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EMISSIONS CHARACTERISTICS OF MODERN OIL HEATING EQUIPMENT

PROJECT REPORT

R. Krajewski, Y. Celebi, R. Coughlan,
T. Butcher, and R.J. McDonald

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Prepared for
BUILDING EQUIPMENT DIVISION
OFFICE OF BUILDING TECHNOLOGIES
UNITED STATES DEPARTMENT OF ENERGY

DEPARTMENT OF APPLIED SCIENCE

BROOKHAVEN NATIONAL LABORATORY
UPTON, LONG ISLAND, NEW YORK 11973

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ABSTRACT

Over the last 10 years there have been some very interesting developments in oil heating. These include higher static pressure burners, air atomizing nozzles, low firing rate nozzles, low heat loss combustion chambers and condensing boilers and furnaces. The current data base on the emissions characteristics of oil-fired residential heating equipment is based primarily on data taken in the 1970's. The objective of the work described in this report is to evaluate the effects of recent developments in oil-fired equipment on emissions.

Detailed emissions measurements have been made on a number of currently available residential oil burners and whole systems selected to represent recent development trends. Some additional data was taken with equipment which is in the prototype stage. These units are a prevaporizing burner and a retention head burner modified with an air atomizing nozzle. Measurements include NO_x, smoke numbers, CO, gas phase hydrocarbon emissions and particulate mass emission rates.

Emissions of smoke, CO and hydrocarbons were found to be significantly greater under cyclic operation for all burners tested. Generally, particulate emission rates were found to be 3 to 4 times greater in cyclic operation than in steady state. Air atomized burners were found to be capable of operation at much lower excess air levels than pressure atomized burners without producing significant amounts of smoke. As burner performance is improved, either through air atomization or prevaporization of the fuel, there appears to be a general trend towards producing CO at lower smoke levels as excess air is decreased. The criteria of adjusting burners for trace smoke may need to be abandoned for advanced burners and replaced with an adjustment for specific excess air levels.

1. INTRODUCTION

Residential oil fired heating systems are widely dispersed emission sources. Their emissions performance can be characterized based on the concentration of soot and hydrocarbons in the flue products venting from the equipment. Within this class of systems, the pressure atomized retention head burner clearly predominates. Over the past five to ten years there have been some very interesting developments in oil-fired heating. Advanced alternatives to the retention head burner as well as alternatives to the standard heating plant are becoming available. Specifically, this includes higher static pressure combustion air fans, air atomization (in Europe), low mass refractory combustion chambers, and condensing furnaces. Prior to this study the data available on the emission characteristics of oil-fired residential heating equipment was based on work done in the 1970's. The objective of the work described in this report was to evaluate characteristics and emissions performance resulting from more recent equipment trends in the residential oil heat sector.

Emission measurements included:

- Particulate (filterable)
- Hydrocarbons
- Carbon Monoxide (CO)
- Nitrous Oxides (NO_x)
- Start-up and shut-down smoke (transient smoke)

For each pollutant, cyclic and steady state emission factors were determined. The emission factor for filterable particulate is a measure of the average emissions per unit of fuel consumed under representative operating conditions. Emission factors are commonly expressed in a variety of units. In this report particulate emissions are expressed as pounds per 1000 gallons of fuel (lbs./1000 gal.). Gas phase emissions are expressed as parts per million (PPM by volume) at 3 percent flue gas O_2. Factors for conversion to other units are listed in Appendix A.

Each test article selected for this project is briefly described in Table 1. Table 1 describes six burner units tested in the laboratory test boiler and two complete systems (one burner/boiler system and one burner/air furnace system) which were tested as such.

LIST OF UNITS TESTED

TABLE 1

UNIT	DESCRIPTION & MODEL	MANUFACTURER	FIRING RATE (gph)
1	Retention Head Model: AF	R.W. Beckett Co. Elyria, Ohio	.5
2	High Pressure Retention Head Model: AFG	R.W. Beckett Co. Elyria, Ohio	1.0
3	High Pressure Retention Head, Model: AFG	R.W. Beckett Co. Elyria, Ohio	.5
4	High Pressure Retention Head, with Pre-Purge and Automatic Combustion Air Control Model: Mectron 3M	Riello Corp. of America	.5
5	Low Mass Packaged Boiler, High Pressure Retention Head Burner (Beckett AFG) Model: System 2000	Energy Kinetics Inc. Clinton, NJ	.85
6	Air Atomized Burner Model: Airtronic	Bentone Electro Oil Laboratory, Sweden	.55
7	Condensing Warm Air Furnace with High Pressure Retention Head Burner (Wayne Blue Angel) Model: U-90-0-02, Ultima EX-95	Yukon Energy Corp. New Brington, Minn.	.65
8	Prototype Burner with Syphon Type Air Atomizing Nozzle	Combustion Technology	.5
9	Prototype Burner with Fuel Pre-Vaporizing Internal Recirculation	Foster Miller (BNL) Carlin Company Windsor, CT	.5

1.1 Background

In the early 1970's a two-year field study of the emission from oil-fired residential heating equipment was performed by Battelle Columbus Laboratories (BCL) under the sponsorship of the United States Environmental Protection Agency (U.S. EPA) and the American Petroleum Institute.[1] The study included 12 furnaces, 18 boilers, and 1 water heater. Of the burners studied, 18 were "conventional head", 9 were retention heads, 2 were shell heads, and 1 was a "low pressure" burner. A few of the units included were in very poor condition and were described as needing replacement. These few very poor burners had a significant effect on the average emissions reported in the study.

Table 2 is adopted from [1] and summarizes the emission results, the standard emission factors which had been adopted by the EPA for residential oil fired systems prior to the BCL study, and new emission factors suggested by BCL.

TABLE 2
Results Summary -- BCL Field Study of
Oil Equipment Emissions
(Early 1970's, Ref. 1)

UNITS	Condition		Mean Emission Factors lb/million Btu			
			CO	HC	NO_x	Particulates
All units	As found	>	.16	.04	.14	.021
	Tuned	>	.12	.02	.14	.016
All units except those needed replacement	As found		.056	.005	.14	.017
	Tuned		.031	.004	---	---
Units with Retention Head Burners Only	As found		.038	.005	.14	.011
	Tuned		.008	.003	.13	.009
Prior EPA Standard Emissions Factors			.036	.021	.086	.071
BCL Suggested Emission Factors			.071	.011	.143	.018
Adopted EPA Emission Factors for Oil			.036	.021	.13	.018

A field assessment of some fossil fuel-fired residential systems was done by TRW Corp. for the EPA in the mid 1970's.[2] Unlike the earlier BCL study this project included detailed measurements of the composition of the organic emissions. The average results for particulates from the oil-fired units was .0098 lbs/million Btu. from this study.

In 1974 the EPA published results from a study of emissions characteristics for fossil fuel fired equipment as performed in their labs.[3] In this study there was a parametric investigation of a number of factors including burner type, chamber type, residence time, and nozzle type. A direct measurement was also made of the emission of CO and hydrocarbons from oil under cyclic operation. The oil burners included both retention head and non-retention head burners. The average results of this study are shown in Table 3.

TABLE 3
Results Summary -- EPA Laboratory Study
(1974 - Ref. 3)

	Average Emission Rates lb/Million Btu	
Operation	CO	HC
Cyclic	.026	.0031

Following their field study Battelle Columbus Labs.[4] did detailed studies of the particulate emissions from two specific oil fired units, a warm air furnace fired with a non-retention head burner and a steel boiler fired with a retention head burner. A primary objective of this study was to examine correlations between smoke numbers and particulate mass emission rates. Measurements were made under both cyclic and steady-state conditions over a wide excess air range. Results for an excess air level which produced trace smoke after four minutes of firing are listed in Table 4.

TABLE 4
Results Summary--BCL Laboratory Study
(1974 - Ref. 4)

Unit	Excess Air (%)	Emissions Factors lbs/Million Btu CO	HC	Particulates
Furnace				
Non-Retention Head				
Steady State	25	.0086	<.0005	.004
Cyclic	25	.010	.0021	.007
Boiler				
Retention Head				
Steady State	35	.017	.0006	.003
Cyclic	35	.025	.004	.003

In 1983 the EPA sponsored some emissions measurements with two modern retention head burners and a blue flame burner manufactured by Blue Ray Systems Inc.[5]. Both types of burners were fired into warm air furnaces. A unique aspect of these tests was that the particulate emissions were measured after the flue gas was diluted with clean air (10/1 dilution). The arrangement is very similar to dilution tunnels used to measure particulate emissions from diesel engines. In contrast, all other reported particulate measurements were made by filtering a portion of the undiluted exhaust (EPA method 5).

During the dilution process volatile hydrocarbons condense on the particulates. This ideally simulates processes which occur in the flue gas plume after leaving the chimney. Results, selected as representative, are listed in Table 5 for steady state and cyclic tests.

For the retention head burner the cycle average NO_x emission factor appears to be unusually low, relative to other reported results. Lower NO_x during cyclic operation is generally expected due to the lower average flame temperatures. For the blue flame burner it is interesting to note that at the very low excess air point (4%) carbon monoxide and unburned hydrocarbon emissions are very high as might be expected but particulate emissions are extraordinarily low.

Table 5
Results Summary - Northrop Services/EPA Study
(1983 Ref. 5)

Burner	Excess Air(%)	Emission Factors Lbs/Million Btu			
		CO	HC	NO_x	Particulates
Retention Head					
Steady State	30	.014	<.0005	.092	.008
Cyclic (1)	37	.015	.002	.024	.012
Blue Flame					
Steady State	4	1.98	.09	.016	.0008
Steady State	18	.013	.0016	.023	.004
Cyclic (1)	18	.01	.009	.009	.004

(1) 10 minutes on/20 minutes off

Some additional data on particulate emissions is also available from a recent study of the Massachusetts Institute of Technology [6] on the characteristics of soot. Using a retention head burner adjusted to a number 1 smoke the average particulate emission rate was found to be 0.0007 and .003 lbs/million Btu in steady state and cyclic operation respectively.

The Acurex Corp. [7] under EPA sponsorship performed an assessment of the emissions from a condensing (Hadwick) boiler fired with M.A.N. blue flame burner. The emission rates for NO_x, CO, and filterable particulates were found to be .085, .028, and .003 lbs/million Btu respectively.

Rockwell International [8], also under EPA sponsorship, developed a low NO_x oil-fired residential furnace. In field tests this system had NO_x emission levels less than .033 lbs/million Btu and emission levels of other components similar to those for more conventional systems.

Brookhaven National Laboratory evaluated the performance of an oil-fired pulse combustion boiler.[9] As part of this laboratory evaluation NO_x emissions were found to be about .029 lbs/million Btu.

In the studies of emissions from heating equipment the rate of emission of SO_2 is generally not measured. Typically 95 percent of the fuel sulphur is emitted as SO_2 and so the emission rate can be easily calculated based on fuel sulphur content. The average sulphur content of No. 2 fuel oil is thought to be about 0.25 percent [16] leading to emissions of 0.26 Lbs./million Btu.

In considering the impact of residential heating on air quality, it is important to consider the magnitude of these emissions relative to all sources. In 1980 the U.S. total emission of SO_2 has been estimated to be 26,954,000 tons of which commercial and residential combustion contributed 1,153,000 tons or about 4.3 percent [17]. Similarly in 1980 the U.S. produced 22,352.000 tons of NO_x of which residential and commercial combustion contributed 1,061,000 tons or 4.7 percent. A modest change in the emissions in these sectors would have a fairly small impact on the national totals.

It should be noted that SO_2 emissions were not calculated as part of the work presented here. However, the effects on equipment performance and longevity due to possible future trends toward increased sulphur content in heating fuel are a growing concern to the oil heat industry. As such, the study of these effects remains an important part of the overall BNL Combustion Equipment Program.

2. MEASUREMENT TECHNIQUE AND INSTRUMENTATION

2.1 Test Boiler

The BNL test bed boiler for the individual burner tests is a Peerless Model No. JOT-35-SPT. This unit is a conventional three section wet base cast iron residential hot water boiler. The wet wall combustion area is lined with a non-production (BNL modified) full open top light-weight refractory combustion chamber which has a wall thickness of about 3/4 inches. The burner mounting plate, which itself is protected by a light-weight refractory slab about 1 inch thick, has been modified to permit direct combustion chamber observation through a 2 inch diameter quartz window. When firing at less than 1 gph one of the boiler heat exchanger passages was blocked from above in order to keep the flue gas temperature above the water dewpoint during transient operation.

2.2 Test Operation

During steady state operation of each burner/system, smoke, hydrocarbon, carbon monoxide and NO_x samples were taken of the flue gas over a range of excess air settings. Then each burner/system was set with an excess air level 10 percentage points higher than that determined for a number one smoke condition. At this fixed fuel/air ratio, cyclic tests were performed.

During the cyclic tests smoke, hydrocarbon, carbon monoxide and NO_x samples were taken repetitively over the burner "on" period. The test boiler was allowed to run automatically using an aquastat which sensed boiler water temperature and controlled the on/off operation of a large fan-coil which served as a heat dump. The time period for cyclic operation was established at 5 minutes on and 15 minutes off through adjustment of the heat rejection rate of the fan-coil which is equipped with a variable speed fan motor. The aquastat high limit was set at 180 Deg.F.

2.3 Particulates and Hydrocarbons

To determine the mass emission rate of soot and hydrocarbons quantitatively, Brookhaven designed and built a sampling system for this project (Figure 1). This sampling train is somewhat different than the standard EPA 5 train in that an indirect flow measurement technique is applied. The train contains in series, the sampling probe, an inline filter, a porous tube mixing assembly, a second inline filter and a sampling pump. The purpose of the first filter is to collect the particulates, and it is maintained at 248 +/- 25 Deg. F. At this temperature some of the hydrocarbons are in the gaseous phase and remain that way while being cooled through dilution until they are detected by the hydrocarbon analyzer. The second filter is installed after the porous tube, and its function is to protect the pump and the hydrocarbon analyzer.

The gas phase hydrocarbons were measured by using a Model 400A Hydrocarbon Analyzer which is built by Beckman Industrial Corp. The Model 400A Hydrocarbon Analyzer utilizes a flame ionization detection method. The sensor is a burner in which a regulated flow of sample gas passes through a flame sustained by regulated flows of air and a fuel gas (40% hydrogen/60% nitrogen). In the mixed flame the hydrocarbon components of the sample stream undergo a complex ionization that produces electrons and positive ions. Polarized electrodes collect these ions, causing current to flow through electronic measuring circuitry. Current flow is proportional to the rate at which carbon atoms enter the burner.

In order to measure the sampling flow rate of the flue gases and maintain the constituents in the gaseous phase while cooling them to a safe temperature (120 Deg.F.) for the hydrocarbon analyzer, the flue sample was diluted continuously with nitrogen after the first filter. This dilution was accomplished by using a porous tube which is assembled concentrically into a larger 3/4" diameter pipe. This assembly was installed after the first filter. Here, the outer tube was pressurized with nitrogen at a known flow rate through a positive displacement meter (Singer Corp., Model No. DTM-200). The nitrogen passed through the wall of the porous tube and mixed with flue gas sample stream.

