.7-4.0              | 43.00<br>(18,500)              | 0.37   | 1.49   | 0.019    | 1                               | 174<br>(0.404)                                                                                                     | --                                                                                                                   | --             | 155<br>(0.361)               | 11                                                   | --                            | # 20-4, WT               | No. 6 oil                | 7-1       |
| 10.5/13.2<br>(36)/(45)                                     | LEA<br>3.0-1.6              | 44.69<br>(19,227)              | 0.49   | 0.19   | 0.08     | 1                               | 183<br>(0.426)                                                                                                     | --                                                                                                                   | --             | 136<br>(0.317)               | 26                                                   | --                            | # 20-2, WT               | No. 6 oil                | 7-1       |
| 5.7/7.3<br>(19.5)/(25)                                     | LEA<br>5.5-3.6              | --                             | --     | --     | --       | 1                               | 87.5<br>(0.203)                                                                                                    | --                                                                                                                   | --             | 63.4<br>(0.147)              | 28                                                   | Stringent                     | # ECCC, WT               | No. 5 oil                | 7-2       |
| 3.7/5.6<br>(12.5)/(19.2)                                   | LEA <sup>a</sup><br>7.6-7.1 | 43.54 <sup>f</sup><br>(18,730) | 0.26   | 1.59   | 0.065    | 1                               | 112<br>(0.260)                                                                                                     | --                                                                                                                   | --             | 105<br>(0.244)               | 6                                                    | Intermediate                  | # 15-123-1,<br>WTG       | MSF oil<br>(No. 5 oil)   | 7-1       |

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Continued

a All reported tests were short-term (3 hr).  
b NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
c Based on average of all tests.  
d Moderate, intermediate or stringent levels discussed in Section 3.  
e First value, temperature (K) of baseline combustion air; second value, temperature (K) of RAP combustion air.  
f MJ/kg (Btu/lb).  
g Fl, firetube; WT, watertube.  
h May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

TABLE 7-9. Concluded

| Actual/Design<br>Heat Input<br>MB (10 <sup>6</sup> Btu/hr) | Control<br>Method | Fuel Characteristics |        |        |          |        | Number of<br>Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                             | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported | Boiler<br>Identification | Remarks                   | Reference |
|------------------------------------------------------------|-------------------|----------------------|--------|--------|----------|--------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|-----------------------------|------------------------------------------------------|-------------------------------|--------------------------|---------------------------|-----------|
|                                                            |                   | Heat<br>Value        | S<br>H | S<br>S | S<br>Ash | S<br>S |                                 |                                                                                                                    | Low                                                                                                                  | High | Average                     |                                                      |                               |                          |                           |           |
| 29.3/36.6<br>(100)/(125)                                   | LEA<br>6.4-4.6    | --                   | 0.52   | 1.15   | 0.006    |        | 1                               | 189<br>(0.440)                                                                                                     | --                                                                                                                   | --   | 178<br>(0.416)              | 6                                                    | --                            | 0 2-6, WT                | PS 300 oil<br>(No. 5 oil) | 7-1       |
| 24.3/29.3<br>(83)/(100)                                    | LEA<br>9.3-5.9    | 42.62<br>(18,333)    | 0.77   | 1.29   | 0.10     |        | 1                               | 257<br>(0.606)                                                                                                     | --                                                                                                                   | --   | 225<br>(0.523)              | 12                                                   | --                            | 0 27-1, WT               | PS 300 oil<br>(No. 5 oil) | 7-1       |
| 15.2/19.0<br>(52)/(65)                                     | LEA<br>4.7-3.6    | 44.0<br>(18,900)     | 0.29   | 1.03   | 0.043    |        | 1                               | 106<br>(0.247)                                                                                                     | --                                                                                                                   | --   | 105<br>(0.244)              | 1                                                    | Intermediate                  | 0 16-2, WT               | No. 6 oil                 | 7-1       |
| 21.1/26.4<br>(72)/(90)                                     | LEA<br>7.4-7.0    | 42.82<br>(18,450)    | 0.26   | 1.04   | 0.031    |        | 1                               | 136<br>(0.321)                                                                                                     | --                                                                                                                   | --   | 121<br>(0.282)              | 12                                                   | Moderate                      | 0 18-2, WT               | No. 6 oil                 | 7-1       |
| 23.4/30.8<br>(80)/(105)                                    | LEA<br>6.3-5.3    | 43.96<br>(18,910)    | 0.26   | 1.03   | 0.032    |        | 1                               | 142<br>(0.330)                                                                                                     | --                                                                                                                   | --   | 116<br>(0.269)              | 18                                                   | Moderate                      | 0 18-3, WT               | No. 6 oil                 | 7-1       |
| 34.9/46.9<br>(119)/(140)                                   | LEA<br>7.2-6.0    | 43.96<br>(18,910)    | 0.26   | 1.03   | 0.032    |        | 1                               | 133<br>(0.309)                                                                                                     | --                                                                                                                   | --   | 131<br>(0.304)              | 2                                                    | --                            | 0 18-4, WT               | No. 6 oil                 | 7-1       |
| 8.5/20.5<br>(29)/(70)                                      | LEA<br>5.3-4.9    | --                   | --     | --     | --       |        | 1                               | 115<br>(0.287)                                                                                                     | --                                                                                                                   | --   | 101 <sup>e</sup><br>(0.235) | 12                                                   | Intermediate                  | 0 28-1, WT               | No. 6 oil                 | 7-1       |
| 35.5/44.0<br>(121)/(150)                                   | LEA<br>5.0-3.1    | 42.34<br>(18,213)    | 0.31   | 2.74   | 0.03     |        | 1                               | 66.8<br>(0.156)                                                                                                    | --                                                                                                                   | --   | 64.4<br>(0.159)             | -2                                                   | Stringent                     | 0 29-5, WT               | No. 6 oil                 | 7-1       |
| 9.4/11.7<br>(32)/(40)                                      | LEA<br>4.3-3.8    | 43.64<br>(18,773)    | 0.30   | 1.91   | 0.07     |        | 1                               | 109<br>(0.254)                                                                                                     | --                                                                                                                   | --   | 100<br>(0.234)              | 8                                                    | Intermediate                  | 0 37-2, WT               | No. 6 oil                 | 7-1       |
| 16.4/25<br>(56)/(65)                                       | LEA<br>7.6-5.4    | --                   | 0.32   | 0.36   | 0.010    |        | 1                               | 186<br>(0.438)                                                                                                     | --                                                                                                                   | --   | 145<br>(0.337)              | 23                                                   | --                            | 0 7-3, WT                | No. 5 oil                 | 7-1       |
| 13.8/17.3<br>(47)/(59.2)                                   | LEA<br>5.0-2.3    | --                   | 0.38   | 0.63   | 0.014    |        | 1                               | 362<br>(0.843)                                                                                                     | --                                                                                                                   | --   | 301<br>(0.699)              | 17                                                   | --                            | 0 2-2, WT                | PS 300 oil<br>(No. 5 oil) | 7-1       |
| 15.2/19.0<br>(52)/(65)                                     | LEA<br>5.7-3.4    | --                   | 0.38   | 0.63   | 0.014    |        | 1                               | 280<br>(0.651)                                                                                                     | --                                                                                                                   | --   | 250<br>(0.581)              | 11                                                   | --                            | 0 2-4, WT                | PS 300 oil<br>(No. 5 oil) | 7-1       |

<sup>a</sup> All reported tests were short-term (3 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate or intermediate operating levels; discussed in Section 2.

<sup>e</sup> Excess oxygen. X, first value is high excess air (baseline) condition; second value is low excess air condition.

<sup>f</sup> MJ/kg (Btu/lb).

<sup>g</sup> FI, Firetube; WT, Watertube.

\* May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

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TABLE 7-10. NO<sub>x</sub> EMISSION TEST DATA FROM RESIDUAL OIL-FIRED INDUSTRIAL BOILERS WITH STAGED COMBUSTION AIR (SCA)

| Actual/Design<br>Heat Input<br>(10 <sup>6</sup> Btu/hr) | Control<br>Method | Fuel Characteristics |        |        |        |          | Number of<br>Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |                 |                              | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported <sup>d</sup> | Boiler<br>Identification | Remarks                                                                 | Reference |
|---------------------------------------------------------|-------------------|----------------------|--------|--------|--------|----------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|-----------------|------------------------------|------------------------------------------------------|--------------------------------------------|--------------------------|-------------------------------------------------------------------------|-----------|
|                                                         |                   | Heat<br>Value        | %<br>H | %<br>S | %<br>S | %<br>Ash |                                 |                                                                                                                    | Low                                                                                                                  | High            | Average                      |                                                      |                                            |                          |                                                                         |           |
| 1.8/3.5<br>(6)/(12)                                     | SCAF<br>φ = 0.76  | 44.679<br>(19,219)   | 0.26   | 0.32   | 0.01   | 0.01     | 1                               | 96.2<br>(0.224)                                                                                                    | --                                                                                                                   | --              | 49.0<br>(0.114)              | 49                                                   | Stringent                                  | 0 ECCC, FTH              | No. 5 oil<br>2% excess O <sub>2</sub><br>Lance depth 2.5<br>diameters   | 7-2       |
| 1.8/3.5<br>(6)/(12)                                     | SCAF<br>φ = 0.65  | 44.67<br>(19,219)    | 0.26   | 0.32   | 0.01   | 0.01     | 2                               | 96.2<br>(0.224)                                                                                                    | 51.9<br>(0.121)                                                                                                      | 51.9<br>(0.121) | 51.9<br>(0.121)              | 46                                                   | Stringent                                  | 0 ECCC, FT               | No. 5 oil<br>4.4% excess O <sub>2</sub><br>Lance depth 2.5<br>diameters | 7-2       |
| 4.0/5.1<br>(13.7)/(17.5)                                | SCAF<br>φ = 1.03  | 43.82<br>(18,790)    | 0.23   | 0.60   | 0.034  | 0.034    | 1                               | 120<br>(0.280)                                                                                                     | --                                                                                                                   | --              | 84.9<br>(0.197)              | 29                                                   | Stringent                                  | 0 19-1, WT               | No. 6 oil<br>3.1% excess O <sub>2</sub><br>Lance depth 1.5 m            | 7-3       |
| 4.2/5.1<br>(14.5)/(17.5)                                | SCAF<br>φ > 1     | 43.82<br>(18,790)    | 0.23   | 0.60   | 0.034  | 0.034    | 1                               | 120<br>(0.280)                                                                                                     | --                                                                                                                   | --              | 70<br>(0.162)                | 42                                                   | Stringent                                  | 0 19-1, WT               | No. 6 oil<br>1.9% excess O <sub>2</sub><br>Lance depth 2.1 m            | 7-3       |
| 11.1/13.2<br>(38)/(45)                                  | SCAF<br>φ > 1     | 42.92<br>(18,466)    | 0.31   | 1.08   | 0.05   | 0.05     | 1                               | 168 <sup>f</sup><br>(0.390)                                                                                        | --                                                                                                                   | --              | 97.4 <sup>f</sup><br>(0.227) | 42                                                   | Intermediate                               | 0 30-2, WT               | No. 6 oil<br>3.3% excess O <sub>2</sub>                                 | 7-3       |

<sup>a</sup> All reported tests were short-term (3 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.

<sup>e</sup> φ = Burner stoichiometry.

<sup>f</sup> φ = Equivalence ratio, defined as ratio of stoichiometric air-fuel ratio to actual air-fuel at the burner.

<sup>g</sup> MJ/kg (Btu/lb).

<sup>h</sup> FI, firetube; WT, watertube.

<sup>i</sup> NO only.

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TABLE 7-11. NO<sub>x</sub> EMISSION TEST DATA FROM RESIDUAL OIL-FIRED INDUSTRIAL BOILERS WITH BURNERS OUT OF SERVICE (BOOS) (Reference 7-1)

| Actual/Design Heat Input MB (10 <sup>6</sup> Btu/hr) | Control Method | Fuel Characteristics |      |      |       | Number of Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |                |                 | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification | Remarks                                                                                 |
|------------------------------------------------------|----------------|----------------------|------|------|-------|------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|----------------|-----------------|------------------------------------------------|-------------------------|-----------------------|-----------------------------------------------------------------------------------------|
|                                                      |                | Heat Value           | % H  | % S  | % Ash |                              |                                                                                                                 | Low                                                                                                               | High           | Average         |                                                |                         |                       |                                                                                         |
| 13.8/17.3<br>(47)/(59.2)                             | BOOS           | --e                  | 0.38 | 0.63 | 0.014 | 2                            | 363<br>(0.845)                                                                                                  | 294<br>(0.684)                                                                                                    | 346<br>(0.807) | 320<br>(0.744)  | 12                                             | --                      | # 2-2, MTF            | Two rows of 3 burners, staggered, middle top burner on air only. PS 300 (No. 5 oil)     |
| 14.9/19.0<br>(51)/(65.0)                             | BOOS           | --                   | 0.38 | 0.63 | 0.014 | 1                            | 275<br>(0.640)                                                                                                  | --                                                                                                                | --             | 248<br>(0.577)  | 10                                             | --                      | # 2-4, MT             | Two rows of 3 burners, staggered, middle bottom burner on air only. PS 300 (No. 5 oil)  |
| 14.4/24.9<br>(49)/(85)                               | BOOS           | --                   | 0.32 | 0.35 | 0.010 | 2                            | 192<br>(0.446)                                                                                                  | 139<br>(0.322)                                                                                                    | 153<br>(0.356) | 146<br>(0.340)  | 24                                             | --                      | # 7-3, MT             | Single row of 4 burners, a middle burner on air only. (No. 5 oil)                       |
| 34.9/46.9<br>(119)/(160)                             | BOOS           | 43.96<br>(18,910)    | 0.26 | 1.03 | 0.032 | 1                            | 133<br>(0.309)                                                                                                  | --                                                                                                                | --             | 94.2<br>(0.219) | 29                                             | Intermediate            | # 18-4, MT            | Two rows of 2 burners, one top burner on air only (No. 6 oil)                           |
| 22.3/30.8<br>(76)/(105)                              | BOOS           | 43.96<br>(18,910)    | 0.26 | 1.03 | 0.032 | 7                            | 134<br>(0.311)                                                                                                  | 122<br>(0.283)                                                                                                    | 128<br>(0.321) | 127<br>(0.296)  | 5                                              | Moderate                | # 18-3, MTF           | Two rows of 2 burners, one top burner on air only. No. 6 oil. Excess O <sub>2</sub> 6%. |
| 17.6/26.4<br>(60)/(90)9                              | BOOS           | 42.82<br>(18,420)    | 0.26 | 1.04 | 0.031 | 1                            | 138<br>(0.321)                                                                                                  | --                                                                                                                | --             | 98.2<br>(0.228) | 29                                             | Intermediate            | # 18-2, MT            | One row of 3 burners, center burner on air only. No. 6 oil                              |
| 8.5/20.5<br>(29)/(70)                                | BOOS           | --                   | --   | --   | --    | 3                            | 128<br>(0.299)                                                                                                  | 125<br>(0.291)                                                                                                    | 137<br>(0.244) | 130<br>(0.303)  | -2                                             | Moderate                | # 28-1, MT            | One row of 3 burners, center burner on air only. No. 6 oil. Excess O <sub>2</sub> 6%    |
| 21/44<br>(70)/(150)                                  | BOOS           | 42.34e<br>(18,213)   | 0.31 | 2.74 | 0.03  | 1                            | 145<br>(0.337)                                                                                                  | --                                                                                                                | --             | 104<br>(0.243)  | 28                                             | Intermediate            | # 29-5, MTF           | Two burners top burners on air only. No. 6 oil. Excess O <sub>2</sub> 5.5%              |

<sup>a</sup> All reported tests were short-term (3 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.

<sup>e</sup> MJ/kg (Btu/lb).

<sup>f</sup> MT, water tube.

<sup>g</sup> Baseline at 71 x 10<sup>6</sup> Btu/hr, 7.4% excess O<sub>2</sub>; BOOS at 60 x 10<sup>6</sup> Btu/hr, 8.2% excess O<sub>2</sub>.

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TABLE 7-12. NO<sub>x</sub> EMISSION TEST DATA FROM RESIDUAL OIL-FIRED INDUSTRIAL BOILERS WITH FLUE GAS RECIRCULATION (FGR)

| Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Control Method | Fuel Characteristics |      |      |       | Number of Tests <sup>e</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> mg NO <sub>2</sub> /J (10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> mg NO <sub>2</sub> /J (10 <sup>6</sup> Btu) |              |              | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported <sup>d</sup> | Boiler Identification | Remarks                     | Reference |
|------------------------------------------------------|----------------|----------------------|------|------|-------|------------------------------|---------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|--------------|--------------|------------------------------------------------|--------------------------------------|-----------------------|-----------------------------|-----------|
|                                                      |                | Heat Value           | % N  | % S  | % Ash |                              |                                                                                             | Low                                                                                           | High         | Average      |                                                |                                      |                       |                             |           |
| 1.2/3.5 (4)/(12)                                     | FGR, 23%       | 44.37f (19,091)      | 0.22 | 0.44 | 0.09  | 2                            | 98.1 (0.288)                                                                                | 95.4 (0.222)                                                                                  | 100 (0.233)  | 97.7 (0.227) | 0                                              | Intermediate                         | # ECCC, FT9           | No. 5 oil                   | 7-2       |
| 1.2/3.5 (4)/(12)                                     | FGR, 40%       | 44.37 (19,091)       | 0.22 | 0.44 | 0.09  | 3                            | 9.99 (0.232)                                                                                | 83.0 (0.193)                                                                                  | 95.9 (0.223) | 88.5 (0.206) | 11                                             | Intermediate                         | # ECCC, FT            | No. 5 oil                   | 7-2       |
| 1.2/3.5 (4)/(12)                                     | FGR, 53%       | 44.37 (19,091)       | 0.22 | 0.44 | 0.09  | 1                            | 94.8 (0.220)                                                                                | --                                                                                            | --           | 63.4 (0.147) | 33                                             | Stringent                            | # ECCC, FT            | No. 5 oil                   | 7-2       |
| 1.8/3.5 (6)/(12)                                     | FGR, 29%       | 44.37 (19,091)       | 0.22 | 0.44 | 0.09  | 1                            | 108 (0.251)                                                                                 | --                                                                                            | --           | 82.5 (0.182) | 24                                             | Stringent                            | # ECCC, FT            | No. 5 oil                   | 7-2       |
| 1.8/3.5 (6)/(12)                                     | FGR, 40%       | 44.37 (19,091)       | 0.22 | 0.44 | 0.09  | 1                            | 108 (0.251)                                                                                 | --                                                                                            | --           | 81.9 (0.190) | 24                                             | Stringent                            | # ECCC, FT            | No. 5 oil                   | 7-2       |
| 3.1/3.5 (10.5)/(12)                                  | FGR, 20%       | 44.37 (19,091)       | 0.22 | 0.44 | 0.09  | 2                            | 95.9 (0.223)                                                                                | 66.2 (0.154)                                                                                  | 71.8 (0.167) | 69.0 (0.160) | 28                                             | Stringent                            | # ECCC, FT            | No. 5 oil                   | 7-2       |
| 2.9/7.3 (10)/(25)                                    | FGR, 21%       | 44.60 (19,108)       | 0.19 | 0.40 | 0.01  | 3                            | 53.9 (0.125)                                                                                | 43.8 (0.102)                                                                                  | 52.4 (0.122) | 47.0 (0.109) | 13                                             | Stringent                            | # ECCC, WT            | No. 5 oil                   | 7-2       |
| 1.9/7.3 (6.5)/(25)                                   | FGR, 17%       | 44.60 (19,108)       | 0.19 | 0.40 | 0.01  | 2                            | 68.4 (0.159)                                                                                | 50.5 (0.117)                                                                                  | 58.9 (0.137) | 55.0 (0.128) | 20                                             | Stringent                            | # ECCC, WT            | No. 5 oil                   | 7-2       |
| 4.4/7.3 (15)/(25)                                    | FGR, 8%        | 44.60 (19,108)       | 0.19 | 0.40 | 0.01  | 3                            | 66.8 (0.155)                                                                                | 65.1 (0.151)                                                                                  | 71.2 (0.166) | 67.9 (0.156) | -2                                             | Stringent                            | # ECCC, WT            | No. 5 oil                   | 7-2       |
| 4.4/7.3 (15)/(25)                                    | FGR, 24%       | 44.60 (19,108)       | 0.19 | 0.40 | 0.01  | 1                            | 66.8 (0.155)                                                                                | --                                                                                            | --           | 65.1 (0.151) | 3                                              | Stringent                            | # ECCC, WT            | No. 5 oil                   | 7-2       |
| 4.2/5.1 (14.4)/(17.5)                                | FGR, 20%       | 45.0 (19,365)        | 0.14 | 0.37 | 0.009 | 1                            | 95 (0.221)                                                                                  | --                                                                                            | --           | 81 (0.188)   | 15                                             | Stringent                            | # 19-1, WT            | Steam atomization No. 6 oil | 7-2       |
| 4.2/5.1 (14.4)/(17.5)                                | FGR, 16%       | 45.0 (19,365)        | 0.14 | 0.37 | 0.009 | 1                            | 90 (0.209)                                                                                  | --                                                                                            | --           | 83 (0.193)   | 8                                              | Stringent                            | # 19-1, WT            | Air atomization No. 6 oil   | 7-1       |

a All reported tests were short-term (3 hr).  
b NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
c Based on average of all tests.  
d Moderate, intermediate or stringent levels discussed in Section 3.  
e Mass percent flue gas recirculated  
f MJ/kg (Btu/lb).  
g FT, firetube; WT, watertube

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TABLE 7-13. NO<sub>x</sub> EMISSION TEST DATA FROM RESIDUAL OIL-FIRED INDUSTRIAL BOILERS WITH COMBINED FLUE GAS RECIRCULATION AND STAGED COMBUSTION AIR (FGR/SCA) (REFERENCE 7-3)

| Actual/Design<br>Heat Input<br>MW (10 <sup>6</sup> Btu/hr) | Control<br>Method                                | Fuel Characteristics |        |        |          | Number of<br>Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                            | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported | Boiler<br>Identification | Remarks                                                      |
|------------------------------------------------------------|--------------------------------------------------|----------------------|--------|--------|----------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|----------------------------|------------------------------------------------------|-------------------------------|--------------------------|--------------------------------------------------------------|
|                                                            |                                                  | Heat<br>Value        | %<br>N | %<br>S | %<br>Ash |                                 |                                                                                                                    | Low                                                                                                                  | High | Average                    |                                                      |                               |                          |                                                              |
| 4.3/5.1<br>(14.6)/(17.5)                                   | FGR, 23.1 <sup>e</sup><br>SCA, 1.01 <sup>f</sup> | 43.649<br>(18,850)   | 0.22   | 0.40   | 0.026    | 1                               | 120<br>(0.280)                                                                                                     | --                                                                                                                   | --   | 90.5<br>(0.210)            | 25                                                   | Intermediate                  | # 19-1, WT               | No. 6 oil<br>4.2% excess O <sub>2</sub><br>Lance depth 1.2 m |
| 4.3/5.1<br>(14.6)/(17.5)                                   | FGR, 23%<br>SCA, 1.1                             | 43.68<br>(18,780)    | 0.23   | 0.40   | 0.034    | 1                               | 130<br>(0.303)                                                                                                     | --                                                                                                                   | --   | 69 <sup>g</sup><br>(0.16)  | 53                                                   | Stringent                     | # 19-1, WT               | No. 6 oil<br>2.9% excess O <sub>2</sub><br>Lance depth 2.1 m |
| 4.3/5.1<br>(14.6)/(17.5)                                   | FGR, 19.6%<br>SCA, 1.21                          | 43.68<br>(18,780)    | 0.23   | 0.40   | 0.034    | 1                               | 130<br>(0.303)                                                                                                     | --                                                                                                                   | --   | 65 <sup>g</sup><br>(0.151) | 50                                                   | Stringent                     | # 19-1, WT               | No. 6 oil<br>1.5% excess O <sub>2</sub><br>Lance depth 1.2 m |

<sup>a</sup> All reported tests were short-term (<3 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.

<sup>e</sup> Mass percent flue gas recirculation.

<sup>f</sup> % = Equivalence ratio, defined as ratio of stoichiometric air-fuel ratio to actual air-fuel ratio at the burner.

<sup>g</sup> MJ/kg (Btu/lb).

<sup>h</sup> WT, Watertube.

<sup>\*</sup> May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

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TABLE 7-14. NO<sub>x</sub> EMISSION TEST DATA FROM RESIDUAL OIL-FIRED INDUSTRIAL BOILERS WITH REDUCED AIR PREHEAT (RAP) (REFERENCE 7-1)

| Actual/Design Heat Input<br>MM (10 <sup>6</sup> Btu/hr) | Control Method     | Fuel Characteristics           |      |      |      | Number of Tests <sup>d</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification | Remarks                               |
|---------------------------------------------------------|--------------------|--------------------------------|------|------|------|------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|----------------|------------------------------------------------|-------------------------|-----------------------|---------------------------------------|
|                                                         |                    | Heat Value                     | S    | S    | S    |                              |                                                                                                                    | Low                                                                                                                  | High | Average        |                                                |                         |                       |                                       |
| 9.1/13.2<br>(31)/(45)                                   | RAP<br>430-350     | 44.69 <sup>f</sup><br>(19,227) | 0.49 | 0.19 | 0.08 | 1                            | 183<br>(0.425)                                                                                                     | --                                                                                                                   | --   | 153<br>(0.355) | 16                                             | --                      | 38-2, WT              | No. 6 oil<br>Excess O <sub>2</sub> 3% |
| 9.4/11.7<br>(32)/(40)                                   | RAP<br>301.5-315.4 | 45.07<br>(19,390)              | 0.30 | 1.91 | 0.07 | 1                            | 109<br>(0.254)                                                                                                     | --                                                                                                                   | --   | 104<br>(0.241) | 5                                              | Moderate                | 37-2, WT              | No. 6 oil<br>Excess O <sub>2</sub> 4% |

<sup>a</sup> All reported tests were short-term (3 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.

<sup>e</sup> First value, temperature (K) of baseline combustion air; second value temperature (K) of RAP combustion air.

<sup>f</sup> MJ/kg (Btu/lb).

