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# ENVIRONMENTAL ASSESSMENT OF COAL- AND OIL-FIRING IN CONTROLLED INDUSTRIAL BOILER, VOLUME I: EXECUTIVE SUMMARY

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TRW, INCORPORATED
REDONDO BEACH, CALIFORNIA

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# Environmental Assessment of Coal- and Oil-firing in a Controlled Industrial Boiler; Volume I. Executive Summary

## Interagency Energy/Environment R&D Program Report

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16. ABSTRACT The report gives results of a comparative multimedia assessment of coal- versus oil-firing in a controlled industrial boiler, to determine relative environmental, energy, economic, and societal impacts. Comprehensive sampling and analyses of gaseous, liquid, and solid emissions from the boiler and its control equipment were conducted to identify criteria pollutants and other species. Major conclusions include: (1) While the quantity of particulates from oil-firing is considerably less than from coal-firing, the particles are generally smaller and more difficult to remove, and the concentration of particulates in the treated flue gas from oil-firing exceeded that from coal-firing. (2) NOx and CO emissions during coal-firing were about triple those during oil-firing. (3) Sulfate emissions from the boiler during coal-firing were about triple those during oil-firing; however, at the outlet of the control equipment, sulfate concentrations were essentially identical. (4) Most trace element emissions (except vanadium, cadmium, lead, cobalt, nickel, and copper) are higher during coal-firing. (5) Oil-firing produces cadmium burdens in vegetation approaching levels which are injurious to man; coal-firing may produce molybdenum levels which are injurious to cattle. (6) The assessment generally supports the national energy plan for increased use of coal by projecting that the environmental insult from coal-firing is not significantly different from that from oil-firing.

17. KEY WORDS AND DOCUMENT ANALYSIS

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| Pollution | Nitrogen Oxides | Pollution Control | 13B | 07B |
| Assessments | Carbon Monoxide | Stationary Sources | 14B | |
| Boilers | Sulfates | Environmental Assessment | 13A | |
| Combustion | Sulfur Oxides | | 21B | |
| Fuel Oil | Trace Elements | Industrial Boilers | 21D | 06A |
| Coal | Chemical Analysis | Particulate | | 07D |
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## Volume I. Executive Summary

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## ABSTRACT

The report gives results of a comparative multimedia assessment of coal versus oil firing in a controlled industrial boiler. Relative environmental, energy, economic, and societal impacts were identified. Comprehensive sampling and analyses of gaseous, liquid, and solid emissions from the boiler and its control equipment were conducted to identify criteria pollutants and other species. Major conclusions include: (1) While the quantity of particulates from oil firing is considerably less than from coal firing, the particles are generally smaller and more difficult to remove, and the concentration of particulates in the treated flue gas from oil firing exceeded that from coal firing. (2) $NO_x$ and CO emissions during coal firing were about triple those during oil firing. (3) Sulfate emissions from the boiler during coal firing were about triple those during oil firing; however, at the outlet of the control equipment, sulfate concentrations were essentially identical. (4) Most trace element emissions (except vanadium, cadmium, lead, cobalt, nickel, and copper) were higher during coal firing. (5) Oil firing produces cadmium burdens in vegetation approaching levels which are injurious to man; coal firing may produce molybdenum levels which are injurious to cattle. (6) The assessment generally supports the national energy plan for increased use of coal by projecting that the environmental insult from controlled coal firing is not significantly different from that from oil firing.

This report was submitted in fulfillment of Contract Number 68-02-2613, Task 8 by TRW Environmental Engineering Division under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from October 24, 1977 to May 5, 1978, and work was completed as of May 5, 1978.

## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| acm/min | -- | Actual Cubic Meters Per Minute |
| ACFM | -- | Actual Cubic Feet Per Minute |
| DSCM | -- | Dry Standard Cubic Meters |
| ESCA | -- | Electron Spectroscopy for Chemical Analyses |
| FGD | -- | Flue Gas Desulfurization |
| ICPOES | -- | Inductively Coupled Plasma Optical Emission Spectroscopy |
| MATE | -- | Minimum Acute Toxicity Effluent |
| NAAQS | -- | National Ambient Air Quality Standards |
| NSPS | -- | New Source Performance Standards |
| SSMS | -- | Spark Source Mass Spectrometry |
| TSP | -- | Total Suspended Particulate |

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## EXECUTIVE SUMMARY

The industrial nations of the world are being forced to simultaneously deal with two very difficult and contradictory problems. The relatively cheap and convenient sources of energy are rapidly being depleted while the need for increasingly stringent control of pollution is making the environmentally acceptable use of the energy sources that are available more difficult. One response to these dual needs has been to use the more abundant high polluting fuels in combustion systems that have sophisticated pollution controls. The technologies that are used to control pollution are new relative to combustion technology. Therefore, the subtle short- and long-term effects of these new technologies are not yet completely known.

The objective of this program is to conduct a comparative, multimedia environmental assessment of oil vs. coal firing in controlled industrial and utility boilers and to draw conclusions about the comparative environmental, energy, and societal impacts of firing oil versus firing coal. A secondary objective of this program is to recommend the approach to be used for subsequent assessments of a variety of combustion related pollution sources.