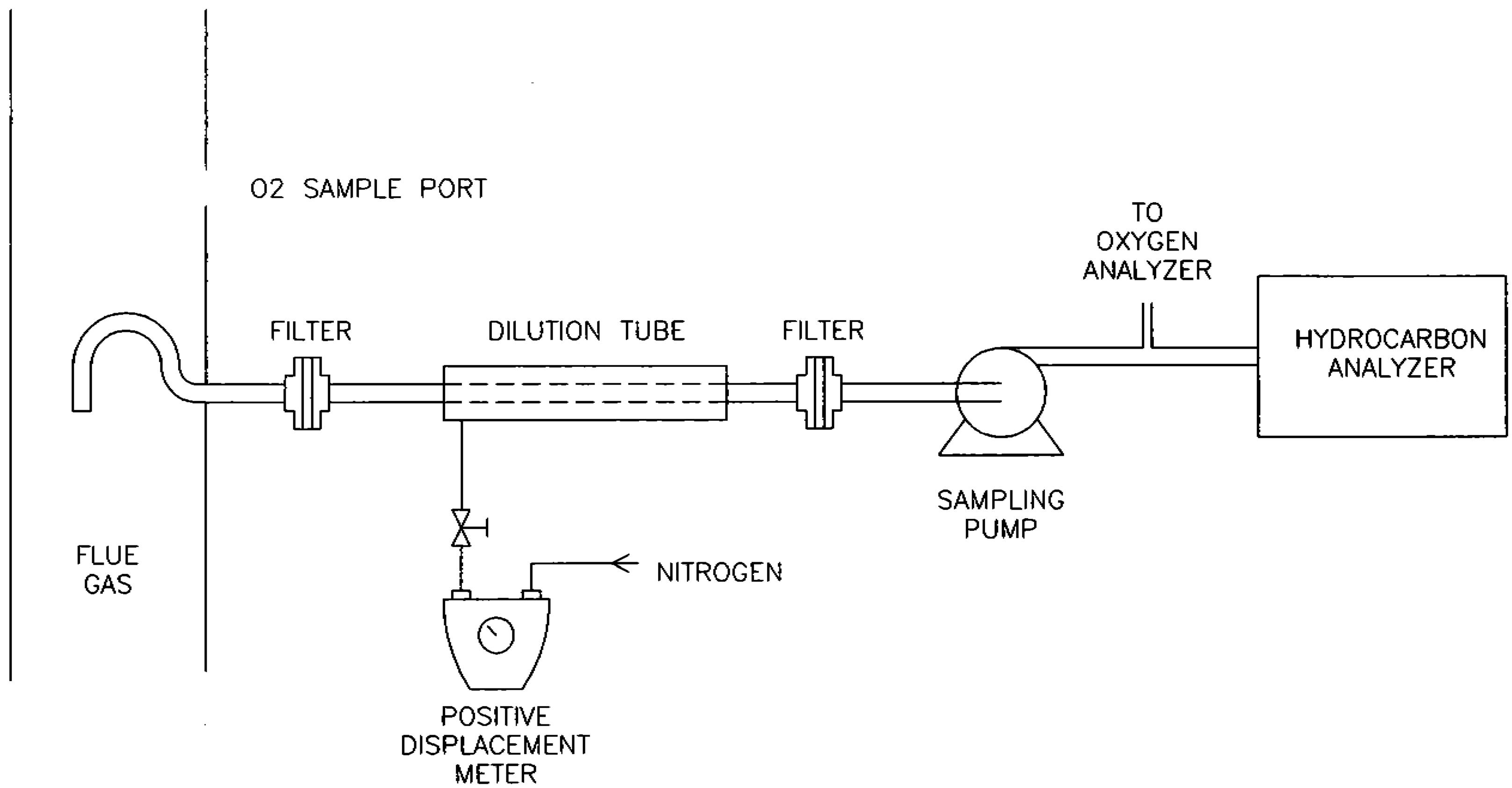


Figure 1. Modified EPA 5 Train Sampling System.

By comparing the oxygen content of the undiluted flue gas with that of the diluted flue gas stream and knowing the flow rate of the diluting nitrogen, the volumetric flow of the sample flue gas stream can be calculated.

High "capture" efficiency random borosilicate glass fiber filters were used for particulate collection. Before use, the filters were desiccated and weighed over a period of several days until no change in weight is detected. After installation of the filters and each time before sampling, the system was leak checked by pressurizing the suction side of the train system to 5 psig. and verifying negligible pressure decay over a period of 10 minutes. The filter assemblies and the balance of the train are wrapped with heat tape which is used through a temperature controller to maintain the system at its operating temperatures.

Before starting a run the system is allowed to reach operating temperature. The sampling probe is then installed and sampling is initiated. The sampling pump is started 30 seconds before the burner is turned on and continues 30 seconds after burner "shut-off" using a timed relay circuit. After use and disassembly from the train, the filters are stored in the desiccator to avoid moisture absorption while the filters equilibrate to room temperature prior to weighing. At the end of each run the probe is rinsed with acetone into pre-weighed dishes. The acetone is allowed to evaporate. The soot rinsed into the dishes is added to the filter catch weight.

To ensure sufficient particulate collection for accurate weighing, each sampling test lasts 16 to 18 hours for steady state tests and for the cyclic tests the burners are operated over 60 to 70 cycles. As mentioned earlier, each cycle is approximately 5 minutes on and 15 minutes off and each cyclic particulate test took about 24 hours to run. Two separate, but identical runs were done to check for consistency in the data. For the steady state tests, two identical runs were also made.

2.4 Carbon Monoxide

The instrument used was a Model 865 carbon monoxide analyzer manufactured by Beckman Industrial Corp. The analyzer produces infrared radiation from two identical sources which then passes through a chopper which interrupts them at a frequency of 10 HZ. The radiation then passes through optical filters to reduce background interference from other infrared-absorbing components. The infrared beams pass through two cells, one a reference cell containing a non-absorbing background gas, the other a sample cell containing a continuous flowing sample. During operation a portion of the infrared radiation is absorbed by carbon monoxide in the sample, with the percentage of infrared radiation absorbed being proportional to the carbon monoxide concentration. The detector is a "gas microphone" based on the Luft principle.

It converts the difference in energy between sample and reference cell to a capacitance change. This capacitance change, equivalent to carbon monoxide concentration, is amplified and indicated on a meter.

2.5 Nitrous Oxide (NO) and Nitrogen Dioxide (NO_2) - NO_x

The system used was Model 955 NO/NO_x analyzer manufactured by Beckman Industrial Corp. The sample is routed through a converter where the NO_2 component is dissociated to form NO. The reaction is:

$$2\ NO_2 \longrightarrow 2NO + O_2$$

Instrument response is proportional to total NO in the converted sample, that is, the sum of the NO originally present in the sample plus the NO resulting from dissociation of NO_x. This combination of NO and NO_2 is commonly designated NO_x.

2.6 Start-Up and Shut-Down Smoke

For transients start-up and shut-down smoke level tests as well as steady state smoke level tests measured at various excess air levels, a Bacharach Instrument Co. "True Spot Smoke Tester" was used. The Bacharach smoke measurement is based on a national standard established by the American Society for Testing and Materials, ASTM #D2156-80. The technique is straightforward. A hand activated suction pump is used to pull a fixed volume of flue gas (.6 cu.ft.) through a fixed cross-section area of standardized filter paper. The darkness of the spot produced is taken as an indicator of smoke emissions, and is compared to a 0-9 smoke spot reference scale.

2.7 Other Equipment

Flue gas oxygen content was measured with a Beckman Model 755 paramagnetic analyzer. Burner air/fuel ratios can be expressed in several ways, including excess air, percent O_2 and percent CO_2. The last is most commonly used in the residential heating field and all measured percent O_2 readings were converted (based on the specific fuel composition) to percent CO_2 and percent excess air.

For all the tests, combustion chamber and stack pressure were measured with a Bacharach Model MZF diaphragm-type draft gauge.

3. EXPERIMENTAL RESULTS

3.1 Unit 1 - Beckett AF 0.5 gph

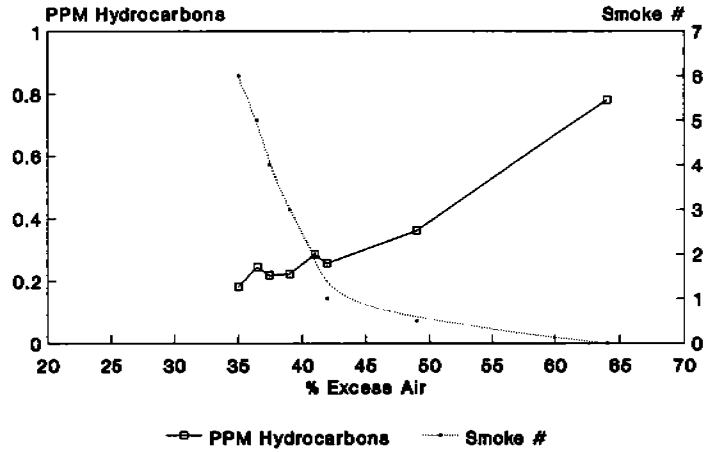
This unit is a standard high speed (3450 RPM) low static pressure (1 inch of water max.) retention head burner and it represents a mature design of this type of burner. The purpose of testing this unit was to establish a base-line against which more advanced designs could be compared. The burner was initially fired at 0.5 gph in the test boiler under steady state conditions. As discussed earlier in Section 2.1, at this low fuel flow rate one of the convective sections in the boiler was blocked to keep flue temperatures above the dew point. Excess air levels were varied between 35 and 65 percent. As previously described in Section 2.2, the steady state gas phase emissions; smoke, hydrocarbons, carbon monoxide, and NO_x were measured at each selected excess air level. Figures 2a and 2b show the steady state gas phase emission data adjusted to 3.0 percent stack O_2 plotted against excess air.

From Figure 2a, it can be seen that a #1 smoke was produced at an excess air level of about 42 percent. Using the criteria described earlier in Section 2.2, 10 percentage points were added to this excess air level to establish the 52 percent excess air requirement for further testing of this particular unit. Trial tests at steady state operating conditions with 52 percent excess air provided emission level data that was consistent with the initial tests. Cyclic tests were performed at this excess air level using the procedure described in Section 2.2 above to control the cycling of the test boiler. Figures 2c and 2d show the as-measured emissions of smoke, hydrocarbons (HC), CO, NO_x, over a typical established firing cycles.

An examination of the data gathered during cyclic tests suggested that some useful qualitative information could be presented regarding the peak values and duration of particulate and gaseous phase emissions. Admittedly, the smoke values are quite discontinuous by the nature of the sampling procedure as described in Section 2.6, but at least a sense of the relative behavior of burners can be gained. To this end the following qualitative summary of as-measured transient spike emission behavior is offered:

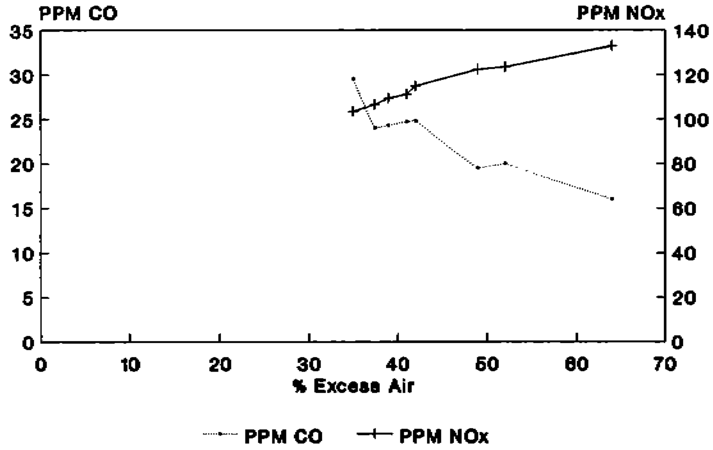
	Burner Start		Burner Stop	
	Peak	Duration	Peak	Duration
Smoke No.	2.8	.5 min.	2.8	.5 min.
ppm HC	17	.3 min.	3.0	.4 min.
ppm CO	125	.5 min.	20	.5 min.

FIGURE 2a - R.W. Beckett Co.
Model AF (Retention Head - .5 gph)
(Steady State)



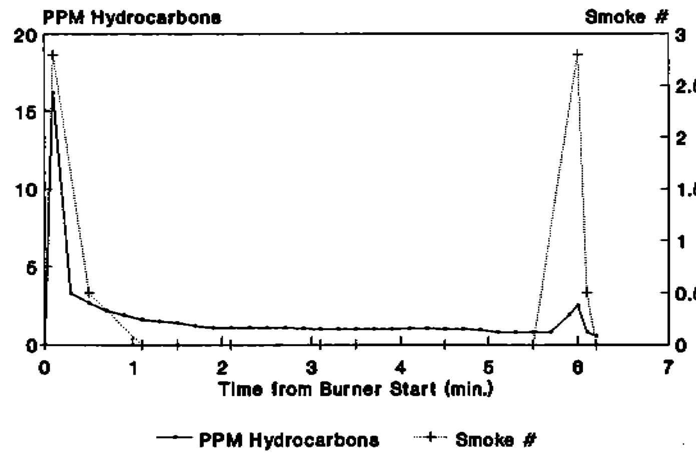
(Hydrocarbon values adjusted to 3% O2)

FIGURE 2b - R.W. Beckett Co.
Model AF (Retention Head - .5 gph)
(Steady State)



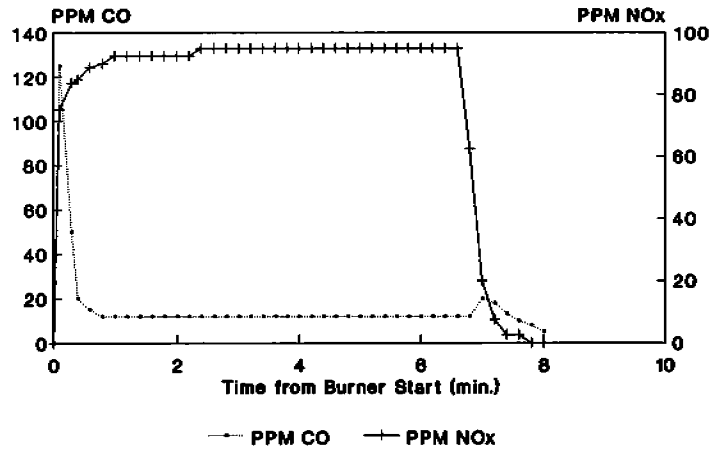
(CO and NOx values adjusted to 3% O2)

FIGURE 2c - R.W. Beckett Co.
Model AF (Retention Head - .5 gph)
(Cyclic @ 52% Excess Air)



(Smoke # and HC are as-measured values)

FIGURE 2d - R.W. Beckett Co.
Model AF (Retention Head - .5 gph)
(Cyclic @ 52% Excess Air)



(CO and NOx are as-measured values)

The results of soot collection and as-measured emissions for both steady state and cyclic operation of the burner were analyzed. Soot quantities are based on the collection and weighing procedures described in Section 2.3 of this report. The emission results for steady state operation are those recorded at 52 percent excess air.