<sup>g</sup> WT, watertube boiler

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TABLE 7-15. NO<sub>x</sub> EMISSION TEST DATA FROM RESIDUAL OIL-FIRED INDUSTRIAL BOILERS WITH LOAD REDUCTION (LR)  
(REFERENCE 7-1)

| Actual/Design<br>Heat Input<br>MM (10 <sup>6</sup> Btu/hr) | Control<br>Method | Fuel Characteristics |        |        |          | Number of<br>Tests <sup>e</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                 | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported | Boiler<br>Identification  | Remarks                                                     |
|------------------------------------------------------------|-------------------|----------------------|--------|--------|----------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|-----------------|------------------------------------------------------|-------------------------------|---------------------------|-------------------------------------------------------------|
|                                                            |                   | Heat<br>Value        | S<br>N | S<br>S | S<br>Ash |                                 |                                                                                                                    | Low                                                                                                                  | High | Average         |                                                      |                               |                           |                                                             |
| -5.0<br>-/(17)                                             | LR<br>126-71      | 43.77f<br>(16,830)   | 0.28   | 1.72   | 0.055    | 1                               | 120<br>(0.279)                                                                                                     | --                                                                                                                   | --   | 104<br>(0.241)  | 13                                                   | Intermediate                  | # 15-2-1, FT <sup>g</sup> | HS <sup>f</sup> (No. 5) oil<br>Excess O <sub>2</sub> 7%     |
| -3.1<br>-/(10.5)                                           | LR<br>104-62      | 43.61<br>(16,760)    | 0.20   | 1.30   | 0.26     | 1                               | 104<br>(0.243)                                                                                                     | --                                                                                                                   | --   | 97.6<br>(0.227) | 6                                                    | Intermediate                  | # 24-TV, FT               | No. 5 oil<br>Excess O <sub>2</sub> 2.5%                     |
| -5.3<br>-/(18)                                             | LR<br>96-42       | 42.31<br>(16,200)    | 0.10   | 1.46   | 0.007    | 1                               | 99.9<br>(0.232)                                                                                                    | --                                                                                                                   | --   | 86.4<br>(0.201) | 14                                                   | Stringent                     | # 26-1, FT                | No. 5 oil, air<br>atomization<br>Excess O <sub>2</sub> 7.3% |
| -5.3<br>-/(18)                                             | LR<br>96-39       | 42.31<br>(16,200)    | 0.10   | 1.46   | 0.007    | 1                               | 90.9<br>(0.211)                                                                                                    | --                                                                                                                   | --   | 87.0<br>(0.202) | 4                                                    | Stringent                     | # 26-1, FT                | No. 5 oil, steam<br>atomization<br>Excess O <sub>2</sub> 7% |
| -3.2<br>-/(11)                                             | LR<br>77-38       | 42.31<br>(16,200)    | 0.10   | 1.46   | 0.007    | 1                               | 99.9<br>(0.232)                                                                                                    | --                                                                                                                   | --   | 90.9<br>(0.211) | 10                                                   | Intermediate                  | # 26-2, FT                | No. 5 oil<br>Excess O <sub>2</sub> 7.5%                     |
| -24.9<br>-/(85)                                            | LR<br>69-46       | --                   | 0.32   | 0.35   | 0.010    | 1                               | 185<br>(0.429)                                                                                                     | --                                                                                                                   | --   | 141<br>(0.329)  | 24                                                   | --                            | # 7-3, WT                 | No. 5 oil<br>Excess O <sub>2</sub> 7.7%                     |
| -26.4<br>-/(90)                                            | LR<br>80-46       | 42.82<br>(16,420)    | 0.26   | 1.04   | 0.031    | 1                               | 160<br>(0.372)                                                                                                     | --                                                                                                                   | --   | 108<br>(0.250)  | 33                                                   | Intermediate                  | # 18-2, WT                | No. 6 oil, Excess O <sub>2</sub><br>8.5%. Preheated air.    |
| -30.8<br>-/(105)                                           | LR<br>76-44       | 44.00<br>(16,930)    | 0.29   | 1.03   | 0.043    | 1                               | 176<br>(0.410)                                                                                                     | --                                                                                                                   | --   | 123<br>(0.287)  | 30                                                   | Moderate                      | # 18-3, WT                | No. 6 oil, Excess O <sub>2</sub><br>7.6%. Preheated air.    |
| -46.9<br>-/(160)                                           | LR<br>75-45       | 44.00<br>(16,930)    | 0.29   | 1.03   | 0.043    | 1                               | 144<br>(0.335)                                                                                                     | --                                                                                                                   | --   | 180<br>(0.419)  | -25                                                  | --                            | # 18-4, WT                | No. 6 oil, excess O <sub>2</sub><br>8%. Preheated air.      |

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Continued

<sup>a</sup> All reported tests were short-term (3 hr).  
<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
<sup>c</sup> Based on average of all tests.  
<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.  
<sup>e</sup> Percent rated load, first value is high load, second value is low load.  
<sup>f</sup> MJ/kg (Btu/lb).  
<sup>g</sup> FT, firetube; WT, watertube.

TABLE 7-15. Concluded

| Actual/Design<br>Heat Input<br>MM (10 <sup>6</sup> Btu/hr) | Control<br>Method | Fuel Characteristics           |        |        |          | Number of<br>Tests <sup>d</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                 | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported | Boiler<br>Identification | Remarks                                                  |
|------------------------------------------------------------|-------------------|--------------------------------|--------|--------|----------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|-----------------|------------------------------------------------------|-------------------------------|--------------------------|----------------------------------------------------------|
|                                                            |                   | Heat<br>Value                  | S<br>H | S<br>S | S<br>Ash |                                 |                                                                                                                    | Low                                                                                                                  | High | Average         |                                                      |                               |                          |                                                          |
| -/44<br>-(150)                                             | LR<br>79-47       | 42.33 <sup>f</sup><br>(18,213) | 0.31   | 2.74   | 0.03     | 1                               | 165<br>(0.384)                                                                                                     | --                                                                                                                   | --   | 145<br>(0.337)  | 12                                                   | --                            | # 29-5, WT9              | No. 6 oil. excess O <sub>2</sub><br>58. Preheated air.   |
| -/17.3<br>-(159)                                           | LR<br>100-81      | --                             | --     | 0.63   | 0.014    | 1                               | 241<br>(0.560)                                                                                                     | --                                                                                                                   | --   | 225<br>(0.523)  | 7                                                    | --                            | # 2-2, WT                | PS 300 (No. 5) oil.<br>Excess O <sub>2</sub> 38          |
| -/19.0<br>-(165)                                           | LR<br>77-48       | --                             | --     | 0.63   | 0.014    | 1                               | 284<br>(0.614)                                                                                                     | --                                                                                                                   | --   | 270<br>(0.628)  | -2                                                   | --                            | # 2-4, WT                | PS 300 (No. 5) oil.<br>Excess O <sub>2</sub> 38          |
| -/36.6<br>-(125)                                           | LR<br>80-30       | --                             | 0.52   | 1.15   | 0.026    | 1                               | 215<br>(0.500)                                                                                                     | --                                                                                                                   | --   | 197<br>(0.448)  | 8                                                    | --                            | #2-6, WT                 | PS300 (No. 5) oil.<br>Excess O <sub>2</sub> 78           |
| -/5.1<br>-(17.5)                                           | LR<br>83-55       | 42.49<br>(18,280)              | 0.44   | 2.80   | 0.044    | 1                               | 219<br>(0.510)                                                                                                     | --                                                                                                                   | --   | 210<br>(0.489)  | 4                                                    | --                            | #19-1, WT                | No. 6 oil.<br>Excess O <sub>2</sub> 68                   |
| -/23.4<br>-(180)                                           | LR<br>75-41       | 43.14<br>(18,560)              | 0.37   | 1.53   | 0.032    | 1                               | 184<br>(0.428)                                                                                                     | --                                                                                                                   | --   | 155<br>(0.361)  | 16                                                   | --                            | #20-4, WT                | No. 6 oil.<br>Excess O <sub>2</sub> 68                   |
| -/29.3<br>-(100)                                           | LR<br>86-55       | 42.62<br>(18,333)              | 0.77   | 1.29   | 0.10     | 1                               | 257<br>(0.598)                                                                                                     | --                                                                                                                   | --   | 246<br>(0.573)  | 4                                                    | --                            | #27-1, WT                | PS 300 (No. 5) oil -<br>Excess O <sub>2</sub> 98         |
| -/3.5<br>-(112)                                            | LR<br>92-46       | 44.34<br>(19,075)              | 0.04   | 0.67   | 0.04     | 1                               | 120<br>(0.280)                                                                                                     | --                                                                                                                   | --   | 110<br>(0.246)  | 8                                                    | Moderate                      | #ECCC, FT                | No. 5 oil. Excess O <sub>2</sub><br>48 (Reference 7-2).  |
| -/7.3<br>-(25)                                             | LR<br>74-26       | 44.40<br>(19,099)              | 0.15   | 0.75   | 0.02     | 1                               | 71.2<br>(0.165)                                                                                                    | --                                                                                                                   | --   | 68.3<br>(0.149) | 4                                                    | Stringent                     | #ECCC, WT                | No. 5 oil Excess O <sub>2</sub><br>4.58 (Reference 7-2). |

<sup>a</sup> All reported tests were short-term (30 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate, Intermediate or stringent level is discussed in Section 3.

<sup>e</sup> Percent rated load, first value is high load, second value is low load.

<sup>f</sup> MJ/kg (Btu/lb)

<sup>g</sup> FI, firetube; WT, watertube

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boiler. The fuel characteristics columns exemplify the differences in fuels that, due to viscosity, are both labeled as No. 6 oils.

Data on  $\text{NO}_x$  emission controls as applied to boilers burning distillate oil are contained in Tables 7-16 through 7-20. The tests were selected because they best fitted the criteria for selection listed in Section 7.1. All of the data resulted from two EPA sponsored field investigations and one subsequent study of a boiler with major modifications (References 7-1, 7-3 through 7-5).

All distillate oils used were classified as No. 2. All had comparable higher heating values and sulfur, nitrogen, and ash contents.

#### 7.4 EMISSION SOURCE TEST DATA FOR GAS-FIRED BOILERS

Emission source test data for  $\text{NO}_x$  controls on industrial boilers burning natural gas are presented in Tables 7-21 through 7-27. A large number of tests were conducted using this fuel under various EPA sponsored programs (References 7-1 through 7-5). The criteria whereby these tests were chosen as representative were presented in Section 7-1.

#### 7.5 DEVELOPING EMISSION SOURCE TEST DATA

EPA is currently sponsoring several field test programs demonstrating combustion modification  $\text{NO}_x$  controls for industrial boilers. These programs include identification of optimal combustion conditions for 11 stoker coal-fired boilers, sponsored jointly with the Department of Energy (References 7-8 and 7-10), and field demonstrations of the TRW low  $\text{NO}_x$  burner for both oil- and gas-firing (References 7-11 and 7-12). The imminent results from these studies should help fill some of the data gaps identified in this study. In addition, several other field tests of these and other combustion controls are being planned, including 30-day continuous monitoring programs (Reference 7-12). The results of these and other test programs should be monitored and incorporated in future updates of the assessment of combustion modification  $\text{NO}_x$  controls.



TABLE 7-16. NO<sub>x</sub> EMISSION TEST DATA FROM DISTILLATE (NO. 2) OIL-FIRED INDUSTRIAL BOILERS WITH LOW EXCESS AIR (LEA) (REFERENCE 7-1)

| Actual/Design Heat Input (10 <sup>6</sup> Btu/hr) | Control Method | Fuel Characteristics |       |      |       | Number of Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |               | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported <sup>d</sup> | Boiler Identification | Remarks                                 |
|---------------------------------------------------|----------------|----------------------|-------|------|-------|------------------------------|-------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|------|---------------|------------------------------------------------|--------------------------------------|-----------------------|-----------------------------------------|
|                                                   |                | Heat Value           | % H   | % S  | % Ash |                              |                                                                                           | Low                                                                                         | High | Average       |                                                |                                      |                       |                                         |
| 1.6/2.9 (5.5)/(10.0)                              | LEA 5.6-3.6    | -- <sup>f</sup>      | --    | 0.23 | --    | 1                            | 96.5 (0.224)                                                                              | --                                                                                          | --   | 85.8 (0.200)  | 11                                             | Moderate                             | #3-2, FTg             | No air preheat.                         |
| 2.7/5.9 (9.3)/(20.0)                              | LEA 5.2-2.7    | --                   | --    | 0.30 | --    | 1                            | 107 (0.248)                                                                               | --                                                                                          | --   | 81.3 (0.189)  | 24                                             | Moderate                             | #4-4, FT              | No air preheat.                         |
| 3.3/3.2 (11.3)/(11)                               | Baseline 4.7   | 45.12 (19,410)       | 0.02  | 0.48 | 0.001 | 1                            | 70.5 (0.164)                                                                              | --                                                                                          | --   | --            | --                                             | Moderate                             | 26-2, FT              | Air atomization                         |
| 4.7/5.3 (15.9)/(18)                               | Baseline 8.0   | 45.12 (19,410)       | 0.02  | 0.48 | 0.001 | 1                            | 63.8 (0.149)                                                                              | --                                                                                          | --   | --            | --                                             | Intermediate                         | 26-1, FT              | Air atomization                         |
| 4.6/5.3 (15.7)/(18)                               | Baseline 8.0   | 45.12 (19,410)       | 0.02  | 0.48 | 0.001 | 1                            | 65.0 (0.151)                                                                              | --                                                                                          | --   | --            | --                                             | Intermediate                         | 26-1, FT              | Air atomization                         |
| 2.0/2.1 (6.7)/(7)                                 | Baseline 6.8   | 45.12 (19,410)       | 0.015 | 0.38 | 0.002 | 1                            | 70.0 (0.163)                                                                              | --                                                                                          | --   | --            | --                                             | Moderate                             | 23-1, FT              | Air atomization                         |
| 3.2/3.8 (11)/(13)                                 | Baseline 3.1   | 45.12 (19,410)       | 0.015 | 0.19 | 0.001 | 1                            | 46.4 (0.108)                                                                              | --                                                                                          | --   | --            | --                                             | Intermediate                         | 24-TV, FT             | Air atomization                         |
| 5.4/8.5 (18.5)/(29.0)                             | LEA 5.9-4.5    | 45.19 (19,440)       | 0.045 | 0.40 | 0.003 | 1                            | 54.4 (0.127)                                                                              | --                                                                                          | --   | 51.6 (0.120)  | 5                                              | Intermediate                         | #1-1, WT              | No air preheat.                         |
| 7.0/8.5 (24.0)/(29.0)                             | LEA 3.8-2.7    | 45.19 (19,440)       | 0.045 | 0.40 | 0.003 | 1                            | 48.2 (0.112)                                                                              | --                                                                                          | --   | 47.7* (0.111) | 1                                              | Intermediate                         | #1-1, WT              | Higher load. No air preheat.            |
| 4.2/8.5 (14.5)/(29.0)                             | LEA 8.2-5.1    | 45.19 (19,440)       | 0.045 | 0.40 | 0.003 | 1                            | 59.5 (0.138)                                                                              | --                                                                                          | --   | 51.6 (0.120)  | 11                                             | Intermediate                         | #1-2, WT              | No air preheat.                         |
| 6.9/8.8 (23.5)/(30)                               | LEA 5.9-2.8    | --                   | 0.031 | 0.22 | 0.001 | 1                            | 69.0 (0.160)                                                                              | --                                                                                          | --   | 58.3 (0.136)  | 16                                             | Intermediate                         | #1-3, WT              |                                         |
| 4.1/5.1 (14)/(17.5)                               | LEA 3.6-2.6    | 45.26 (19,470)       | 0.006 | 0.06 | 0.001 | 1                            | 37.0 (0.086)                                                                              | --                                                                                          | --   | 35.9* (0.083) | 3                                              | Stringent                            | # 19-1, WTg           | Steam atomization. No air preheat.      |
| 4.1/5.1 (14)/(17.5)                               | LEA 3.0-1.6    | 45.26 (19,470)       | 0.006 | 0.06 | 0.001 | 1                            | 51.0 (0.119)                                                                              | --                                                                                          | --   | 50.5 (0.117)  | 1                                              | Intermediate                         | # 19-1, WT            | Air atomization. No air preheat.        |
| 3.4/5.1 (11.6)/(17.5)                             | LEA 4.3-3.7    | 45.26 (19,470)       | 0.006 | 0.06 | 0.001 | 1                            | 46.0 (0.107)                                                                              | --                                                                                          | --   | 46.0 (0.107)  | 0                                              | Intermediate                         | # 19-1, WT            | Mechanized atomization. No air preheat. |
| 25.8/32.2 (88)/(110)                              | LEA 5.7-3.8    | 44.95 (19,340)       | 0.01  | 0.18 | 0.004 | 1                            | 102 (0.236)                                                                               | --                                                                                          | --   | 93.7 (0.218)  | 8                                              | --                                   | # 17-T-8, WT          |                                         |

<sup>a</sup> All reported tests were short-term (3 hr).  
<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
<sup>c</sup> Based on average of all tests.  
<sup>d</sup> Moderate, Intermediate or Stringent levels discussed in Section 3.  
<sup>e</sup> Excess oxygen, %; first value is high excess air (baseline) condition; second value is low excess air condition.  
<sup>f</sup> MJ/kg (Btu/lb).  
<sup>g</sup> FT, firetube; WT, watertube.  
<sup>h</sup> May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

TABLE 7-17. NO<sub>x</sub> EMISSION TEST DATA FROM DISTILLATE (NO. 2) OIL-FIRED INDUSTRIAL BOILERS WITH FLUE GAS RECIRCULATION (FGR) (REFERENCE 7-3)

| Actual/Design Heat Input MM (10 <sup>6</sup> Btu/hr) | Control Method        | Fuel Characteristics        |        |      |        | Number of Tests <sup>d</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> ng NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> ng NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |              |              | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification | Remarks                                       |
|------------------------------------------------------|-----------------------|-----------------------------|--------|------|--------|------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|--------------|--------------|------------------------------------------------|-------------------------|-----------------------|-----------------------------------------------|
|                                                      |                       | Heat Value                  | S      | H    | S      | S                            |                                                                                                                 | Low                                                                                                               | High         | Average      |                                                |                         |                       |                                               |
| 4.3/5.1 (14.6)/(17.5)                                | FGA, 208 <sup>e</sup> | 45.61 <sup>f</sup> (19,610) | 0.008  | 0.14 | 0.001  | 0.001                        | 2                                                                                                               | 17.4 (0.040)                                                                                                      | 18.5 (0.043) | 18.0 (0.042) | 73                                             | Stringent               | #19-1, WT9            | Excess O <sub>2</sub> 0.8%<br>No air preheat. |
| 4.3/5.1 (14.6)/(17.5)                                | FGA, 158              | 45.78 (19,640)              | <0.001 | 0.10 | <0.001 | <0.001                       | 1                                                                                                               | --                                                                                                                | --           | 25 (0.058)   | 50                                             | Stringent               | #19-1, WT             | Excess O <sub>2</sub> 1%<br>No air preheat.   |

<sup>a</sup> All reported tests were short-term (<3 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.

<sup>e</sup> Mass percent flue gas recirculated.

<sup>f</sup> MJ/kg (Btu/lb).

<sup>g</sup> WT, watertube.

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TABLE 7-18. NO<sub>x</sub> EMISSION TEST DATA FROM DISTILLATE (NO. 2) OIL-FIRED INDUSTRIAL BOILERS WITH STAGED COMBUSTION AIR (SCA) (REFERENCE 7-3)

| Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Control Method         | Fuel Characteristics        |        |      |        | Number of Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> ng NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> ng NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |              |                           | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification | Remarks                                                      |
|------------------------------------------------------|------------------------|-----------------------------|--------|------|--------|------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|--------------|---------------------------|------------------------------------------------|-------------------------|-----------------------|--------------------------------------------------------------|
|                                                      |                        | Heat Value                  | S H    | S S  | S Ash  |                              |                                                                                                                 | Low                                                                                                               | High         | Average                   |                                                |                         |                       |                                                              |
| 4.3/5.1 (14.5)/(17.5)                                | SCA, $\phi_B = 1.04^e$ | 45.61 <sup>f</sup> (19,610) | 0.008  | 0.14 | 0.001  | 2                            | 66.0 (0.153)                                                                                                    | 54.0 (0.126)                                                                                                      | 55.1 (0.128) | 54.6 <sup>g</sup> (0.127) | 17                                             | Intermediate            | #19-1, WT9            | Excess O <sub>2</sub> 3.1% Lance depth, 1.8 m.               |
| 4.3/5.1 (14.5)/(17.5)                                | SCA, $\phi_B = 1.10$   | 45.78 (19,600)              | <0.001 | 0.10 | <0.001 | 1                            | 66.0 (0.153)                                                                                                    | --                                                                                                                | --           | 29.0 (0.066)              | 44                                             | Stringent               | #19-1, WT             | Excess O <sub>2</sub> 2.6% Lance depth 2.1 m.                |
| 4.3/5.1 (14.5)/(17.5)                                | SCA, $\phi_B = 1.10$   | 45.78 (19,600)              | <0.001 | 0.10 | <0.001 | 1                            | 56 (0.13)                                                                                                       | --                                                                                                                | --           | 39 <sup>g</sup> (0.091)   | 30                                             | Stringent               | #19-1, WT             | Excess O <sub>2</sub> 3% Lance depth, 2.1 m. No air preheat. |

<sup>a</sup> All reported tests were short-term (<3 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.

<sup>e</sup>  $\phi_B$  = Equivalence ratio, defined as ratio of stoichiometric air-fuel ratio to actual air-fuel ratio at burner.

<sup>f</sup> MJ/kg (Btu/lb).

<sup>g</sup> WT, watertube.

<sup>h</sup> May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

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TABLE 7-19. NO<sub>x</sub> TEST DATA FROM DISTILLATE (NO. 2) OIL-FIRED INDUSTRIAL BOILERS WITH COMBINED FLUE GAS RECIRCULATION AND STAGED COMBUSTION AIR (FGR/SCA) (REFERENCE 7-3)

| Actual/Design Heat Input<br>MB (10 <sup>6</sup> Btu/hr) | Control Method                      | Fuel Characteristics |       |      |       |       | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /d (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /d (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                 | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification | Remarks                                                               |
|---------------------------------------------------------|-------------------------------------|----------------------|-------|------|-------|-------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|-----------------|------------------------------------------------|-------------------------|-----------------------|-----------------------------------------------------------------------|
|                                                         |                                     | Heat Value           | S     | S    | S     | S     |                                                                                                                    | Low                                                                                                                  | High | Average         |                                                |                         |                       |                                                                       |
| 4.3/5.1<br>(14.6)/(17.5)                                | FGR, 26.38%<br>SCA, $\phi_g = 1.10$ | --                   | --    | --   | --    | --    | 67.4<br>(0.157)                                                                                                    | --                                                                                                                   | --   | 18.0<br>(0.042) | 73                                             | Stringent               | 019-1, WPH            | Excess O <sub>2</sub> 3.5%.<br>Lance depth, 1.2 m.<br>No air preheat. |
| 4.3/5.1<br>(14.6)/(17.5)                                | FGR, 26%<br>SCA, $\phi_g = 1.1$     | 45.619<br>(19,610)   | 0.008 | 0.14 | 0.001 | 0.001 | 67.4<br>(0.157)                                                                                                    | -                                                                                                                    | -    | 16<br>(0.036)   | 77                                             | Stringent               | 019-1, WT             | Excess O <sub>2</sub> 2.5%.<br>Lance depth, 2.1 m.<br>No air preheat. |

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- a All reported tests were short-term (3 hr).  
b NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
c Based on average of all tests.  
d Moderate, intermediate or stringent levels discussed in Section 3.  
e Mass percent flue gas recirculated.  
f Equivalence ratio, defined as ratio of stoichiometric air-fuel ratio to actual air-fuel ratio at the burner.  
g MJ/kg (Btu/lb).  
h WT, water tube.