### INTRODUCTION

This report presents the comparative assessment of controlled industrial boilers. The major technical input for this assessment was feed stream and emissions characterization data collected as part of the Conventional Combustion Emission Assessment Program. These data were derived from rigorous sampling and analysis and specify the types and quantities of all solid, liquid, and gaseous pollutant species of interest in each of the inlet and outlet streams of a controlled oil- and coal-fired industrial boiler. A comprehensive assessment of each fuel type in the controlled industrial boiler was accomplished to determine:

- The types and amounts of pollutants that are released during coal and oil combustion in an uncontrolled boiler:
- The types and amounts of pollutants that are released during the combustion of each fuel in a controlled boiler;

- The effectiveness of the controls with respect to each controlled pollutant;
- If the control devices modify pollutants that pass through the controls;
- If the controls themselves create pollutants.

The comprehensive assessment results for the oil and coal-fired industrial boiler were then used in a comparative emission assessment to determine the differences in the types and quantities of all pollutant species of interest.

The results of the industrial comparative emission assessments were then evaluated to determine what conclusions could be drawn about the oil versus coal firing. The comparative impacts identified were summarized by environmental, energy, economic, and societal categories.

This report is organized in three volumes. Volume I is the Executive Summary. The comparative assessment of emissions and their impacts is presented in Volume II. Volume III describes the test site, the sampling and analysis activities; presents the comprehensive assessments of coal and oil firing; and provides the appendices which contain detailed test and analysis results.

There are a number of significant differences in the quantities, characteristics, and impacts of the emissions resulting from coal and oil firing in a controlled industrial boiler. In the following paragraphs the most important of these differences are summarized. It should be kept in mind, however, that the conclusions are based on tests conducted on only one industrial boiler, one type of coal, and one type of oil. It should not be assumed that these conclusions apply to all industrial boilers under all circumstances. The results of this program should, perhaps, best be thought of as a good indication of the impact differences between coal and oil firing and as a set of guidelines on which future work can be based.

TEST AND ANALYSIS

The test unit used for this assessment is a dual fuel industrial process steam boiler operated by the Firestone Tire and Rubber Company in Pottstown, Pennsylvania. The 10 megawatt equivalent boiler is equipped with a pilot FMC, Inc. flue gas desulfurization (FGD) unit that is designed to treat approximately one-third of the flue gas produced by the boiler when it is operating at full load (3 megawatt equivalent). The boiler was originally designed to burn coal but was later modified to burn either high volatile eastern bituminous coal or Number 6 fuel oil. Table 1 presents a list of the major boiler parameters. The boiler has no $NO_x$ controls.

The boiler produces four liquid waste streams: boiler feed water pretreatment waste, steam drum blowdown, mud drum blowdown and cooling water. All liquid waste streams except the cooling water are mixed with process waste water from elsewhere in the plant. This combined stream is then pumped directly into the municipal sewerage system. The boiler cooling water is pumped directly into the municipal sewerage system without mixing with other plant waste streams.

TABLE 1. SUMMARY OF BOILER PARAMETERS

| | |
|---|---|
| Boiler type: | Oil/pulverized coal;<br>face fired;<br>integral furnace;<br>dry bottom |
| Manufacturer: | Babcock and Wilcox, Type P-22 EL |
| Type of burner: | Circular conical |
| Number of burners: | 3 |
| Burner arrangement: | Triangular, one face |
| Air preheater: | Yes |
| Fuel: | Number of 6 fuel oil;<br>High volatile bituminous coal,<br>Class II, Group 2, of ASTM D388 |
| Design steam rate: | 45,000 kg/hr (100,000 lb/hr); |
| Use: | Process steam |

The pilot FGD unit is a double alkali scrubber that produces only a solid cake as a waste product. The scrubber does not produce a liquid waste stream. It is designed as a sulfur dioxide ($SO_2$) and particulate control device, and will operate on either fuel without modification.

Test and Analysis Summary

Sampling and analysis of gaseous, liquid, and solid pollutants were conducted according to the EPA Level 1/Level 2 criteria, except that both Level 1 and Level 2 sampling were conducted simultaneously because of program time constraints. Level 1/Level 2 analysis procedures were followed except Level 2 analysis was conducted prior to receiving the results of Level 1 analysis in those cases where sample degradation was anticipated. Figure 2 shows the sampling locations. Table 2 summarizes the samples taken and analyses conducted.