The cyclic emission results are average quantities evaluated by integrating the emission curves over the burner "on" period. The following table provides this summary:

Beckett AF (0.5 gph at 53% Excess Air)

	Steady State	Cyclic
Soot *	0.10	0.41
ppm HC	0.31	1.94
ppm CO	15.0	15.4
ppm NO_x	92.5	90.2

(*) Lb./1000 gal. fuel

From the steady state flue gas emission results the following can be concluded. The Beckett AF burner fired at 0.5 gph operated at relatively high excess air and generated negligible smoke and low levels of Hydrocarbons, CO, and NO_x.

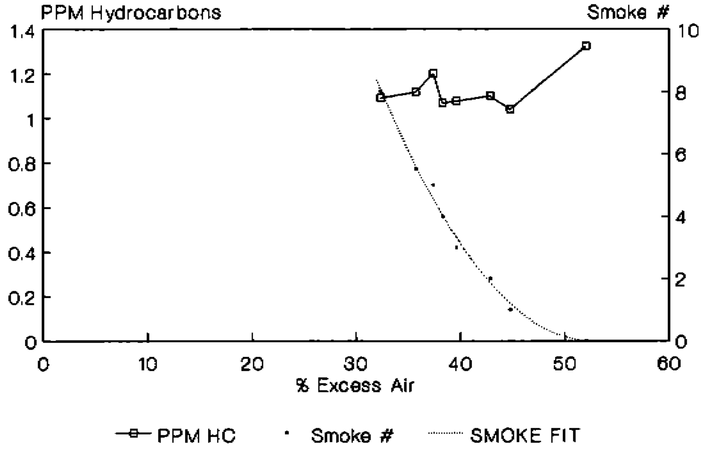
It should be noted that the procedures described above were essentially adhered to for all of the subsequent burner/system tests and reporting described in this report.

3.2 Units 2 & 3 - Beckett AFG 0.5 gph and 1.0 gph

This currently marketed unit is an upgraded version of the AF in that it has a high static pressure fan (3 inches of water). This feature is of particular interest because it has been shown to reduce start-up smoke peaks [10]. Testing was performed for two separate oil flow rates, 0.5 and 1.0 gal. per hour. Again the aforementioned test sequences were performed at each of the fuel flow rates.

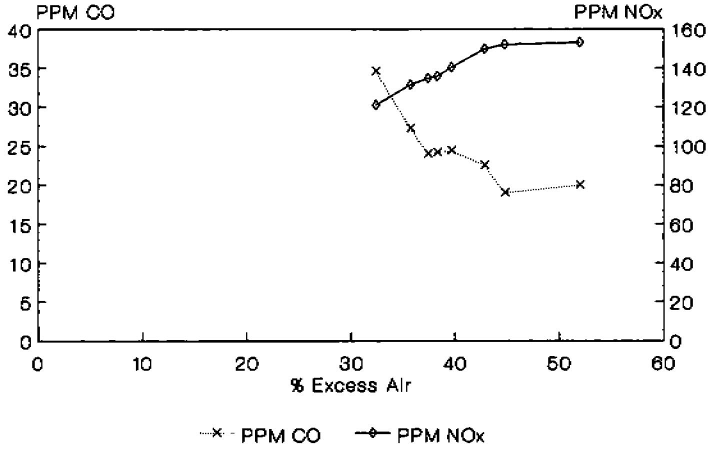
Figures 3a and 3b illustrate the adjusted steady state gas phase emissions for this burner using the 0.5 gph nozzle. The excess air requirement for subsequent testing was established at 50 percent based on the criteria described earlier. Cyclic performance tests were conducted and the as-measured results are shown graphically in Figures 3c and 3d.

FIGURE 3a - R.W. Beckett Co.
Model AFG (H.P. Ret. Head - 0.5 gph)
(Steady State)



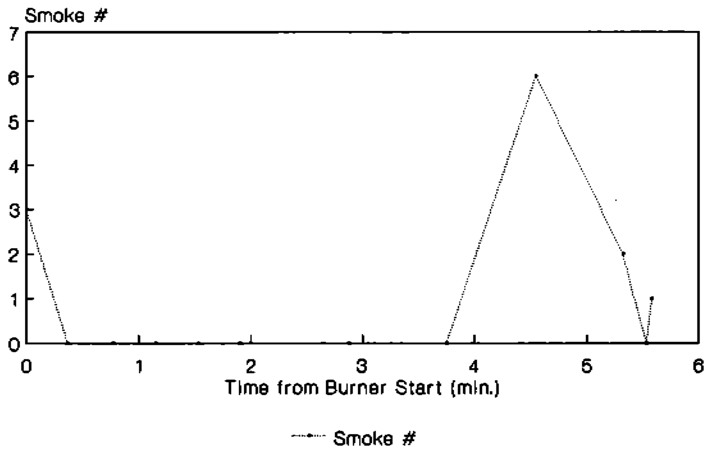
(Hydrocarbon values adjusted to 3% O2)

FIGURE 3b - R.W. Beckett Co.
Model AFG (H.P. Ret. Head - 0.5 gph)
(Steady State)



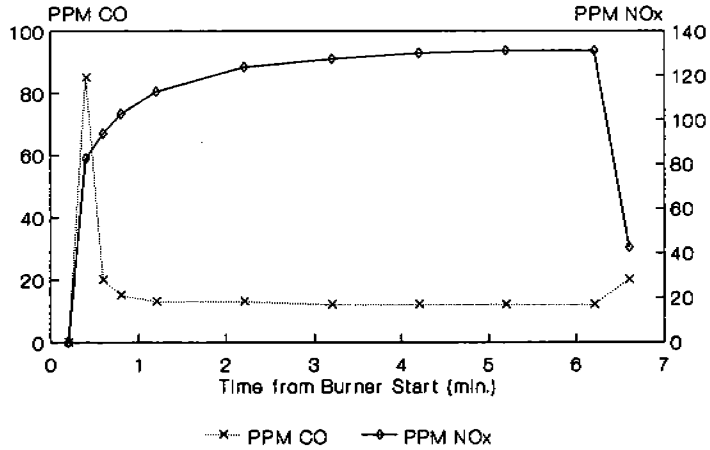
(CO and NOx values adjusted to 3% O2)

FIGURE 3c - R.W. Beckett Co.
Model AFG (H.P. Ret. Head - 0.5 gph)
(Cyclic @ 52% Excess Air)



(Smoke # is an as-measured value)

FIGURE 3d - R.W. Beckett Co.
Model AFG (H.P. Ret. Head - 0.5 gph)
(Cyclic @ 52% Excess Air)



(CO and NOx are as-measured values)

The following qualitative observations of the as-measured transient spike emission for these tests is as follows:

	Burner Start		Burner Stop	
	Peak	Duration	Peak	Duration
Smoke No.	3.0	.3 min.	6.0	1.8 min.
ppm HC	(Hydrocarbon data not available)			
ppm CO	85.0	.3 min.	20.0	.5 min.

A summary of the soot accumulations and as-measured emissions for steady state and cyclic operation of this burner is as follows:

Beckett AFG (0.5 gph 52% Excess Air)

	Steady State	Cyclic
Soot *	0.13	0.38
ppm HC	0.91	----
ppm CO	15.0	19.3
ppm NO_x	115.0	90.3

(*) Lb./1000 gal. fuel

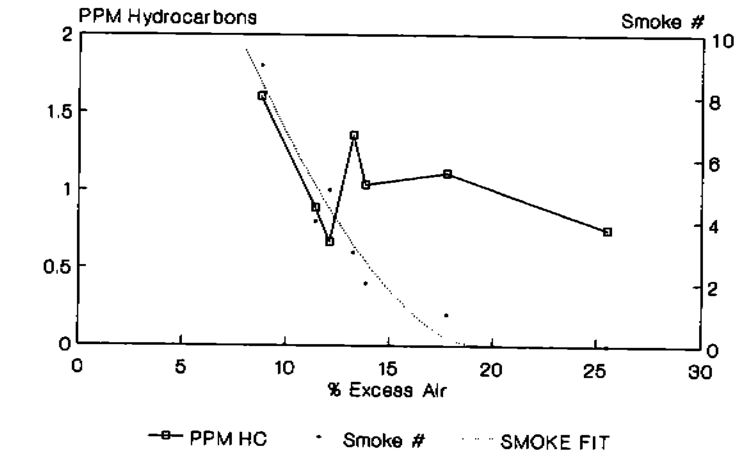
The Beckett AFG was also evaluated at a firing rate of 1.0 gph. Figures 4a and 4b show the adjusted steady state emissions plotted against excess air. On the basis of these tests it was judged that an excess air level of 26 percent was appropriate for subsequent testing. Figures 4c and 4d show the as-measured cyclic emissions performance of the burner at this excess air level.

The observed as-measured transient spike behavior of the burner under cyclic operation was judged to have the following qualitative characteristics:

	Burner Start		Burner Stop	
	Peak	Duration	Peak	Duration
Smoke No.	1.5	0.5 min.	5.0	1.0 min.
ppm HC	0.9	Full Cyc.*	0.6	0.5 min.
ppm CO	50.0	0.3 min.	30.0	0.3 min.

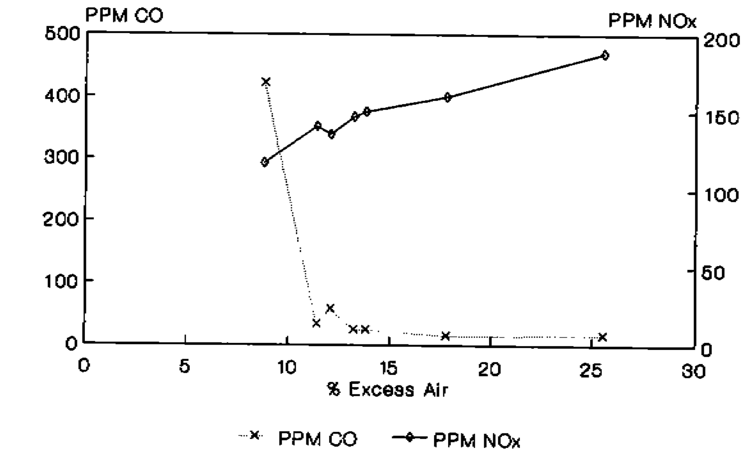
(*) Exponential-like Decay Observed

FIGURE 4a - R.W. Beckett Co.
Model AFG (H.P. Ret. Head - 1.0 gph)
(Steady State)



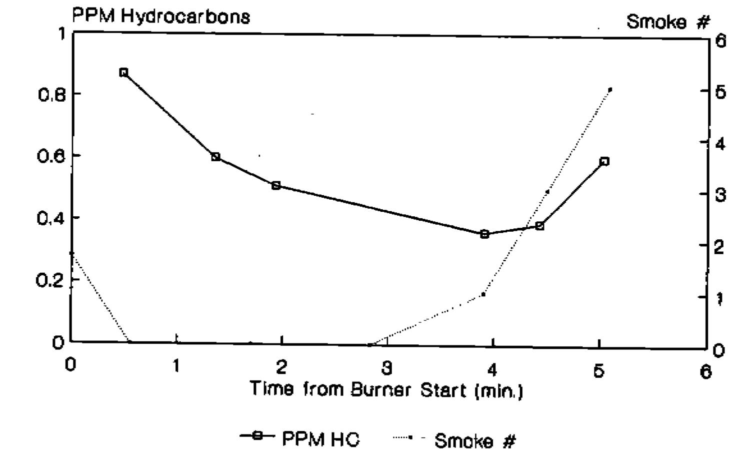
(Hydrocarbon values adjusted to 3% O2)

FIGURE 4b - R.W. Beckett Co.
Model AFG (H.P. Ret. Head - 1.0 gph)
(Steady State)



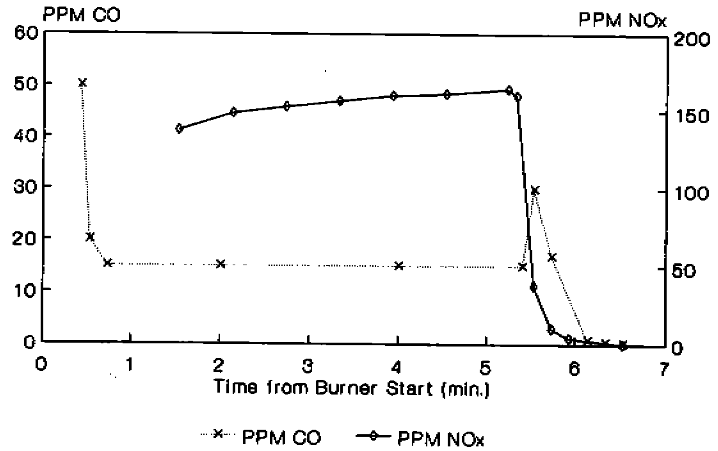
(CO and NOx values adjusted to 3% O2)

FIGURE 4c - R.W. Beckett Co.
Model AFG (H.P. Ret. Head - 1.0 gph)
(Cyclic @ 26% Excess Air)



(Smoke # and HC are as-measured values)

FIGURE 4d - R.W. Beckett Co.
Model AFG (H.P. Ret. Head - 1.0 gph)
(Cyclic @ 26% Excess Air)



(CO and NOx are as-measured values)

The overall as-measured steady state and cyclic performance in terms of soot accumulation and integrated gaseous phase emissions is summarized as follows:

Beckett AFG (1.0 gph at 26% Excess Air)

	Steady State	Cyclic
Soot *	0.08	0.28
ppm HC	0.69	0.55
ppm CO	15.0	14.7
ppm NO_x	172.5	119.7

(*) Lb./1000 gal. fuel

3.3 Unit 4 - Riello 3M at 0.5 gph

This burner is a European design of the retention head type and uses a high static pressure fan. In addition, the burner features an air pre-purge cycle and an automatic combustion air control. Figures 5a and 5b illustrate the steady state particulate and adjusted gaseous emissions. As-measured emissions over the firing cycle are shown in Figures 5c and 5d.