TABLE 7-20. NO<sub>x</sub> EMISSION TEST DATA FROM DISTILLATE (NO. 2) OIL-FIRED INDUSTRIAL BOILERS WITH LOAD REDUCTION (LR) (REFERENCE 7-1)

| Actual/Design Heat Input (10 <sup>6</sup> Btu/hr) | Control Method     | Fuel Characteristics |       |      |       | Number of Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                 | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification | Remarks                                                              |
|---------------------------------------------------|--------------------|----------------------|-------|------|-------|------------------------------|-------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|------|-----------------|------------------------------------------------|-------------------------|-----------------------|----------------------------------------------------------------------|
|                                                   |                    | Heat Value           | S     | S    | S     |                              |                                                                                           | Low                                                                                         | High | Average         |                                                |                         |                       |                                                                      |
| -12.9<br>-(110.0)                                 | 70-30 <sup>e</sup> | -- <sup>f</sup>      | --    | 0.23 | --    | 1                            | 95.8<br>(0.223)                                                                           | --                                                                                          | --   | 86.4<br>(0.201) | 10                                             | Moderate                | #3-2, FT9             | Excess O <sub>2</sub> 7%<br>No air preheat.                          |
| -15.9<br>-(120)                                   | 92.5-46.5          | --                   | --    | 0.30 | --    | 1                            | 106<br>(0.247)                                                                            | --                                                                                          | --   | 106<br>(0.242)  | -2                                             | --                      | #4-4, FT              | Excess O <sub>2</sub> 5.4%<br>No air preheat.                        |
| -18.5<br>-(129)                                   | 81-64              | 45.19<br>(19,440)    | 0.045 | 0.40 | 0.003 | 1                            | 44.3<br>(0.103)                                                                           | --                                                                                          | --   | 51.6<br>(0.170) | -17                                            | Intermediate            | #1-1, WT              | Excess O <sub>2</sub> 4%<br>No air preheat.                          |
| -18.5<br>-(129)                                   | 66-50              | 45.19<br>(19,440)    | 0.045 | 0.40 | 0.003 | 1                            | 48.8<br>(0.113)                                                                           | --                                                                                          | --   | 51.6<br>(0.120) | -6                                             | Intermediate            | #1-2, WT              | Excess O <sub>2</sub> 5%<br>No air preheat.                          |
| -156.6<br>-(1200)                                 | 45-18              | 45.07<br>(19,390)    | 0.013 | 0.31 | 0.003 | 1                            | 58.3<br>(0.136)                                                                           | --                                                                                          | --   | 60.6<br>(0.141) | -4                                             | Intermediate            | #36-6, WT             | Excess O <sub>2</sub> increased from 3.3% to 9.0%<br>No air preheat. |
| -146.3<br>-(158)                                  | 89-73              | --                   | 0.018 | 0.23 | 0.005 | 1                            | 151<br>(0.351)                                                                            | --                                                                                          | --   | 104<br>(0.241)  | 31                                             | --                      | #6-3, WT              | Excess O <sub>2</sub> 5%.                                            |
| -132.2<br>-(110)                                  | 80-30              | 44.96<br>(19,340)    | 0.01  | 0.18 | 0.004 | 1                            | 114<br>(0.265)                                                                            | --                                                                                          | --   | 88.6<br>(0.206) | 22                                             | Moderate                | #17-TB, WT            | Excess O <sub>2</sub> 8%.                                            |

<sup>a</sup> All reported tests were short-term (3 hr).  
<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
<sup>c</sup> Based on average of all tests.  
<sup>d</sup> Moderate, Intermediate or stringent levels discussed in Section 3.  
<sup>e</sup> Percent rated load, first value is high load (baseline), second value is low load.  
<sup>f</sup> MJ/kg (Btu/lb).  
<sup>g</sup> FF, firetube; WT, watertube

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TABLE 7-21. NO<sub>x</sub> EMISSION TEST DATA FROM GAS-FIRED INDUSTRIAL BOILERS WITH LOW EXCESS AIR (LEA)

| Actual/Design<br>PM (10 <sup>6</sup> Btu/hr) | Control<br>Method | Fuel Characteristics         |                     |        |          | Number of<br>Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                              | Percent<br>NO <sub>x</sub> Reduction <sup>c</sup> | Control<br>Level<br>Supported <sup>d</sup> | Boiler<br>Identification | Remarks                    | Reference |
|----------------------------------------------|-------------------|------------------------------|---------------------|--------|----------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|------------------------------|---------------------------------------------------|--------------------------------------------|--------------------------|----------------------------|-----------|
|                                              |                   | Heat<br>Value                | %<br>H <sub>2</sub> | %<br>S | %<br>Ash |                                 |                                                                                                                    | Low                                                                                                                  | High | Average                      |                                                   |                                            |                          |                            |           |
| 1.46/2.9<br>(5.0)/(10.0)                     | LEA<br>8.0-3.6    | 36.65 <sup>f</sup><br>(1108) | --                  | --     | --       | 1                               | 51.0<br>(0.119)                                                                                                    | --                                                                                                                   | --   | 33.7<br>(0.078)              | 34                                                | Stringent                                  | # 3-2, FT <sup>g</sup>   | No air preheat             | 7-1       |
| 4.1/5.9<br>(14.0)/(20)                       | LEA<br>6.8-0.7    | 36.65<br>(1108)              | --                  | --     | --       | 1                               | 55.1<br>(0.126)                                                                                                    | --                                                                                                                   | --   | 40.3<br>(0.094)              | 27                                                | Stringent                                  | # 4-4, FT                | No air preheat             | 7-1       |
| 2.6/5.9<br>(9.0)/(20)                        | LEA<br>6.8-1.2    | 36.65<br>(1108)              | --                  | --     | --       | 1                               | 52.5<br>(0.122)                                                                                                    | --                                                                                                                   | --   | 43.3<br>(0.101)              | 18                                                | Stringent                                  | # 4-4, FT                | Low load<br>No air preheat | 7-1       |
| 2.3/2.9<br>(8.0)/(10.0)                      | LEA<br>5.1-1.9    | 36.65<br>(1108)              | --                  | --     | --       | 1                               | 28.6<br>(0.064)                                                                                                    | --                                                                                                                   | --   | 20.4 <sup>e</sup><br>(0.047) | 29                                                | Stringent                                  | # 5-248-3, FT            | No air preheat             | 7-1       |
| 1.9/2.3<br>(6.4)/(8.0)                       | LEA<br>11.0-3.2   | 36.65<br>(1108)              | --                  | --     | --       | 1                               | 31.6<br>(0.074)                                                                                                    | --                                                                                                                   | --   | 24.0<br>(0.054)              | 24                                                | Stringent                                  | # 5-248-1, FT            | No air preheat             | 7-1       |
| 3.6/3.1<br>(12.4)/(10.5)                     | LEA<br>4.1-3.1    | 31.96<br>(964)               | --                  | --     | --       | 1                               | 31.6<br>(0.074)                                                                                                    | --                                                                                                                   | --   | 32.6<br>(0.076)              | -3                                                | Stringent                                  | # 24-TV, FT              | No air preheat             | 7-1       |
| 5.0/5.3<br>(17.2)/(18)                       | LEA<br>7.2-2.7    | 31.89<br>(964)               | --                  | --     | --       | 1                               | 29.6<br>(0.066)                                                                                                    | --                                                                                                                   | --   | 39.8<br>(0.090)              | -31                                               | Stringent                                  | # 26-1, FT               | No air preheat             | 7-1       |
| 3.05/3.2<br>(10.4)/(11)                      | LEA<br>3.6-2.9    | 31.89<br>(964)               | --                  | --     | --       | 1                               | 47.9<br>(0.111)                                                                                                    | --                                                                                                                   | --   | 46.4 <sup>e</sup><br>(0.113) | -1                                                | Intermediate                               | # 26-2, FT               | No air preheat             | 7-1       |
| 1.1/3.5<br>(3.8)/(12)                        | LEA<br>11.5-8.0   | --                           | --                  | --     | --       | 1                               | 53.6<br>(0.124)                                                                                                    | --                                                                                                                   | --   | 44.9<br>(0.104)              | 16                                                | Intermediate                               | # ECC, FT                | No air preheat             | 7-2       |
| 2.0/2.5<br>(6.8)/(12)                        | LEA<br>9.0-4.5    | --                           | --                  | --     | --       | 1                               | 52.0<br>(0.121)                                                                                                    | --                                                                                                                   | --   | 45.9<br>(0.107)              | 12                                                | Intermediate                               | # ECC, FT                | No air preheat             | 7-2       |

All reported tests were short-term (<3 hr).  
<sup>a</sup> No. emissions determined by chemiluminescence in all cases.  
<sup>b</sup> Based on average of all tests.  
<sup>c</sup> Moderate, intermediate or stringent levels discussed in Section 3.  
<sup>d</sup> Excess oxygen, %; first value is high excess air (baseline) condition, second value is low excess air condition.  
<sup>e</sup> Fuel/air (Btu/lb).  
<sup>f</sup> BTU, first/last; UT, water/steam.  
<sup>g</sup> May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

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Continued

TABLE 7-21. Continued

| Actual/Design<br>Heat Input<br>MM (10 <sup>6</sup> Btu/hr) | Control<br>Method           | Fuel Characteristics         |        |        |          | Number of<br>Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg M <sub>2</sub> /J (lb M <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg M <sub>2</sub> /J (lb M <sub>2</sub> /10 <sup>6</sup> Btu) |                 |                              | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported <sup>d</sup> | Boiler<br>Identification | Remarks        | Reference |
|------------------------------------------------------------|-----------------------------|------------------------------|--------|--------|----------|---------------------------------|------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|-----------------|------------------------------|------------------------------------------------------|--------------------------------------------|--------------------------|----------------|-----------|
|                                                            |                             | Heat<br>Value                | %<br>H | %<br>S | %<br>Ash |                                 |                                                                                                                  | Low                                                                                                                | High            | Average                      |                                                      |                                            |                          |                |           |
| 6.9/8.5<br>(23.5)/(29)                                     | LEA<br>4.5-1.9 <sup>e</sup> | 36.65 <sup>f</sup><br>(1108) | --     | --     | --       | 1                               | 36.7<br>(0.085)                                                                                                  | --                                                                                                                 | --              | 33.1<br>(0.077)              | 10                                                   | Stringent                                  | 0 1-1, WT <sup>g</sup>   | No air preheat | 7-1       |
| 5.0/8.5<br>(17.0)/(29)                                     | LEA<br>6.4-2.2              | 36.65<br>(1108)              | --     | --     | --       | 1                               | 37.7<br>(0.088)                                                                                                  | --                                                                                                                 | --              | 39.8<br>(0.093)              | -6                                                   | Stringent                                  | 0 1-2, WT                | No air preheat | 7-1       |
| 3.2/7.3<br>(11.0)/(25)                                     | LEA<br>8.9-5.0              | 36.65<br>(1108)              | --     | --     | --       | 1                               | 41.8<br>(0.097)                                                                                                  | --                                                                                                                 | --              | 7.14<br>(0.0166)             | 83                                                   | Stringent                                  | 0 5-718-3, WT            | No air preheat | 7-1       |
| 25/32<br>(87)/(110)                                        | LEA<br>8.1-2.0              | 37.35<br>(1129)              | --     | --     | --       | 1                               | 47.9<br>(0.111)                                                                                                  | --                                                                                                                 | --              | 82.1<br>(0.191)              | -71                                                  | Moderate                                   | 0 10-5, WT               | No air preheat | 7-1       |
| 4.1/5.1<br>(14)/(17.5)                                     | LEA<br>3.2-2.0              | 33.84<br>(1023)              | --     | --     | --       | 1                               | 30.1<br>(0.070)                                                                                                  | --                                                                                                                 | --              | 28.0<br>(0.065)              | 7                                                    | Stringent                                  | 0 19-1, WT               | No air preheat | 7-1       |
| 47/59<br>(160)/(200)                                       | LEA<br>3.7-1.3              | 27.50<br>(831)               | --     | --     | --       | 1                               | 97.9<br>(0.228)                                                                                                  | --                                                                                                                 | --              | 97.4<br>(0.227)              | 1                                                    | --                                         | 0 39-8108, WT            | No air preheat | 7-1       |
| 2.9-4.1/7.3<br>(10-14)/(25)                                | LEA<br>6.3-2.4              | --                           | --     | --     | --       | 2                               | 34.7<br>(0.081)                                                                                                  | 30.6<br>(0.071)                                                                                                    | 31.1<br>(0.072) | 30.9<br>(0.072)              | 11                                                   | Stringent                                  | 0 ECCC, WT <sup>g</sup>  | No air preheat | 7-2       |
| 7.0/8.8<br>(24)/(30)                                       | LEA<br>5.7-2.7              | 36.65<br>(1108)              | --     | --     | --       | 1                               | 49.0<br>(0.113)                                                                                                  | --                                                                                                                 | --              | 39.3<br>(0.091)              | 20                                                   | Stringent                                  | 0 1-3, WT                |                | 7-1       |
| 40/47<br>(135)/(160)                                       | LEA<br>3.8-2.6              | 37.35<br>(1129)              | --     | --     | --       | 1                               | 191<br>(0.402)                                                                                                   | --                                                                                                                 | --              | 173<br>(0.402)               | 9                                                    | --                                         | 0 9-BC-6, WT             |                | 7-1       |
| 23/38<br>(77)/(130)                                        | LEA<br>6.6-6.1              | 34.73<br>(1050)              | --     | --     | --       | 1                               | 105<br>(0.253)                                                                                                   | --                                                                                                                 | --              | 100<br>(0.234)               | 4                                                    | --                                         | 0 32-4, WT               |                | 7-1       |
| 44/73<br>(150)/(250)                                       | LEA<br>6.5-3.7              | 34.63<br>(1047)              | --     | --     | --       | 1                               | 96.4<br>(0.224)                                                                                                  | --                                                                                                                 | --              | 87.2<br>(0.203)              | 10                                                   | Moderate                                   | 0 34-2, WT               |                | 7-1       |
| 12/13<br>(40)/(45)                                         | LEA<br>1.9-1.4              | 33.81<br>(1011)              | --     | --     | --       | 1                               | 112<br>(0.261)                                                                                                   | --                                                                                                                 | --              | 92.8 <sup>h</sup><br>(0.216) | 17                                                   | --                                         | 0 38-2, WT               |                | 7-1       |

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Continued

<sup>a</sup> All reported tests were short-term (3 hr).

<sup>b</sup> NO<sub>x</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup> Based on average of all tests.

<sup>d</sup> Moderate, intermediate or stringent levels discussed in Section 3.

<sup>e</sup> Excess oxygen, %; first value is high excess air (baseline) condition, second value is low excess air condition.

<sup>f</sup> MJ/m<sup>3</sup> (Btu/lb).

<sup>g</sup> WT, watertube.

<sup>h</sup> May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

TABLE 7-21. Concluded

| Actual/Design Heat Input (10 <sup>6</sup> Btu/hr) | Control Method | Fuel Characteristics |    |    |    | Number of Tests | Baseline SO <sub>2</sub> Emissions <sup>a</sup> (lb SO <sub>2</sub> /10 <sup>6</sup> Btu) |    |    | Controlled SO <sub>2</sub> Emissions <sup>b</sup> (lb SO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                           | Percent SO <sub>2</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification | Remarks        | Reference |
|---------------------------------------------------|----------------|----------------------|----|----|----|-----------------|-------------------------------------------------------------------------------------------|----|----|---------------------------------------------------------------------------------------------|------|---------------------------|------------------------------------------------|-------------------------|-----------------------|----------------|-----------|
|                                                   |                | Heat Value           | S  | S  | S  |                 |                                                                                           |    |    | Low                                                                                         | High | Average                   |                                                |                         |                       |                |           |
| 16/19.0 (53)/(65.0)                               | LEA 4.5-3.0    | 36.157 (1108)        | -- | -- | -- | 1               | 43.9 (0.102)                                                                              | -- | -- | --                                                                                          | --   | 43.9 <sup>a</sup> (0.102) | 0                                              | Stringent               | 0 2-4, WT             | No air preheat | 7-1       |
| 14.5/18 (49.4)/(60)                               | LEA 5.2-2.5    | 37.35 (1129)         | -- | -- | -- | 1               | 53.0 (0.123)                                                                              | -- | -- | --                                                                                          | --   | 56.1 (0.130)              | -8                                             | Intermediate            | 0 10-4, WT            | No air preheat | 7-1       |
| 35/46.3 (120)/(158)                               | LEA 13.1-10.8  | 33.65 (1108)         | -- | -- | -- | 1               | 168 (0.391)                                                                               | -- | -- | --                                                                                          | --   | 127 (0.295)               | 24                                             | --                      | 0 6-3, WT             |                | 7-1       |
| 13.5/18 (46)/(60)                                 | LEA 2.6-1.4    | 37.35 (1129)         | -- | -- | -- | 1               | 123 (0.286)                                                                               | -- | -- | --                                                                                          | --   | 80.1 <sup>a</sup> (0.188) | 35                                             | Moderate                | 0 9-8C-1, WT          |                | 7-1       |
| 53.9/65.9 (164)/(225)                             | LEA 6.1-4.4    | 51.21 (1548)         | -- | -- | -- | 1               | 102 (0.237)                                                                               | -- | -- | --                                                                                          | --   | 70.9 <sup>a</sup> (0.165) | 30                                             | Moderate                | 0 12-24, WT           |                | 7-1       |
| 8.8/21 (30)/(70)                                  | LEA 5.7-3.7    | 37.3 (1000)          | -- | -- | -- | 1               | 100 (0.234)                                                                               | -- | -- | --                                                                                          | --   | 84.7 (0.197)              | 22                                             | Moderate                | 0 28-1, WT            |                | 7-1       |
| 35/44 (120)/(150)                                 | LEA 5.3-3.2    | 37.3 (1000)          | -- | -- | -- | 1               | 76 (0.177)                                                                                | -- | -- | --                                                                                          | --   | 81.6 (0.190)              | -4                                             | Moderate                | 0 29-5, WT            |                | 7-1       |
| 24/35 (83)/(120)                                  | LEA 4.4-2.2    | 39.1 (1051)          | -- | -- | -- | 1               | 117 (0.273)                                                                               | -- | -- | --                                                                                          | --   | 111 (0.258)               | 5                                              | --                      | 0 32-1, WT            |                | 7-1       |

<sup>a</sup>All reported tests were short-term (<3 hr).

<sup>b</sup>SO<sub>2</sub> emissions determined by chemiluminescence in all cases.

<sup>c</sup>Based on average of all tests.

Moderate, intermediate or stringent levels discussed in Section 3.

Excess oxygen, %; first value is high excess air (baseline) condition, second value is low excess air condition.

(lb SO<sub>2</sub>/10<sup>6</sup> Btu/hr).

WT, Watertube.

\* May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

T-1613



TABLE 7-22. NO<sub>x</sub> EMISSION TEST DATA FROM NATURAL GAS-FIRED INDUSTRIAL BOILERS WITH STAGED COMBUSTION AIR (SCA) (REFERENCE 7-3)

| Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Control Method                 | Fuel Characteristics |     |     |       | Number of Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                           | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification | Remarks                                                                               |
|------------------------------------------------------|--------------------------------|----------------------|-----|-----|-------|------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|------|---------------------------|------------------------------------------------|-------------------------|-----------------------|---------------------------------------------------------------------------------------|
|                                                      |                                | Heat Value           | % H | % S | % Ash |                              |                                                                                                                 | Low                                                                                                               | High | Average                   |                                                |                         |                       |                                                                                       |
| 2.5/3.5 (8.5)/(12)                                   | SCAF<br>φ = 57%                | --                   | --  | --  | --    | 1                            | 36.3 (0.084)                                                                                                    | --                                                                                                                | --   | 34.5 (0.080)              | 5                                              | Stringent               | # ECC, FTH            | Overall excess O <sub>2</sub> : 2.9% (SCA), 1.9% (baseline) (Ref. 7-2) No air preheat |
| 1.2/3.5 (4)/(12)                                     | SCAF<br>φ = 129%               | --                   | --  | --  | --    | 1                            | 28.0 (0.065)                                                                                                    | --                                                                                                                | --   | 23.6 <sup>e</sup> (0.055) | 16                                             | Stringent               | # ECC, FT             | Overall excess O <sub>2</sub> : 7.6% (SCA), 8.0% (baseline) (Ref. 7-2) No air preheat |
| 4.3/5.1 (14.5)/(17.5)                                | SCAF<br>φ <sub>B</sub> = 0.97% | 38.69 (1035)         | --  | --  | --    | 1                            | 45.9 (0.107)                                                                                                    | --                                                                                                                | --   | 25.0 (0.058)              | 46                                             | Stringent               | # 19-1, WT            | Lance at 2.1 m Overall excess O <sub>2</sub> 2.8% No air preheat                      |
| 11.3/13.2 (38.7)/(45)                                | SCAF<br>φ <sub>B</sub> = NA    | 37.7 (1011)          | --  | --  | --    | 1                            | 82.1 (0.191)                                                                                                    | --                                                                                                                | --   | 56.6 (0.132)              | 31                                             | Intermediate            | # 30-2, WT            | Overall excess O <sub>2</sub> 2.25%                                                   |

<sup>a</sup>All reported tests were short-term (K3 hr).  
<sup>b</sup>NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
<sup>c</sup>Based on average of all tests.  
<sup>d</sup>Quadrant, intermediate or stringent levels discussed in Section 3.  
<sup>e</sup>φ<sub>B</sub> = Burner stoichiometry.  
<sup>f</sup>φ<sub>B</sub> = Equivalence ratio, defined as ratio of stoichiometric air-fuel ratio to actual air-fuel ratio at the burner.  
<sup>g</sup>NO<sub>2</sub>/m<sup>3</sup> (Btu/lb).  
<sup>h</sup>WT, firetube, WT, watertube.  
<sup>i</sup>May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

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TABLE 7-23. NO<sub>x</sub> EMISSION TEST DATA FROM NATURAL GAS-FIRED INDUSTRIAL BOILERS WITH FLUE GAS RECIRCULATION (FGR)

| Actual/Design Heat Input MW (10 <sup>6</sup> Btu/hr) | Control Method | Fuel Characteristics |     |     |         | Baseline NO <sub>x</sub> Emissions <sup>b</sup> mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |              |                          | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification  | Remarks                                                            | Reference |
|------------------------------------------------------|----------------|----------------------|-----|-----|---------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|--------------|--------------------------|------------------------------------------------|-------------------------|------------------------|--------------------------------------------------------------------|-----------|
|                                                      |                | Heat Value           | % S | % S | % S Ash |                                                                                                                 | Low                                                                                                               | High         | Average                  |                                                |                         |                        |                                                                    |           |
| 1.75/3.5 (6)/(12)                                    | FGR, 30%       | --                   | --  | --  | --      | 41 (0.095)                                                                                                      | 10 (0.023)                                                                                                        | 14 (0.032)   | 13 (0.030)               | 68                                             | Stringent               | Ø ECC, FT <sup>f</sup> | Excess O <sub>2</sub> 4%<br>No air preheat                         | 7-2       |
| 1.75/3.5 (6)/(12)                                    | FGR, 50%       | --                   | --  | --  | --      | 41 (0.095)                                                                                                      | 8.2 (0.019)                                                                                                       | 9.2 (0.021)  | 8.9 (0.021)              | 79                                             | Stringent               | Ø ECC, FT              | Excess O <sub>2</sub> 4%<br>No air preheat                         | 7-2       |
| 1.75/3.5 (6)/(12)                                    | FGR, 30%       | --                   | --  | --  | --      | 33 (0.077)                                                                                                      | --                                                                                                                | --           | 9.2 <sup>g</sup> (0.021) | 72                                             | Stringent               | Ø ECC, FT              | Excess O <sub>2</sub> 1.2%<br>No air preheat                       | 7-2       |
| 1.75/3.5 (6)/(12)                                    | FGR, 50%       | --                   | --  | --  | --      | 33 (0.077)                                                                                                      | 3.1 (0.0071)                                                                                                      | 5.5 (0.015)  | 4.4 (0.010)              | 86                                             | Stringent               | Ø ECC, FT              | Excess O <sub>2</sub> 3.5%<br>No air preheat                       | 7-2       |
| 2.3/3.5 (8)/(12)                                     | FGR, 55%       | --                   | --  | --  | --      | 36 (0.084)                                                                                                      | 5.2 (0.012)                                                                                                       | 7.0 (0.016)  | 6.0 <sup>g</sup> (0.014) | 84                                             | Stringent               | Ø ECC, FT              | Comparatively high load. Excess O <sub>2</sub> 2%. No air preheat. | 7-2       |
| 2.0/7.3 (7)/(25)                                     | FGR, 12%       | --                   | --  | --  | --      | 27 (0.062)                                                                                                      | 12 (0.028)                                                                                                        | 15 (0.036)   | 14 (0.031)               | 48                                             | Stringent               | Ø ECC, WT              | Excess O <sub>2</sub> 1-3%<br>No air preheat                       | 7-2       |
| 2.0/7.3 (7)/(25)                                     | FGR, 25%       | --                   | --  | --  | --      | 27 (0.062)                                                                                                      | 6.5 (0.015)                                                                                                       | 10 (0.023)   | 8.2 (0.019)              | 70                                             | Stringent               | Ø ECC, WT              | Excess O <sub>2</sub> 1-3%<br>No air preheat                       | 7-2       |
| 2.8/7.3 (9.5)/(25)                                   | FGR, 22%       | --                   | --  | --  | --      | 22 (0.050)                                                                                                      | 7.0 (0.016)                                                                                                       | 9.2 (0.021)  | 8.1 (0.019)              | 63                                             | Stringent               | Ø ECC, WT              | Excess O <sub>2</sub> 1.2-2.6%<br>No air preheat                   | 7-2       |
| 4.2/5.1 (14.5)/(17.5)                                | FGR, 8%        | 34,249 (1035)        | --  | --  | --      | 52 (0.121)                                                                                                      | 21 (0.049)                                                                                                        | 29 (0.067)   | 25 (0.058)               | 52                                             | Stringent               | Ø 19-1, WT             | Excess O <sub>2</sub> 1.5-3.1%<br>No air preheat                   | 7-3       |
| 4.2/5.1 (14.5)/(17.5)                                | FGR, 20%       | 34,24 (1035)         | --  | --  | --      | 45.9 (0.107)                                                                                                    | 11.2 (0.076)                                                                                                      | 12.2 (0.028) | 11.7 (0.027)             | 75                                             | Stringent               | Ø 19-1, WT             | Excess O <sub>2</sub> 2.5-3.2%<br>No air preheat                   | 7-3       |

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<sup>a</sup>All reported tests were short-term (30 hr).  
<sup>b</sup>NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
<sup>c</sup>Based on average of all tests.  
<sup>d</sup>Moderate, intermediate or stringent levels discussed in Section 3.  
<sup>e</sup>Mass percent flue gas recirculated.  
<sup>f</sup>FT, firetube, WT, watertube.  
<sup>g</sup>94W/m<sup>2</sup> (84W/m<sup>2</sup>).  
<sup>h</sup>May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

TABLE 7-24. NO<sub>x</sub> TEST DATA FROM NATURAL GAS-FIRED INDUSTRIAL BOILERS WITH COMBINED FLUE GAS RECIRCULATION AND STAGED COMBUSTION (FGR/SCA) (REFERENCE 7-3)

| Actual/Design<br>Heat Input<br>MM (10 <sup>6</sup> Btu/hr) | Control<br>Method                      | Fuel Characteristics |        |        |          | Number of<br>Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                 | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported | Boiler<br>Identification | Remarks                                                 |
|------------------------------------------------------------|----------------------------------------|----------------------|--------|--------|----------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|-----------------|------------------------------------------------------|-------------------------------|--------------------------|---------------------------------------------------------|
|                                                            |                                        | Heat<br>Value        | %<br>H | %<br>S | %<br>Ash |                                 |                                                                                                                    | Low                                                                                                                  | High | Average         |                                                      |                               |                          |                                                         |
| 4.0/5.1<br>(13.7)/(17.5)                                   | FGR, 17.8%<br>SCA,<br>$\phi_g = 0.067$ | 34,249<br>(1035)     | --     | --     | --       | 1                               | 45.9<br>(0.107)                                                                                                    | --                                                                                                                   | --   | 11.2<br>(0.026) | 76                                                   | Stringent                     | # 19-1, MTH              | Overall excess O <sub>2</sub><br>3.3%<br>No air preheat |

<sup>a</sup>All reported tests were short-term (3 hr).  
<sup>b</sup>NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
<sup>c</sup>Based on average of all tests.  
 Moderate, intermediate or stringent levels discussed in Section 3.  
 $\phi_g$  = Equivalence ratio, defined as ratio of stoichiometric air-fuel ratio to actual air-fuel ratio at the burner.  
 H<sub>2</sub>, water vapor.

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TABLE 7-25. NO<sub>x</sub> EMISSION TEST DATA FROM NATURAL GAS-FIRED INDUSTRIAL BOILERS WITH LOAD REDUCTION (LR)

| Actual/Design Heat Input MB (10 <sup>6</sup> Btu/hr) | Control Method  | Fuel Characteristics |    |    |    | Number of Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                 | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification | Remarks                                    | Reference |
|------------------------------------------------------|-----------------|----------------------|----|----|----|------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|------|-----------------|------------------------------------------------|-------------------------|-----------------------|--------------------------------------------|-----------|
|                                                      |                 | Heat Value           | S  | N  | S  | S                            |                                                                                                                 | Low                                                                                                               | High | Average         |                                                |                         |                       |                                            |           |
| --/2.9<br>--/(10)                                    | LR<br>100-50e   | 36.65/<br>(1108)     | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 91.0<br>(0.119) | -10                                            | Intermediate            | Ø 3-2, FT9            | No air preheat                             | 7-1       |
| --/5.8<br>--/(20)                                    | LR<br>92.5-45   | 36.65<br>(1108)      | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 92.5<br>(0.122) | 0                                              | Intermediate            | Ø 4-4, FT             | No air preheat                             | 7-1       |
| --/2.9<br>--/(10)                                    | LR<br>100-50    | 36.65<br>(1108)      | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 90.1<br>(0.070) | -5                                             | Stringent               | Ø 5-24B-3, FT         | No air preheat                             | 7-1       |
| --/2.3<br>--/(80)                                    | LR<br>100-40    | 36.65<br>(1108)      | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 28.0<br>(0.085) | 29                                             | Stringent               | Ø 5-24B-1, FT         | No air preheat                             | 7-1       |
| --/3.8<br>--/(13.0)                                  | LR<br>95/32     | 31.96<br>(966)       | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 34.7<br>(0.081) | -10                                            | Stringent               | Ø 24-TY, FT           | No air preheat                             | 7-1       |
| --/5.8<br>--/(20.0)                                  | LR<br>62.5-21   | 31.99<br>(967)       | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 37.2<br>(0.087) | 15                                             | Stringent               | Ø 25-1, FT            | No air preheat                             | 7-1       |
| --/3.2<br>--/(11)                                    | LR<br>47-25     | 31.89<br>(964)       | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 43.4<br>(0.101) | 1                                              | Stringent               | Ø 26-2, FT            | No air preheat                             | 7-1       |
| --/5.2<br>--/(18)                                    | LR<br>95.6-42.8 | 31.89<br>(964)       | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 27.5<br>(0.064) | 7                                              | Stringent               | Ø 26-1, FT            | No air preheat                             | 7-1       |
| --/8.4<br>--/(29)                                    | LR<br>83-64     | 36.65<br>(1108)      | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 42.8<br>(0.100) | -2                                             | Stringent               | Ø 1-1, WT             | Excess O <sub>2</sub> 3%<br>No air preheat | 7-1       |
| --/8.4<br>--/(29)                                    | LR<br>62-26     | 36.65<br>(1108)      | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 92.0<br>(0.121) | -32                                            | Intermediate            | Ø 1-1, WT             | Excess O <sub>2</sub> 8%<br>No air preheat | 7-1       |
| --/8.4<br>--/(29)                                    | LR<br>85-59     | 36.65<br>(1108)      | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 39.8<br>(0.093) | -1                                             | Stringent               | Ø 1-2, WT             | No air preheat                             | 7-1       |
| --/7.3<br>--/(25)                                    | LR<br>80-44     | 36.65<br>(1108)      | -- | -- | -- | --                           | 1                                                                                                               | --                                                                                                                | --   | 7.1<br>(0.017)  | 82                                             | Stringent               | Ø 5-716-3, WT         | No air preheat                             | 7-1       |

<sup>a</sup>All reported tests were short-term (≤3 hr).  
<sup>b</sup>NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
<sup>c</sup>Based on average of all tests.  
 Moderate, intermediate or stringent levels discussed in Section 3.  
 Excess O<sub>2</sub> is high load (baseline), second value is low load.  
 SF, firetube; WT, watertube.