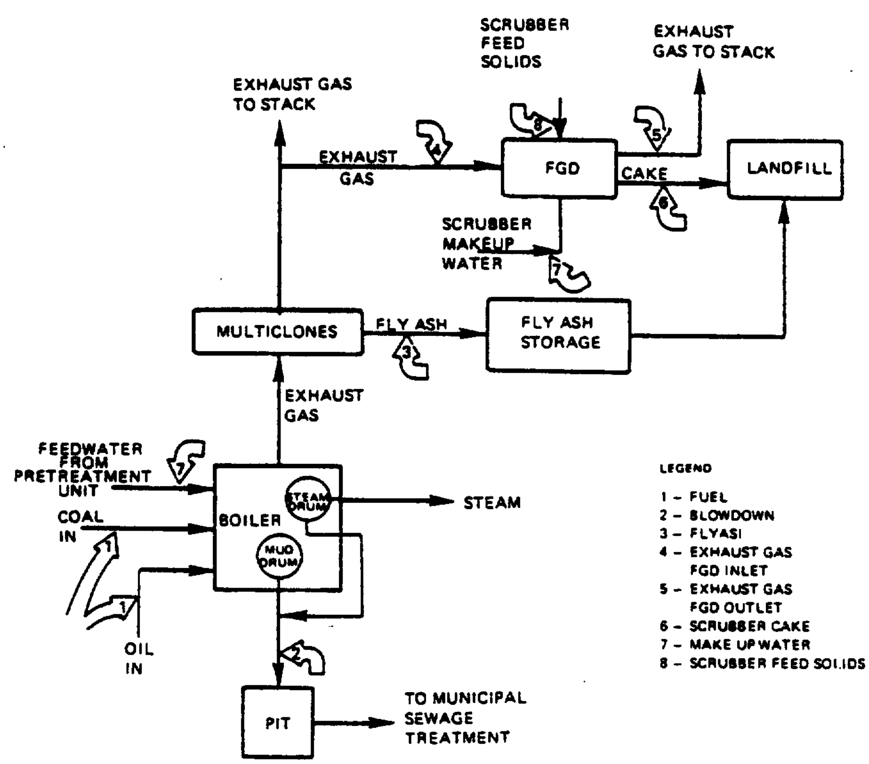


Figure 2. Diagram of boiler and flue gas desulfurization system showing sampling locations.

TABLE 2. PARAMETERS SAMPLED FOR COAL AND OIL FIRING

| Location | Parameter | Sampling Method | Analysis |
|---|---|---|---|
| 1 | FUEL (coal & oil) | Grab | |
| | C, H, N, S, ash, moisture, heating value | | Ultimate (lab) |
| | Inorganics | | Level II (lab) |
| 2 | COMBINED BLOWDOWN | Composite dipper | On-site HACH kit |
| | Alkalinity/acidity | | |
| | pH | | |
| | conductivity | | |
| | hardness | | |
| | TSS | | |
| | nitrate | | |
| | sulfate | | |
| | sulfite | | |
| | phosphate | | |
| | ammonia | | |
| | nitrogen | | |
| | organics | | Level 1 & 2 (lab) |
| 3 | FLYASH | Composite grab | |
| | inorganics | | Level 1 & 2 (lab) |
| | organics | | Level 1 & 2 (lab) |
| 4&5 | FLUE GAS (inlet & outlet) | | |
| | CO | Continuous, Beckman Model 865 | Direct reading |
| | | Grab (bag) | GC (TCD) on site |
| | $CO_2$ | Grab (bag) | GC (TCD) on site |
| | $NO/NO_2/NO_x$ | Continuous, TECO Model 10A | Direct reading |
| | $N_2, O_2$ | Grab (bag) | GC (TCD) on site |
| | $SO_2$ | Continuous, TECO Model 41 | Direct reading |
| | $SO_2/SO_3$ $H_2SO_4$, HCl, HF, particulate sulfate, | Goksoyr-Ross | Level 2 (lab) |
| | total hydrocarbons (as $CH_4$) | Continuous, Beckman Model 400 | Direct reading |
| | $C_1$ - $C_6$ organics | Grab (bag) | GC (FID) on site |
| | | SASS | Level 1 (lab) |
| | particulate & vapor | Method 5 | Level 2 (lab) |
| | particulate sizing | Anderson impactor | Level 1 |
| | | SASS | Level 2 |
| 6 | SCRUBBER CAKE | Composite grab | |
| | inorganics | | Level 1 & 2 (lab) |
| | organics | | Level 1 & 2 (lab) |
| 7 | BOILER & SCRUBBER MAKEUP WATER | Top grab | |
| | organics | | Level 1 (lab) |
| | inorganics | | Not required |
| 8 | SCRUBBER MAKEUP SOLIDS | Grab | Not required |

## EMISSIONS

Table 3 summarizes the annual emissions resulting from coal and oil firing. The table presents estimates of air emissions both before (inlet) and after (outlet) the scrubber. Liquid effluent and solid waste rates are presented for both the controlled and uncontrolled cases.

Outlet emissions were determined on the basis of 100 percent of the flue gas being treated by the scrubber. It was assumed that additional scrubber modules, identical to the existing one, could be added such that all of the flue gas was processed in exactly the same manner as the fraction that actually passed through the scrubber. In this way, emissions from the pilot scrubber could be scaled up to represent the total flue gas flow. All emissions data and conclusions are based on this assumption.

## COMPREHENSIVE ASSESSMENT OF COAL FIRING

### Criteria Pollutants

Uncontrolled emissions of criteria pollutants generally corresponded well with values reported in AP-42. Although $NO_x$ emissions were slightly higher than the average AP-42 value, they appear to be within the normal range for similar industrial units.

$NO_x$ reductions varying from approximately 0 to 24 percent were measured across the scrubber. However, the magnitude of $NO_x$ reductions could not be correlated to changes in variables monitored during the test period (i.e., temperature, gas flow rate, liquid/gas ratio, boiler load, etc.). For this reason, it is considered feasible that observed $NO_x$ reductions are a sampling phenomenon, perhaps related to leaks in the sample train.

Sulfur dioxide removal data indicated an average scrubber efficiency of 97 percent. Controlled $SO_2$ emissions were 36.3 ng/J (0.08 pounds/MM Btu) which is less than either existing or proposed NSPS limitations for utility boilers.