A qualitative analysis of the cyclic spike transient emission data resulted in the following observations:

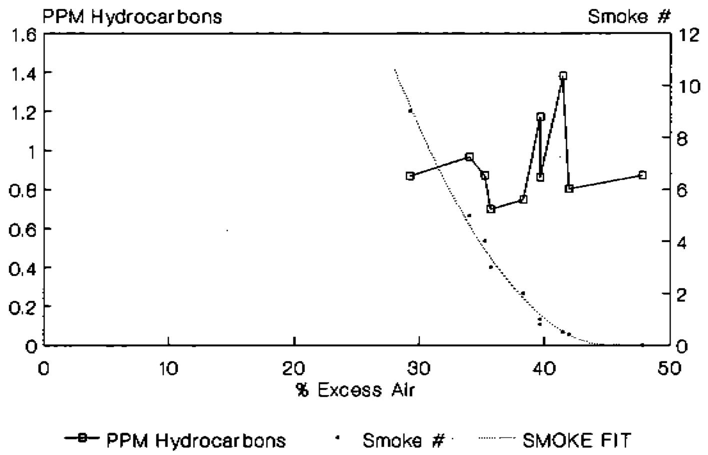
	Burner Start		Burner Stop	
	Peak	Duration	Peak	Duration
Smoke No.	2.0	0.6 min.	1.0	0.5 min.
ppm HC	11.5	0.5 min.	1.2	0.1 min.
ppm CO	150.0	0.6 min.	0	0

A summary of the steady state and cyclic as-measured particulate and gaseous emissions is as follows:

Riello (0.5 gph at 49% Excess Air)

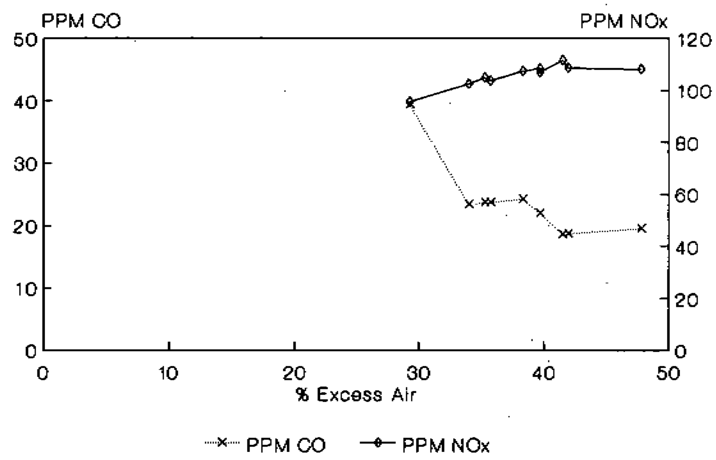
	Steady State	Cyclic
Soot	0.14	0.43
ppm HC	0.79	1.59
ppm CO	15.0	33.7
ppm NO_x	83.5	80.0

FIGURE 5a - RIELLO MECTRON
Model 3M (H.P. Ret. Head - 0.5 gph)
(Steady State)



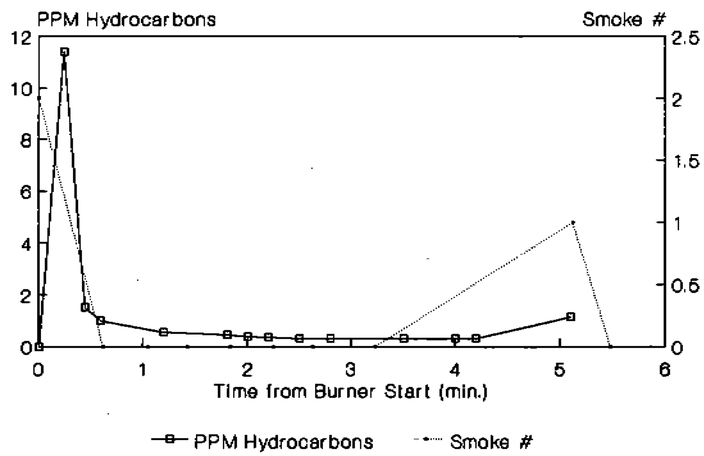
(Hydrocarbon values adjusted to 3% O2)

FIGURE 5b - RIELLO MECTRON
Model 3M (H.P. Ret. Head - 0.5 gph)
(Steady State)



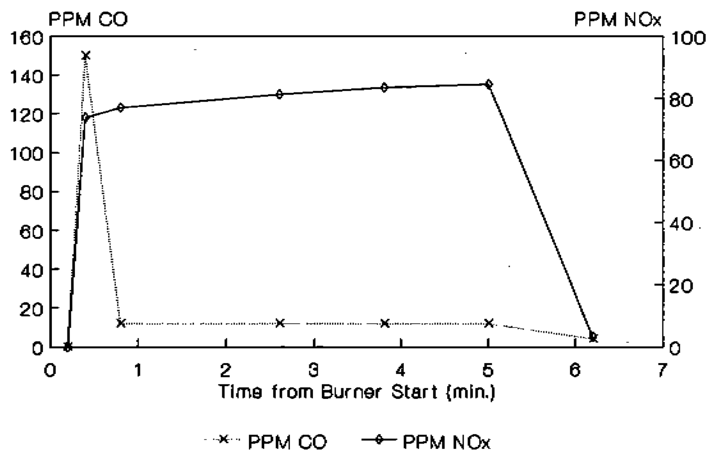
(CO and NOx values adjusted to 3% O2)

FIGURE 5c - RIELLO MECTRON
Model 3M (H.P. Ret. Head - 0.5 gph)
(Cyclic @ 49% Excess Air)



(Smoke # and HC are as-measured values)

FIGURE 5d - RIELLO MECTRON
Model 3M (H.P. Ret. Head - 0.5 gph)
(Cyclic @ 49% Excess Air)



(CO and NOx are as-measured values)

3.4 Unit 5 - Energy Kinetics System 2000 System

This test article is a packaged boiler, that is, a boiler with burner ready for installation in a residence and connection to the distribution loop. The boiler consists of a unique low water mass heat exchanger which is wound in a spiral shape. The center of the spiral forms the combustion zone which contains a compact six sided light weight refractory combustion chamber. A high static pressure retention head burner is supplied with the boiler and was used in these tests. This burner is a Beckett AFG supplied with an "FO" head and 0.85 gph nozzle.

Because this unit has a combustion chamber with refractory on six sides, high NO_x emissions resulting from higher flame temperatures were expected. The results, however, indicated NO_x levels comparable to other burners tested. Figures 6a and 6b show the adjusted steady state emissions as a function of excess air setting. The system can run at quite low excess air levels without smoke and the particulate emission rate tests were done at a selected 26 percent excess air level. Figures 6c and 6d illustrate the as-measured emissions over a typical firing cycle. Additional tests were run at 50 percent excess air which represented actual settings recommended for the field installation of these units and these results are shown in Figures 6e and 6f.

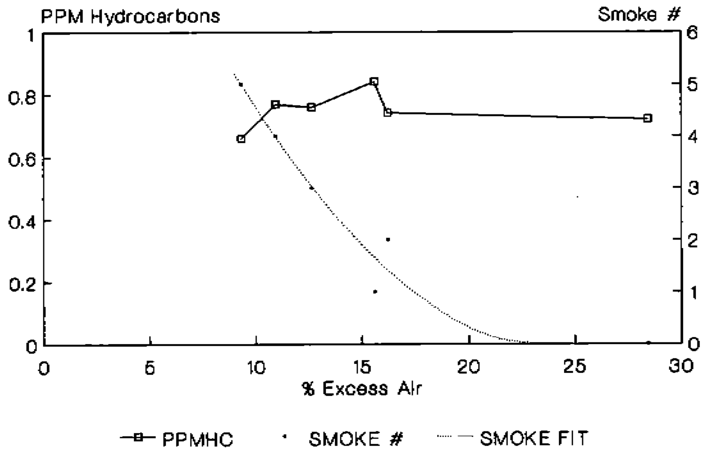
A qualitative analysis of the as-measured cyclic emissions at 26 and 50 percent excess air (E.A.) levels revealed the following results:

	Burner Start (26% E.A.)		Burner Stop (26% E.A.)	
	Peak	Duration	Peak	Duration
Smoke No.	5.0	0.6 min.	0	0
ppm HC	17.0	0.5 min.	3.5	0.4 min
ppm CO	40.0	Full Cycle*	37.0	0.5 min

	Burner Start (50% E.A.)		Burner Stop (50% E.A.)	
	Peak	Duration	Peak	Duration
Smoke No.	2.8	0.5 min.	0	0
ppm HC	12.0	0.2 min.	0	0
ppm CO	40.0	1.25 min.*	25.0	0.5 min.

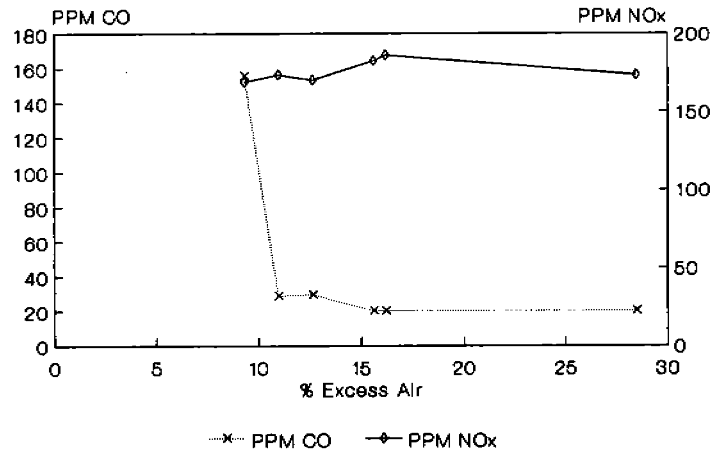
(*) Exponential-like decay

FIGURE 6a - Energy Kinetics System 2000 - Beckett AFG (Steady State @ 0.85 gph)



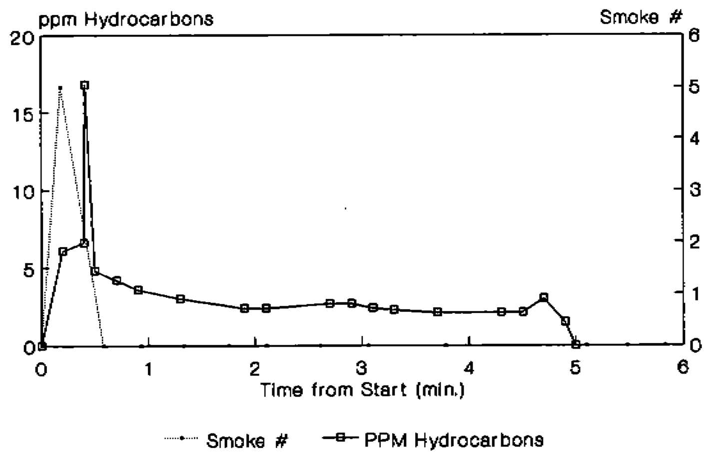
(Hydrocarbon values adjusted to 3% O2)

FIGURE 6b - Energy Kinetics System 2000 - Beckett AFG (Steady State @ 0.85 gph)



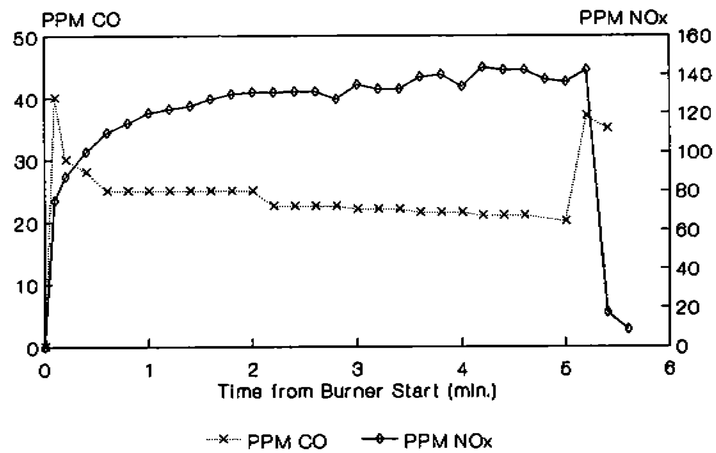
(CO and NOx values adjusted to 3% O2)

FIGURE 6c - Energy Kinetics System 2000 - Beckett AFG (Cyclic @ 0.85 gph & 26% Excess Air)



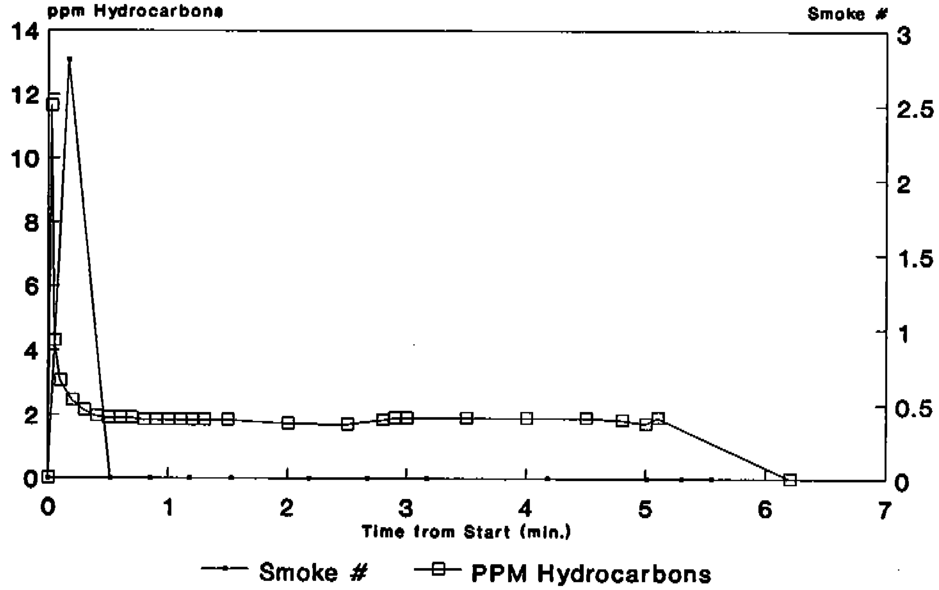
(Smoke # and HC are as-measured values)

FIGURE 6d - Energy Kinetics System 2000 - Beckett AFG (Cyclic @ 0.85 gph & 26% Excess Air)



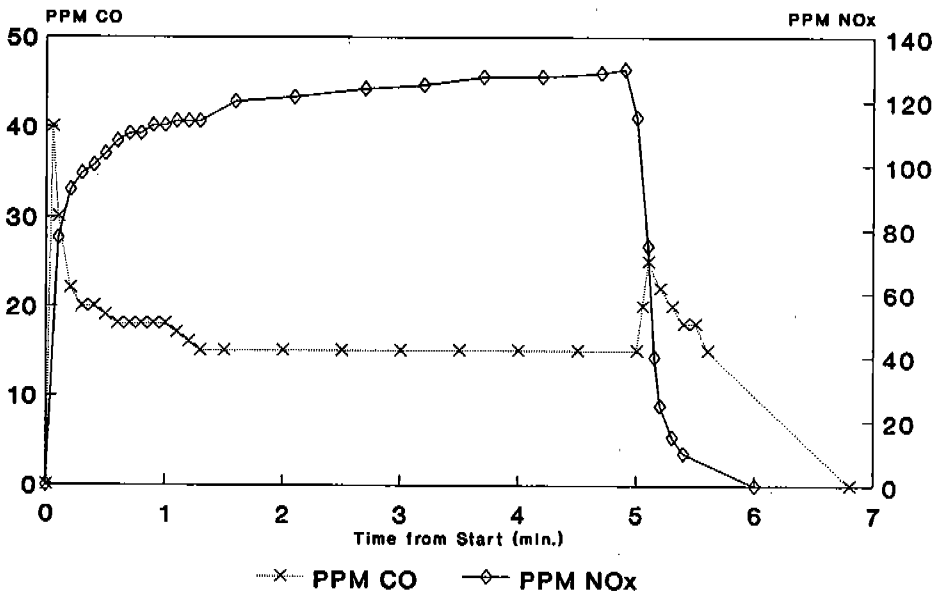
(CO and NOx are as-measured values)