Continued

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TABLE 7-25. Concluded

| Actual/Design Heat Input (10 <sup>6</sup> Btu/hr) | Control Method | Fuel Characteristics        |    |    |    | Number of Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                              | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification   | Remarks                                       | Reference |
|---------------------------------------------------|----------------|-----------------------------|----|----|----|------------------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------------------|------|------------------------------|------------------------------------------------|-------------------------|-------------------------|-----------------------------------------------|-----------|
|                                                   |                | Heat Value                  | S  | S  | S  |                              |                                                                              | Low                                                                            | High | Average                      |                                                |                         |                         |                                               |           |
| --/32.2<br>--/(110)                               | LR 90-27e      | 42.1 <sup>f</sup><br>(1129) | -- | -- | -- | 1                            | 53.2<br>(0.147)                                                              | --                                                                             | --   | 54.5<br>(0.127)              | 14                                             | Intermediate            | # 10-5, WT <sup>g</sup> | Excess O <sub>2</sub> 7%<br>No air preheat    | 7-1       |
| --/5.1<br>--/(17.5)                               | LR 91-70       | 38.1<br>(1023)              | -- | -- | -- | 1                            | 28.6<br>(0.066)                                                              | --                                                                             | --   | 30.5<br>(0.071)              | -7                                             | Stringent               | # 19-1, WT              | Excess O <sub>2</sub> 3%<br>No air preheat    | 7-1       |
| --/29.3<br>--/(100)                               | LR 75-20       | 36.4<br>(976)               | -- | -- | -- | 1                            | 57.6<br>(0.134)                                                              | --                                                                             | --   | 51.5<br>(0.120)              | 11                                             | Intermediate            | # 27-1, WT              | Excess O <sub>2</sub> 6.8%<br>No air preheat  | 7-1       |
| --/17.6<br>--/(60)                                | LR 101-42      | 42.1<br>(1129)              | -- | -- | -- | 1                            | 58.7<br>(0.136)                                                              | --                                                                             | --   | 55.1<br>(0.126)              | 6                                              | Intermediate            | # 10-4, WT              | Excess O <sub>2</sub> 3.8%<br>No air preheat  | 7-1       |
| --/7.3<br>--/(25)                                 | LR 78-41       | --                          | -- | -- | -- | 1                            | 33.2<br>(0.077)                                                              | --                                                                             | --   | 35.4<br>(0.082)              | -7                                             | Stringent               | # ECCO, WT              | No air preheat                                | 7-2       |
| --/3.5<br>--/(12)                                 | LR 73-31       | --                          | -- | -- | -- | 1                            | 45.9<br>(0.107)                                                              | --                                                                             | --   | 45.0<br>(0.105)              | 2                                              | Stringent               | # ECCO, FT              | No air preheat                                | 7-2       |
| --/46.3<br>--/(158)                               | LR 95-39       | 36.65<br>(1108)             | -- | -- | -- | 1                            | 178<br>(0.415)                                                               | --                                                                             | --   | 53.0<br>(0.123)              | 70                                             | Intermediate            | # 6-3, WT               | Excess O <sub>2</sub> 12.5%<br>No air preheat | 7-1       |
| --/46.9<br>--/(160)                               | LR 94-79       | 42.1<br>(1129)              | -- | -- | -- | 1                            | 206<br>(0.479)                                                               | --                                                                             | --   | 181<br>(0.421)               | 12                                             | --                      | # 9-BC-6, WT            | Excess O <sub>2</sub> 4%<br>No air preheat    | 7-1       |
| --/18<br>--/(60)                                  | LR 90-57       | 42.1<br>(1129)              | -- | -- | -- | 1                            | 125<br>(0.290)                                                               | --                                                                             | --   | 70.4 <sup>e</sup><br>(0.164) | 44                                             | Moderate                | # 9-BC-1, WT            | Excess O <sub>2</sub> 2%<br>No air preheat    | 7-1       |
| --/65.9<br>--/(225)                               | LR 100-58      | 37.8<br>(1016)              | -- | -- | -- | 1                            | 104<br>(0.241)                                                               | --                                                                             | --   | 89.8<br>(0.209)              | 14                                             | Moderate                | # 12-24, WT             | Excess O <sub>2</sub> 5.5%<br>No air preheat  | 7-1       |

All reported tests were short-term (3 hr).  
 NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
 Based on average of all tests.  
 ePercent load; first value is high load (baseline), second value is low load.  
 fBTU/lb (Btu/lb).  
 gFT, firetube; WT, watertube.  
 \*May involve unacceptable operating conditions leading to high CO and/or smoke emissions.

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TABLE 7-26. NO<sub>x</sub> EMISSION TEST DATA FROM NATURAL GAS-FIRED INDUSTRIAL BOILERS WITH REDUCED AIR PREHEAT (RAP)  
(REFERENCE 7-1)

| Actual/Design<br>Heat Input<br>MB (10 <sup>6</sup> Btu/hr) | Control<br>Method | Fuel Characteristics         |        |        |          | Number of<br>Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup><br>mg NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |      |                 | Percent<br>NO <sub>x</sub><br>Reduction <sup>c</sup> | Control<br>Level<br>Supported | Boiler<br>Identification | Remarks                    |
|------------------------------------------------------------|-------------------|------------------------------|--------|--------|----------|---------------------------------|--------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------|-----------------|------------------------------------------------------|-------------------------------|--------------------------|----------------------------|
|                                                            |                   | Heat<br>Value                | X<br>N | X<br>S | X<br>Ash |                                 |                                                                                                                    | Low                                                                                                                  | High | Average         |                                                      |                               |                          |                            |
| 58.6/73.2<br>(200)/(250)                                   | RAP<br>383-300    | 38.0 <sup>f</sup><br>(11047) | --     | --     | --       | 1                               | 94.9<br>(0.221)                                                                                                    | --                                                                                                                   | --   | 70.9<br>(0.165) | 25                                                   | Moderate                      | # 34-2, WT9              | Excess O <sub>2</sub> 2.7% |
| 44/73.2<br>(150)/(250)                                     | RAP<br>391-308    | 38.0<br>(11047)              | --     | --     | --       | 1                               | 108<br>(0.250)                                                                                                     | --                                                                                                                   | --   | 58.7<br>(0.136) | 45                                                   | Intermediate                  | # 34-2, WT               | Excess O <sub>2</sub> 4.7% |
| 11/13<br>(39)/(45)                                         | RAP<br>550-480    | 37.7<br>(11011)              | --     | --     | --       | 1                               | 112<br>(0.261)                                                                                                     | --                                                                                                                   | --   | 63.2<br>(0.147) | 44                                                   | Intermediate                  | # 38-2, WT               | Excess O <sub>2</sub> 1.7% |

<sup>a</sup>All reported tests were short-term (3 hr).  
<sup>b</sup>NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
<sup>c</sup>Based on average of all tests.  
<sup>d</sup>Moderate, intermediate or stringent levels discussed in Section 3.  
<sup>e</sup>Operating air temperature (K), first value is baseline, second is reduced air preheat temperature.  
<sup>f</sup>MB/MB (Btu/lb).

WT, water tube.

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TABLE 7-27. NO<sub>x</sub> EMISSION TEST DATA FROM NATURAL GAS-FIRED INDUSTRIAL BOILERS WITH BURNERS OUT OF SERVICE (BOOS) (REFERENCE 7-1)

| Actual/Design Heat Input Mw (10 <sup>6</sup> Btu/hr) | Control Method | Fuel Characteristics     |     |     |       | Number of Tests <sup>a</sup> | Baseline NO <sub>x</sub> Emissions <sup>b</sup> ng NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) | Controlled NO <sub>x</sub> Emissions <sup>b</sup> ng NO <sub>2</sub> /J (lb NO <sub>2</sub> /10 <sup>6</sup> Btu) |               |               | Percent NO <sub>x</sub> Reduction <sup>c</sup> | Control Level Supported | Boiler Identification | Remarks                                                                              |
|------------------------------------------------------|----------------|--------------------------|-----|-----|-------|------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|---------------|---------------|------------------------------------------------|-------------------------|-----------------------|--------------------------------------------------------------------------------------|
|                                                      |                | Heat Value               | X N | X S | X Ash |                              |                                                                                                                 | Low                                                                                                               | High          | Average       |                                                |                         |                       |                                                                                      |
| 13.5/17.6 (46)/(60)                                  | BOOS           | 42.1 <sup>e</sup> (1129) | --  | --  | --    | 3                            | 123 (0.287)                                                                                                     | 96.9 (0.225)                                                                                                      | 107.1 (0.249) | 102.5 (0.238) | 17                                             | --                      | # 9-BC-1, WT          | Two rows of two burners, one upper BOOS burner on air only. Excess O <sub>2</sub> 3% |
| 8.5/20.5 (24)/(70)                                   | BOOS           | 37.3 (1000)              | --  | --  | --    | 3                            | 108 (0.251)                                                                                                     | 49 (0.113)                                                                                                        | 70 (0.619)    | 60.3 (0.140)  | 44                                             | Intermediate            | # 28-1, WT            | One row of three burners. Center burner on air only. Excess O <sub>2</sub> 5.5%      |
| 17.9/35.2 (61)/(120)                                 | BOOS           | 39.1 (1050)              | --  | --  | --    | 2                            | 105 (0.246)                                                                                                     | 74 (0.172)                                                                                                        | 80 (0.186)    | 77 (0.179)    | 27                                             | Moderate                | # 32-1, WT            | Two rows of two burners, both upper burners on air only. Excess O <sub>2</sub> 4.4%  |

<sup>a</sup>All reported tests were short-term (C3 hr).  
<sup>b</sup>NO<sub>x</sub> emissions determined by chemiluminescence in all cases.  
<sup>c</sup>Based on average of all tests.  
 Moderate, intermediate or stringent levels discussed in Section 3.  
 CH<sub>4</sub>/m<sup>3</sup> (Btu/ft<sup>3</sup>).  
 Fuel, water tube.  
 9800S load, 41 x 10<sup>6</sup> Btu.

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## REFERENCES FOR SECTION 7

- 7-1 Hunter, S. C. and H. J. Buening, , "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers -- Phases I and II (Data Supplement)," EPA-600/2-77-122, NTIS-PB 270 112/6AS, June 1977.
- 7-2 Cichanowicz, J. E., et al., "Pollutant Control Techniques for Package Boilers. Phase I Hardware Modifications and Alternate Fuels," Draft Report, under EPA Contract No. 68-02-1498, November 1976.
- 7-3 Carter, W. A., et al., "Emissions Reduction on Two Industrial Boilers with Major Combustion Modifications," EPA 600-7-78-099a, NTIS-PB 283 109, June 1978.
- 7-4 Cato, G. A., et al., "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers -- Phase I," EPA-650/2-74-078a, NTIS-PB 238 920/AS, October 1974.
- 7-5 Cato, G. A., et al., "Field Testing: Application of Combustion Modifications to Control Pollutant Emissions from Industrial Boilers -- Phase II," EPA-600/2-76-086a, NTIS PB-253 500/AS, April 1976.
- 7-6 Heap, M. P., et al., "Reduction of Nitrogen Oxide Emissions from Field Operating Package Boilers, Phase III," EPA-600/2-77-025, NTIS-PB 269 277, January 1977.
- 7-7 Maloney, K. L., et al., "Low-sulfur Western Coal Use in Existing Small and Intermediate Size Boilers," EPA-600/7-78-153a, NTIS PB-287-937/AS, July 1978.
- 7-8 Gabrielson, J. E., et al., "Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement - Site A," EPA-600/7-78-136a, NTIS PB-285-972/AS, July 1978.
- 7-9 Lips, H. I., and E. B. Higginbotham, "Field Testing of an Industrial Stoker Coal-Fired Boiler -- Effects of Combustion Modification NO<sub>x</sub> Control on Emissions -- Site B," Acurex Report TR-79-18/EE, EPA Contract No. 68-02-2160, Acurex Corporation, Mountain View, CA, August 1978.
- 7-10 Langsjoen, P. L., et al., "Test Results of Modern Coal Fired Stoker Boilers for Emissions and Efficiency," presented at the American Power Conference, Chicago, Illinois, April 23-25, 1979. .
- 7-11 Matthews, B. J., TRW, Inc., Redondo Beach, California, Letter to W. Peters, EPA IERL-RTP, NC, March 23, 1979.
- 7-12 Hall, R. E., IERL-RTP, NC, Telecommunication with K. J. Lim, Acurex Corporation, May 18, 1979.



## APPENDIX A

### COST DETAILS

Following are listed tables of estimated capital costs and annualized costs for combustion modification NO<sub>x</sub> control techniques. Tables are presented for each combination of typical boiler type/candidate control system. All assumptions (capital recovery factor, load factors, engineering estimate factors, etc.) are all discussed in Sections 4 and 5. The format followed is that requested by EPA:EAB. These tables supplement the summary cost tables presented in Section 4.

TABLE A-1. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR  
OPERATION ON A NEW 59 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$16,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 5,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 21,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 27,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> | <u>0</u>              |                  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 27,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-1 and 4-10 through 4-13.

<sup>b</sup>From Annual Cost Table (see following table).

VALENTINE, FISHER & TOMLINSON  
CONSULTING ENGINEERS

COMPUTER PRINT-OUT OF ATMOSPHERIC EMISSION DATA

JOB NAME EPA FIREPLACE

DATE 4 AUGUST 1975

PREPARED BY SWANSON

APPROVED \_\_\_\_\_

PAGE 1 OF 1

SUBJECT FIREPLACE EMISSIONS RUN# 7

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|           |               |          |           |          |           |            |               |
|-----------|---------------|----------|-----------|----------|-----------|------------|---------------|
| 00.530    | <b>VOLm</b>   | 0.005    | <b>VH</b> | 0.020    | <b>VH</b> |            |               |
| 09.65     | <b>Pm</b>     | 605      | <b>Ts</b> | 605      | <b>Ts</b> | 0.111107   | <b>Ka</b>     |
| 530       | <b>Tstd</b>   | 0.046531 |           | 0.024910 |           |            |               |
| 540       | <b>Tm</b>     |          |           |          |           | 0.03       | <b>Cp</b>     |
|           |               | 0.01     | <b>VH</b> | 0.01     | <b>VH</b> | 7.674170   | <b>Vo</b>     |
| 00.518640 | <b>VOLstd</b> | 630      | <b>Ts</b> | 635      | <b>Ts</b> | 1.170      | <b>As</b>     |
|           |               | 0.509900 |           | 0.510920 |           |            |               |
| 0.62670   | <b>VOLw</b>   |          |           |          |           | 531.750900 | <b>Qo</b>     |
|           |               | 0.012    |           | 0.012    |           |            |               |
| 0.401500  | <b>M</b>      | 625      |           | 630      |           | 530        | <b>Tstd</b>   |
|           |               | 0.738610 |           | 0.749545 |           | 635        | <b>Ts</b>     |
| 0.275005  | <b>MF</b>     |          |           |          |           | 22.01      | <b>Psn</b>    |
| 20.05     | <b>Wd</b>     | 0.0125   |           | 0.015    |           |            |               |
|           |               | 620      |           | 625      |           | 423.801264 | <b>Qos</b>    |
| 08.500437 | <b>Ww</b>     | 0.783882 |           | 3.061662 |           |            |               |
|           |               |          |           |          |           |            |               |
| 1.006205  | <b>Cd</b>     | 0.01     |           | 0.015    |           | 635        | <b>Ts</b>     |
|           |               | 630      |           | 620      |           | 530        | <b>Tstd</b>   |
| 29.61     | <b>Psn</b>    | 0.509980 |           | 0.049590 |           | 29.61      | <b>Psn</b>    |
|           |               |          |           |          |           | 60         | <b>T</b>      |
| 1.005220  | <b>Cs</b>     |          |           |          |           | 0.00136    | <b>An</b>     |
|           |               | 0.0125   |           | 0.012    |           |            |               |
|           |               | 630      |           | 625      |           |            |               |
|           |               | 0.806243 |           | 0.738612 |           | 7.174276   | <b>Vn</b>     |
|           |               |          |           |          |           | 24.711514  | <b>I</b>      |
|           |               | 0.015    |           | 0.012    |           |            |               |
|           |               | 620      |           | 625      |           | 72.5       | <b>A</b>      |
|           |               | 0.049590 |           | 0.738612 |           | 0.030429   | <b>Co</b>     |
|           |               |          |           |          |           |            |               |
|           |               | 0.012    |           | 0.015    |           |            |               |
|           |               | 611      |           | 620      |           | 0.2        | <b>N</b>      |
|           |               | 0.707766 |           | 0.049590 |           | 0.065740   | <b>C</b>      |
|           |               |          |           |          |           |            |               |
|           |               | 0.01     |           | 0.015    |           |            |               |
|           |               | 635      |           | 610      |           | 0.144071   | <b>PMRp</b>   |
|           |               | 0.617250 |           | 0.024896 |           | 72.5       | <b>Pf</b>     |
|           |               |          |           |          |           | 1.170      | <b>As</b>     |
|           |               | 0.015    |           |          |           | 60         | <b>T</b>      |
|           |               | 680      |           |          |           | 0.00136    | <b>An</b>     |
|           |               | 0.193743 |           |          |           |            |               |
|           |               |          |           |          |           |            |               |
|           |               | 0.02     |           |          |           | 0.137301   | <b>PMRar</b>  |
|           |               | 605      |           |          |           |            |               |
|           |               | 0.701351 |           |          |           | 0.141126   | <b>PMRavg</b> |
|           |               |          |           |          |           |            |               |
|           |               |          |           |          |           | 0.2        | <b>N</b>      |
|           |               |          |           |          |           | 0.004465   | <b>C'</b>     |

TABLE A-3. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION  
ON A NEW 59 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$26,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$12,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 38,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 7,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 47,000</u> |
| Land                                                               |                       | <u>--</u>        |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 4,450</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 51,450</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-1 and 4-10 through 4-13.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-4. ESTIMATED INCREMENTAL ANNUAL COSTS FOR STAGED COMBUSTION  
ON A NEW 59 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | <u>0</u>              |                  |
| Supervision                          | <u>0</u>              |                  |
| Maintenance labor                    |                       |                  |
| Maintenance materials                |                       |                  |
| Replacement parts                    |                       |                  |
| Electricity -- fan                   | <u>\$12,612</u>       |                  |
| Steam                                | <u>0</u>              |                  |
| Cooling water                        | <u>0</u>              |                  |
| Process water                        | <u>0</u>              |                  |
| Fuel                                 | <u>\$ 2,953</u>       |                  |
| Waste disposal                       | <u>0</u>              |                  |
| Chemicals                            | <u>0</u>              |                  |
| Total direct cost                    |                       | <u>\$ 17,817</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>--</u>             |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 1,880</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$ 7,520</u>       |                  |
| Total capital charges                |                       | <u>\$ 9,400</u>  |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 27,217</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-5. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB)  
FOR A NEW 59 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 38,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 7,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 47,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 0</u>      |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 47,000</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5)  
<sup>b</sup>From Annual Cost Table (see following Table).

TABLE A-6. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB)  
ON A NEW 59 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                                           |                |  |                  |
|-----------------------------------------------------------|----------------|--|------------------|
| Direct cost                                               |                |  |                  |
| Direct labor                                              |                |  |                  |
| Supervision                                               |                |  |                  |
| Maintenance labor                                         |                |  |                  |
| Maintenance materials                                     |                |  |                  |
| Replacement parts                                         |                |  |                  |
| Electricity                                               |                |  |                  |
| Steam                                                     |                |  |                  |
| Cooling water                                             |                |  |                  |
| Process water                                             |                |  |                  |
| Fuel                                                      |                |  |                  |
| Waste disposal                                            |                |  |                  |
| Chemicals                                                 |                |  |                  |
| Total direct cost                                         |                |  | <u>\$ 17,800</u> |
| Overhead                                                  |                |  |                  |
| Payroll (30% of direct labor)                             | Included above |  |                  |
| Plant (26% of labor, parts & maint.)                      | Included above |  |                  |
| Total overhead cost                                       |                |  |                  |
| By-product credits                                        |                |  | <u>( )</u>       |
| Capital charges                                           |                |  |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | \$ 1,880       |  |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | \$ 7,520       |  |                  |
| Total capital charges                                     |                |  | <u>\$ 9,400</u>  |
| TOTAL ANNUALIZED COSTS                                    |                |  | <u>\$ 27,200</u> |

<sup>a</sup>LNB operation is assumed to cost no more than staged combustion  
(see Sections 4 and 5).

TABLE A-7. ESTIMATED INCREMENTAL CAPITAL COSTS FOR AMMONIA INJECTION  
ON A NEW 59 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$235,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 | <u>Included above</u> |                  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$237,000</u> |
| Land                                                               |                       | <u>--</u>        |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 8,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$245,000</u> |

<sup>a</sup>Ammonia injection costs are extrapolations from utility boiler data  
(References 4-4 and 4-5).

<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-8. ESTIMATED INCREMENTAL ANNUAL COSTS FOR AMMONIA INJECTION  
ON A NEW 59 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                      |                       |                   |
|--------------------------------------|-----------------------|-------------------|
| Direct cost                          |                       |                   |
| Direct labor                         | _____                 |                   |
| Supervision                          | _____                 |                   |
| Maintenance labor                    | _____                 |                   |
| Maintenance materials                | _____                 |                   |
| Replacement parts                    | _____                 |                   |
| Electricity                          | _____                 |                   |
| Steam                                | _____                 |                   |
| Cooling water                        | _____                 |                   |
| Process water                        | _____                 |                   |
| Fuel                                 | _____                 |                   |
| Waste disposal                       | _____                 |                   |
| Chemicals                            | _____                 |                   |
| Total direct cost                    |                       | <u>\$ 31,084</u>  |
| Overhead                             |                       |                   |
| Payroll (30% of direct labor)        | <u>Included</u> above |                   |
| Plant (26% of labor, parts & maint.) | <u>Included</u> above |                   |
| Total overhead cost                  |                       |                   |
| By-product credits                   |                       | <u>(        )</u> |
| Capital charges                      |                       |                   |
| G & A, taxes and insurance           |                       |                   |
| (4% of total turnkey costs)          | <u>\$ 9,400</u>       |                   |
| Capital recovery factor              |                       |                   |
| (16% of total turnkey costs)         | <u>\$38,000</u>       |                   |
| Total capital charges                |                       | <u>\$ 47,400</u>  |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 78,484</u>  |

<sup>a</sup>Ammonia injection costs are extrapolations from utility boiler data  
(References 4-4 and 4-5).