## TABLE 3. ANNUAL EMISSIONS

| Pollutant | | kg/year | | | | | |
|---|---|---|---|---|---|---|---|
| | | Scrubber Inlet | | | Scrubber Outlet | | |
| | | Coal Firing | Oil Firing | Coal/Oil | Coal Firing | Oil Firing | Coal/Oil |
| Gaseous | NOx (as $NO_2$) | 500,810 | 164,230 | 3.05 | 442,520 | 157,390 | 2.81 |
| | $SO_2$ | 1,127,300 | 906,202 | 1.24 | 36,800 | 24,453 | 1.51 |
| | $SO_3$ | 6,184 | 7,249 | 0.85 | 4,157 | 5,183 | 0.80 |
| | $SO_4^{=}$ | 67,214 | 20,894 | 3.22 | 8,110 | 8,303 | 0.98 |
| | CO | 16,119 | 4,991 | 3.23 | 14,497 | 4,845 | 2.99 |
| | Organics (as $CH_4$) | 5,870 | 2,272 | 2.58 | 6,377 | 2,500 | 2.55 |
| | $C_1 - C_6$† | <5,606 | <4,164 | -- | <5,606 | <4,164 | -- |
| | $C_7 - C_{16}$ | 345 | 155 | 2.22 | 274 | 18 | 15.2 |
| | $C_{16}$+ | 2,311 | 2,381 | 0.97 | 335 | 392 | 0.85 |
| | Total Particulates | 2,991,760 | 53,832 | 55.6 | 18,856 | 13,686 | 1.38 |
| | <1μ | -- | -- | -- | 11,691 | 11,359 | 1.03 |
| | 1 - 3μ | -- | -- | -- | 5,657 | 1,642 | 3.45 |
| | 3 - 10μ | -- | -- | -- | 1,320 | 634 | 1.93 |
| | >10μ | -- | -- | -- | 188 | 0‡ | -- |
| | | $m^3$/year | | | | | |
| Liquid | Blowdown/Waste Water | ~76,000 | ~ 76,000 | ~ 1 | ~ 76,000 | ~76,000 | ~ 1 |
| | Cooling Water | ~86,000 | ~ 86,000 | ~ 1 | 86,000 | ~86,000 | ~ 1 |
| Solid | Bottom Ash | ~ 778,600 | ~ 7,600 | ~ 103 | ~ 778,600 | ~ 7,600 | ~103 |
| | Fly Ash | ~1,800,000 | ~ 15,000 | ~ 120 | ~1,800,000 | ~15,000 | ~120 |
| | Scrubber Cake | 0 | 0 | -- | 8,054,100 | 3,011,000 | 2.67 |

*Assuming 100% load, 45 weeks per year (7,560 hrs/year).

†These values represent the detection limit of the instrument used.

‡These values represent oil firing particulate with a minimum of coal ash contamination.

Mass balance data indicate that the multiclone unit upstream of the scrubber was removing little or no fly ash during the test period. The scrubber was found to remove 99.4 percent of the inlet particulate.

Inorganics

Although the removal efficiency for total particulates is high, there appears to be a net increase in emission rates across the scrubber for particulates less than 3 μm in size. This net increase can be attributed to the poor removal efficiency of the scrubber for fine particulates, and to the sodium bisulfate ($NaHSO_4$) and calcium sulfite hemihydrate ($CaSO_3 \cdot 1/2H_2O$) particulates generated by the scrubber. Both $NaHSO_4$ and $CaSO_3 \cdot 1/2H_2O$ have been identified at the scrubber outlet but not at the inlet.

The relatively poor removal efficiency (approximately 30%) for $SO_3$ across the scrubber is an indication that $SO_3$ is either present as very fine aerosols in the scrubber inlet, or is converted to very fine aerosols as the flue gas stream is rapidly cooled inside the scrubber.

Analysis has shown that while there may be higher surface concentrations of sulfur-containing compounds in the particulates emitted from the scrubber, most of the sulfur-containing compounds are probably present as solid sulfates and sulfites. Thus, it is conceivable that sulfuric acid vapor is condensed and deposited on the particulates emitted, whereas sodium bisulfate and calcium sulfite hemihydrate are emitted as fine, solid particulates.

The overall sulfur balance indicates that over 92 percent of the fuel sulfur is emitted as $SO_2$, less than 1 percent of the fuel sulfur is emitted as $SO_3$, and approximately 3 percent of the fuel sulfur is emitted as $SO_4^{=}$.

The overall removal efficiency for trace elements across the scrubber is 99.5 percent. Of the 22 major trace elements, 18 exceed their MATE values at the scrubber inlet and four at the scrubber outlet. The four trace elements in the scrubber flue gas that pose a potential hazard are arsenic, chromium, iron, and nickel. In addition, the emission concentration of beryllium at the scrubber outlet is equal to its MATE value. The relative removal efficiency for trace elements across the scrubber can be explained by enrichment theory. In general, trace elements that occur as element vapors or form volatile compounds at furnace temperatures are more concentrated in the smaller particulates, as a result of subsequent condensation and surface adsorption. These are the same trace elements that are removed less efficiently by the scrubber.

Mass balance closure for most of the trace elements have been found to be in the 75 to 107 percent range. This closure instills confidence on the validity of the sampling and analysis data for trace elements.