FIGURE [6e] - Energy Kinetics
System 2000 with Beckett AFG Burner
(Cyclic @ .85 gph & 49% Excess Air)



(Smoke # and HC are as-measured values)

FIGURE [6f] - Energy Kinetics
System 2000 with Beckett AFG burner
(Cyclic @ .85 gph and 49% Excess Air)



(CO and NOx are as-measured values)

A summary of the steady state and integrated cyclic emissions was developed from the as-measured data. This summary is as follows:

Energy Kinetics System 2000 Summary (26% & 50% E.A)

	Steady State		Cyclic	
	(26%)	(50%)	(26%)	(50%)
Soot *	0.13	0.06	0.64	0.28
ppm HC	0.65	0.37	3.45	0.3 est
ppm CO	18.0	20.0	27.6	25.0 est
ppm NO_x	155.0	130.0	124.0	130.0 est

(*) Lb./1000 gal. fuel

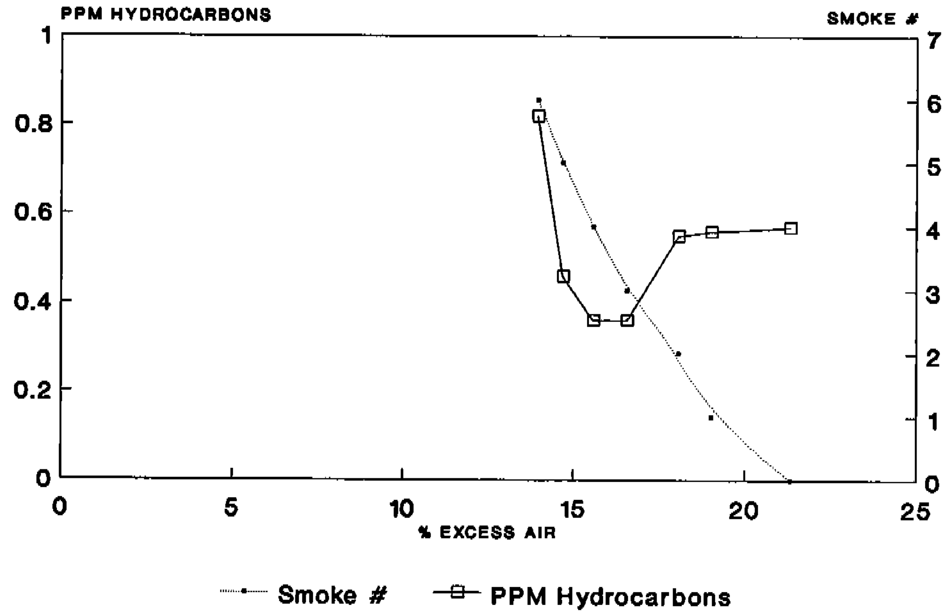
3.5 Unit 6 - Airtronic Burner at 0.55 gph

This unit, which is currently marketed in Europe [11] has an atomizing system based, in principal, on that developed for commercial medical nebulizers [12,13]. The burner is of interest because it is capable of variable firing rate ranging from 0.2 to 0.8 gph. The principle of atomization and subsequent combustion of the fuel is very different from that of the conventional pressure atomized retention head burner. In the Airtronic burner atomization system, fuel is supplied to the outside of a hollow hemispherical surface which contains a small aperture. The liquid fuel spreads out over the convex surface in a thin film where it is ruptured by a low pressure air stream issuing from the aperture. The resulting dispersion of fine liquid drops are immediately mixed with primary combustion air and ignited. With the addition of directionally controlled secondary combustion air complete combustion of the air/fuel mixture takes place within the flame tube of the burner.

Steady state and cyclic particulate and gas emissions tests were performed at .55 gph over a range of excess air levels. Figures 7a and 7b illustrate the adjusted steady state and gas phase emissions for the Airtronic burner. Based on the burner's performance a 29 percent excess air level was selected for the first cyclic tests. Additional cyclic tests were conducted at 50 percent excess air.

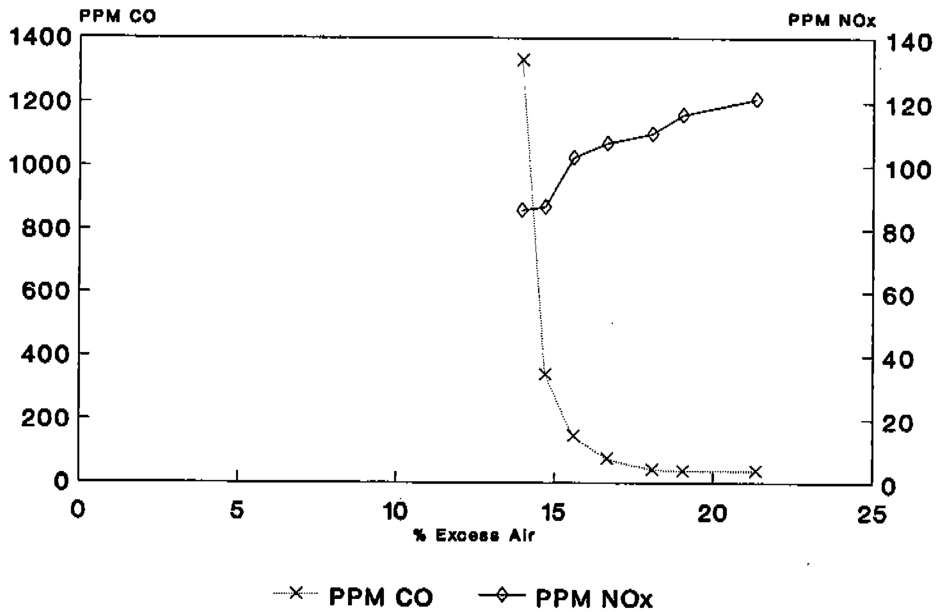
The Airtronic burner exhibited no start-up and shut-down smoke at the 29 percent excess air level. The lowest limit of excess air for smokeless transients was not identified but is less than 29 percent. The shape of the start-up hydrocarbon emission transient was different from other units tested. Rather than a sharp peak and rapid fall the emission persisted and exhibited an exponential-like fall.

FIGURE 7a - AIRTRONIC
Babington Air Atomizing Burner
(Steady State @ 0.55gph)



(Hydrocarbons are adjusted to 3% O2)

FIGURE 7b - AIRTRONIC
Babington Air Atomizing Burner
(Steady State @ 0.55 gph)



(CO and HC values are adjusted to 3% O2)

While steady state particulate emissions were lower than the other units tested, cyclic emissions were similar in amplitude to those of other units. Figures 7c, 7d, 7e and 7f show the as-measured cyclic emissions plotted against time.

The following is a qualitative summary of the results of these tests at excess air (E.A.) levels of 29 and 50 percent respectively:

	Burner Start (29% E.A.)		Burner Stop (29% E.A.)	
	Peak	Duration	Peak	Duration
Smoke No.	0	0	0	0
ppm HC	13.2	Full Cycle*	9.0	0.2 min.
ppm CO	155.0	0.3 min.	250.0	2.5 min.

	Burner Start (50% E.A.)		Burner Stop (50% E.A.)	
	Peak	Duration	Peak	Duration
Smoke No.	0	0	0	0
ppm HC	7.8	Full Cycle*	4.0	0.2 min.
ppm CO	86.0	0.3 min.	80.0	1.0 min.

(*) Exponential-like decay

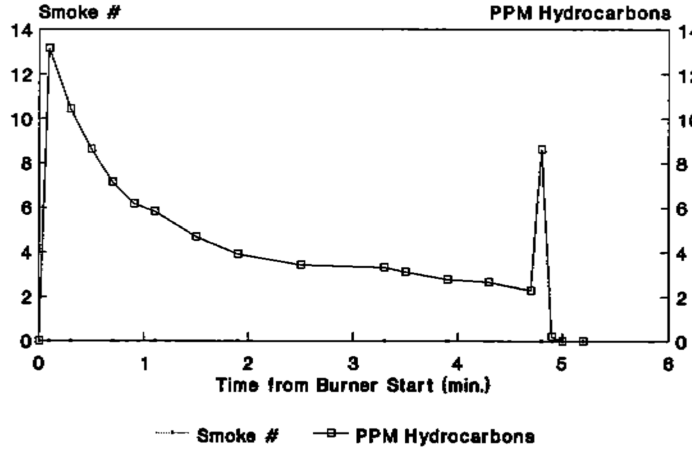
A summary of the as-measured particulate and integrated gaseous phase emissions for steady state and cyclic operation of the Airtronic burner is presented as follows:

Airtronic Burner (0.55 gph.)
(29% & 50% excess air)

	Steady State		Cyclic	
	(29%)	(50%)	(29%)	(50%)
Soot *	0.09	0.07	0.34	0.23
ppm HC	0.48	0.72	2.82	1.8
ppm CO	25.0	15.0	52.8	18.3
ppm NO_x	115.0	97.5	94.3	88.4

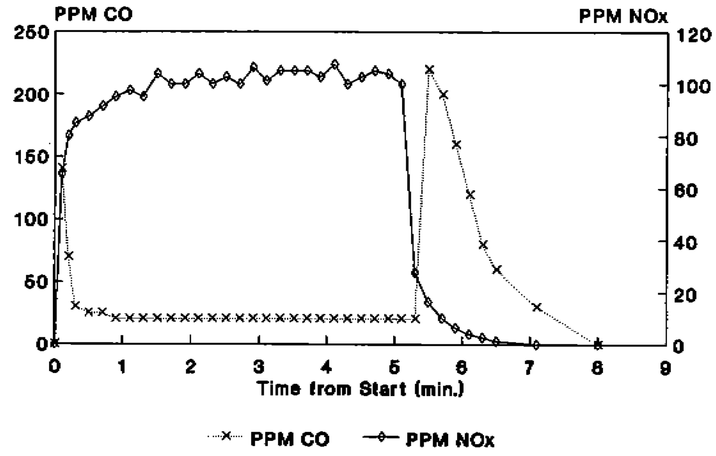
(*) Lb./1000 gal. fuel

FIGURE 7c - AIRTRONIC
Babington Air Atomizing
(Cyclic @ 0.55gph and 28 % Excess Air)



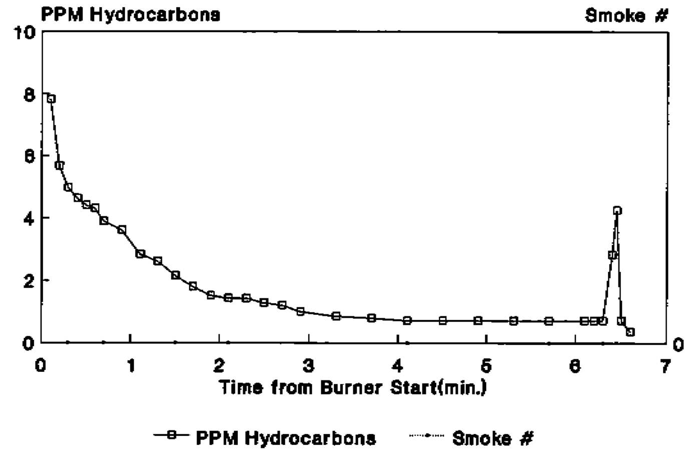
(Hydrocarbons are as-measured values)

FIGURE 7d - AIRTRONIC
Babington Air Atomizing
(Cyclic @ 0.55 gph and 28% Excess Air)



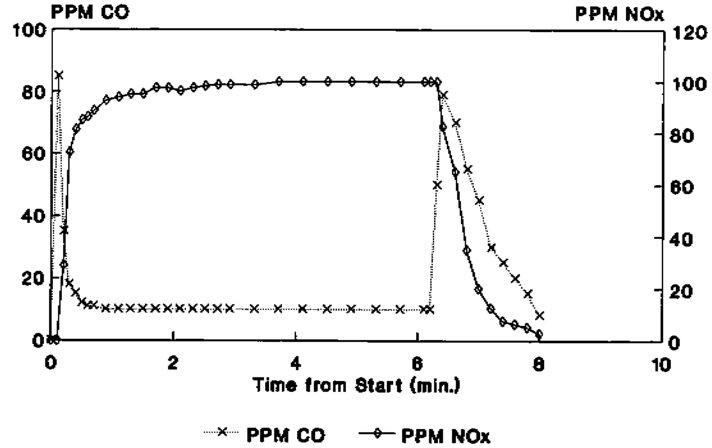
(CO and NOx are as-measured values)

FIGURE 7e - AIRTRONIC
Babington Air Atomizing
(Cyclic @ 0.55 gph and 50% Excess air)



(Hydrocarbons are as-measured values)

FIGURE 7f - AIRTRONIC
Babington Air Atomizing
(Cyclic @ 0.55gph and 50% Excess Air)



(CO and NOx are as-measured values)

3.6 Unit 7 - Yukon Warm Air Furnace

This test article is a packaged warm air furnace containing a heat exchanger capable of condensing operation resulting in a stack temperature as low as 136 Deg. F. The system is fired with a Wayne Blue Angel high static pressure retention head burner at .65 gph and is equipped with a delayed ignition solenoid valve.

Particulate analysis was performed differently than for other units tested. At temperatures below 150 Deg. F. sulfuric acid in the flue gas condenses from the gas phase to form a liquid aerosol which greatly adds to the apparent total mass of particulates collected. With the Yukon system the nozzle and filter assembly was first rinsed with isopropyl alcohol through the filter disk to remove sulfuric acid at the end of the run. Following this, the probe internals were flushed with acetone as had been done with the other systems.

The Yukon system has an induced draft fan which comes on 30 seconds before the burner and stays on five minutes after the burner shuts off. Particulate emissions samples were taken with the system operating at a 34 percent excess air level. Start-up smoke numbers, however, were found to be unusually high with the Yukon at about a number 8.5 Bacharach. This is consistent with earlier BNL tests which also showed higher start-up smoke in condensing systems. In addition, the start up hydrocarbon emissions exhibited a long exponential-like fall similar to that of the Airtronic burner in the test boiler.

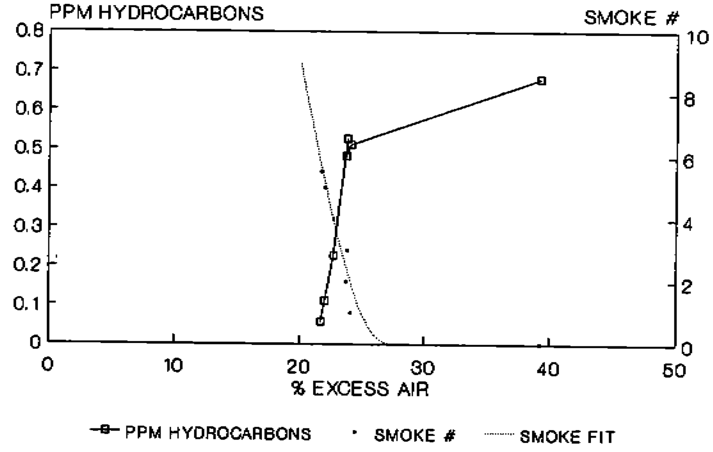
Figures 8a and 8b show the adjusted steady state gas phase emissions and smoke number versus excess air. In Figures 8c and 8d the transient smoke and as-measured emissions are shown over a typical firing cycle.