TABLE A-9. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR  
OPERATION ON A NEW 44 MW COAL-FIRED SPREADER STOKER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$13,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 4,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 17,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 3,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 22,000</u> |
| Land                                                               |                       | <u>-</u>         |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>0</u>         |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 22,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-10 through 4-15.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-10. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW EXCESS AIR OPERATION  
ON A NEW 44 MW COAL-FIRED SPREADER STOKER<sup>a</sup>

|                                      |                       |                   |
|--------------------------------------|-----------------------|-------------------|
| Direct cost                          |                       |                   |
| Direct labor                         | <u>0</u>              |                   |
| Supervision                          | <u>0</u>              |                   |
| Maintenance labor                    | }                     |                   |
| Maintenance materials                |                       |                   |
| Replacement parts                    |                       | <u>\$ 1,000</u>   |
| Electricity                          |                       | <u>Negligible</u> |
| Steam                                | <u>0</u>              |                   |
| Cooling water                        | <u>0</u>              |                   |
| Process water                        | <u>0</u>              |                   |
| Fuel                                 | <u>\$(2,332)</u>      |                   |
| Waste disposal                       | <u>0</u>              |                   |
| Chemicals                            | <u>0</u>              |                   |
| Total direct cost                    |                       | <u>\$ (1,332)</u> |
| Overhead                             |                       |                   |
| Payroll (30% of direct labor)        |                       |                   |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                   |
| Total overhead cost                  |                       | <u>\$ (1,332)</u> |
| By-product credits                   |                       | <u>( )</u>        |
| Capital charges                      |                       |                   |
| G & A, taxes and insurance           |                       |                   |
| (4% of total turnkey costs)          | <u>\$ 880</u>         |                   |
| Capital recovery factor              |                       |                   |
| (16% of total turnkey costs)         | <u>\$ 3,520</u>       |                   |
| Total capital charges                |                       | <u>\$ 4,400</u>   |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 3,068</u>   |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-11. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION  
ON A NEW 44 MW COAL-FIRED SPREADER STOKER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$13,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 4,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 17,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 3,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 22,000</u> |
| Land                                                               |                       | <u>--</u>        |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 200</u>    |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 22,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-10 through 4-15.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-12. ESTIMATED INCREMENTAL ANNUAL COSTS FOR STAGED COMBUSTION  
ON A NEW 44 MW COAL-FIRED SPREADER STOKER<sup>a</sup>

|                                      |                       |                   |
|--------------------------------------|-----------------------|-------------------|
| Direct cost                          |                       |                   |
| Direct labor                         | <u>0</u>              |                   |
| Supervision                          | <u>0</u>              |                   |
| Maintenance labor                    | }                     |                   |
| Maintenance materials                |                       |                   |
| Replacement parts                    |                       | <u>\$ 1,000</u>   |
| Electricity                          |                       | <u>Negligible</u> |
| Steam                                | <u>0</u>              |                   |
| Cooling water                        | <u>0</u>              |                   |
| Process water                        | <u>0</u>              |                   |
| Fuel                                 | <u>0</u>              |                   |
| Waste disposal                       | <u>0</u>              |                   |
| Chemicals                            | <u>0</u>              |                   |
| Total direct cost                    |                       | <u>\$ 1,000</u>   |
| Overhead                             |                       |                   |
| Payroll (30% of direct labor)        | <u>0</u>              |                   |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                   |
| Total overhead cost                  |                       | <u>--</u>         |
| By-product credits                   |                       | <u>( )</u>        |
| Capital charges                      |                       |                   |
| G & A, taxes and insurance           |                       |                   |
| (4% of total turnkey costs)          | <u>\$ 880</u>         |                   |
| Capital recovery factor              |                       |                   |
| (16% of total turnkey costs)         | <u>\$ 3,520</u>       |                   |
| Total capital charges                |                       | <u>\$ 4,400</u>   |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 5,400</u>   |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-13. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION  
ON A NEW 25 MW COAL-FIRED SPREADER STOKER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$10,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 3,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 13,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 2,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 17,000</u> |
| Land                                                               |                       | <u>--</u>        |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 150</u>    |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 17,150</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-10 through 4-15.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-14. ESTIMATED INCREMENTAL ANNUAL COSTS FOR STAGED COMBUSTION  
ON A NEW 25 MW COAL-FIRED SPREADER STOKER<sup>a</sup>

|                                      |                       |                   |
|--------------------------------------|-----------------------|-------------------|
| Direct cost                          |                       |                   |
| Direct labor                         | <u>0</u>              |                   |
| Supervision                          | <u>0</u>              |                   |
| Maintenance labor                    | }                     |                   |
| Maintenance materials                |                       |                   |
| Replacement parts                    |                       | <u>\$ 750</u>     |
| Electricity                          |                       | <u>Negligible</u> |
| Steam                                | <u>0</u>              |                   |
| Cooling water                        | <u>0</u>              |                   |
| Process water                        | <u>0</u>              |                   |
| Fuel                                 | <u>0</u>              |                   |
| Waste disposal                       | <u>0</u>              |                   |
| Chemicals                            | <u>0</u>              |                   |
| Total direct cost                    |                       | <u>\$ 750</u>     |
| Overhead                             |                       |                   |
| Payroll (30% of direct labor)        | <u>-</u>              |                   |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                   |
| Total overhead cost                  |                       | <u>--</u>         |
| By-product credits :                 |                       | <u>( )</u>        |
| Capital charges                      |                       |                   |
| G & A, taxes and insurance           |                       |                   |
| (4% of total turnkey costs)          | <u>\$ 680</u>         |                   |
| Capital recovery factor              |                       |                   |
| (16% of total turnkey costs)         | <u>\$ 2,720</u>       |                   |
| Total capital charges                |                       | <u>\$ 3,400</u>   |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 4,150</u>   |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-15. ESTIMATED INCREMENTAL CAPITAL COSTS FOR AMMONIA INJECTION  
ON A NEW 25 MW COAL-FIRED SPREADER STOKER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$100,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 | <u>Included</u> above |                  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$102,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 3,400</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 10,540</u> |

<sup>a</sup>Ammonia injection costs are extrapolations from utility boiler data (References 4-4 and 4-5).

<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-16. ESTIMATED INCREMENTAL ANNUAL COSTS FOR AMMONIA INJECTION  
ON A NEW 25 MW COAL-FIRED SPREADER STOKER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | _____                 |                  |
| Supervision                          | _____                 |                  |
| Maintenance labor                    | _____                 |                  |
| Maintenance materials                | _____                 |                  |
| Replacement parts                    | _____                 |                  |
| Electricity                          | _____                 |                  |
| Steam                                | _____                 |                  |
| Cooling water                        | _____                 |                  |
| Process water                        | _____                 |                  |
| Fuel                                 | _____                 |                  |
| Waste disposal                       | _____                 |                  |
| Chemicals                            | _____                 |                  |
| Total direct cost                    |                       | <u>\$ 13,625</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>Included above</u> |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 4,080</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$16,320</u>       |                  |
| Total capital charges                |                       | <u>\$ 20,400</u> |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 34,025</u> |

<sup>a</sup>Ammonia injection costs are extrapolations from utility boiler data  
(References 4-4 and 4-5).

TABLE A-17. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR  
OPERATION ON A NEW 22 MW COAL-FIRED CHAIN GRATE STOKER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$10,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 3,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 13,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 2,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 17,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 0</u>      |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 17,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-10 through 4-15.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-18. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW EXCESS AIR OPERATION ON A NEW 22 MW COAL-FIRED CHAIN GRATE STOKER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | <u>0</u>              |                  |
| Supervision                          | <u>0</u>              |                  |
| Maintenance labor                    | }                     |                  |
| Maintenance materials                |                       | <u>\$ 1,000</u>  |
| Replacement parts                    |                       |                  |
| Electricity                          |                       | <u>small</u>     |
| Steam                                | <u>0</u>              |                  |
| Cooling water                        | <u>0</u>              |                  |
| Process water                        | <u>0</u>              |                  |
| Fuel                                 | <u>\$(2,286)</u>      |                  |
| Waste disposal                       | <u>0</u>              |                  |
| Chemicals                            | <u>0</u>              |                  |
| Total direct cost                    |                       | <u>\$(1,286)</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        |                       |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 680</u>         |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$ 2,720</u>       |                  |
| Total capital charges                |                       | <u>\$ 3,400</u>  |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 2,114</u>  |

<sup>a</sup>Energy usage is discussed in Section 5.

TABLE A-19. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR  
OPERATION ON A NEW 9 MW COAL-FIRED UNDERFEED STOKER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$ 8,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 2,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 10,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 2,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 14,000</u> |
| Land                                                               |                       | <u>--</u>        |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 0</u>      |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 14,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-10 through 4-15.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE D-20. QUANTITY OF CADMIUM IN SOLID WASTE FROM NON-SCCP  
SOURCES IN 1978

| Source Category              | 1978 Emissions in Mg/Yr |
|------------------------------|-------------------------|
| Remelting of Steel           | 832                     |
| Copper Smelting              | 247                     |
| Fire Refiners                | 246                     |
| Slag                         | (61)                    |
| Sludge                       | (165)                   |
| Dust                         | (20)                    |
| Electrolytic Sludge          | 1                       |
| Lead Smelting                | 221                     |
| 1° Refining                  | 214                     |
| Sludge                       | (127)                   |
| Slag                         | (87)                    |
| 2° Refining, Scrubber Sludge | 7                       |
| Zinc Smelting                | 161                     |
| Electrolytic, Sludge         | 33                      |
| Pyrometallurgic              | 128                     |
| Sludge                       | (52)                    |
| Retort residue               | (76)                    |
| Ferrous Foundaries           | 4.8                     |
| Slag                         | 1.5                     |
| Sludge                       | 1.5                     |
| Dust                         | 1.8                     |
| Ferrous Alloys               | 2.4                     |
| Dust                         | 1.5                     |
| Sludge                       | 0.9                     |
| Paints                       | 0.8                     |
| Batteries                    | 2.4                     |

TABLE A-21. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR OPERATION  
ON A NEW 4.4 MW RESIDUAL OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                                                    |                       |                 |
|--------------------------------------------------------------------|-----------------------|-----------------|
| Equipment cost                                                     |                       |                 |
| Basic equipment (includes freight)                                 | _____                 |                 |
| Required auxiliaries                                               | _____                 |                 |
| Total equipment cost                                               | <u>\$ 5,000</u>       |                 |
| Installation costs, direct                                         |                       |                 |
| Foundations and supports                                           | _____                 |                 |
| Ductwork                                                           | _____                 |                 |
| Stack                                                              | _____                 |                 |
| Piping                                                             | _____                 |                 |
| Insulation                                                         | _____                 |                 |
| Painting                                                           | _____                 |                 |
| Electrical                                                         | _____                 |                 |
| Total installation cost                                            | <u>\$ 1,000</u>       |                 |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 6,000</u> |
| Installation costs, indirect                                       |                       |                 |
| Engineering                                                        |                       |                 |
| (10% of direct costs)                                              | <u>Included</u> above |                 |
| Construction and field expense                                     |                       |                 |
| (10% of direct costs)                                              | <u>Included</u> above |                 |
| Construction fees                                                  |                       |                 |
| (10% of direct costs)                                              | <u>Included</u> above |                 |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                 |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                 |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u> |
| Contingencies                                                      |                       |                 |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 1,000</u> |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 9,000</u> |
| Land                                                               |                       |                 |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 0</u>     |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 9,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-22. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW EXCESS AIR OPERATION ON A NEW 4.4 MW RESIDUAL OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                      |                       |                   |
|--------------------------------------|-----------------------|-------------------|
| Direct cost                          |                       |                   |
| Direct labor                         | <u>0</u>              |                   |
| Supervision                          | <u>0</u>              |                   |
| Maintenance labor                    | <u>0</u>              |                   |
| Maintenance materials                | <u>\$ 350</u>         |                   |
| Replacement parts                    |                       |                   |
| Electricity                          | <u>small</u>          |                   |
| Steam                                | <u>0</u>              |                   |
| Cooling water                        | <u>0</u>              |                   |
| Process water                        | <u>0</u>              |                   |
| Fuel                                 | <u>\$ (770)</u>       |                   |
| Waste disposal                       | <u>0</u>              |                   |
| Chemicals                            | <u>0</u>              |                   |
| Total direct cost                    |                       | <u>\$ (420)</u>   |
| Overhead                             |                       |                   |
| Payroll (30% of direct labor)        | <u>-</u>              |                   |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                   |
| Total overhead cost                  |                       | <u>          </u> |
| By-product credits                   |                       | <u>( )</u>        |
| Capital charges                      |                       |                   |
| G & A, taxes and insurance           |                       |                   |
| (4% of total turnkey costs)          | <u>\$ 360</u>         |                   |
| Capital recovery factor              |                       |                   |
| (16% of total turnkey costs)         | <u>\$ 1,440</u>       |                   |
| Total capital charges                |                       | <u>\$ 1,800</u>   |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 1,380</u>   |

<sup>a</sup>Energy usage is discussed in Section 5.

TABLE A-23. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION  
ON A NEW 4.4 MW RESIDUAL OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$ 7,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 7,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 14,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 3,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 19,000</u> |
| Land                                                               |                       | <u>--</u>        |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 1,435</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 20,435</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-24. ESTIMATED INCREMENTAL ANNUAL COSTS FOR STAGED COMBUSTION  
ON A NEW 4.4 MW RESIDUAL OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                      |                 |                 |
|--------------------------------------|-----------------|-----------------|
| Direct cost                          |                 |                 |
| Direct labor                         | <u>0</u>        |                 |
| Supervision                          | <u>0</u>        |                 |
| Maintenance labor                    |                 | }               |
| Maintenance materials                | <u>\$ 850</u>   |                 |
| Replacement parts                    |                 |                 |
| Electricity                          | <u>\$ 631</u>   |                 |
| Steam                                | <u>0</u>        |                 |
| Cooling water                        | <u>0</u>        |                 |
| Process water                        | <u>0</u>        |                 |
| Fuel                                 | <u>\$ 857</u>   |                 |
| Waste disposal                       | <u>0</u>        |                 |
| Chemicals                            | <u>0</u>        |                 |
| Total direct cost                    |                 | <u>\$ 2,338</u> |
| Overhead                             |                 |                 |
| Payroll (30% of direct labor)        | <u>--</u>       |                 |
| Plant (26% of labor, parts & maint.) | Included above  |                 |
| Total overhead cost                  |                 | <u>--</u>       |
| By-product credits                   |                 | <u>( )</u>      |
| Capital charges                      |                 |                 |
| G & A, taxes and insurance           |                 |                 |
| (4% of total turnkey costs)          | <u>\$ 760</u>   |                 |
| Capital recovery factor              |                 |                 |
| (16% of total turnkey costs)         | <u>\$ 3,040</u> |                 |
| Total capital charges                |                 | <u>\$ 3,800</u> |
| TOTAL ANNUALIZED COSTS               |                 | <u>\$ 6,138</u> |

<sup>a</sup>Energy usage is discussed in Section 5.

TABLE A-25. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW NO<sub>x</sub> BURNERS  
(LNB) ON A NEW 4.4 MW RESIDUAL OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 14,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 3,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 19,000</u> |
| Land                                                               | _____                 |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> | _____                 |                  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 19,000</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion and most likely will cost less (see Sections 4 and 5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-26. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB) ON A NEW 4.4 MW RESIDUAL OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                      |                                         |                                                                  |
|--------------------------------------|-----------------------------------------|------------------------------------------------------------------|
| Direct cost                          |                                         |                                                                  |
| Direct labor                         | <u>0</u>                                |                                                                  |
| Supervision                          | <u>0</u>                                |                                                                  |
| Maintenance labor                    |                                         |                                                                  |
| Maintenance materials                |                                         |                                                                  |
| Replacement parts                    | <u>\$ 850</u>                           |                                                                  |
| Electricity                          |                                         |                                                                  |
| Steam                                | <u>Depends</u> if pressure drop changes |                                                                  |
| Cooling water                        | <u>0</u>                                |                                                                  |
| Process water                        | <u>0</u>                                |                                                                  |
| Fuel                                 | <u>Probably small</u>                   |                                                                  |
| Waste disposal                       |                                         |                                                                  |
| Chemicals                            |                                         |                                                                  |
| Total direct cost                    |                                         | <u>\$ 2,338</u> (using same value as used for staged combustion) |
| Overhead                             |                                         |                                                                  |
| Payroll (30% of direct labor)        |                                         |                                                                  |
| Plant (26% of labor, parts & maint.) |                                         |                                                                  |
| Total overhead cost                  |                                         | <u>--</u>                                                        |
| By-product credits                   |                                         | <u>( )</u>                                                       |
| Capital charges                      |                                         |                                                                  |
| G & A, taxes and insurance           |                                         |                                                                  |
| (4% of total turnkey costs)          | <u>\$ 720</u>                           |                                                                  |
| Capital recovery factor              |                                         |                                                                  |
| (16% of total turnkey costs)         | <u>\$ 3,080</u>                         |                                                                  |
| Total capital charges                |                                         | <u>\$ 3,800</u>                                                  |
| TOTAL ANNUALIZED COSTS               |                                         | <u>\$ 6,138</u>                                                  |

<sup>a</sup>LNB operation is assumed to cost no more than staged combustion and will probably cost less (see Sections 4 and 5).

TABLE A-27. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR OPERATION  
ON A NEW 44 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$10,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 3,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 13,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 2,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 17,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> | <u>0.</u>             |                  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 17,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-28. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW EXCESS AIR OPERATION  
ON A NEW 44 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                      |                       |                   |
|--------------------------------------|-----------------------|-------------------|
| Direct cost                          |                       |                   |
| Direct labor                         | <u>0</u>              |                   |
| Supervision                          | <u>0</u>              |                   |
| Maintenance labor                    | }                     |                   |
| Maintenance materials                |                       |                   |
| Replacement parts                    |                       |                   |
|                                      |                       | <u>\$ 750</u>     |
| Electricity                          |                       | <u>Negligible</u> |
| Steam                                |                       | <u>0</u>          |
| Cooling water                        |                       | <u>0</u>          |
| Process water                        |                       | <u>0</u>          |
| Fuel                                 |                       | <u>\$(20,734)</u> |
| Waste disposal                       |                       | <u>0</u>          |
| Chemicals                            |                       | <u>0</u>          |
| Total direct cost                    |                       | <u>\$(19,984)</u> |
| Overhead                             |                       |                   |
| Payroll (30% of direct labor)        | <u>-</u>              |                   |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                   |
| Total overhead cost                  |                       |                   |
| By-product credits                   |                       | <u>( )</u>        |
| Capital charges                      |                       |                   |
| G & A, taxes and insurance           |                       |                   |
| (4% of total turnkey costs)          | <u>\$ 680</u>         |                   |
| Capital recovery factor              |                       |                   |
| (16% of total turnkey costs)         | <u>\$ 2,720</u>       |                   |
| Total capital charges                |                       | <u>\$ 3,400</u>   |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$(16,584)</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-29. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION  
ON A NEW 44 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$15,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$10,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 5,329</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 37,329</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-30. ESTIMATED INCREMENTAL ANNUAL COSTS FOR STAGED COMBUSTION  
ON A NEW 44 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                      |                 |                  |
|--------------------------------------|-----------------|------------------|
| Direct cost                          |                 |                  |
| Direct labor                         | <u>0</u>        |                  |
| Supervision                          | <u>0</u>        |                  |
| Maintenance labor                    | }               |                  |
| Maintenance materials                |                 |                  |
| Replacement parts                    |                 |                  |
|                                      |                 | <u>\$ 1,500</u>  |
| Electricity                          |                 | <u>\$ 9,250</u>  |
| Steam                                |                 | <u>0</u>         |
| Cooling water                        |                 | <u>0</u>         |
| Process water                        |                 | <u>0</u>         |
| Fuel                                 |                 | <u>\$10,566</u>  |
| Waste disposal                       |                 | <u>0</u>         |
| Chemicals                            |                 | <u>0</u>         |
| Total direct cost                    |                 | <u>\$ 21,317</u> |
| Overhead                             |                 |                  |
| Payroll (30% of direct labor)        | <u>-</u>        |                  |
| Plant (26% of labor, parts & maint.) | <u>Included</u> | above            |
| Total overhead cost                  |                 | <u>--</u>        |
| By-product credits                   |                 | <u>( )</u>       |
| Capital charges                      |                 |                  |
| G & A, taxes and insurance           |                 |                  |
| (4% of total turnkey costs)          | <u>\$ 1,280</u> |                  |
| Capital recovery factor              |                 |                  |
| (16% of total turnkey costs)         | <u>\$ 5,120</u> |                  |
| Total capital charges                |                 | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS               |                 | <u>\$ 31,317</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-31. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW NO<sub>x</sub> BURNERS  
(LNB) ON A NEW 44 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               | _____                 |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> | _____                 |                  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 32,000</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).  
<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-32. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB) ON A NEW 44 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                                           |                 |                  |
|-----------------------------------------------------------|-----------------|------------------|
| Direct cost                                               |                 |                  |
| Direct labor                                              | <u>0</u>        |                  |
| Supervision                                               | <u>0</u>        |                  |
| Maintenance labor                                         | }               |                  |
| Maintenance materials                                     |                 |                  |
| Replacement parts                                         |                 | <u>\$ 1,500</u>  |
| Electricity                                               |                 | <u>?</u>         |
| Steam                                                     |                 | <u>0</u>         |
| Cooling water                                             |                 | <u>0</u>         |
| Process water                                             |                 | <u>0</u>         |
| Fuel                                                      |                 | <u>?</u>         |
| Waste disposal                                            |                 | <u>0</u>         |
| Chemicals                                                 |                 | <u>0</u>         |
| Total direct cost                                         |                 | <u>\$ 21,000</u> |
| Overhead                                                  |                 |                  |
| Payroll (30% of direct labor)                             | <u>-</u>        |                  |
| Plant (26% of labor, parts & maint.)                      | <u>Included</u> | above            |
| Total overhead cost                                       |                 | <u>--</u>        |
| By-product credits                                        |                 | <u>( )</u>       |
| Capital charges                                           |                 |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | <u>\$ 1,280</u> |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | <u>\$ 5,120</u> |                  |
| Total capital charges                                     |                 | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS                                    |                 | <u>\$ 27,400</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

TABLE A-33. ESTIMATED INCREMENTAL CAPITAL COSTS FOR AMMONIA INJECTION  
ON A NEW 44 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$180,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 | <u>Included above</u> |                  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$182,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 6,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$188,000</u> |

<sup>a</sup>Ammonia injection costs are extrapolated from utility boiler data (References 4-4 and 4-5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-34. ESTIMATED INCREMENTAL ANNUAL COSTS FOR AMMONIA INJECTION  
ON A NEW 44 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                      |                 |                  |
|--------------------------------------|-----------------|------------------|
| Direct cost                          |                 |                  |
| Direct labor                         | _____           |                  |
| Supervision                          | _____           |                  |
| Maintenance labor                    | _____           |                  |
| Maintenance materials                | _____           |                  |
| Replacement parts                    | _____           |                  |
| Electricity                          | _____           |                  |
| Steam                                | _____           |                  |
| Cooling water                        | _____           |                  |
| Process water                        | _____           |                  |
| Fuel                                 | _____           |                  |
| Waste disposal                       | _____           |                  |
| Chemicals                            | _____           |                  |
| Total direct cost                    |                 | <u>\$ 24,000</u> |
| Overhead                             |                 |                  |
| Payroll (30% of direct labor)        | Included above  |                  |
| Plant (26% of labor, parts & maint.) | Included above  |                  |
| Total overhead cost                  |                 |                  |
| By-product credits                   |                 | ( )              |
| Capital charges                      |                 |                  |
| G & A, taxes and insurance           |                 |                  |
| (4% of total turnkey costs)          | <u>\$ 7,200</u> |                  |
| Capital recovery factor              |                 |                  |
| (16% of total turnkey costs)         | <u>\$28,800</u> |                  |
| Total capital charges                |                 | <u>\$ 36,000</u> |
| TOTAL ANNUALIZED COSTS               |                 | <u>\$ 60,000</u> |

<sup>a</sup>Ammonia injection costs are extrapolated from utility boiler data  
(References 4-4 and 4-5).

TABLE A-35. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR OPERATION  
ON A NEW 4.4 MW DISTILLATE OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                                                    |                       |                 |
|--------------------------------------------------------------------|-----------------------|-----------------|
| Equipment cost                                                     |                       |                 |
| Basic equipment (includes freight)                                 | _____                 |                 |
| Required auxiliaries                                               | _____                 |                 |
| Total equipment cost                                               | <u>\$ 5,000</u>       |                 |
| Installation costs, direct                                         |                       |                 |
| Foundations and supports                                           | _____                 |                 |
| Ductwork                                                           | _____                 |                 |
| Stack                                                              | _____                 |                 |
| Piping                                                             | _____                 |                 |
| Insulation                                                         | _____                 |                 |
| Painting                                                           | _____                 |                 |
| Electrical                                                         | _____                 |                 |
| Total installation cost                                            | <u>\$ 1,000</u>       |                 |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 6,000</u> |
| Installation costs, indirect                                       |                       |                 |
| Engineering                                                        |                       |                 |
| (10% of direct costs)                                              | <u>Included above</u> |                 |
| Construction and field expense                                     |                       |                 |
| (10% of direct costs)                                              | <u>Included above</u> |                 |
| Construction fees                                                  |                       |                 |
| (10% of direct costs)                                              | <u>Included above</u> |                 |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                 |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                 |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u> |
| Contingencies                                                      |                       |                 |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 1,000</u> |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 9,000</u> |
| Land                                                               | ____                  |                 |
| Working capital (25% of total direct operating costs) <sup>b</sup> | <u>0</u>              |                 |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 9,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-36. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW EXCESS AIR OPERATION  
-ON A NEW 4.4 MW DISTILLATE OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                      |                       |                   |
|--------------------------------------|-----------------------|-------------------|
| Direct cost                          |                       |                   |
| Direct labor                         | <u>0</u>              |                   |
| Supervision                          | <u>0</u>              |                   |
| Maintenance labor                    | }                     |                   |
| Maintenance materials                |                       | <u>\$ 350</u>     |
| Replacement parts                    |                       |                   |
| Electricity                          |                       | <u>Negligible</u> |
| Steam                                | <u>0</u>              |                   |
| Cooling water                        | <u>0</u>              |                   |
| Process water                        | <u>0</u>              |                   |
| Fuel                                 | <u>\$ (870)</u>       |                   |
| Waste disposal                       |                       |                   |
| Chemicals                            |                       |                   |
| Total direct cost                    |                       | <u>\$ (520)</u>   |
| Overhead                             |                       |                   |
| Payroll (30% of direct labor)        | <u>--</u>             |                   |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                   |
| Total overhead cost                  |                       | <u>--</u>         |
| By-product credits                   |                       | <u>( )</u>        |
| Capital charges                      |                       |                   |
| G & A, taxes and insurance           |                       |                   |
| (4% of total turnkey costs)          | <u>\$ 360</u>         |                   |
| Capital recovery factor              |                       |                   |
| (16% of total turnkey costs)         | <u>\$ 1,440</u>       |                   |
| Total capital charges                |                       | <u>\$ 1,800</u>   |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 1,280</u>   |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-37. ESTIMATED INCREMENTAL CAPITAL COSTS FOR FLUE GAS RECIRCULATION  
ON A NEW 4.4 MW DISTILLATE OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | <u>          </u>     |                  |
| Required auxiliaries                                               | <u>          </u>     |                  |
| Total equipment cost                                               | <u>\$ 9,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | <u>          </u>     |                  |
| Ductwork                                                           | <u>          </u>     |                  |
| Stack                                                              | <u>          </u>     |                  |
| Piping                                                             | <u>          </u>     |                  |
| Insulation                                                         | <u>          </u>     |                  |
| Painting                                                           | <u>          </u>     |                  |
| Electrical                                                         | <u>          </u>     |                  |
| Total installation cost                                            | <u>\$ 5,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 14,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 3,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 19,000</u> |
| Land                                                               |                       | <u>--</u>        |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 875</u>    |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 19,875</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-38. ESTIMATED INCREMENTAL ANNUAL COSTS DUE TO FLUE GAS RECIRCULATION  
ON A NEW 4.4 MW DISTILLATE OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                      |                       |                 |
|--------------------------------------|-----------------------|-----------------|
| Direct cost                          |                       |                 |
| Direct labor                         | <u>0</u>              |                 |
| Supervision                          | <u>0</u>              |                 |
| Maintenance labor                    | }                     |                 |
| Maintenance materials                |                       | <u>\$ 850</u>   |
| Replacement parts                    |                       |                 |
| Electricity - Fan                    |                       | <u>\$ 1,733</u> |
| Steam                                |                       | <u>0</u>        |
| Cooling water                        |                       | <u>0</u>        |
| Process water                        |                       | <u>0</u>        |
| Fuel                                 |                       | <u>\$ 914</u>   |
| Waste disposal                       |                       | <u>0</u>        |
| Chemicals                            |                       | <u>0</u>        |
| Total direct cost                    |                       | <u>\$ 3,497</u> |
| Overhead                             |                       |                 |
| Payroll (30% of direct labor)        | <u>--</u>             |                 |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                 |
| Total overhead cost                  |                       | <u>--</u>       |
| By-product credits                   |                       | <u>( )</u>      |
| Capital charges                      |                       |                 |
| G & A, taxes and insurance           |                       |                 |
| (4% of total turnkey costs)          | <u>\$ 760</u>         |                 |
| Capital recovery factor              |                       |                 |
| (16% of total turnkey costs)         | <u>\$ 3,040</u>       |                 |
| Total capital charges                |                       | <u>\$ 3,800</u> |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 7,297</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-39. ESTIMATED INCREMENTAL CAPITAL COSTS OF LOW NO<sub>x</sub> BURNERS (LNB)  
ON A NEW 4.4 MW DISTILLATE OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 14,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 3,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 19,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 500</u>    |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 19,500</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).  
<sup>b</sup>From Annual Cost Table (see following table)