## Organics

Total organic emissions were generally less than 9 ng/J (0.02 pound/MM Btu) and these emissions appear to be primarily $C_1$ to $C_6$ hydrocarbons and hydrocarbons heavier than $C_{16}$. While uncontrolled emission rates for $C_7$ to $C_{16}$ and higher hydrocarbons are low, emissions of these organics were further reduced by 21% to 35% in the scrubber unit.

Polycyclic organic material (POM) was not found in the scrubber inlet or outlet at detection limits of 0.3 $\mu g/m^3$. MATE values for most POM's are greater than this detection limit. However, since the MATE values for at least two POM compounds - benzo(a)pyrene and dibenz(a,h)anthracene - are less than 0.3 $\mu g/m^3$, additional GC/MS analyses at higher sensitivity would be required to conclusively preclude the presence of all POM's at MATE levels.

## Liquid Effluents

The combined wastewater stream generated from the boiler operation may not pose an environmental hazard, since the discharge concentrations of most inorganics and organics are all well below their MATE values. However, based on the uncertainty in SSMS analyses, cobalt, cadmium, nickel and copper may exceed their MATE values based on ecological considerations.

## Solid Waste

The scrubber cake produced contains a significant amount of coal fly ash. With the exception of boron, trace element concentrations in the scrubber cake far exceeded their MATE values. Because the trace elements may leach from the disposed scrubber cake, these solid wastes must be disposed of in specially designed landfills.

## COMPREHENSIVE ASSESSMENT OF OIL FIRING

### Criteria Pollutants

Uncontrolled emissions of criteria pollutants do not generally correspond with emission factors from AP-42. $NO_x$ emissions were nearly 23% lower than the AP-42 emission factor, although they appear to be within the normal range for similar industrial units. CO emissions were nearly 63% lower than the AP-42 emission factor. $SO_2$ and total hydrocarbons corresponded well with their respective AP-42 emission factors. Particulate emissions, in the absence of coal ash contamination, are approximately twice the value tabulated in AP-42.

Sulfur dioxide removal data indicated an average scrubber efficiency of 97%. Controlled $SO_2$ emissions were 26.8 ng/J (0.06 lb/MM Btu) which is less than either existing or proposed NSPS limitations for utility boilers.

### Inorganics

Particulate removal data indicate that, on the average, scrubber efficiency was 84% during the test period. However, based on particulate catches essentially free of coal ash contamination, the scrubber efficiency was approximately 75% for oil firing particulates.

When emissions are uncontrolled, over 90% of the sulfur in the fuel feed is emitted as $SO_2$, less than 1% as $SO_3$, and 1.5% as $SO_4^=$.

$SO_2$ is efficiently removed by the scrubber (97 to 98% efficiency). The $SO_3$ removal efficiency (28 to 29%) suggests that $SO_3$ is associated with fine particulates or aerosols. $SO_4^=$ is about 60% removed by the scrubber, and so is probably associated with the larger particulates.

Of the 22 major trace elements analyzed in the flue gas stream, 11 exceeded their MATE values at the scrubber inlet while only 5 exceeded MATE values at the scrubber outlet. These 5 elements are arsenic, cadmium, chromium, nickel and vanadium. With the exception of chromium, elements exceeding their MATE values at the scrubber outlet were removed from the flue gas stream with efficiencies lower than the overall average removal efficiency of 87%.

Beryllium emissions were 0.001 $mg/m^3$ after scrubbing; this corresponds to half the MATE value for this element. At this emission concentration, the National Standard for Hazardous Air Pollutants limitation of 10 grams beryllium per day would only be exceeded by boilers of 100 MW capacity or greater.

Mass balance closure for 10 of the 20 trace elements analyzed is between 50 and 136 percent. Poorer mass balance closure was obtained for the remainder of the trace elements due to the extremely low concentrations and/or contamination of the scrubber recycle solution by coal firing components.

Organics

Organic emissions determined by FID analysis were generally less than 5 ng/J (0.01 lb/MM Btu) and appear to be composed primarily of $C_1$ to $C_6$ hydrocarbons and organics heavier than $C_{16}$. However, gas chromatograph and gravimetric data indicate that FID values may be low by a factor of 2 to 3. Approximately 88 and 83% of the $C_7$ to $C_{16}$ and higher than $C_{16}$ organics, respectively, were removed by the scrubber.

The organic compounds identified in the gas samples were generally not representative of combustion-generated organic materials, but were compounds associated with materials used in the sampling equipment and in various analytical procedures. This again confirms the low level of organic emissions.

Polycyclic organic material (POM) was not found in the scrubber inlet or outlet streams at detection limits of 0.3 $\mu g/m^3$. MATE values for most POMs are greater than this detection limit. However, since the MATE values for at least two POM compounds - benzo(a)pyrene and dibenz(a,h)anthracene - are less than 0.3 $\mu g/m^3$, additional GC/MS analysis at higher sensitivity would be required to conclusively preclude the presence of all POMs at MATE levels.

Liquid Effluents

The combined wastewater stream from the boiler operation may not pose an environmental hazard in terms of organic materials since the discharge concentrations of organics are all well below their MATE values. A similar conclusion may be drawn with respect to inorganic materials since inorganics, with the exception of nickel and copper, did not exceed their MATE values for liquid streams. Owing to uncertainty associated with SSMS analysis, nickel and copper may exceed their MATE values although this is not necessarily the case.