As a qualitative summary the following spike transient evaluation was made of as-measured emission data from cyclic tests:

	Burner Start		Burner Stop	
	Peak	Duration	Peak	Duration
Smoke No.	8.5	1.2 min.	0	0
ppm HC	28.0	Full Cyc.*	2.5	0.3 min.
ppm CO	55.0	0.25 min.	30.0	1.0 min.

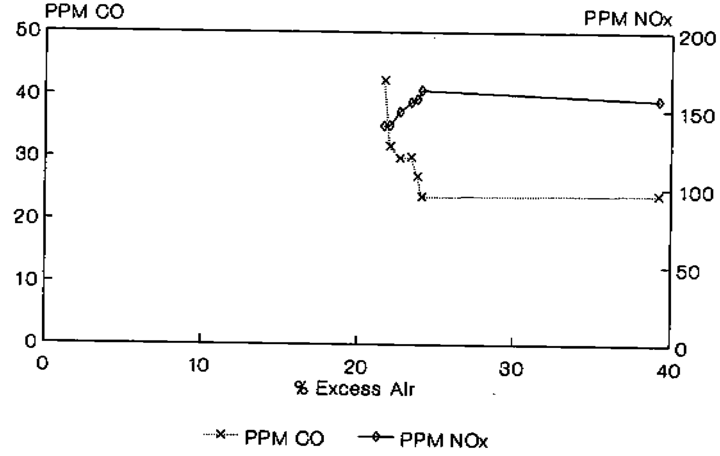
(*) Exponential-like decay

FIGURE 8a - Yukon Warm Air Furnace
Wayne Blue Angel (H.P. Ret. Head Burner)
(Steady State @ 0.65 gph)



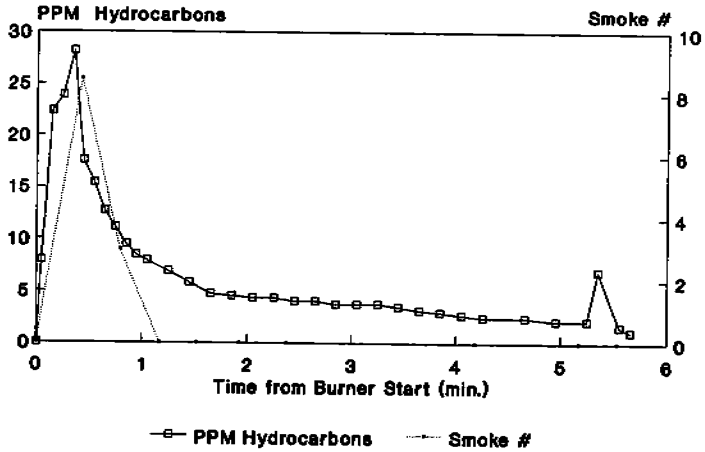
(Hydrocarbon value adjusted to 3% O2)

FIGURE 8b - Yukon Warm Air Furnace
Wayne Blue Angel (H.P. Ret. Head Burner)
(Steady State @ 0.65 gph)



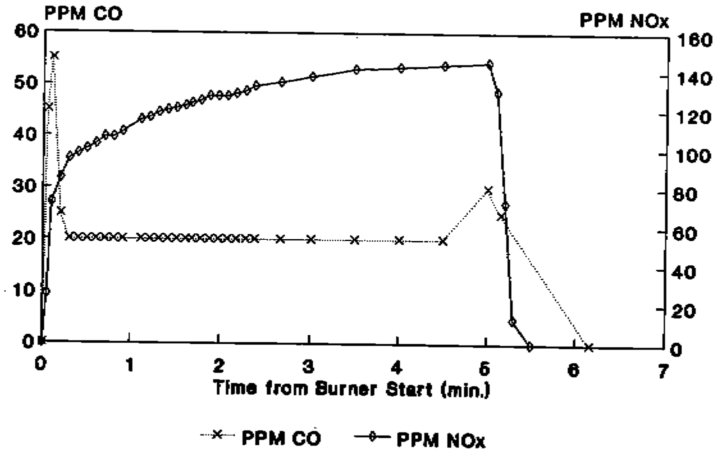
(CO and NOx values adjusted to 3% O2)

FIGURE 8c - YUKON WARM AIR FURNACE
Wayne Blue Angel (H.P. Ret. Head Burner)
(Cyclic @ 0.65 gph and 34% Excess Air)



(Hydrocarbons are as-measured values)

FIGURE 8d - YUKON WARM AIR FURNACE
Wayne Blue Angel .65 gph.
(Cyclic @ 0.65 gph and 34% Excess Air)



(CO and NOx are as-measured values)

In terms of as-measured steady state and integrated cyclic particulate and gaseous phase emissions the following summary is offered:

Yukon Warm Air Furnace (.65 gph. and 34% Excess Air)

	Steady State	Cyclic
Soot *	0.12	0.33
ppm HC	0.61	6.26
ppm CO	20.0	26.5
ppm NO_x	128.8	123.0

(*) Lb./1000 gal. fuel

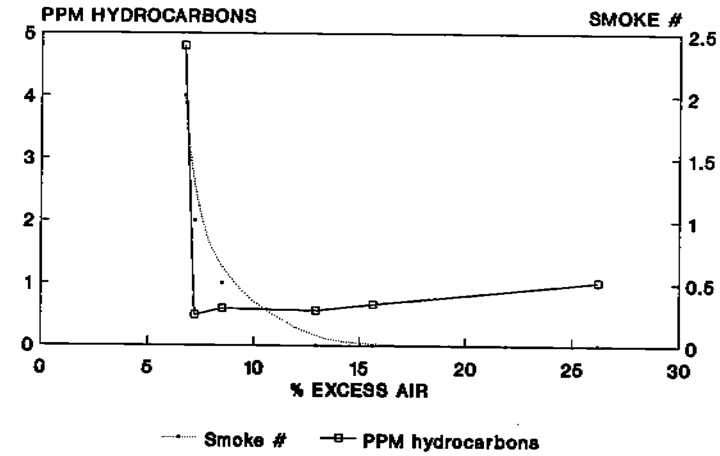
3.7 Unit 8 - BNL Prototype Burner at 0.5 gph

The Brookhaven burner was built around an air atomizing siphon type nozzle [14]. This nozzle is a Delavan Model "3061 0-1" and is commonly used in portable "construction" heaters which fire Kerosene and small waste oil incinerator burners sometimes used in automobile garages. The nozzle assembly and ignitor were adapted to a Beckett AFG burner using an MC airtube and L1 head. This highly modified burner was installed in the Peerless test boiler. The procedures for particulate and other emissions were identical to those conducted on other units.

The adjusted steady state test results are shown in Figures 9a and 9b. Figure 9a illustrates the zero smoke point which was obtained at a very low excess air level of 13 percent. At this level of combustion air, the carbon monoxide emissions are quite low. An interesting point is the "gas-like" behavior of the system illustrated by the tendency towards an increase in carbon monoxide prior to an increase in smoke number as the excess air is decreased toward zero.

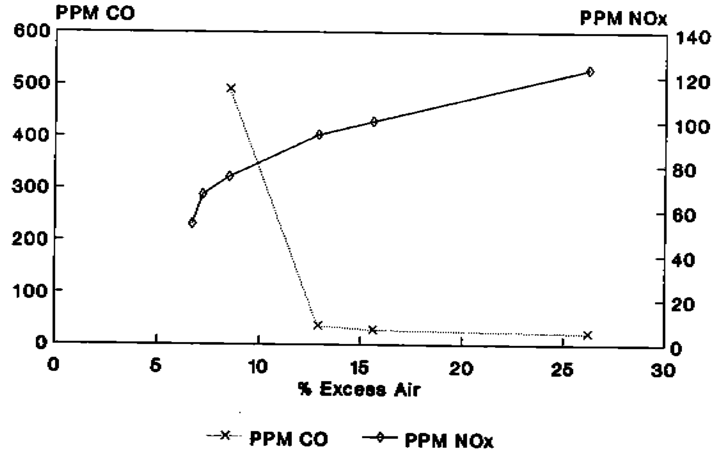
The number one smoke point was developed at an excess air level of about 7 percent. In order to achieve some consistency between the test results for the BNL burner and other units tested, an excess air level of 25 percent was used for subsequent testing. Particulate and gaseous emission samples were taken at this excess air level and the start-up and shut-down smoke levels were found to be practically zero. Figures 9c and 9d show the as-measured transient smoke and gaseous emissions resulting from the cyclic tests.

FIGURE 9a - B.N.L BURNER
PROTOTYPE BURNER
(Steady State @ 0.5 gph)



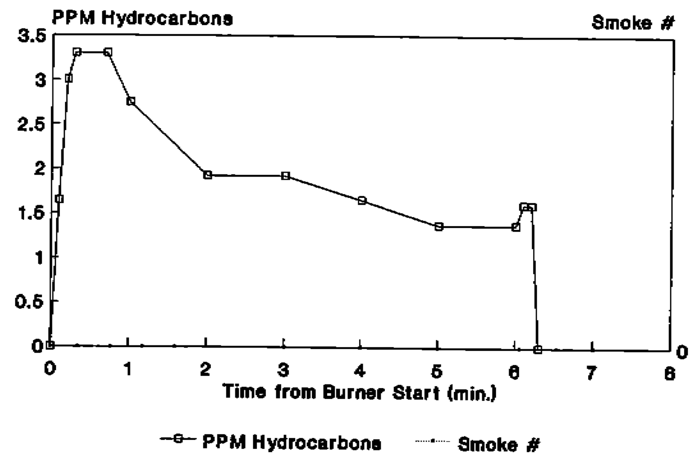
(Hydrocarbon values adjusted to 3% O2)

FIGURE 9b - B.N.L BURNER
PROTOTYPE BURNER
(Steady State @ 0.5 gph)



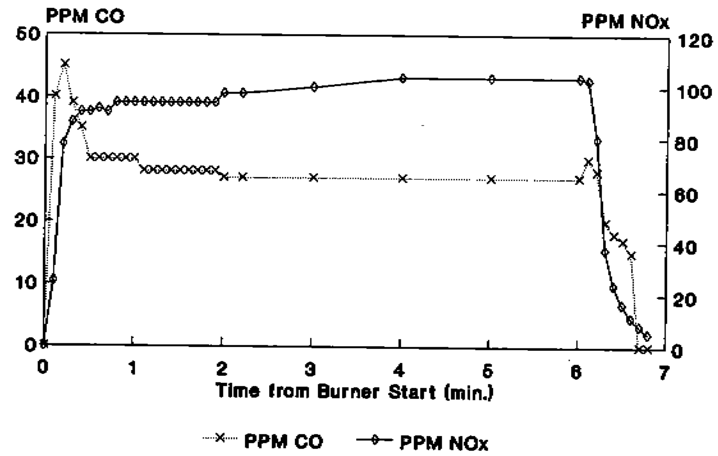
(CO and NOx values adjusted to 3% O2)

FIGURE 9c - B.N.L. BURNER
PROTOTYPE BURNER
(Cyclic @ 0.5 gph and 25% Excess Air)



(HC and Smoke # are as-measured values)

FIGURE 9d - B.N.L. BURNER
PROTOTYPE BURNER
(Cyclic @ 0.5 gph and 25% Excess Air)



(CO and NOx are as-measured values)

A qualitative analysis of the cyclic spike transient emission data resulted in the following observations:

	Burner Start		Burner Stop	
	Peak	Duration	Peak	Duration
Smoke No.	0	0	0	0
ppm HC	3.3	Full cyc.*	1.7	0.2 min.
ppm CO	50.0	2.0 min.*	30.0	0.25 min.

(*) Exponential-like decay

The as-measured steady state and integrated cyclic particulate and gaseous emissions are summarized as follows;

BNL Prototype (0.5 gph and 25% Excess Air)

	Steady State	Cyclic
Soot *	0.12	0.34
ppm HC	0.94	2.33
ppm CO	20.0	25.0
ppm NO_x	112.5	86.3

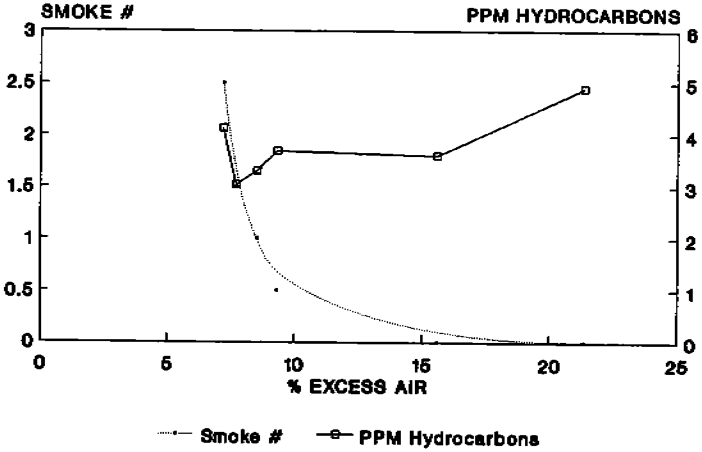
(*) Lb./1000 gal. fuel

3.8 Unit 9 - Foster Miller Burner at 0.447 gph

This unit is a variable firing rate burner originally developed by Foster Miller Associates, Inc. under contract with BNL [15]. The burner is of the combination atomizing/vaporizing type with the feature of internal recirculation of combustion products. The fundamental burner principle is to premix and prevaporize fuel in hot air and then burn this homogeneous mixture from a multiport flameholder. As a result of this design and mode of operation the burner exhibits attributes associated with blue-flame burners.

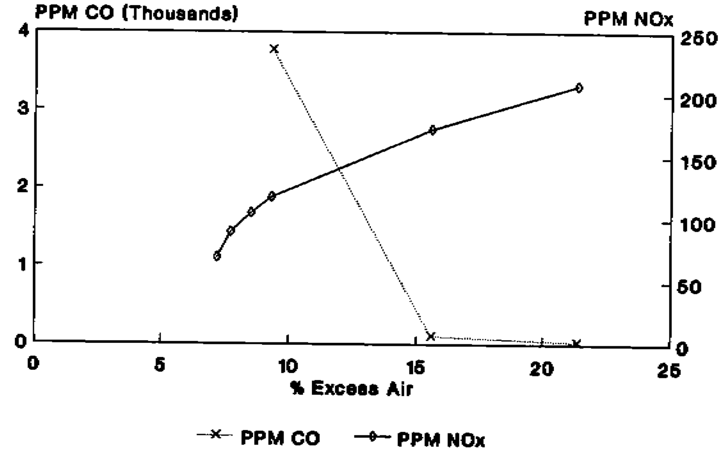
Figures 10a and 10b show the smoke number and the adjusted gaseous phase emissions under steady state operation of the burner. Evaluation of the excess air requirements for a smoke number of 1.0 indicated that an excess air level of about 24 percent was appropriate for subsequent cyclic testing. Figures 10c and 10d illustrate the transient as-measured emission data gathered during cyclic testing.