TABLE A-40. ESTIMATED INCREMENTAL ANNUAL COSTS OF LOW NO<sub>x</sub> BURNERS (LNB)  
ON A NEW 4.4 MW DISTILLATE OIL-FIRED FIRETUBE BOILER<sup>a</sup>

|                                                           |       |                 |
|-----------------------------------------------------------|-------|-----------------|
| Direct cost                                               |       |                 |
| Direct labor                                              | _____ |                 |
| Supervision                                               | _____ |                 |
| Maintenance labor                                         | _____ |                 |
| Maintenance materials                                     | _____ |                 |
| Replacement parts                                         | _____ |                 |
| Electricity                                               | _____ |                 |
| Steam                                                     | _____ |                 |
| Cooling water                                             | _____ |                 |
| Process water                                             | _____ |                 |
| Fuel                                                      | _____ |                 |
| Waste disposal                                            | _____ |                 |
| Chemicals                                                 | _____ |                 |
| Total direct cost                                         |       | <u>\$ 1,900</u> |
| Overhead                                                  |       |                 |
| Payroll (30% of direct labor)                             | _____ |                 |
| Plant (26% of labor, parts & maint.)                      | _____ |                 |
| Total overhead cost                                       |       | _____           |
| By-product credits                                        |       | <u>( )</u>      |
| Capital charges                                           |       |                 |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | _____ |                 |
| Capital recovery factor<br>(16% of total turnkey costs)   | _____ |                 |
| Total capital charges                                     |       | <u>\$ 3,400</u> |
| TOTAL ANNUALIZED COSTS                                    |       | <u>\$ 5,300</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

TABLE A-41. ESTIMATED INCREMENTAL CAPITAL COSTS FOR FLUE GAS RECIRCULATION  
ON A NEW 29 MW DISTILLATE OIL-FIRED FIRETUBE BOILER WITHOUT  
AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$13,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 7,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 6,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 32,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-42. ESTIMATED INCREMENTAL ANNUAL COSTS FOR FLUE GAS RECIRCULATION  
ON A NEW 29 MW DISTILLATE OIL-FIRED FIRETUBE BOILER WITHOUT  
AN AIR PREHEATER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | <u>0</u>              |                  |
| Supervision                          | <u>0</u>              |                  |
| Maintenance labor                    |                       |                  |
| Maintenance materials                | <u>\$ 1,200</u>       |                  |
| Replacement parts                    |                       |                  |
| Electricity - Fan                    | <u>\$14,718</u>       |                  |
| Steam                                | <u>0</u>              |                  |
| Cooling water                        | <u>0</u>              |                  |
| Process water                        | <u>0</u>              |                  |
| Fuel                                 | <u>\$ 8,494</u>       |                  |
| Waste disposal                       | <u>0</u>              |                  |
| Chemicals                            | <u>0</u>              |                  |
| Total direct cost                    |                       | <u>\$ 24,412</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>-</u>              |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 1,040</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$ 4,160</u>       |                  |
| Total capital charges                |                       | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 29,612</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-43. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB)  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITHOUT  
AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 3,750</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 29,750</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).  
<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-44. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB)  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITHOUT  
AN AIR PREHEATER<sup>a</sup>

|                                                           |       |                  |
|-----------------------------------------------------------|-------|------------------|
| Direct cost                                               |       |                  |
| Direct labor                                              | _____ |                  |
| Supervision                                               | _____ |                  |
| Maintenance labor                                         | _____ |                  |
| Maintenance materials                                     | _____ |                  |
| Replacement parts                                         | _____ |                  |
| Electricity                                               | _____ |                  |
| Steam                                                     | _____ |                  |
| Cooling water                                             | _____ |                  |
| Process water                                             | _____ |                  |
| Fuel                                                      | _____ |                  |
| Waste disposal                                            | _____ |                  |
| Chemicals                                                 | _____ |                  |
| Total direct cost                                         |       | <u>\$ 15,000</u> |
| Overhead                                                  |       |                  |
| Payroll (30% of direct labor)                             | _____ |                  |
| Plant (26% of labor, parts & maint.)                      | _____ |                  |
| Total overhead cost                                       |       |                  |
| By-product credits                                        |       | <u>( )</u>       |
| Capital charges                                           |       |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | _____ |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | _____ |                  |
| Total capital charges                                     |       | <u>\$ 4,800</u>  |
| TOTAL ANNUALIZED COSTS                                    |       | <u>\$ 19,800</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

TABLE A-45. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER  
WITHOUT AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$13,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 7,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       | _____            |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 3,775</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 29,775</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-46. ESTIMATED INCREMENTAL ANNUAL COSTS OF STAGED COMBUSTION  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER  
WITHOUT AN AIR PREHEATER<sup>a</sup>

|                                                           |                 |                  |
|-----------------------------------------------------------|-----------------|------------------|
| Direct cost                                               |                 |                  |
| Direct labor                                              | <u>0</u>        |                  |
| Supervision                                               | <u>0</u>        |                  |
| Maintenance labor                                         | }               |                  |
| Maintenance materials                                     |                 | <u>\$ 1,200</u>  |
| Replacement parts                                         |                 |                  |
| Electricity - Fan                                         |                 | <u>\$ 6,307</u>  |
| Steam                                                     |                 | <u>0</u>         |
| Cooling water                                             |                 | <u>0</u>         |
| Process water                                             |                 | <u>0</u>         |
| Fuel                                                      |                 | <u>\$ 7,597</u>  |
| Waste disposal                                            |                 | <u>0</u>         |
| Chemicals                                                 |                 | <u>0</u>         |
| Total direct cost                                         |                 | <u>\$ 15,103</u> |
| Overhead                                                  |                 |                  |
| Payroll (30% of direct labor)                             | <u>-</u>        |                  |
| Plant (26% of labor, parts & maint.)                      | Included above  |                  |
| Total overhead cost                                       |                 |                  |
| By-product credits                                        |                 | <u>( )</u>       |
| Capital charges                                           |                 |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | <u>\$ 1,080</u> |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | <u>\$ 4,120</u> |                  |
| Total capital charges                                     |                 | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS                                    |                 | <u>\$ 20,303</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-47. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER  
WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$ 8,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 2,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 10,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 2,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 14,000</u> |
| Land                                                               | _____                 |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> | <u>0</u>              |                  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 14,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-48. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW EXCESS AIR OPERATION ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                       |                   |
|--------------------------------------|-----------------------|-------------------|
| Direct cost                          |                       |                   |
| Direct labor                         | <u>0</u>              |                   |
| Supervision                          | <u>0</u>              |                   |
| Maintenance labor                    | <u>          </u>     |                   |
| Maintenance materials                | <u>\$ 600</u>         |                   |
| Replacement parts                    | <u>          </u>     |                   |
| Electricity                          | <u>Negligible</u>     |                   |
| Steam                                | <u>0</u>              |                   |
| Cooling water                        | <u>0</u>              |                   |
| Process water                        | <u>0</u>              |                   |
| Fuel                                 | <u>\$(4,018)</u>      |                   |
| Waste disposal                       | <u>0</u>              |                   |
| Chemicals                            | <u>0</u>              |                   |
| Total direct cost                    |                       | <u>\$ (3,418)</u> |
| Overhead                             |                       |                   |
| Payroll (30% of direct labor)        | <u>-</u>              |                   |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                   |
| Total overhead cost                  |                       | <u>          </u> |
| By-product credits                   |                       | <u>( )</u>        |
| Capital charges                      |                       |                   |
| G & A, taxes and insurance           |                       |                   |
| (4% of total turnkey costs)          | <u>\$ 560</u>         |                   |
| Capital recovery factor              |                       |                   |
| (16% of total turnkey costs)         | <u>\$ 2,240</u>       |                   |
| Total capital charges                |                       | <u>\$ 2,800</u>   |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ (618)</u>   |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-49. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER  
WITH AN AIR PREHEATER

|                                                                    |                 |                 |
|--------------------------------------------------------------------|-----------------|-----------------|
| Equipment cost                                                     |                 |                 |
| Basic equipment (includes freight)                                 | _____           |                 |
| Required auxiliaries                                               | _____           |                 |
| Total equipment cost                                               | <u>0</u>        |                 |
| Installation costs, direct                                         |                 |                 |
| Foundations and supports                                           | _____           |                 |
| Ductwork                                                           | _____           |                 |
| Stack                                                              | _____           |                 |
| Piping                                                             | _____           |                 |
| Insulation                                                         | _____           |                 |
| Painting                                                           | _____           |                 |
| Electrical                                                         | _____           |                 |
| Total installation cost                                            | <u>0</u>        |                 |
| Total Direct Costs (equipment + installation)                      |                 | <u>0</u>        |
| Installation costs, indirect                                       |                 |                 |
| Engineering                                                        |                 |                 |
| (10% of direct costs)                                              | _____           |                 |
| Construction and field expense                                     |                 |                 |
| (10% of direct costs)                                              | _____           |                 |
| Construction fees                                                  |                 |                 |
| (10% of direct costs)                                              | _____           |                 |
| Start-up (2% of direct costs)                                      | _____           |                 |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u> |                 |
| Total Indirect Costs                                               |                 | <u>\$ 2,000</u> |
| Contingencies                                                      |                 |                 |
| (20% of direct and indirect costs)                                 | _____           |                 |
| Total Turnkey Costs (direct + indirect + contingencies)            |                 | <u>\$ 2,000</u> |
| Land                                                               |                 |                 |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                 | <u>\$ 5,000</u> |
| GRAND TOTAL (turnkey + land + working capital)                     |                 | <u>\$ 7,000</u> |

<sup>a</sup>From Annual Cost Table (see following table).

TABLE A-50. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                                           |                 |                  |
|-----------------------------------------------------------|-----------------|------------------|
| Direct cost                                               |                 |                  |
| Direct labor                                              | <u>0</u>        |                  |
| Supervision                                               | <u>0</u>        |                  |
| Maintenance labor                                         | <u>0</u>        |                  |
| Maintenance materials                                     | <u>0</u>        |                  |
| Replacement parts                                         | <u>0</u>        |                  |
| Electricity                                               | <u>0</u>        |                  |
| Steam                                                     | <u>0</u>        |                  |
| Cooling water                                             | <u>0</u>        |                  |
| Process water                                             | <u>0</u>        |                  |
| Fuel                                                      | <u>\$23,388</u> |                  |
| Waste disposal                                            | <u>0</u>        |                  |
| Chemicals                                                 | <u>0</u>        |                  |
| Total direct cost                                         |                 | <u>\$ 23,388</u> |
| Overhead                                                  |                 |                  |
| Payroll (30% of direct labor)                             | <u>--</u>       |                  |
| Plant (26% of labor, parts & maint.)                      | <u>--</u>       |                  |
| Total overhead cost                                       |                 |                  |
| By-product credits                                        |                 | <u>( )</u>       |
| Capital charges                                           |                 |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | <u>\$ 80</u>    |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | <u>\$ 320</u>   |                  |
| Total capital charges                                     |                 | <u>\$ 400</u>    |
| TOTAL ANNUALIZED COSTS                                    |                 | <u>\$ 23,788</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-51. ESTIMATED INCREMENTAL CAPITAL COSTS FOR FLUE GAS RECIRCULATION  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER  
WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$13,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 7,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                       | <u>\$ 6,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 32,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-52. ESTIMATED INCREMENTAL ANNUAL COSTS FOR FLUE GAS RECIRCULATION  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                      |                 |                  |
|--------------------------------------|-----------------|------------------|
| Direct cost                          |                 |                  |
| Direct labor                         | <u>0</u>        |                  |
| Supervision                          | <u>0</u>        |                  |
| Maintenance labor                    | }               |                  |
| Maintenance materials                |                 |                  |
| Replacement parts                    |                 |                  |
|                                      |                 | <u>\$ 1,200</u>  |
| Electricity                          |                 | <u>\$14,718</u>  |
| Steam                                |                 | <u>0</u>         |
| Cooling water                        |                 | <u>0</u>         |
| Process water                        |                 | <u>0</u>         |
| Fuel                                 |                 | <u>\$ 8,494</u>  |
| Waste disposal                       |                 | <u>0</u>         |
| Chemicals                            |                 | <u>0</u>         |
| Total direct cost                    |                 | <u>\$ 24,412</u> |
| Overhead                             |                 |                  |
| Payroll (30% of direct labor)        | <u>--</u>       |                  |
| Plant (26% of labor, parts & maint.) | <u>Included</u> | above            |
| Total overhead cost                  |                 | <u>--</u>        |
| By-product credits                   |                 | <u>( )</u>       |
| Capital charges                      |                 |                  |
| G & A, taxes and insurance           |                 |                  |
| (4% of total turnkey costs)          | <u>\$ 1,040</u> |                  |
| Capital recovery factor              |                 |                  |
| (16% of total turnkey costs)         | <u>\$ 4,160</u> |                  |
| Total capital charges                |                 | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS               |                 | <u>\$ 29,612</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-53. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB)  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                       | <u>\$ 3,750</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 29,750</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).  
<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-54. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB)  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                                           |       |                  |
|-----------------------------------------------------------|-------|------------------|
| Direct cost                                               |       |                  |
| Direct labor                                              | _____ |                  |
| Supervision                                               | _____ |                  |
| Maintenance labor                                         | _____ |                  |
| Maintenance materials                                     | _____ |                  |
| Replacement parts                                         | _____ |                  |
| Electricity                                               | _____ |                  |
| Steam                                                     | _____ |                  |
| Cooling water                                             | _____ |                  |
| Process water                                             | _____ |                  |
| Fuel                                                      | _____ |                  |
| Waste disposal                                            | _____ |                  |
| Chemicals                                                 | _____ |                  |
| Total direct cost                                         |       | <u>\$ 15,000</u> |
| Overhead                                                  |       |                  |
| Payroll (30% of direct labor)                             | _____ |                  |
| Plant (26% of labor, parts & maint.)                      | _____ |                  |
| Total overhead cost                                       |       |                  |
| By-product credits                                        |       | <u>( )</u>       |
| Capital charges                                           |       |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | _____ |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | _____ |                  |
| Total capital charges                                     |       | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS                                    |       | <u>\$ 20,200</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

TABLE A-55. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$13,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 7,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                       | <u>\$ 3,778</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 29,778</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-56. ESTIMATED INCREMENTAL ANNUAL COSTS FOR STAGED COMBUSTION  
ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | <u>0</u>              |                  |
| Supervision                          | <u>0</u>              |                  |
| Maintenance labor                    | }                     |                  |
| Maintenance materials                |                       | <u>\$ 1,200</u>  |
| Replacement parts                    |                       |                  |
| Electricity - Fan                    |                       | <u>\$ 6,307</u>  |
| Steam                                |                       | <u>0</u>         |
| Cooling water                        |                       | <u>0</u>         |
| Process water                        |                       | <u>0</u>         |
| Fuel                                 |                       | <u>\$ 7,605</u>  |
| Waste disposal                       |                       | <u>0</u>         |
| Chemicals                            |                       | <u>0</u>         |
| Total direct cost                    |                       | <u>\$ 15,112</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>-</u>              |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 1,040</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$ 4,160</u>       |                  |
| Total capital charges                |                       | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 20,312</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-57. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT AND FLUE GAS RECIRCULATION ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$13,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 7,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                       | <u>\$ 12,000</u> |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 38,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table)

TABLE A-58. ESTIMATED INCREMENTAL ANNUAL COSTS OF REDUCED AIR PREHEAT AND FLUE GAS RECIRCULATION ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | <u>0</u>              |                  |
| Supervision                          | <u>0</u>              |                  |
| Maintenance labor                    | }                     |                  |
| Maintenance materials                |                       | <u>\$ 1,200</u>  |
| Replacement parts                    |                       |                  |
| Electricity - Fan                    |                       | <u>\$14,718</u>  |
| Steam                                |                       | <u>0</u>         |
| Cooling water                        |                       | <u>0</u>         |
| Process water                        |                       | <u>0</u>         |
| Fuel                                 |                       | <u>\$31,757</u>  |
| Waste disposal                       |                       | <u>0</u>         |
| Chemicals                            |                       | <u>0</u>         |
| Total direct cost                    |                       | <u>\$ 47,675</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>-</u>              |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 1,040</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$ 4,160</u>       |                  |
| Total capital charges                |                       | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 52,875</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-59. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT AND LOW NO<sub>x</sub> BURNERS ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                       | <u>\$ 4,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 30,000</u> |

<sup>a</sup>LNB operation is assumed to cost no more than staged combustion (see Sections 4 and 5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-60. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT AND LOW NO<sub>x</sub> BURNERS ON A NEW 29 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                           |       |                  |
|-----------------------------------------------------------|-------|------------------|
| Direct cost                                               |       |                  |
| Direct labor                                              |       |                  |
| Supervision                                               | _____ |                  |
| Maintenance labor                                         | _____ |                  |
| Maintenance materials                                     | _____ |                  |
| Replacement parts                                         | _____ |                  |
| Electricity - Fan                                         | _____ |                  |
| Steam                                                     | _____ |                  |
| Cooling water                                             | _____ |                  |
| Process water                                             | _____ |                  |
| Fuel                                                      | _____ |                  |
| Waste disposal                                            | _____ |                  |
| Chemicals                                                 | _____ |                  |
| Total direct cost                                         |       | <u>\$ 38,000</u> |
| Overhead                                                  |       |                  |
| Payroll (30% of direct labor)                             | _____ |                  |
| Plant (26% of labor, parts & maint.)                      | _____ |                  |
| Total overhead cost                                       |       |                  |
| By-product credits                                        |       | <u>( )</u>       |
| Capital charges                                           |       |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | _____ |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | _____ |                  |
| Total capital charges                                     |       | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS                                    |       | <u>\$ 43,200</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

TABLE A-61. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR  
OPERATION ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE  
BOILER WITHOUT AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$ 8,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 2,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 10,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 2,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 14,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>a</sup> | <u>0</u>              |                  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 14,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-62. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW EXCESS AIR OPERATION ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE BOILER WITHOUT AN AIR PREHEATER<sup>a</sup>

|                                      |                       |                   |
|--------------------------------------|-----------------------|-------------------|
| Direct cost                          |                       |                   |
| Direct labor                         | <u>0</u>              |                   |
| Supervision                          | <u>0</u>              |                   |
| Maintenance labor                    | }                     |                   |
| Maintenance materials                |                       |                   |
| Replacement parts                    |                       | <u>\$ 600</u>     |
| Electricity                          |                       | <u>Negligible</u> |
| Steam                                | <u>0</u>              |                   |
| Cooling water                        | <u>0</u>              |                   |
| Process water                        | <u>0</u>              |                   |
| Fuel                                 | <u>\$(4,990)</u>      |                   |
| Waste disposal                       | <u>0</u>              |                   |
| Chemicals                            | <u>0</u>              |                   |
| Total direct cost                    |                       | <u>\$ (4,390)</u> |
| Overhead                             |                       |                   |
| Payroll (30% of direct labor)        | <u>-</u>              |                   |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                   |
| Total overhead cost                  |                       |                   |
| By-product credits                   |                       | <u>( )</u>        |
| Capital charges                      |                       |                   |
| G & A, taxes and insurance           |                       |                   |
| (4% of total turnkey costs)          | <u>\$ 560</u>         |                   |
| Capital recovery factor              |                       |                   |
| (16% of total turnkey costs)         | <u>\$ 2,240</u>       |                   |
| Total capital charges                |                       | <u>\$ 2,800</u>   |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ (1,590)</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-63. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT  
OPERATION ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE  
BOILER WITH AN AIR PREHEATER

|                                                                    |                 |                 |
|--------------------------------------------------------------------|-----------------|-----------------|
| Equipment cost                                                     |                 |                 |
| Basic equipment (includes freight)                                 | _____           |                 |
| Required auxiliaries                                               | _____           |                 |
| Total equipment cost                                               | <u>0</u>        |                 |
| Installation costs, direct                                         |                 |                 |
| Foundations and supports                                           | _____           |                 |
| Ductwork                                                           | _____           |                 |
| Stack                                                              | _____           |                 |
| Piping                                                             | _____           |                 |
| Insulation                                                         | _____           |                 |
| Painting                                                           | _____           |                 |
| Electrical                                                         | _____           |                 |
| Total installation cost                                            | <u>0</u>        |                 |
| Total Direct Costs (equipment + installation)                      |                 | <u>0</u>        |
| Installation costs, indirect                                       |                 |                 |
| Engineering                                                        |                 |                 |
| (10% of direct costs)                                              | _____           |                 |
| Construction and field expense                                     |                 |                 |
| (10% of direct costs)                                              | _____           |                 |
| Construction fees                                                  |                 |                 |
| (10% of direct costs)                                              | _____           |                 |
| Start-up (2% of direct costs)                                      | _____           |                 |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u> |                 |
| Total Indirect Costs                                               |                 | <u>\$ 2,000</u> |
| Contingencies                                                      |                 |                 |
| (20% of direct and indirect costs)                                 | _____           |                 |
| Total Turnkey Costs (direct + indirect + contingencies)            |                 | <u>\$ 2,000</u> |
| Land                                                               |                 |                 |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                 | <u>\$ 5,000</u> |
| GRAND TOTAL (turnkey + land + working capital)                     |                 | <u>\$ 7,000</u> |

<sup>a</sup>From Annual Cost Table (see following table).



TABLE A-64. ESTIMATED INCREMENTAL ANNUAL COSTS DUE TO REDUCED AIR PREHEAT OPERATION FOR A NEW 29 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                           |                        |                  |                  |
|-----------------------------------------------------------|------------------------|------------------|------------------|
| Direct cost                                               |                        |                  |                  |
| Direct labor                                              | <u>0</u>               |                  |                  |
| Supervision                                               | <u>0</u>               |                  |                  |
| Maintenance labor                                         |                        |                  |                  |
| Maintenance materials                                     | <u>0</u>               |                  |                  |
| Replacement parts                                         |                        |                  |                  |
| Electricity                                               | Possible small savings |                  |                  |
| Steam                                                     | <u>0</u>               |                  |                  |
| Cooling water                                             | <u>0</u>               |                  |                  |
| Process water                                             | <u>0</u>               |                  |                  |
| Fuel                                                      | <u>\$20,330</u>        |                  |                  |
| Waste disposal                                            | <u>0</u>               |                  |                  |
| Chemicals                                                 | <u>0</u>               |                  |                  |
| Total direct cost                                         |                        | <u>\$ 20,330</u> |                  |
| Overhead                                                  |                        |                  |                  |
| Payroll (30% of direct labor)                             | <u>-</u>               |                  |                  |
| Plant (26% of labor, parts & maint.)                      | <u>-</u>               |                  |                  |
| Total overhead cost                                       |                        | <u>--</u>        |                  |
| By-product credits                                        |                        | <u>( )</u>       |                  |
| Capital charges                                           |                        |                  |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | <u>\$ 80</u>           |                  |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | <u>\$ 320</u>          |                  |                  |
| Total capital charges                                     |                        | <u>\$ 400</u>    |                  |
| TOTAL ANNUALIZED COSTS                                    |                        |                  | <u>\$ 20,730</u> |

<sup>a</sup>Energy used by RAP is described in Section 5.

TABLE A-65. ESTIMATED INCREMENTAL CAPITAL COSTS FOR FLUE GAS  
RECIRCULATION ON A NEW 29 MW NATURAL GAS-FIRED  
WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$13,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 7,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       | _____            |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 5,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 31,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-66. ESTIMATED INCREMENTAL ANNUAL COSTS FOR FLUE GAS RECIRCULATION  
ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE BOILER  
WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | <u>0</u>              |                  |
| Supervision                          | <u>0</u>              |                  |
| Maintenance labor                    | }                     |                  |
| Maintenance materials                |                       |                  |
| Replacement parts                    |                       | <u>\$ 1,200</u>  |
| Electricity - Fan                    |                       | <u>\$14,717</u>  |
| Steam                                |                       | <u>0</u>         |
| Cooling water                        |                       | <u>0</u>         |
| Process water                        |                       | <u>0</u>         |
| Fuel                                 |                       | <u>\$ 5,672</u>  |
| Waste disposal                       |                       | <u>0</u>         |
| Chemicals                            |                       | <u>0</u>         |
| Total direct cost                    |                       | <u>\$ 21,589</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>-</u>              |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 1,040</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$ 4,160</u>       |                  |
| Total capital charges                |                       | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 26,784</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-67. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED  
COMBUSTION ON A NEW 29 MW NATURAL GAS-FIRED  
WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$13,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 7,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 3,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 29,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-68. ESTIMATED INCREMENTAL ANNUAL COSTS FOR STAGED COMBUSTION  
ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE BOILER  
WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | <u>0</u>              |                  |
| Supervision                          | <u>0</u>              |                  |
| Maintenance labor                    | }                     |                  |
| Maintenance materials                |                       | <u>\$ 1,200</u>  |
| Replacement parts                    |                       |                  |
| Electricity - Fan                    |                       | <u>\$ 6,307</u>  |
| Steam                                |                       | <u>0</u>         |
| Cooling water                        |                       | <u>0</u>         |
| Process water                        |                       | <u>0</u>         |
| Fuel                                 |                       | <u>\$ 4,907</u>  |
| Waste disposal                       |                       | <u>0</u>         |
| Chemicals                            |                       | <u>0</u>         |
| Total direct cost                    |                       | <u>\$ 12,414</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>-</u>              |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 1,040</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$ 4,160</u>       |                  |
| Total capital charges                |                       | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 17,614</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-69. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB) ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 3,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 29,000</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-70. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB) ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                      |       |                  |
|--------------------------------------|-------|------------------|
| Direct cost                          |       |                  |
| Direct labor                         | _____ |                  |
| Supervision                          | _____ |                  |
| Maintenance labor                    | _____ |                  |
| Maintenance materials                | _____ |                  |
| Replacement parts                    | _____ |                  |
| Electricity                          | _____ |                  |
| Steam                                | _____ |                  |
| Cooling water                        | _____ |                  |
| Process water                        | _____ |                  |
| Fuel                                 | _____ |                  |
| Waste disposal                       | _____ |                  |
| Chemicals                            | _____ |                  |
| Total direct cost                    |       | <u>\$ 12,000</u> |
| Overhead                             |       |                  |
| Payroll (30% of direct labor)        | _____ |                  |
| Plant (26% of labor, parts & maint.) | _____ |                  |
| Total overhead cost                  |       |                  |
| By-product credits                   |       | <u>(     )</u>   |
| Capital charges                      |       |                  |
| G & A, taxes and insurance           |       |                  |
| (4% of total turnkey costs)          | _____ |                  |
| Capital recovery factor              |       |                  |
| (16% of total turnkey costs)         | _____ |                  |
| Total capital charges                |       | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS               |       | <u>\$ 17,200</u> |

<sup>a</sup>LNB operation is assumed to cost no more than staged combustion (see Sections 4 and 5).