## Solid Waste

With the exceptions of antimony, boron, molybdenum and zinc, trace element concentrations in the scrubber cake exceed their MATE values. Because the trace elements may leach from the disposed scrubber cake, these solid wastes must be disposed of in specially designed landfills.

## COMPARATIVE EMISSIONS ASSESSMENT

### Criteria Pollutants

Uncontrolled emissions of criteria pollutants produced during coal firing correspond well with emission factors from AP-42. This observation does not generally hold true for oil fired emissions. Full load $NO_x$ emissions from oil firing were 19% lower than the AP-42 emission factor, although they appear to be within the normal range for similar industrial units. CO emissions from oil firing were nearly 63% lower than the AP-42 emission factor. Oil-fired $SO_2$ and total hydrocarbons correspond well with their respective AP-42 emission factors. Particulate emissions from oil firing, in the absence of coal ash contamination, are approximately twice the value tabulated in AP-42.

$NO_x$ emissions increased with increasing load for both coal and oil firing, as expected. Available data indicate that for boiler loadings between 90 and 100%, $NO_x$ emissions from coal firing are approximately three times greater than from oil firing.

Observed reductions of $NO_x$ emissions for coal firing and early oil firing tests appear to be due, at least in part, to air leakage into the scrubber outlet sampling line. Data from later oil firing tests, not known to be subject to leakage problems, indicate that $NO_x$ removal across the scrubber is on the order of 2%.

Uncontrolled CO emissions from coal firing were 15.9 ng/J (0.04 lb/MM Btu) while those from oil firing were 5.47 ng/J (0.01 lb/MM Btu). This factor of three difference is at variance with AP-42 data indicating that CO emissions from oil firing are 23% lower than those from coal firing. Apparent reductions in CO emissions across the scrubber are not considered significant due to air leakage in the sampling train and the low sensitivity of analysis at the measured CO concentrations.

Uncontrolled $SO_2$ emission rates during coal and oil firing were 1112 ng/J (2.59 lb/MM Btu) and 993 ng/J (2.31 lb/MM Btu), respectively. Removal data indicate an average scrubber removal efficiency of 97% during both coal and oil firing. Controlled $SO_2$ emissions for coal and oil firing were 36.3 ng/J (0.08 lb/MM Btu) and 26.8 ng/J (0.06 lb/MM Btu), respectively, which are lower than either existing or proposed NSPS limitations.

Particulate loadings prior to scrubbing were 2951 ng/J (6.86 lb/MM Btu) during coal firing and 59.0 ng/J (0.14 lb/MM Btu) during oil firing, in the absence of coal ash contamination. Scrubbing removed 99% of the coal-fired particulates and 75% of the oil-fired particulates. The lower removal efficiency obtained during oil firing is attributed to the increased fraction of particles smaller than 3 µm; at least 21% of the uncontrolled oil-fired particulates are less than 3 µm in diameter while substantially less than 1% of uncontrolled coal-fired particulates are under 3 µm.

There appeared to be a net increase in emission rates across the scrubber for coal fired particulates less than 3 µm in size. This net increase can be attributed to the poor removal efficiency of the scrubber for fine particulates, and to the sodium bisulfate ($NaHSO_4$) and calcium sulfite hemihydrate ($CaSO_3 \cdot 1/2H_2O$) particulates generated by the scrubber. Both $NaHSO_4$ and $CaSO_3 \cdot 1/2H_2O$ have been identified at the scrubber outlet but not at the inlet. Although a very slight increase in oil-fired particulates in the 1-3 µm range was observed, a net decrease in particulates less than 3 µm was observed during oil firing. Based on the results of coal firing tests, it appears reasonable that scrubber generated particulates were present in the scrubber outlet stream during oil firing but that the high fine particulate loading associated with oil firing masked detection of these materials.

Inorganics

Of the 23 major trace elements analyzed in the flue gas stream during coal firing, 18 exceed their MATE values at the scrubber inlet and four at the scrubber outlet. Similarly, for oil firing, 11 exceeded their MATE values at the scrubber inlet while five exceeded their MATE values at the scrubber outlet. Elements exceeding their MATE values at the scrubber outlet and which are common to both fuels are arsenic, chromium and nickel. Additionally, iron exceeded its MATE value at the scrubber outlet during coal firing as did cadmium and vanadium during oil firing. The overall removal of trace elements across the scrubber is 99% for coal firing and 87% for oil firing.

Beryllium emissions after scrubbing were less than or equal to the beryllium MATE value during coal and oil firing. At the measured emission concentrations, the National Standard for Hazardous Air Pollutants limitation of 10 grams beryllium per day would only be exceeded by boilers of 50 MW capacity for coal firing and 100 MW capacity for oil firing.

The fraction of fuel sulfur converted to $SO_3$ during oil firing was 50 to 75% higher than during coal firing. In contrast, the fraction of fuel sulfur converted to sulfates during coal firing was twice that during oil firing.

Sulfates are more efficiently removed than $SO_3$ (60% removal for oil firing and 88% for coal firing). This indicates that $SO_4^{=}$ is probably associated with the larger particulates, which are more efficiently removed than smaller particulates. The higher sulfate removal from the coal flue gases is explained by the higher particulate loading during coal firing.