FIGURE 10a - FOSTER MILLER
EXPERIMENTAL PREVAPORIZING BURNER
(Steady State @ 0.447 gph)



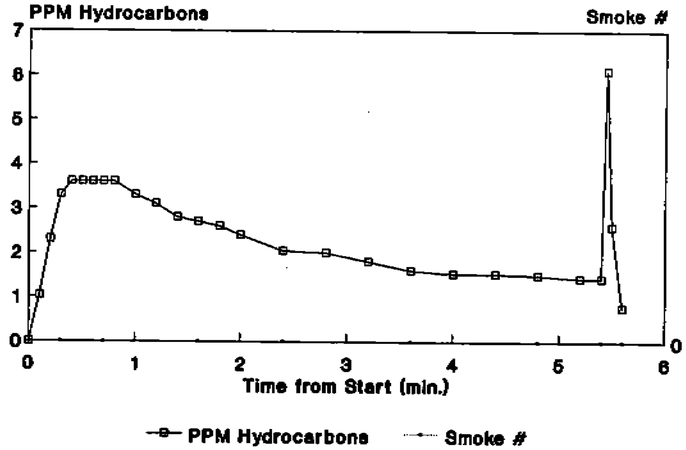
(Hydrocarbon values adjusted to 3% O2)

FIGURE 10b - FOSTER MILLER
EXPERIMENTAL PREVAPORIZING BURNER
(Steady State @ 0.447 gph)



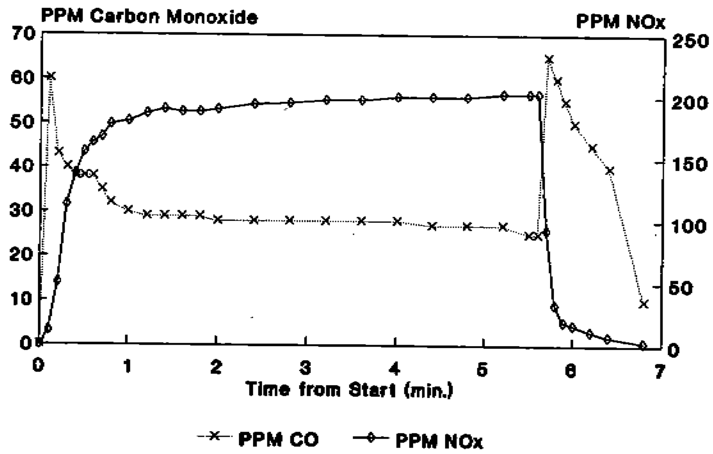
(CO and NOx values adjusted to 3% O2)

FIGURE 10c - FOSTER MILLER
EXPERIMENTAL PREVAPORIZING BURNER
(Cyclic @ 0.447 gph and 24% Excess Air)



(HC and Smoke # are as-measured values)

FIGURE 10d - FOSTER MILLER
EXPERIMENTAL PREVAPORIZING BURNER
(Cyclic @ 0.447 gph and 24% Excess Air)



(CO and NOx are as-measured values)

Through evaluation of the results of emission tests some qualitative information has been developed regarding the spike transient performance of this burner.

The following is a summary of the as-measured smoke number and gaseous emissions during the cyclic operation of the burner:

	Burner Start		Burner Stop	
	Peak	Duration	Peak	Duration
Smoke No.	0	0	0	0
ppm HC	3.6	Full Cyc.*	6.2	0.2 min.
ppm CO	60.0	2.0 *	67.0	1.0 min.

(*) Exponential-like decay

The as-measured results of particulate collection and gaseous emissions were evaluated for steady state and cyclic operation of the burner. The results of this evaluation are as follows:

Foster Miller (.447 gph at 24% Excess Air)

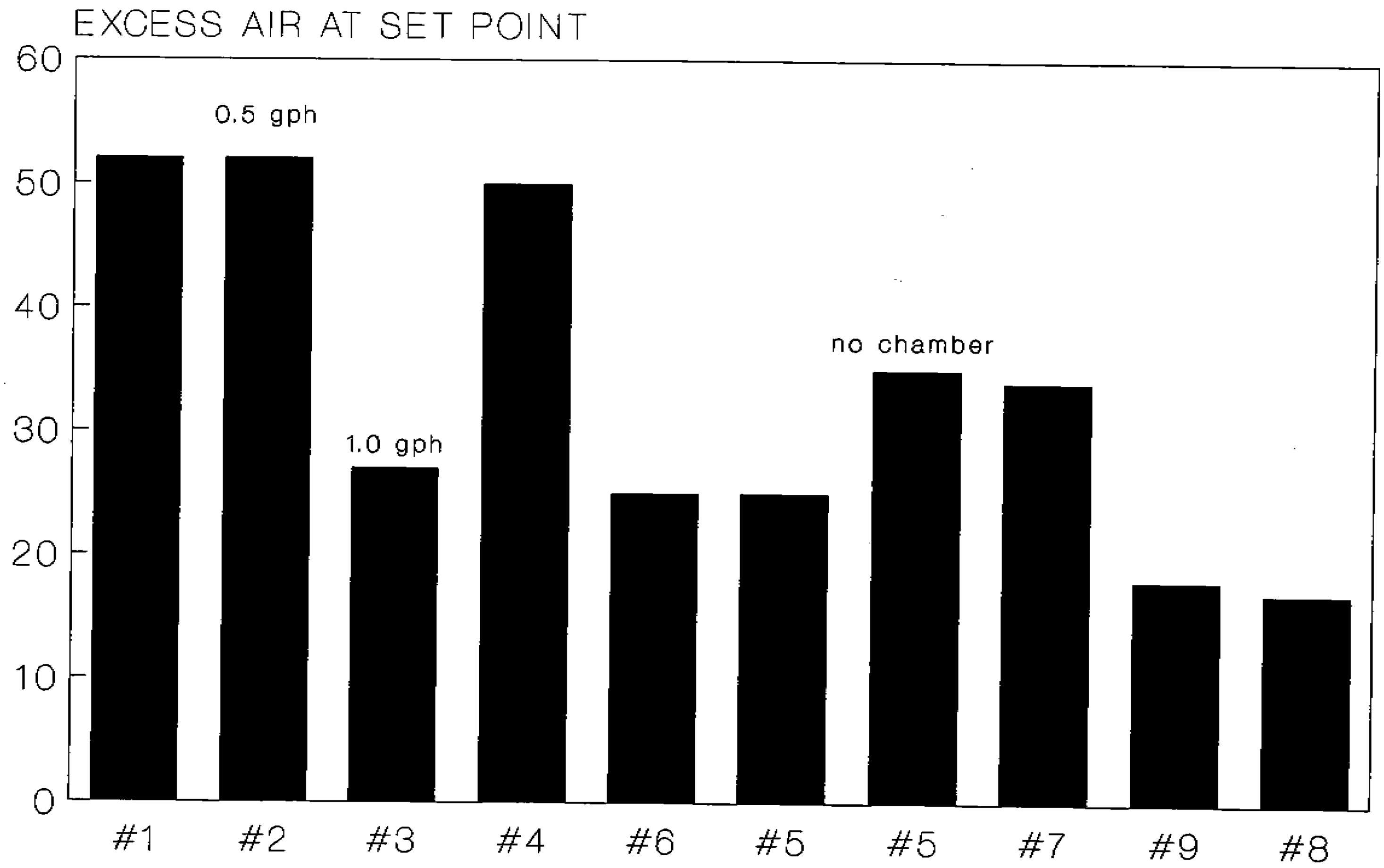
	Steady State	Cyclic
Soot *	(No soot collection was possible)	
ppm HC	2.34	2.2 est.
ppm CO	25.0	35.0 est.
ppm NO_x	197.5	50.0 est.

(*) Lb./1000 gal. fuel

4. RESULTS

Figure 11 shows the excess air at the set point defined in Section 2.2 above. This is considered as the first figure of merit for comparing different burner systems. For burner units 2 and 3, Figure 11 shows that a reduction in firing rate from 1.0 to 0.5 gph requires an increase in the excess air. This is a typical result due in part to the lower air velocities at the lower firing rate. At 0.5 gph all of the retention head burners tested in the cast iron boiler (units 1, 2, 3 and 4) require essentially the same excess air. All of the air atomized burners which were fired into the same boiler could be operated at much lower excess air levels. The burner fired into the low mass boiler could also be operated at lower excess air levels, due to both the higher firing rate and the combustion chamber used.

FIGURE 11 - EXCESS AIR AT THE SET POINT



SHOWN BY UNIT NUMBER - SEE TABLE 1

Figure 11 shows the excess air set point for this system with the chamber removed which illustrates how much lower the excess air setting can be with this unit when using the chamber. The retention head burner which was fired into the condensing furnace could also be operated at fairly low excess air levels.

Figure 12 shows the steady state CO emissions for all of the units tested. In every case the CO emission levels were very low. It is interesting to note the relatively high CO, however, for the case of the low mass boiler without a combustion chamber. For units 5 and 6, results are included for the setpoint excess air levels as shown in Figure 11 and a higher excess air level set at 50%.

The steady state emissions of NO_x are shown in Figure 13. For unit 3 higher steady state NO_x levels are shown at the 1 gph firing rate. This is most likely due to increased flame temperatures at the higher firing rate. For the case of the low mass system (unit 5), removal of the combustion chamber significantly reduced the measured NO_x emissions. It is interesting to note the NO_x levels for the prevaporizing burner (unit 9), which are high relative to those measured for the other burners at the same firing rate.

Figure 14 shows a comparison of the startup and shutdown smoke numbers for all of the units tested. The two air atomized burners tested and the prevaporizing burner did not produce any smoke transients. The retention head units (units 5 and 7) showed a startup smoke transient, but no shutdown transient. Note that in both cases a fuel solenoid valve was used. In the case of the air atomizing burner (unit 6) the startup peak of HC was much longer in duration although typical in magnitude. The effect that this might have on heat exchanger fouling is uncertain. The highest emission peaks for both CO and HC were observed in the case of the low mass unit (unit 5) with the combustion chamber removed. Here the peak emissions were 10 times greater than observed in other systems. Note that this is not how the system is built by the manufacturer. A lot of effort went into design of the chamber and it is an integral part of the system when shipped by the factory.

The particulate emission rate for all of the units in both steady state and cyclic tests is shown in Figure 15. In all cases the cyclic emissions are significantly greater than those measured during steady state, on the average 4 times as much. The lowest cyclic particulate emission rate was observed with the air atomizing burner (unit 6) at the increased excess air level. In cyclic tests the highest particulate emissions were realized for the low mass system (unit 5). It seems likely that this unit suffered more during the time required to warm up the chamber than other systems.

When this unit was operated at an excess air level similar to the other retention head burners at 0.5 gph (50%) the cyclic particulate emission rate was found to be among the lowest measured. Particulate emission tests have not been done to date with the prevaporizing burner because of concerns over the ability of this prototype to run reliably over the required test duration.

FIGURE 12 - STEADY STATE CO (PPM)