TABLE A-81. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION  
ON A NEW 117 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$39,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$24,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 63,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 13,000</u> |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 78,000</u> |
| Land                                                               |                       | <u>--</u>        |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 9,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 87,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-1 and 4-10 through 4-13.  
<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-72. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT AND STAGED COMBUSTION ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                           |                       |                  |
|-----------------------------------------------------------|-----------------------|------------------|
| Direct cost                                               |                       |                  |
| Direct labor                                              | <u>0</u>              |                  |
| Supervision                                               | <u>0</u>              |                  |
| Maintenance labor                                         | }                     |                  |
| Maintenance materials                                     |                       | <u>\$ 1,200</u>  |
| Replacement parts                                         |                       |                  |
| Electricity - Fan                                         |                       | <u>\$ 6,307</u>  |
| Steam                                                     | <u>0</u>              |                  |
| Cooling water                                             | <u>0</u>              |                  |
| Process water                                             | <u>0</u>              |                  |
| Fuel                                                      | <u>\$25,416</u>       |                  |
| Waste disposal                                            | <u>0</u>              |                  |
| Chemicals                                                 | <u>0</u>              |                  |
| Total direct cost                                         |                       | <u>\$ 32,923</u> |
| Overhead                                                  |                       |                  |
| Payroll (30% of direct labor)                             | <u>-</u>              |                  |
| Plant (26% of labor, parts & maint.)                      | <u>Included above</u> |                  |
| Total overhead cost                                       |                       |                  |
| By-product credits                                        |                       | <u>( )</u>       |
| Capital charges                                           |                       |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | <u>\$ 1,080</u>       |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | <u>\$ 4,160</u>       |                  |
| Total capital charges                                     |                       | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS                                    |                       | <u>\$ 38,123</u> |

<sup>a</sup>Energy use is discussed in Section 5).

TABLE A-73. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT  
AND FLUE GAS RECIRCULATION ON A NEW 29 MW NATURAL GAS-FIRED  
WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$13,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 7,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 10,000</u> |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 36,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-74. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT AND FLUE GAS RECIRCULATION ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | <u>0</u>              |                  |
| Supervision                          | <u>0</u>              |                  |
| Maintenance labor                    |                       | }                |
| Maintenance materials                | <u>\$ 1,200</u>       |                  |
| Replacement parts                    |                       |                  |
| Electricity - Fan                    | <u>\$14,717</u>       |                  |
| Steam                                | <u>0</u>              |                  |
| Cooling water                        | <u>0</u>              |                  |
| Process water                        | <u>0</u>              |                  |
| Fuel                                 | <u>\$26,001</u>       |                  |
| Waste disposal                       | <u>0</u>              |                  |
| Chemicals                            | <u>0</u>              |                  |
| Total direct cost                    |                       | <u>\$ 41,918</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>-</u>              |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 1,080</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$ 4,120</u>       |                  |
| Total capital charges                |                       | <u>\$ 5,200</u>  |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 47,118</u> |

<sup>a</sup>Energy use is discussed in Section 5).

TABLE A-75. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT AND LOW NO<sub>x</sub> BURNERS ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 20,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 4,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 26,000</u> |
| Land                                                               | _____                 |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> | _____                 |                  |
| GRAND TOTAL (turnkey + land + working capital)                     | _____                 | _____            |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-76. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT (RAP) AND LOW NO<sub>x</sub> BURNERS (LNB) ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                           |                 |                  |
|-----------------------------------------------------------|-----------------|------------------|
| Direct cost                                               |                 |                  |
| Direct labor                                              | _____           |                  |
| Supervision                                               | _____           |                  |
| Maintenance labor                                         | _____           |                  |
| Maintenance materials                                     | _____           |                  |
| Replacement parts                                         | _____           |                  |
| Electricity - Fan                                         | _____           |                  |
| Steam                                                     | _____           |                  |
| Cooling water                                             | _____           |                  |
| Process water                                             | _____           |                  |
| Fuel                                                      | <u>\$20,330</u> | RAP              |
| Waste disposal                                            | _____           |                  |
| Chemicals                                                 | _____           |                  |
| Total direct cost                                         |                 | <u>\$ 32,330</u> |
| Overhead                                                  |                 |                  |
| Payroll (30% of direct labor)                             | Included above  |                  |
| Plant (26% of labor, parts & maint.)                      | Included above  |                  |
| Total overhead cost                                       |                 | _____            |
| By-product credits                                        |                 | ( _____ )        |
| Capital charges                                           |                 |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | <u>\$ 960</u>   |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | <u>\$ 3,840</u> |                  |
| Total capital charges                                     |                 | <u>\$ 4,800</u>  |
| TOTAL ANNUALIZED COSTS                                    |                 | <u>\$ 37,130</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion and RAP energy use is described in Section 5.

TABLE A-77. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT  
AND NH<sub>3</sub> INJECTION FOR A NEW 29 MW NATURAL GAS-FIRED  
WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$116,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 | <u>Included</u> above |                  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$118,000</u> |
| Land                                                               |                       | _____            |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 9,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$127,000</u> |

<sup>a</sup>NH<sub>3</sub> injection costs are extrapolated from utility boiler data (References 4-4 and 4-5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-78. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT (RAP) AND NH<sub>3</sub> INJECTION ON A NEW 29 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                 |                           |
|--------------------------------------|-----------------|---------------------------|
| Direct cost                          |                 |                           |
| Direct labor                         | _____           |                           |
| Supervision                          | _____           |                           |
| Maintenance labor                    | _____           |                           |
| Maintenance materials                | <u>\$15,831</u> | NH <sub>3</sub> injection |
| Replacement parts                    | _____           |                           |
| Electricity - Fan                    | _____           |                           |
| Steam                                | _____           |                           |
| Cooling water                        | _____           |                           |
| Process water                        | _____           |                           |
| Fuel                                 | <u>\$20,330</u> | RAP                       |
| Waste disposal                       | _____           |                           |
| Chemicals                            | _____           |                           |
| Total direct cost                    |                 | <u>\$ 36,161</u>          |
| Overhead                             |                 |                           |
| Payroll (30% of direct labor)        | <u>Included</u> | above                     |
| Plant (26% of labor, parts & maint.) | <u>Included</u> | above                     |
| Total overhead cost                  |                 | _____                     |
| By-product credits                   |                 | <u>( )</u>                |
| Capital charges                      |                 |                           |
| G & A, taxes and insurance           |                 |                           |
| (4% of total turnkey costs)          | <u>\$ 4,720</u> |                           |
| Capital recovery factor              |                 |                           |
| (16% of total turnkey costs)         | <u>\$18,880</u> |                           |
| Total capital charges                |                 | <u>\$ 23,600</u>          |
| TOTAL ANNUALIZED COSTS               |                 | <u>\$ 59,361</u>          |

<sup>a</sup>Ammonia injection costs are extrapolated from utility boiler data (References 4-4 and 4-5) and RAP energy use is from Section 5.

TABLE A-79. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR  
OPERATION ON A NEW 117 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$25,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$10,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 35,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 7,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 44,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> | <u>0</u>              |                  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 44,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-1 and 4-10 through 4-13.

<sup>b</sup>From Annual Cost Table (see next table).



TABLE A-80. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW EXCESS AIR OPERATION  
ON A NEW 117 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                                           |                       |                   |
|-----------------------------------------------------------|-----------------------|-------------------|
| Direct cost                                               |                       |                   |
| Direct labor                                              | <u>0</u>              |                   |
| Supervision                                               | <u>0</u>              |                   |
| Maintenance labor                                         | }                     |                   |
| Maintenance materials                                     |                       | <u>\$ 2,100</u>   |
| Replacement parts                                         |                       |                   |
| Electricity                                               |                       | <u>Negligible</u> |
| Steam                                                     | <u>0</u>              |                   |
| Cooling water                                             | <u>0</u>              |                   |
| Process water                                             | <u>0</u>              |                   |
| Fuel                                                      | <u>(\$12,356)</u>     |                   |
| Waste disposal                                            | <u>0</u>              |                   |
| Chemicals                                                 | <u>0</u>              |                   |
| Total direct cost                                         |                       | <u>\$(10,256)</u> |
| Overhead                                                  |                       |                   |
| Payroll (30% of direct labor)                             | <u>--</u>             |                   |
| Plant (26% of labor, parts & maint.)                      | <u>Included above</u> |                   |
| Total overhead cost                                       |                       |                   |
| By-product credits                                        |                       | <u>( )</u>        |
| Capital charges                                           |                       |                   |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | <u>\$ 1,760</u>       |                   |
| Capital recovery factor<br>(16% of total turnkey costs)   | <u>\$ 7,040</u>       |                   |
| Total capital charges                                     |                       | <u>\$ 8,800</u>   |
| TOTAL ANNUALIZED COSTS                                    |                       | <u>\$ 1,456</u>   |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-81. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION  
ON A NEW 117 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$39,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$24,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 63,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 13,000</u> |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 78,000</u> |
| Land                                                               |                       | <u>--</u>        |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 9,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 87,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-1 and 4-10 through 4-13.  
<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-82. ESTIMATED INCREMENTAL ANNUAL COSTS FOR STAGED COMBUSTION  
ON A NEW 117 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | <u>0</u>              |                  |
| Supervision                          | <u>0</u>              |                  |
| Maintenance labor                    | }                     |                  |
| Maintenance materials                |                       |                  |
| Replacement parts                    |                       | <u>\$ 3,900</u>  |
| Electricity -- fan                   |                       | <u>\$25,224</u>  |
| Steam                                | <u>0</u>              |                  |
| Cooling water                        | <u>0</u>              |                  |
| Process water                        | <u>0</u>              |                  |
| Fuel                                 | <u>\$ 5,906</u>       |                  |
| Waste disposal                       | <u>0</u>              |                  |
| Chemicals                            | <u>0</u>              |                  |
| Total direct cost                    |                       | <u>\$ 35,030</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>--</u>             |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 3,120</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$12,480</u>       |                  |
| Total capital charges                |                       | <u>\$ 15,600</u> |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 50,630</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-83. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB)  
FOR A NEW 117 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 63,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 13,000</u> |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 78,000</u> |
| Land                                                               |                       | _____            |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 0</u>      |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 78,000</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5  
<sup>b</sup>From Annual Cost Table (see following Table).

TABLE A-84. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB)  
ON A NEW 117 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | _____                 |                  |
| Supervision                          | _____                 |                  |
| Maintenance labor                    | _____                 |                  |
| Maintenance materials                | _____                 |                  |
| Replacement parts                    | _____                 |                  |
| Electricity                          | _____                 |                  |
| Steam                                | _____                 |                  |
| Cooling water                        | _____                 |                  |
| Process water                        | _____                 |                  |
| Fuel                                 | _____                 |                  |
| Waste disposal                       | _____                 |                  |
| Chemicals                            | _____                 |                  |
| Total direct cost                    |                       | <u>\$ 35,000</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>Included above</u> |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>(      )</u>  |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 3,120</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$12,480</u>       |                  |
| Total capital charges                |                       | <u>\$ 15,600</u> |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 50,630</u> |

<sup>a</sup>LNB operation is assumed to cost no more than staged combustion  
(see Sections 4 and 5).

TABLE A-85. ESTIMATED INCREMENTAL CAPITAL COSTS FOR AMMONIA INJECTION  
ON A NEW 117 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$470,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 | <u>Included</u> above |                  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$472,000</u> |
| Land                                                               |                       | <u>--</u>        |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 16,000</u> |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$488,000</u> |

<sup>a</sup>Ammonia injection costs are extrapolations from utility boiler data  
(References 4-4 and 4-5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-86. ESTIMATED INCREMENTAL ANNUAL COSTS FOR AMMONIA INJECTION  
ON A NEW 117 MW PULVERIZED COAL-FIRED BOILER<sup>a</sup>

|                                      |                 |                  |
|--------------------------------------|-----------------|------------------|
| Direct cost                          |                 |                  |
| Direct labor                         |                 |                  |
| Supervision                          |                 |                  |
| Maintenance labor                    |                 |                  |
| Maintenance materials                |                 |                  |
| Replacement parts                    |                 |                  |
| Electricity                          |                 |                  |
| Steam                                |                 |                  |
| Cooling water                        |                 |                  |
| Process water                        |                 |                  |
| Fuel                                 |                 |                  |
| Waste disposal                       |                 |                  |
| Chemicals                            |                 |                  |
| Total direct cost                    |                 | <u>\$ 62,168</u> |
| Overhead                             |                 |                  |
| Payroll (30% of direct labor)        | Included above  |                  |
| Plant (26% of labor, parts & maint.) | Included above  |                  |
| Total overhead cost                  |                 |                  |
| By-product credits                   |                 | <u>( )</u>       |
| Capital charges                      |                 |                  |
| G & A, taxes and insurance           |                 |                  |
| (4% of total turnkey costs)          | <u>\$18,800</u> |                  |
| Capital recovery factor              |                 |                  |
| (16% of total turnkey costs)         | <u>\$76,000</u> |                  |
| Total capital charges                |                 | <u>\$ 94,800</u> |
| TOTAL ANNUALIZED COSTS               |                 | <u>\$156,968</u> |

<sup>a</sup>Ammonia injection costs are extrapolations from utility boiler data  
(References 4-4 and 4-5).

TABLE A-87. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR OPERATION  
ON A NEW 8.8 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$ 7,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 2,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 9,000</u>  |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 1,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 12,000</u> |
| Land                                                               | _____                 |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>0</u>         |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 12,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-88. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW EXCESS AIR OPERATION  
ON A NEW 8.8 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                      |                       |                   |
|--------------------------------------|-----------------------|-------------------|
| Direct cost                          |                       |                   |
| Direct labor                         | <u>0</u>              |                   |
| Supervision                          | <u>0</u>              |                   |
| Maintenance labor                    | }                     |                   |
| Maintenance materials                |                       |                   |
| Replacement parts                    |                       |                   |
|                                      |                       | <u>\$ 500</u>     |
| Electricity                          |                       | <u>Negligible</u> |
| Steam                                |                       | <u>0</u>          |
| Cooling water                        |                       | <u>0</u>          |
| Process water                        |                       | <u>0</u>          |
| Fuel                                 |                       | <u>\$ (4,147)</u> |
| Waste disposal                       |                       | <u>0</u>          |
| Chemicals                            |                       | <u>0</u>          |
| Total direct cost                    |                       | <u>\$ (3,647)</u> |
| Overhead                             |                       |                   |
| Payroll (30% of direct labor)        | <u>-</u>              |                   |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                   |
| Total overhead cost                  |                       |                   |
| By-product credits                   |                       | <u>( )</u>        |
| Capital charges                      |                       |                   |
| G & A, taxes and insurance           |                       |                   |
| (4% of total turnkey costs)          | <u>\$ 480</u>         |                   |
| Capital recovery factor              |                       |                   |
| (16% of total turnkey costs)         | <u>\$ 1,920</u>       |                   |
| Total capital charges                |                       | <u>\$ 2,400</u>   |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ (1,247)</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-89. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION  
ON A NEW 8.8 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$10,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 7,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 17,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 3,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 22,000</u> |
| Land                                                               |                       | _____            |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 2,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 24,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-90. ESTIMATED INCREMENTAL ANNUAL COSTS FOR STAGED COMBUSTION  
ON A NEW 8.8 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                      |                 |                 |
|--------------------------------------|-----------------|-----------------|
| Direct cost                          |                 |                 |
| Direct labor                         | <u>0</u>        |                 |
| Supervision                          | <u>0</u>        |                 |
| Maintenance labor                    | }               |                 |
| Maintenance materials                |                 |                 |
| Replacement parts                    |                 |                 |
|                                      |                 | <u>\$ 1,000</u> |
| Electricity                          |                 | <u>\$ 1,650</u> |
| Steam                                |                 | <u>0</u>        |
| Cooling water                        |                 | <u>0</u>        |
| Process water                        |                 | <u>0</u>        |
| Fuel                                 |                 | <u>\$ 2,113</u> |
| Waste disposal                       |                 | <u>0</u>        |
| Chemicals                            |                 | <u>0</u>        |
| Total direct cost                    |                 | <u>\$ 4,763</u> |
| Overhead                             |                 |                 |
| Payroll (30% of direct labor)        | <u>-</u>        |                 |
| Plant (26% of labor, parts & maint.) | <u>Included</u> | above           |
| Total overhead cost                  |                 | <u>--</u>       |
| By-product credits                   |                 | <u>( )</u>      |
| Capital charges                      |                 |                 |
| G & A, taxes and insurance           |                 |                 |
| (4% of total turnkey costs)          | <u>\$ 880</u>   |                 |
| Capital recovery factor              |                 |                 |
| (16% of total turnkey costs)         | <u>\$ 3,520</u> |                 |
| Total capital charges                |                 | <u>\$ 4,400</u> |
| TOTAL ANNUALIZED COSTS               |                 | <u>\$ 9,163</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-91. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW NO<sub>x</sub> BURNERS  
(LNB) ON A NEW 8.8 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 17,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 3,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 22,000</u> |
| Land                                                               | _____                 |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> | _____                 |                  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 22,000</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-92. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW NO<sub>x</sub> BURNERS  
(LNB) ON A NEW 8.8 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                      |                       |                 |
|--------------------------------------|-----------------------|-----------------|
| Direct cost                          |                       |                 |
| Direct labor                         | <u>0</u>              |                 |
| Supervision                          | <u>0</u>              |                 |
| Maintenance labor                    | }                     |                 |
| Maintenance materials                |                       | <u>\$ 1,000</u> |
| Replacement parts                    |                       |                 |
| Electricity                          |                       | <u>?</u>        |
| Steam                                |                       | <u>0</u>        |
| Cooling water                        |                       | <u>0</u>        |
| Process water                        |                       | <u>0</u>        |
| Fuel                                 |                       | <u>?</u>        |
| Waste disposal                       |                       | <u>0</u>        |
| Chemicals                            |                       | <u>0</u>        |
| Total direct cost                    |                       | <u>\$ 4,500</u> |
| Overhead                             |                       |                 |
| Payroll (30% of direct labor)        | <u>-</u>              |                 |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                 |
| Total overhead cost                  |                       | <u>--</u>       |
| By-product credits                   |                       | <u>( )</u>      |
| Capital charges                      |                       |                 |
| G & A, taxes and insurance           |                       |                 |
| (4% of total turnkey costs)          | <u>\$ 880</u>         |                 |
| Capital recovery factor              |                       |                 |
| (16% of total turnkey costs)         | <u>\$ 3,520</u>       |                 |
| Total capital charges                |                       | <u>\$ 4,400</u> |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 8,900</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

TABLE A-93. ESTIMATED INCREMENTAL CAPITAL COSTS FOR AMMONIA INJECTION  
ON A NEW 8.8 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 70,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 | <u>Included</u> above |                  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 72,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 1,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 73,000</u> |

<sup>a</sup>Ammonia injection costs are extrapolated from utility boiler data (References 4-4 and 4-5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-94. ESTIMATED INCREMENTAL ANNUAL COSTS FOR AMMONIA INJECTION  
ON A NEW 8.8 MW RESIDUAL OIL-FIRED WATERTUBE BOILER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | _____                 |                  |
| Supervision                          | _____                 |                  |
| Maintenance labor                    | _____                 |                  |
| Maintenance materials                | _____                 |                  |
| Replacement parts                    | _____                 |                  |
| Electricity                          | _____                 |                  |
| Steam                                | _____                 |                  |
| Cooling water                        | _____                 |                  |
| Process water                        | _____                 |                  |
| Fuel                                 | _____                 |                  |
| Waste disposal                       | _____                 |                  |
| Chemicals                            | _____                 |                  |
| Total direct cost                    |                       | <u>\$ 5,000</u>  |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>Included</u> above |                  |
| Plant (26% of labor, parts & maint.) | <u>Included</u> above |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>(      )</u>  |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 2880</u>        |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$11,520</u>       |                  |
| Total capital charges                |                       | <u>\$ 14,400</u> |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 19,400</u> |

<sup>a</sup>Ammonia injection costs are extrapolated from utility boiler data  
(References 4-4 and 4-5).

TABLE A-95. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW EXCESS AIR  
ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER  
WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$10,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$ 3,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 13,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 2,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 17,000</u> |
| Land                                                               |                       | <u>--</u>        |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>0</u>         |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 17,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-96. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW EXCESS AIR  
OPERATION ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE  
BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                       |                   |
|--------------------------------------|-----------------------|-------------------|
| Direct cost                          |                       |                   |
| Direct labor                         | <u>0</u>              |                   |
| Supervision                          | <u>0</u>              |                   |
| Maintenance labor                    | }                     |                   |
| Maintenance materials                |                       | <u>\$ 750</u>     |
| Replacement parts                    |                       |                   |
| Electricity                          |                       | <u>Negligible</u> |
| Steam                                | <u>0</u>              |                   |
| Cooling water                        | <u>0</u>              |                   |
| Process water                        | <u>0</u>              |                   |
| Fuel                                 | <u>\$(6,027)</u>      |                   |
| Waste disposal                       | <u>0</u>              |                   |
| Chemicals                            | <u>0</u>              |                   |
| Total direct cost                    |                       | <u>\$ (5,277)</u> |
| Overhead                             |                       |                   |
| Payroll (30% of direct labor)        | <u>-</u>              |                   |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                   |
| Total overhead cost                  |                       |                   |
| By-product credits                   |                       | <u>( )</u>        |
| Capital charges                      |                       |                   |
| G & A, taxes and insurance           |                       |                   |
| (4% of total turnkey costs)          | <u>\$ 680</u>         |                   |
| Capital recovery factor              |                       |                   |
| (16% of total turnkey costs)         | <u>\$ 2,720</u>       |                   |
| Total capital charges                |                       | <u>\$ 3,400</u>   |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ (1877)</u>  |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-97. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT  
ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER  
WITH AN AIR PREHEATER

|                                                                    |                              |                              |
|--------------------------------------------------------------------|------------------------------|------------------------------|
| Equipment cost                                                     |                              |                              |
| Basic equipment (includes freight)                                 | <u>          </u>            |                              |
| Required auxiliaries                                               | <u>          </u>            |                              |
| Total equipment cost                                               | <u>          0          </u> |                              |
| Installation costs, direct                                         |                              |                              |
| Foundations and supports                                           | <u>          </u>            |                              |
| Ductwork                                                           | <u>          </u>            |                              |
| Stack                                                              | <u>          </u>            |                              |
| Piping                                                             | <u>          </u>            |                              |
| Insulation                                                         | <u>          </u>            |                              |
| Painting                                                           | <u>          </u>            |                              |
| Electrical                                                         | <u>          </u>            |                              |
| Total installation cost                                            | <u>          0          </u> |                              |
| Total Direct Costs (equipment + installation)                      |                              | <u>          0          </u> |
| Installation costs, indirect                                       |                              |                              |
| Engineering                                                        |                              |                              |
| (10% of direct costs)                                              | <u>          </u>            |                              |
| Construction and field expense                                     |                              |                              |
| (10% of direct costs)                                              | <u>          </u>            |                              |
| Construction fees                                                  |                              |                              |
| (10% of direct costs)                                              | <u>          </u>            |                              |
| Start-up (2% of direct costs)                                      | <u>          </u>            |                              |
| Performance tests (minimum \$2000)                                 | <u>    \$ 2,000    </u>      |                              |
| Total Indirect Costs                                               |                              | <u>    \$ 2,000    </u>      |
| Contingencies                                                      |                              |                              |
| (20% of direct and indirect costs)                                 |                              | <u>          </u>            |
| Total Turnkey Costs (direct + indirect + contingencies)            |                              | <u>    \$ 2,000    </u>      |
| Land                                                               |                              | <u>          </u>            |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                              | <u>    \$ 8,770    </u>      |
| GRAND TOTAL (turnkey + land + working capital)                     |                              | <u>    \$ 10,770    </u>     |

<sup>a</sup>From Annual Cost Table (see following table).