Uncontrolled chloride and fluoride loadings were higher during coal firing (5 and 0.2 ng/J, respectively) than during oil firing (0.2 and 0.02 ng/J, respectively). This was attributed, in the case of chlorides, to a higher fuel chlorine content for coal than for oil. Chlorides were removed with better than 99% efficiency from coal flue gases and with about 51% efficiency from oil flue gases. This difference was attributed to the higher particulate removal efficiency for coal particulates. Fluorides were removed with greater than 86% and about 87% efficiency for coal and oil firing, respectively. Uncontrolled nitrate emissions were 0.08 ng/J during oil firing, and nitrates were removed from oil flue gases with 57% efficiency.

Organics

Polycyclic organic material (POM) was not found in the scrubber inlet or outlet at detection limits of 0.3 $\mu g/m^3$ for either coal or oil firing. MATE values for most POM's are greater than this detection limit. However, since the MATE values for at least two POM compounds - benzo(a)pyrene and dibenz(a,h)anthracene - are less than 0.3 $\mu g/m^3$, additional GC/MS analyses at higher sensitivity would be required to conclusively preclude the presence of all POM's at MATE levels.

Organic emissions for coal and oil firing were very similar. Total organic emissions were less than 9 ng/J (0.02 lb/MM Btu) for both tests, and these emissions appear to be primarily $C_1$ to $C_6$ hydrocarbons and organics heavier than $C_{16}$. While uncontrolled emission rates for both coal and oil firing are low, emissions of these organics were further reduced by about 75% to 85% in the scrubber unit.

The organic compounds identified in the gas samples from both coal and oil firing were generally not representative of combustion-generated organic materials, but were compounds associated with materials used in the sampling equipment and in various analytical procedures. This again confirms the low level of organic emissions.

Liquid Waste

The combined waste water stream from the boiler operation may not pose an environmental hazard in terms of organic materials since the discharge concentrations of organics are well below their MATE values for both coal and oil firing. The same conclusion may be drawn for inorganic compounds with the exception of cobalt, nickel, copper and cadmium for coal firing and nickel and copper for oil firing since these metals may exceed their MATE values.

## Solid Waste

The scrubber cake produced when either fuel is burned contains concentrations of trace elements high enough to exceed most MATE values. Because of these high concentrations the scrubber cake must be disposed of in specially designed landfills.

## COMPARATIVE ENVIRONMENTAL ASSESSMENT

The difference in environmental insult expected to result between coal and oil combustion emissions from a single controlled 10 MW industrial boiler is insignificant. This is because: 1) there are only slight differences in the emissions levels of the pollutants, or 2) the absolute impact of either fuel use is insignificant. The environmental impacts of emissions from a cluster of controlled 10 MW industrial boilers are potentially significant. The impacts include health effects, material damages, and ecological effects from high levels of $SO_2$, $NO_x$ and suspended particulate matter; health effects and ecological damage due to trace metal accumulation in soils and plants; and aesthetic degradation from visibility reduction and waste disposal sites.

The risk of environmental damage from emissions of controlled industrial boilers, whether oil or coal-fired, is considerably less than the risk posed by emissions from uncontrolled industrial boilers. It should be noted that this finding is based on an exceptional facility. The reference facility is very well run and maintained, and emissions are low.

The environmental acceptability of a cluster of controlled industrial boilers is more dependent on site specific factors (e.g., background pollution levels, location and number of other sources) than type of fuel utilized. Careful control of the site specific factors can avert potential environmental damages and generally compensate for any differential effects arising between the use of coal or oil.

With the possible exception of ambient levels of $NO_x$, the risk of violating the National Ambient Air Quality Standards (NAAQS) due to the operation of clusters of controlled industrial boilers is essentially the same whether the fuel combusted is coal or oil. Based on tests of the reference 10 MW boiler (which was not controlled for $NO_x$ emissions), localized $NO_x$ concentrations produced by coal firing are estimated to be twice the level of that resulting from oil firing, and greater than the levels permitted by the NAAQS for 24-hour and one year averaging periods.

Short term (3 hour and 24 hour averaging times) maximum ambient concentrations present the most significant air pollution problem resulting from operation of controlled industrial boilers. Restrictions imposed by the NAAQS for short term ambient levels would be most constraining to boiler operation in areas where air quality is already only marginally acceptable. Expected long term concentrations arising from boiler emissions would not appear to pose a risk for violation of the NAAQS.

Coal firing appears to produce a greater enrichment of trace elements in the flue gas desulfurization cake than oil firing produces. However, the scrubber cake resulting from either coal or oil firing contains sufficient amounts of heavy metals and toxic substances to pose difficult waste disposal problems.

The impact categories considered include public health, ecology, societal, economic, and energy. The specific findings with respect to the various impact categories are summarized briefly below.

Health Effects

Based on the Lundy/Grahn Model for health effects associated with suspended sulfate levels, regional emissions levels from controlled oil or coal-fired industrial boilers would not be expected to cause a significant impact on regional health. Emissions from uncontrolled boilers would result in substantially greater levels of regional suspended sulfate levels, and the associated health effects would be an order of magnitude greater.