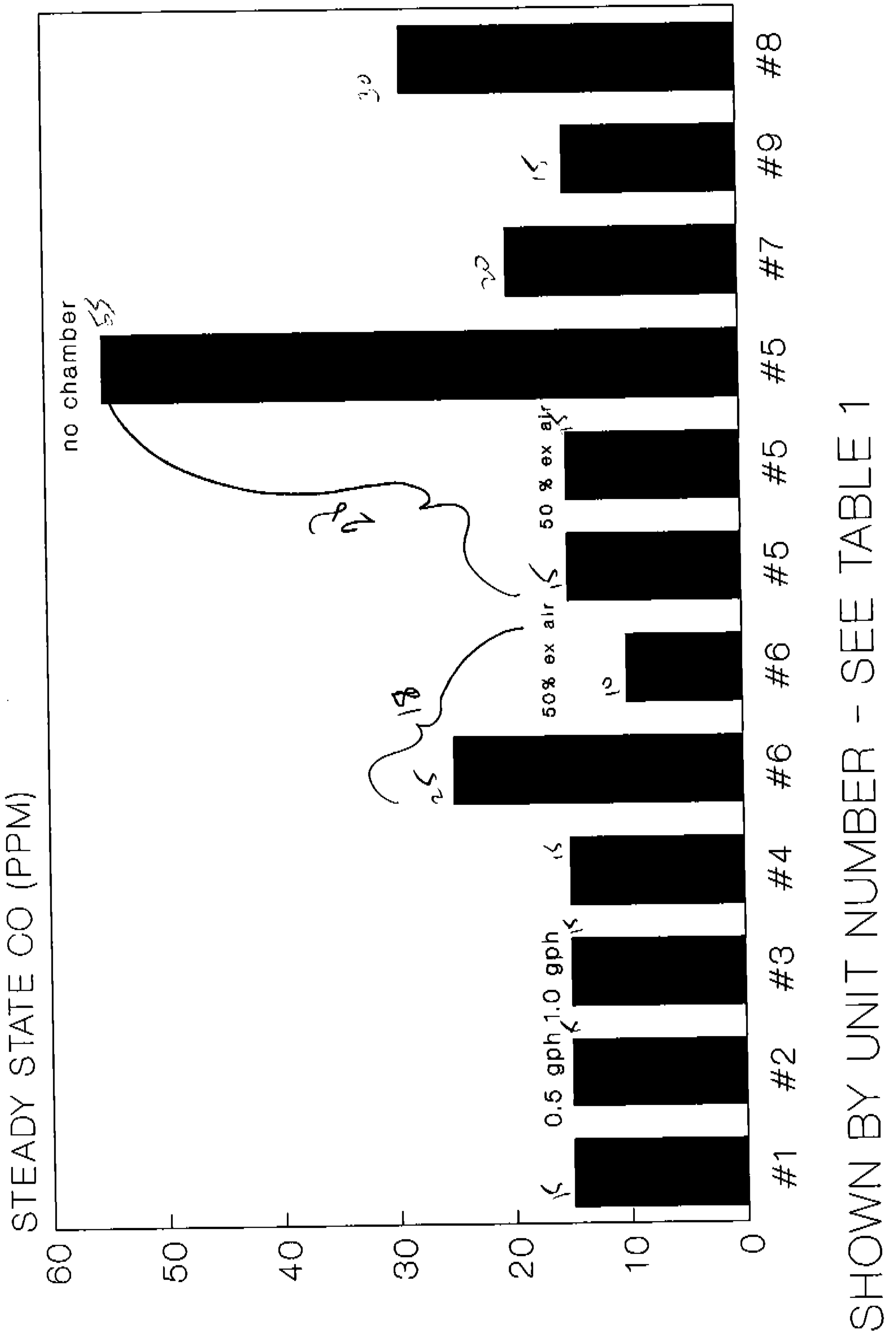
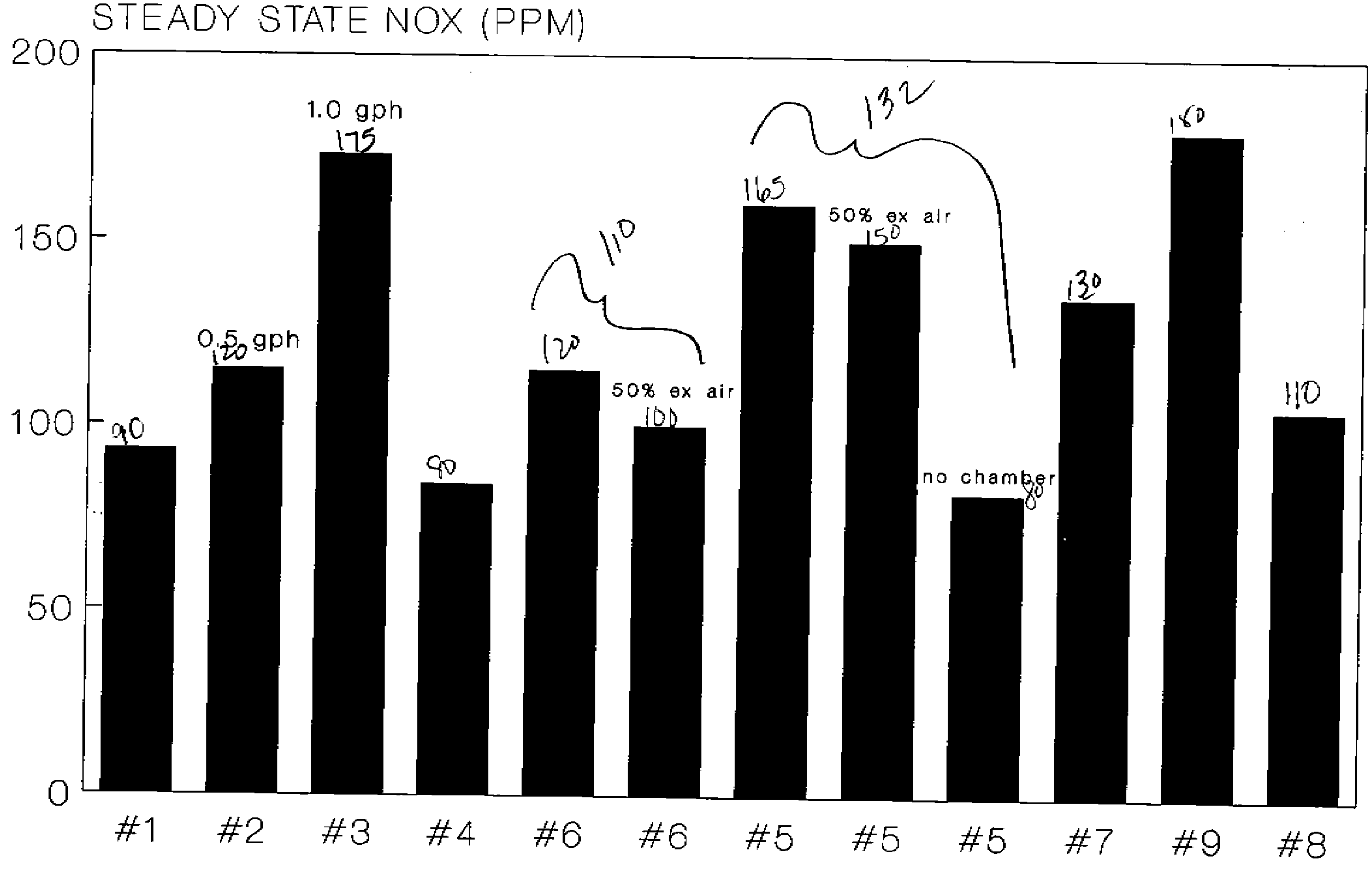
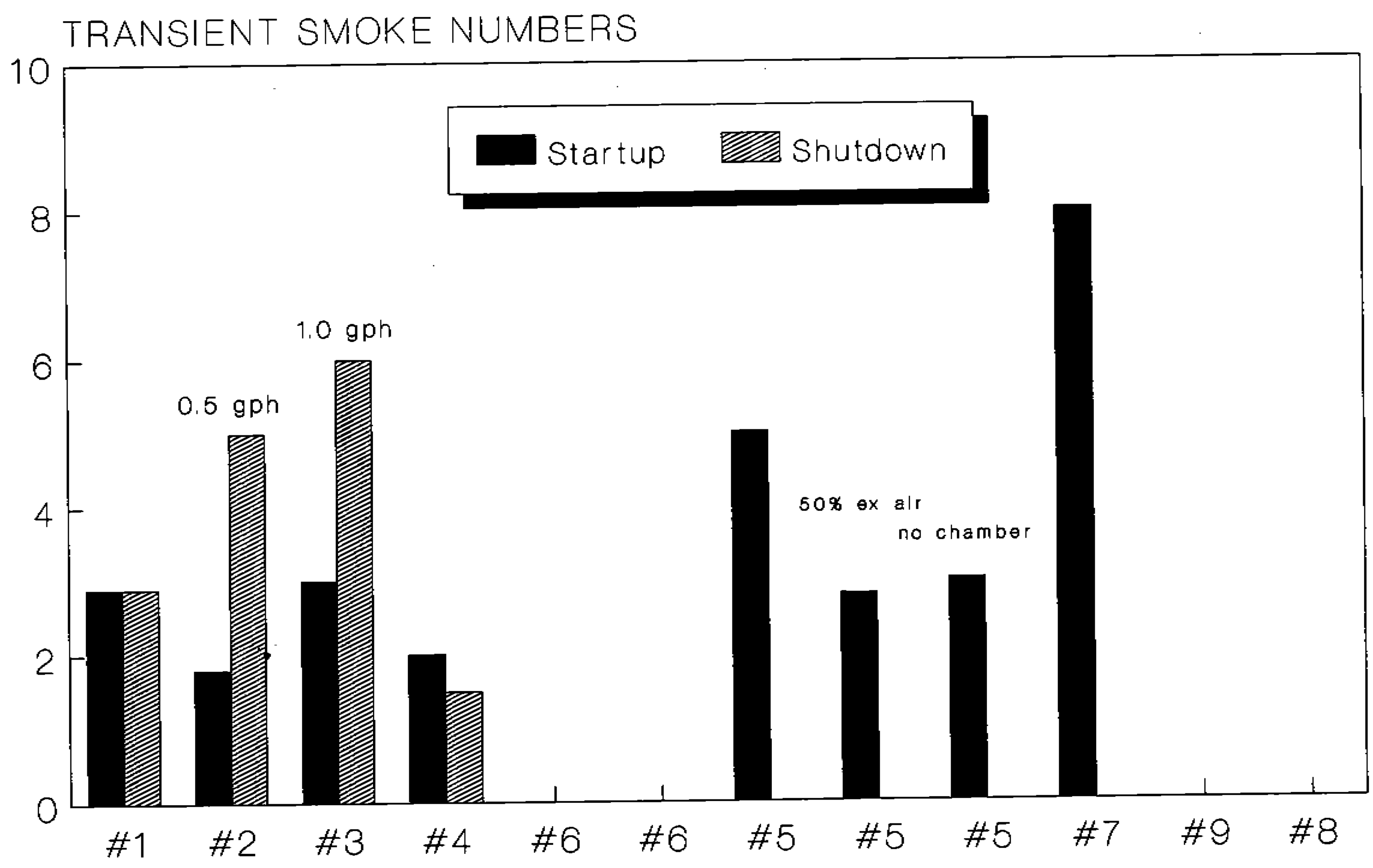


FIGURE 13 - STEADY STATE NOx (PPM)



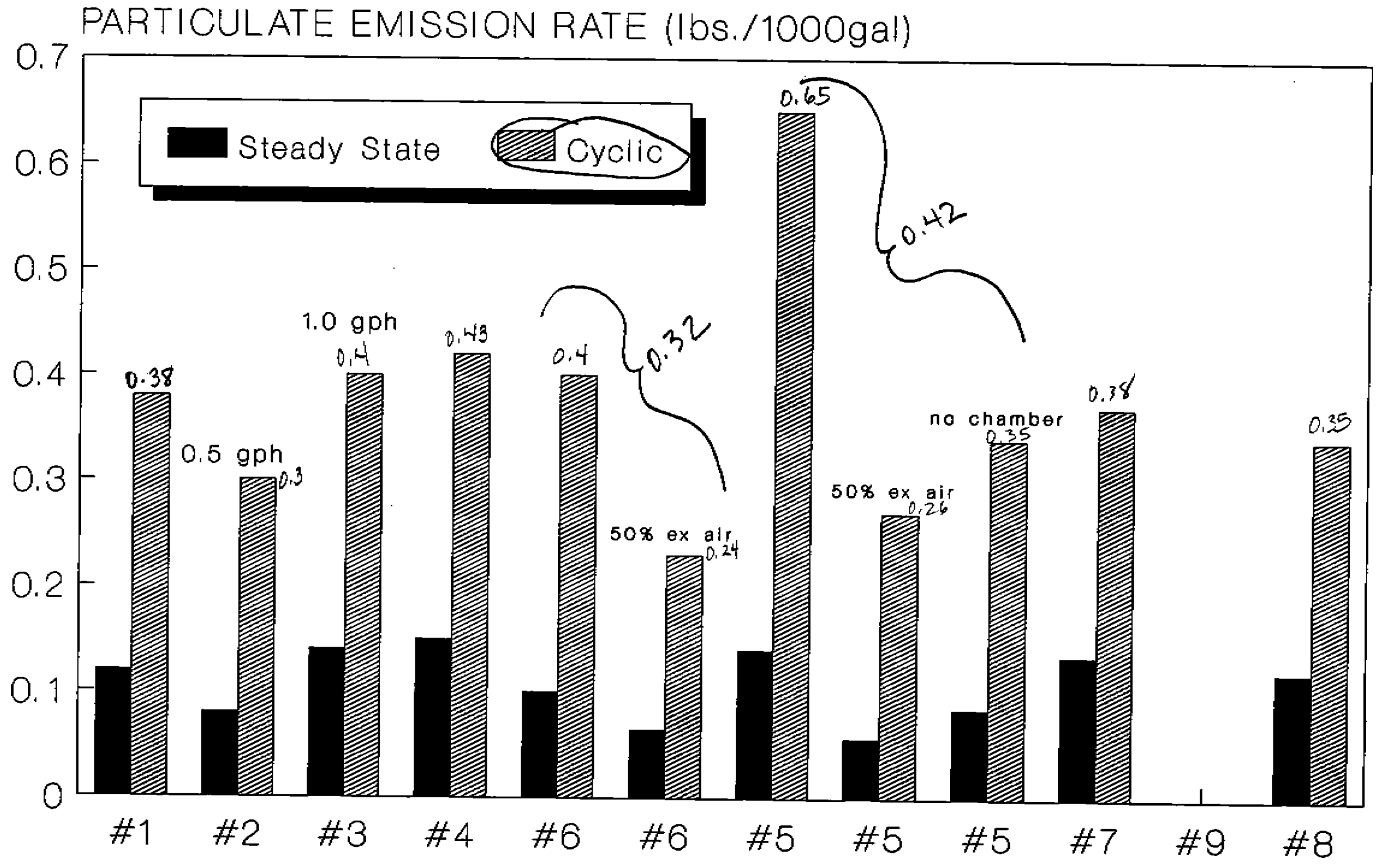
SHOWN BY UNIT NUMBER - SEE TABLE 1

FIGURE 14 - TRANSIENT SMOKE NUMBERS



SHOWN BY UNIT NUMBER - SEE TABLE 1

FIGURE 15 - PARTICULATE EMISSIONS



SHOWN BY UNIT NUMBER - SEE TABLE 1

5. CONCLUSIONS

In general the emission rates for particulates as presented in this report were found to be low for all systems, on the order of 0.2 to 0.6 lbs./1000 gal. in cyclic operation. This could be compared to the average result found in the Battelle field study of 2.5 lbs./1000 gal. The results of the Battelle study are currently used by the EPA to assess the relative contribution of residential oil heating equipment to the national inventory of emissions, which to date is not a major concern of the EPA. It might be expected that the field study would produce higher emission than would be obtained under controlled laboratory studies. Still, the results presented in this report indicate that under proper conditions modern retention head burners can operate cleanly. A summary of these results is presented in Table 6.

TABLE 6
Results Summary -- BNL Laboratory Study (1988)
Seven Systems Evaluated

	Emission Factors Lbs./million Btu			
	CO	HC	NO_x	Particulates
Minimum	.016	.00096	.120	.0024
Maximum	.046	.0036	.181	.0030
Average	.026	.00174	.150	.0027

The use of advanced air atomizing burners can lead to significant additional reductions in particulate emissions if these are operated with modest excess air levels.

Overall, cyclic operation still contributes most of the particulates which are emitted, and improving this cyclic performance may hold the greatest opportunity for realizing even cleaner systems in the near future.

Without a combustion chamber higher transient emission levels of HC and CO are realized, but NO_x is reduced. The impact that higher HC transients may have on heat exchanger fouling is not known.

6. CLOSING DISCUSSIONS

At present the U.S. EPA is using an emission factor for particulates from oil-fired heating equipment of 0.018 lbs./million Btu. It seems very likely that this comes from the field study of 33 units which was done by Battelle Columbus Laboratory 15 years ago. More recent laboratory data with newer equipment properly adjusted indicates much lower levels of particulate emissions--on the order of .003 lbs./million Btu in cyclic operation. In assessing the impact of oil use on total particulate emissions in the future, it seems most reasonable to assume that modern equipment will be used as older systems are being replaced. Flame retention head burner technology already accounts for 60-70% of existing in-place oil-fired appliances. While it may be too optimistic to assume that the average field unit will operate as well as units under controlled conditions in the laboratory, the emission factor of 0.018 is clearly too high.

In assessing the impact of different combustion systems on air quality an additional factor which should be considered is seasonal efficiency. Emission factors are generally based on firing rate. Thus, if two systems have identical emission factors, the less efficient of the two will contribute more to air quality degradation.

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APPENDIX

CONVERSION OF UNITS

MULTIPLIERS TO CONVERT EMISSION FACTORS FROM g/kg TO OTHER UNITS FOR NO. 2 OIL (a)

To obtain emission factor in these units	Multiply emission factor in g/kg fuel by
Gaseous pollutants and particulate:	
kg/1000 liter fuel	0.862
g/million calories input	0.092
lb/1000 lb fuel	1.000
lb/million BTU input	7.194
Gaseous pollutants (b):	
ppm at 3% O_2, dry basis	$\frac{1770}{MW}$
ppm at 0% O_2, dry basis	$\frac{2065}{MW}$
ppm at 12% CO_2	$\frac{1597}{MW}$
Particulates:	
lb/million scf flue gas at 3% O_2	4.58
lb/million scf flue gas at 0% O_2	5.27
lb/million scf flue gas at 12% CO_2	4.13

(a) Typical No. 2 fuel oil having 33 API gravity

(b) MW = molecular weight of pollutant