TABLE A-98. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT  
ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                                           |          |           |           |
|-----------------------------------------------------------|----------|-----------|-----------|
| Direct cost                                               |          |           |           |
| Direct labor                                              | 0        |           |           |
| Supervision                                               | 0        |           |           |
| Maintenance labor                                         | 0        |           |           |
| Maintenance materials                                     | 0        |           |           |
| Replacement parts                                         | 0        |           |           |
| Electricity                                               | 0        |           |           |
| Steam                                                     | 0        |           |           |
| Cooling water                                             | 0        |           |           |
| Process water                                             | 0        |           |           |
| Fuel                                                      | \$35,082 |           |           |
| Waste disposal                                            | 0        |           |           |
| Chemicals                                                 | 0        |           |           |
| Total direct cost                                         |          | \$ 35,082 |           |
| Overhead                                                  |          |           |           |
| Payroll (30% of direct labor)                             | --       |           |           |
| Plant (26% of labor, parts & maint.)                      | --       |           |           |
| Total overhead cost                                       |          |           |           |
| By-product credits                                        |          | ( )       |           |
| Capital charges                                           |          |           |           |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | \$ 80    |           |           |
| Capital recovery factor<br>(16% of total turnkey costs)   | \$ 320   |           |           |
| Total capital charges                                     |          | \$ 400    |           |
| TOTAL ANNUALIZED COSTS                                    |          |           | \$ 35,482 |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-99. ESTIMATED INCREMENTAL CAPITAL COSTS FOR FLUE GAS RECIRCULATION  
ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER  
WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$15,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$10,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                       | <u>\$ 9,080</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 41,080</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-100. ESTIMATED INCREMENTAL ANNUAL COSTS FOR FLUE GAS RECIRCULATION  
ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                      |                 |                  |
|--------------------------------------|-----------------|------------------|
| Direct cost                          |                 |                  |
| Direct labor                         | <u>0</u>        |                  |
| Supervision                          | <u>0</u>        |                  |
| Maintenance labor                    | }               |                  |
| Maintenance materials                |                 |                  |
| Replacement parts                    |                 | <u>\$ 1,500</u>  |
| Electricity                          |                 | <u>\$22,077</u>  |
| Steam                                |                 | <u>0</u>         |
| Cooling water                        |                 | <u>0</u>         |
| Process water                        |                 | <u>0</u>         |
| Fuel                                 |                 | <u>\$12,741</u>  |
| Waste disposal                       |                 | <u>0</u>         |
| Chemicals                            |                 | <u>0</u>         |
| Total direct cost                    |                 | <u>\$ 36,318</u> |
| Overhead                             |                 |                  |
| Payroll (30% of direct labor)        | <u>--</u>       |                  |
| Plant (26% of labor, parts & maint.) | Included above  |                  |
| Total overhead cost                  |                 | <u>--</u>        |
| By-product credits                   |                 | <u>( )</u>       |
| Capital charges                      |                 |                  |
| G & A, taxes and insurance           |                 |                  |
| (4% of total turnkey costs)          | <u>\$ 1,280</u> |                  |
| Capital recovery factor              |                 |                  |
| (16% of total turnkey costs)         | <u>\$ 5,120</u> |                  |
| Total capital charges                |                 | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS               |                 | <u>\$ 42,718</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-101. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB)  
ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       | _____            |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                       | <u>\$ 5,500</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 37,500</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-102. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB)  
ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                                           |       |                  |
|-----------------------------------------------------------|-------|------------------|
| Direct cost                                               |       |                  |
| Direct labor                                              | _____ |                  |
| Supervision                                               | _____ |                  |
| Maintenance labor                                         | _____ |                  |
| Maintenance materials                                     | _____ |                  |
| Replacement parts                                         | _____ |                  |
| Electricity                                               | _____ |                  |
| Steam                                                     | _____ |                  |
| Cooling water                                             | _____ |                  |
| Process water                                             | _____ |                  |
| Fuel                                                      | _____ |                  |
| Waste disposal                                            | _____ |                  |
| Chemicals                                                 | _____ |                  |
| Total direct cost                                         |       | <u>\$ 22,000</u> |
| Overhead                                                  |       |                  |
| Payroll (30% of direct labor)                             | _____ |                  |
| Plant (26% of labor, parts & maint.)                      | _____ |                  |
| Total overhead cost                                       |       |                  |
| By-product credits                                        |       | <u>( )</u>       |
| Capital charges                                           |       |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | _____ |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | _____ |                  |
| Total capital charges                                     |       | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS                                    |       | <u>\$ 28,400</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

TABLE A-103. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION  
ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$15,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$10,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                       | <u>\$ 5,592</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 37,592</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-104. ESTIMATED INCREMENTAL ANNUAL COSTS FOR STAGED COMBUSTION  
ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH  
AN AIR PREHEATER<sup>a</sup>

|                                                           |                       |                  |
|-----------------------------------------------------------|-----------------------|------------------|
| Direct cost                                               |                       |                  |
| Direct labor                                              | <u>0</u>              |                  |
| Supervision                                               | <u>0</u>              |                  |
| Maintenance labor                                         | }                     |                  |
| Maintenance materials                                     |                       | <u>\$ 1,500</u>  |
| Replacement parts                                         |                       |                  |
| Electricity - Fan                                         |                       | <u>\$ 9,460</u>  |
| Steam                                                     |                       | <u>0</u>         |
| Cooling water                                             |                       | <u>0</u>         |
| Process water                                             |                       | <u>0</u>         |
| Fuel                                                      |                       | <u>\$11,407</u>  |
| Waste disposal                                            |                       | <u>0</u>         |
| Chemicals                                                 |                       | <u>0</u>         |
| Total direct cost                                         |                       | <u>\$ 22,367</u> |
| Overhead                                                  |                       |                  |
| Payroll (30% of direct labor)                             | <u>-</u>              |                  |
| Plant (26% of labor, parts & maint.)                      | <u>Included above</u> |                  |
| Total overhead cost                                       |                       |                  |
| By-product credits                                        |                       | <u>( )</u>       |
| Capital charges                                           |                       |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | <u>\$ 1,280</u>       |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | <u>\$ 5,120</u>       |                  |
| Total capital charges                                     |                       | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS                                    |                       | <u>\$ 28,767</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-105. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT AND FLUE GAS RECIRCULATION ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$15,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$10,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                       | <u>\$ 17,000</u> |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 49,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table)

TABLE A-106. ESTIMATED INCREMENTAL ANNUAL COSTS OF REDUCED AIR PREHEAT AND FLUE GAS RECIRCULATION ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                 |                  |
|--------------------------------------|-----------------|------------------|
| Direct cost                          |                 |                  |
| Direct labor                         | <u>0</u>        |                  |
| Supervision                          | <u>0</u>        |                  |
| Maintenance labor                    | }               |                  |
| Maintenance materials                |                 |                  |
| Replacement parts                    |                 |                  |
|                                      |                 | <u>\$ 1,500</u>  |
| Electricity - Fan                    |                 | <u>\$22,077</u>  |
| Steam                                |                 | <u>0</u>         |
| Cooling water                        |                 | <u>0</u>         |
| Process water                        |                 | <u>0</u>         |
| Fuel                                 |                 | <u>\$47,636</u>  |
| Waste disposal                       |                 | <u>0</u>         |
| Chemicals                            |                 | <u>0</u>         |
| Total direct cost                    |                 | <u>\$ 71,213</u> |
| Overhead                             |                 |                  |
| Payroll (30% of direct labor)        | <u>-</u>        |                  |
| Plant (26% of labor, parts & maint.) | Included above  |                  |
| Total overhead cost                  |                 |                  |
| By-product credits                   |                 | <u>( )</u>       |
| Capital charges                      |                 |                  |
| G & A, taxes and insurance           |                 |                  |
| (4% of total turnkey costs)          | <u>\$ 1,280</u> |                  |
| Capital recovery factor              |                 |                  |
| (16% of total turnkey costs)         | <u>\$ 5,120</u> |                  |
| Total capital charges                |                 | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS               |                 | <u>\$ 77,613</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-107. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT AND LOW NO<sub>x</sub> BURNERS ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                       | <u>\$ 6,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 38,000</u> |

<sup>a</sup>LNB operation is assumed to cost no more than staged combustion (see Sections 4 and 5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-108. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT AND LOW NO<sub>x</sub> BURNERS ON A NEW 44 MW DISTILLATE OIL-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                           |       |                  |
|-----------------------------------------------------------|-------|------------------|
| Direct cost                                               |       |                  |
| Direct labor                                              | _____ |                  |
| Supervision                                               | _____ |                  |
| Maintenance labor                                         | _____ |                  |
| Maintenance materials                                     | _____ |                  |
| Replacement parts                                         | _____ |                  |
| Electricity - Fan                                         | _____ |                  |
| Steam                                                     | _____ |                  |
| Cooling water                                             | _____ |                  |
| Process water                                             | _____ |                  |
| Fuel                                                      | _____ |                  |
| Waste disposal                                            | _____ |                  |
| Chemicals                                                 | _____ |                  |
| Total direct cost                                         |       | <u>\$ 60,000</u> |
| Overhead                                                  |       |                  |
| Payroll (30% of direct labor)                             | _____ |                  |
| Plant (26% of labor, parts & maint.)                      | _____ |                  |
| Total overhead cost                                       |       | _____            |
| By-product credits                                        |       | <u>( )</u>       |
| Capital charges                                           |       |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | _____ |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | _____ |                  |
| Total capital charges                                     |       | <u>\$ 6400</u>   |
| TOTAL ANNUALIZED COSTS                                    |       | <u>\$ 66,400</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

TABLE A-109. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT  
OPERATION ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE  
BOILER WITH AN AIR PREHEATER

|                                                                    |                 |                 |
|--------------------------------------------------------------------|-----------------|-----------------|
| Equipment cost                                                     |                 |                 |
| Basic equipment (includes freight)                                 | _____           |                 |
| Required auxiliaries                                               | _____           |                 |
| Total equipment cost                                               | <u>0</u>        |                 |
| Installation costs, direct                                         |                 |                 |
| Foundations and supports                                           | _____           |                 |
| Ductwork                                                           | _____           |                 |
| Stack                                                              | _____           |                 |
| Piping                                                             | _____           |                 |
| Insulation                                                         | _____           |                 |
| Painting                                                           | _____           |                 |
| Electrical                                                         | _____           |                 |
| Total installation cost                                            | <u>0</u>        |                 |
| Total Direct Costs (equipment + installation)                      |                 | <u>0</u>        |
| Installation costs, indirect                                       |                 |                 |
| Engineering                                                        |                 |                 |
| (10% of direct costs)                                              | _____           |                 |
| Construction and field expense                                     |                 |                 |
| (10% of direct costs)                                              | _____           |                 |
| Construction fees                                                  |                 |                 |
| (10% of direct costs)                                              | _____           |                 |
| Start-up (2% of direct costs)                                      | _____           |                 |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u> |                 |
| Total Indirect Costs                                               |                 | <u>\$ 2,000</u> |
| Contingencies                                                      |                 |                 |
| (20% of direct and indirect costs)                                 | _____           |                 |
| Total Turnkey Costs (direct + indirect + contingencies)            |                 | <u>\$ 2,000</u> |
| Land                                                               |                 |                 |
| Working capital (25% of total direct operating costs) <sup>a</sup> |                 | <u>\$ 7,000</u> |
| GRAND TOTAL (turnkey + land + working capital)                     |                 | <u>\$ 9,000</u> |

<sup>a</sup>From Annual Cost Table (see following table).

TABLE A-110. ESTIMATED INCREMENTAL ANNUAL COSTS DUE TO REDUCED AIR PREHEAT OPERATION FOR A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                           |                               |                  |
|-----------------------------------------------------------|-------------------------------|------------------|
| Direct cost                                               |                               |                  |
| Direct labor                                              | <u>0</u>                      |                  |
| Supervision                                               | <u>0</u>                      |                  |
| Maintenance labor                                         | <u>          </u>             |                  |
| Maintenance materials                                     | <u>0</u>                      |                  |
| Replacement parts                                         | <u>          </u>             |                  |
| Electricity                                               | <u>Possible small savings</u> |                  |
| Steam                                                     | <u>0</u>                      |                  |
| Cooling water                                             | <u>0</u>                      |                  |
| Process water                                             | <u>0</u>                      |                  |
| Fuel                                                      | <u>\$30,495</u>               |                  |
| Waste disposal                                            | <u>0</u>                      |                  |
| Chemicals                                                 | <u>0</u>                      |                  |
| Total direct cost                                         |                               | <u>\$ 30,495</u> |
| Overhead                                                  |                               |                  |
| Payroll (30% of direct labor)                             | <u>-</u>                      |                  |
| Plant (26% of labor, parts & maint.)                      | <u>-</u>                      |                  |
| Total overhead cost                                       |                               | <u>--</u>        |
| By-product credits                                        |                               | <u>( )</u>       |
| Capital charges                                           |                               |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | <u>\$ 80</u>                  |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | <u>\$ 320</u>                 |                  |
| Total capital charges                                     |                               | <u>\$ 400</u>    |
| TOTAL ANNUALIZED COSTS                                    |                               | <u>\$ 30,895</u> |

<sup>a</sup>Energy used by RAP is described in Section 5.

TABLE A-111. ESTIMATED INCREMENTAL CAPITAL COSTS FOR FLUE GAS  
RECIRCULATION ON A NEW 44 MW NATURAL GAS-FIRED  
WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$15,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$10,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 8,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 40,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-112. ESTIMATED INCREMENTAL ANNUAL COSTS FOR FLUE GAS RECIRCULATION  
ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER  
WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | <u>0</u>              |                  |
| Supervision                          | <u>0</u>              |                  |
| Maintenance labor                    | }                     |                  |
| Maintenance materials                |                       | <u>\$ 1,500</u>  |
| Replacement parts                    |                       |                  |
| Electricity - Fan                    |                       | <u>\$22,076</u>  |
| Steam                                |                       | <u>0</u>         |
| Cooling water                        |                       | <u>0</u>         |
| Process water                        |                       | <u>0</u>         |
| Fuel                                 |                       | <u>\$ 8,508</u>  |
| Waste disposal                       |                       | <u>0</u>         |
| Chemicals                            |                       | <u>0</u>         |
| Total direct cost                    |                       | <u>\$ 32,084</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>-</u>              |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 1,280</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$ 5,120</u>       |                  |
| Total capital charges                |                       | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 38,484</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-113. ESTIMATED INCREMENTAL CAPITAL COSTS FOR STAGED COMBUSTION ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$15,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$10,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       | _____            |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 4,500</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 36,500</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-114. ESTIMATED INCREMENTAL ANNUAL COSTS FOR STAGED COMBUSTION  
ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER  
WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                       |                  |
|--------------------------------------|-----------------------|------------------|
| Direct cost                          |                       |                  |
| Direct labor                         | <u>0</u>              |                  |
| Supervision                          | <u>0</u>              |                  |
| Maintenance labor                    |                       |                  |
| Maintenance materials                |                       |                  |
| Replacement parts                    | <u>\$ 1,500</u>       |                  |
| Electricity - Fan                    | <u>\$ 9,460</u>       |                  |
| Steam                                | <u>0</u>              |                  |
| Cooling water                        | <u>0</u>              |                  |
| Process water                        | <u>0</u>              |                  |
| Fuel                                 | <u>\$ 7,360</u>       |                  |
| Waste disposal                       | <u>0</u>              |                  |
| Chemicals                            | <u>0</u>              |                  |
| Total direct cost                    |                       | <u>\$ 18,320</u> |
| Overhead                             |                       |                  |
| Payroll (30% of direct labor)        | <u>-</u>              |                  |
| Plant (26% of labor, parts & maint.) | <u>Included above</u> |                  |
| Total overhead cost                  |                       |                  |
| By-product credits                   |                       | <u>( )</u>       |
| Capital charges                      |                       |                  |
| G & A, taxes and insurance           |                       |                  |
| (4% of total turnkey costs)          | <u>\$ 1,280</u>       |                  |
| Capital recovery factor              |                       |                  |
| (16% of total turnkey costs)         | <u>\$ 5,120</u>       |                  |
| Total capital charges                |                       | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS               |                       | <u>\$ 24,720</u> |

<sup>a</sup>Energy usage is described in Section 5.

TABLE A-115. ESTIMATED INCREMENTAL CAPITAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB) ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       | _____            |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 4,000</u>  |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 36,000</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-116. ESTIMATED INCREMENTAL ANNUAL COSTS FOR LOW NO<sub>x</sub> BURNERS (LNB) ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                           |       |                  |
|-----------------------------------------------------------|-------|------------------|
| Direct cost                                               |       |                  |
| Direct labor                                              | _____ |                  |
| Supervision                                               | _____ |                  |
| Maintenance labor                                         | _____ |                  |
| Maintenance materials                                     | _____ |                  |
| Replacement parts                                         | _____ |                  |
| Electricity                                               | _____ |                  |
| Steam                                                     | _____ |                  |
| Cooling water                                             | _____ |                  |
| Process water                                             | _____ |                  |
| Fuel                                                      | _____ |                  |
| Waste disposal                                            | _____ |                  |
| Chemicals                                                 | _____ |                  |
| Total direct cost                                         |       | <u>\$ 18,000</u> |
| Overhead                                                  |       |                  |
| Payroll (30% of direct labor)                             | _____ |                  |
| Plant (26% of labor, parts & maint.)                      | _____ |                  |
| Total overhead cost                                       |       | _____            |
| By-product credits                                        |       | <u>( )</u>       |
| Capital charges                                           |       |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | _____ |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | _____ |                  |
| Total capital charges                                     |       | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS                                    |       | <u>\$ 24,400</u> |

<sup>a</sup>LNB operation is assumed to cost no more than staged combustion (see Sections 4 and 5).

TABLE A-117. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT AND STAGED COMBUSTION ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$15,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$10,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       | _____            |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 12,000</u> |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 44,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-118. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT AND STAGED COMBUSTION ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                           |                       |                  |
|-----------------------------------------------------------|-----------------------|------------------|
| Direct cost                                               |                       |                  |
| Direct labor                                              | <u>0</u>              |                  |
| Supervision                                               | <u>0</u>              |                  |
| Maintenance labor                                         | }                     |                  |
| Maintenance materials                                     |                       | <u>\$ 1,500</u>  |
| Replacement parts                                         |                       |                  |
| Electricity - Fan                                         |                       | <u>\$ 9,460</u>  |
| Steam                                                     |                       | <u>0</u>         |
| Cooling water                                             |                       | <u>0</u>         |
| Process water                                             |                       | <u>0</u>         |
| Fuel                                                      |                       | <u>\$38,124</u>  |
| Waste disposal                                            |                       | <u>0</u>         |
| Chemicals                                                 |                       | <u>0</u>         |
| Total direct cost                                         |                       | <u>\$ 49,084</u> |
| Overhead                                                  |                       |                  |
| Payroll (30% of direct labor)                             | <u>-</u>              |                  |
| Plant (26% of labor, parts & maint.)                      | <u>Included above</u> |                  |
| Total overhead cost                                       |                       |                  |
| By-product credits                                        |                       | <u>( )</u>       |
| Capital charges                                           |                       |                  |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | <u>\$ 1,280</u>       |                  |
| Capital recovery factor<br>(16% of total turnkey costs)   | <u>\$ 5,120</u>       |                  |
| Total capital charges                                     |                       | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS                                    |                       | <u>\$ 55,484</u> |

<sup>a</sup>Energy use is discussed in Section 5.

TABLE A-119. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT AND FLUE GAS RECIRCULATION ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | <u>\$15,000</u>       |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | <u>\$10,000</u>       |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       | _____            |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 15,000</u> |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$ 47,000</u> |

<sup>a</sup>Costs are engineering estimates based on References 4-9 through 4-12, 4-14, and 4-17 through 4-20.

<sup>b</sup>From Annual Cost Table (see following table).



TABLE A-120. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT AND FLUE GAS RECIRCULATION ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                 |                  |
|--------------------------------------|-----------------|------------------|
| Direct cost                          |                 |                  |
| Direct labor                         | <u>0</u>        |                  |
| Supervision                          | <u>0</u>        |                  |
| Maintenance labor                    | }               |                  |
| Maintenance materials                |                 |                  |
| Replacement parts                    |                 |                  |
|                                      |                 | <u>\$ 1,500</u>  |
| Electricity - Fan                    |                 | <u>\$22,076</u>  |
| Steam                                |                 | <u>0</u>         |
| Cooling water                        |                 | <u>0</u>         |
| Process water                        |                 | <u>0</u>         |
| Fuel                                 |                 | <u>\$39,002</u>  |
| Waste disposal                       |                 | <u>0</u>         |
| Chemicals                            |                 | <u>0</u>         |
| Total direct cost                    |                 | <u>\$ 62,578</u> |
| Overhead                             |                 |                  |
| Payroll (30% of direct labor)        | <u>-</u>        |                  |
| Plant (26% of labor, parts & maint.) | Included above  |                  |
| Total overhead cost                  |                 |                  |
| By-product credits                   |                 | <u>( )</u>       |
| Capital charges                      |                 |                  |
| G & A, taxes and insurance           |                 |                  |
| (4% of total turnkey costs)          | <u>\$ 1,280</u> |                  |
| Capital recovery factor              |                 |                  |
| (16% of total turnkey costs)         | <u>\$ 5,120</u> |                  |
| Total capital charges                |                 | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS               |                 | <u>\$ 68,978</u> |

<sup>a</sup>Energy use is discussed in Section 5.

TABLE A-121. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT AND LOW NO<sub>x</sub> BURNERS ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$ 25,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included above</u> |                  |
| Start-up (2% of direct costs)                                      | <u>Included above</u> |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 |                       | <u>\$ 5,000</u>  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$ 32,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>12,000</u>    |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>44,000</u>    |

<sup>a</sup>LNB is assumed to cost no more than staged combustion (see Sections 4 and 5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-122. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT (RAP) AND LOW NO<sub>x</sub> BURNERS (LNB) ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                      |                 |                  |
|--------------------------------------|-----------------|------------------|
| Direct cost                          |                 |                  |
| Direct labor                         | _____           |                  |
| Supervision                          | _____           |                  |
| Maintenance labor                    | _____           |                  |
| Maintenance materials                | _____           |                  |
| Replacement parts                    | _____           |                  |
| Electricity - Fan                    | _____           |                  |
| Steam                                | _____           |                  |
| Cooling water                        | _____           |                  |
| Process water                        | _____           |                  |
| Fuel                                 | <u>\$30,495</u> | RAP              |
| Waste disposal                       | _____           |                  |
| Chemicals                            | _____           |                  |
| Total direct cost                    |                 | <u>\$ 49,000</u> |
| Overhead                             |                 |                  |
| Payroll (30% of direct labor)        | <u>Included</u> | above            |
| Plant (26% of labor, parts & maint.) | <u>Included</u> | above            |
| Total overhead cost                  |                 |                  |
| By-product credits                   |                 | <u>( )</u>       |
| Capital charges                      |                 |                  |
| G & A, taxes and insurance           |                 |                  |
| (4% of total turnkey costs)          | <u>\$</u>       |                  |
| Capital recovery factor              |                 |                  |
| (16% of total turnkey costs)         | <u>\$</u>       |                  |
| Total capital charges                |                 | <u>\$ 6,400</u>  |
| TOTAL ANNUALIZED COSTS               |                 | <u>\$ 55,400</u> |

<sup>a</sup>LNB is assumed to cost no more than staged combustion and RAP energy use is described in Section 5.

TABLE A-123. ESTIMATED INCREMENTAL CAPITAL COSTS FOR REDUCED AIR PREHEAT AND NH<sub>3</sub> INJECTION FOR A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                                    |                       |                  |
|--------------------------------------------------------------------|-----------------------|------------------|
| Equipment cost                                                     |                       |                  |
| Basic equipment (includes freight)                                 | _____                 |                  |
| Required auxiliaries                                               | _____                 |                  |
| Total equipment cost                                               | _____                 |                  |
| Installation costs, direct                                         |                       |                  |
| Foundations and supports                                           | _____                 |                  |
| Ductwork                                                           | _____                 |                  |
| Stack                                                              | _____                 |                  |
| Piping                                                             | _____                 |                  |
| Insulation                                                         | _____                 |                  |
| Painting                                                           | _____                 |                  |
| Electrical                                                         | _____                 |                  |
| Total installation cost                                            | _____                 |                  |
| Total Direct Costs (equipment + installation)                      |                       | <u>\$180,000</u> |
| Installation costs, indirect                                       |                       |                  |
| Engineering                                                        |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction and field expense                                     |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Construction fees                                                  |                       |                  |
| (10% of direct costs)                                              | <u>Included</u> above |                  |
| Start-up (2% of direct costs)                                      | <u>Included</u> above |                  |
| Performance tests (minimum \$2000)                                 | <u>\$ 2,000</u>       |                  |
| Total Indirect Costs                                               |                       | <u>\$ 2,000</u>  |
| Contingencies                                                      |                       |                  |
| (20% of direct and indirect costs)                                 | <u>Included</u> above |                  |
| Total Turnkey Costs (direct + indirect + contingencies)            |                       | <u>\$182,000</u> |
| Land                                                               |                       |                  |
| Working capital (25% of total direct operating costs) <sup>b</sup> |                       | <u>\$ 13,000</u> |
| GRAND TOTAL (turnkey + land + working capital)                     |                       | <u>\$195,000</u> |

<sup>a</sup>NH<sub>3</sub> injection costs are extrapolated from utility boiler data (References 4-4 and 4-5).

<sup>b</sup>From Annual Cost Table (see following table).

TABLE A-124. ESTIMATED INCREMENTAL ANNUAL COSTS FOR REDUCED AIR PREHEAT (RAP) AND NH<sub>3</sub> INJECTION ON A NEW 44 MW NATURAL GAS-FIRED WATERTUBE BOILER WITH AN AIR PREHEATER<sup>a</sup>

|                                                           |                 |                                              |
|-----------------------------------------------------------|-----------------|----------------------------------------------|
| Direct cost                                               |                 |                                              |
| Direct labor                                              | _____           |                                              |
| Supervision                                               | _____           |                                              |
| Maintenance labor                                         | _____           |                                              |
| Maintenance materials                                     | <u>\$24,000</u> | NH <sub>3</sub> injection (all direct costs) |
| Replacement parts                                         | _____           |                                              |
| Electricity - Fan                                         | _____           |                                              |
| Steam                                                     | _____           |                                              |
| Cooling water                                             | _____           |                                              |
| Process water                                             | _____           |                                              |
| Fuel                                                      | <u>\$30,495</u> | RAP                                          |
| Waste disposal                                            | _____           |                                              |
| Chemicals                                                 | _____           |                                              |
| Total direct cost                                         |                 | <u>\$ 54,495</u>                             |
| Overhead                                                  |                 |                                              |
| Payroll (30% of direct labor)                             | Included above  |                                              |
| Plant (26% of labor, parts & maint.)                      | Included above  |                                              |
| Total overhead cost                                       |                 |                                              |
| By-product credits                                        |                 | <u>( )</u>                                   |
| Capital charges                                           |                 |                                              |
| G & A, taxes and insurance<br>(4% of total turnkey costs) | <u>\$ 7,280</u> |                                              |
| Capital recovery factor<br>(16% of total turnkey costs)   | <u>\$29,120</u> |                                              |
| Total capital charges                                     |                 | <u>\$ 36,400</u>                             |
| TOTAL ANNUALIZED COSTS                                    |                 | <u>\$ 90,895</u>                             |

<sup>a</sup>Ammonia injection costs are extrapolated from utility boiler data (References 4-4 and 4-5) and RAP energy use is from Section 5.

APPENDIX B  
LIST OF COMMON ABBREVIATIONS

|                 |                                  |
|-----------------|----------------------------------|
| BOOS            | Burners out of service           |
| CO              | Carbon monoxide                  |
| EPA             | Environmental Protection Agency  |
| FGR             | Flue gas recirculation           |
| HC              | Hydrocarbon                      |
| LEA             | Low excess air                   |
| LNB             | Low NO <sub>x</sub> burner       |
| LR              | Load reduction                   |
| N <sub>2</sub>  | Nitrogen                         |
| NH <sub>3</sub> | Ammonia                          |
| NO <sub>x</sub> | Nitrogen oxides                  |
| O <sub>2</sub>  | Oxygen                           |
| OFA             | Overfire air                     |
| PAH (PNA)       | Polynuclear aromatic hydrocarbon |
| POM             | Polycyclic organic matter        |
| RAP             | Reduced air preheat              |
| SCA             | Staged combustion air            |
| SFA             | Sidefire air                     |
| SIP             | State implementation plan        |
| SO <sub>2</sub> | Sulfur dioxide                   |
| SO <sub>3</sub> | Sulfur trioxide                  |
| UHC             | Unburned hydrocarbon             |

| TECHNICAL REPORT DATA<br>(Please read Instructions on the reverse before completing)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                 |                                                                       |                                |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|-----------------------------------------------------------------------|--------------------------------|
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| 16. ABSTRACT<br>The report gives results of an assessment of current and developing combustion modification NOx control technology for coal-, oil-, and natural-gas-fired industrial boilers. Control effectiveness and applicability, reliability and availability, process impacts, capital and operating costs, energy impacts, and environmental impacts are evaluated. Currently available techniques are capable of moderate (10-25%) NOx reductions for coal- and residual-oil-fired boilers and major (40-70%) reductions for distillate-oil- and gas-fired units with minimal adverse operating impacts. Combustion modifications are estimated to increase the cost of steam by only 1-2%, but could increase the initial capital cost of a boiler by 1-20%. Analysis of measured or postulated incremental emissions, other than NOx, indicates that these emissions are generally unaffected when preferred NOx controls are implemented, although further testing is warranted. |                 |                                                                       |                                |
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| Air Pollution                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Operating Costs | Air Pollution Control                                                 | 13B                            |
| Assessments                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Fossil Fuels    | Stationary Sources                                                    | 14B 21D                        |
| Combustion Control                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Dust            | Particulate                                                           | 21B 11G                        |
| Nitrogen Oxides                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Aerosols        | Combustion Modification                                               | 07B 07D                        |
| Boilers                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Trace Elements  | Industrial Boilers                                                    | 13A 06A                        |
| Capitalized Costs                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                 | Emission Factors                                                      | 14A, 05A                       |
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