Emissions from clusters of controlled industrial boilers are expected to cause significant adverse health effects in a localized area near the plant cluster. Oil firing would be expected to result in localized health effects about one third less severe than those resulting from coal firing. The increase in mortality attributable to either controlled coal or oil firing is appreciable less than that associated with uncontrolled industrial boilers emitting higher levels of particulates and $SO_x$.

The impact of solid waste generation on health is essentially the same for controlled coal firing and oil firing, provided suitable land disposal techniques are employed to assure minimal leaching rates and migration of trace elements to groundwater and the terrestrial environment.

Addition of cadmium to a localized environment in the quantities produced by clustered controlled industrial boilers may result in cadmium concentrations in living plants approaching levels injurious to man. Because cigarettes contain significant cadmium levels, smokers are more apt to achieve thresholds of observable symptoms for cadmium exposure when consuming additional cadmium via the food chain.

The concentration of metals in runoff waters due to controlled oil firing is predicted to be slightly less than that occurring from controlled coal firing; in either case, hazard to human health by drinking water is remote.

Trace element emissions from clusters of controlled industrial boilers may significantly increase local background levels in drinking water, plant tissue, soil, and the atmosphere; however, the expected increases in the levels of such elements are generally several orders of magnitude less than allowable exposure levels. Oil firing is estimated to cause cadmium burdens in plants approaching levels injurious to man, and coal firing may produce plant concentrations of molybdenum which are injurious to cattle.

Ecology

The potential for crop damage from either controlled coal firing or oil firing depends greatly on ambient levels of $NO_x$, $SO_2$, or trace element soil concentrations. If such levels are presently high, localized plant damage would be expected to occur within a 1 to 2 km range from a controlled boiler cluster. Leaf destruction from $SO_2$ exposure would be expected to be slightly more severe in the vicinity of a cluster of controlled boilers which are coal-fired as opposed to oil-fired. For boilers uncontrolled for $NO_x$ emissions, plant damage would be expected to be significantly greater in the vicinity of the coal-fired cluster, owing to higher levels of ambient $NO_x$ produced. The likelihood of damage occuring in plants due to emissions of trace elements from either controlled oil or coal firing is remote, with the possible exception of injury due to elevated levels of molybdenum and cadmium in plant tissue resulting from coal firing and oil firing, respectively.

The effect of emissions from industrial boilers on trace element burdens in plants would be greater via soil uptake than by foliar interception. This is because soil concentrations are the result of accumulative long term exposure to boiler emissions whereas foliar exposure is determined by the immediate deposition rate of emissions on the plant surface and the lifetime of the leaf.

The impact of fossil fuel combustion in controlled oil or coal-fired boilers on plant damage via acid precipitation would be insignificant. The levels of suspended sulfate (the origin of acid rain) would be essentially the same whether the controlled boilers are coal or oil fired.

Measurement and analyses of leaching rates at experimental waste disposal sites indicate that landfills of untreated flue gas desulfurization system scrubber cake can be constructed such that significant adverse impacts will not occur.

Societal

The impact of boiler emissions on corrosion in the local area near a cluster of controlled industrial boilers would be significant. The corrosion rate would be slightly greater when the boilers are coal-fired. However, the extent of this overall impact (oil or coal) is minor compared to that which occurs when industrial boilers are uncontrolled.

The increase in annual TSP and soiling damages in the vicinity of a cluster of controlled industrial boilers would result in additional cleaning and maintenance costs about 10 to 15% greater than that already experienced in a typical urban area. The cleaning costs may be slightly greater when the boilers are coal-fired.

Emissions of particulate matter from controlled industrial boilers would result in visibility reduction. This aesthetic degradation would occur in a localized area near the boiler cluster, and would occur to essentially the same extent whether the boilers are oil or coal fired.

Total land disposal requirements for scrubber cake waste generated by controlled coal firing are three times greater than those for controlled oil firing. Waste disposal of the scrubber wastes may result in significant depreciation of property value and aesthetic degredation in the area of the disposal site. These impacts would be more severe if boilers use coal rather than oil.

Economic

The differential direct economic impact between emissions from coal firing and oil firing is generally insignificant with the possible exception of some differences occurring in a limited localized area near clusters of boilers. The extent of the incremental direct economic impacts is proportional to the extent of the incremental environmental damages.

Differential second order economic impacts, such as changes in hospital employment, alteration of taxes, or changes in income, are expected to be insignificant between emissions from controlled oil and coal-fired industrial boilers.

Energy

At the present time, the comparative assessment of the effects of emissions from controlled oil and coal-fired industrial boilers tends to support the national energy plan for intensified utilization of coal. The fuel choice of oil or coal is a relatively minor issue concerning the environmental acceptability of controlled industrial boilers; other site specific and plant design factors exert a greater effect on environmental damages. While it was shown that fuel choice caused significant differences in impacts to occur when the boiler is uncontrolled for $NO_x$ emissions, these differences may be mitigated by the addition of $NO_x$ control technologies with minimal overall cost impact.

As concern for environmental protection increases, the issue may not be whether coal or oil use is more environmentally acceptable, but whether the increasing use of fossil fuels can be continued at the present levels of control technology without potential long term damages. If it is found that long term effects of pollution (e.g., trace metals accumulation, lake acidity from acid rains) from fossil fuel combustion and other sources are environmentally unacceptable, it is clear that energy use may be affected. Energy cost will increase with increasing control requirements, possibly to the level where other cleaner forms of energy become more competitive.