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SMALL OIL-FIRED HEATING EQUIPMENT: THE EFFECTS OF FUEL QUALITY

Wailin Litzke

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Energy Efficiency & Conservation Division
Department of Applied Science
Brookhaven National Laboratory
Upton, New York 11973

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1.0 ABSTRACT

The physical and chemical characteristics of fuel can affect its flow, atomization, and combustion, all of which help to define the overall performance of a heating system. The objective of this study was to evaluate the effects of some important parameters of fuel quality on the operation of oil-fired residential heating equipment. The primary focus was on evaluating the effects of the fuel's sulfur content, aromatics content, and viscosity. Since the characteristics of heating fuel are generally defined in terms of standards (such as ASTM, or state and local fuel-quality requirements), the adequacy and limitations of such specifications also will be discussed.

Liquid fuels are complex and their properties cannot generally be varied without affecting other properties. To the extent possible, test fuels were specially blended to meet the requirements of the ASTM limits but, at the same time, significant changes were made to the fuels to isolate and vary the selected parameters over broad ranges.

A series of combustion tests were conducted using three different types of burners - a flame-retention head burner, a high static-pressure-retention head burner, and an air-atomized burner. With some adjustments, such modern equipment generally can operate acceptably within a wide range of fuel properties. From the experimental data, the limits of some of the properties could be estimated. The property which most significantly affects the equipment's performance is viscosity. Highly viscous fuels are poorly atomized and incompletely burnt, resulting in higher flue gas emissions. Although the sulfur content of the fuel did not significantly affect performance during these short-term studies, other work done at BNL demonstrated that long-term effects due to sulfur can be detrimental in terms of fouling and scale formation on boiler heat exchanger tubes. [1]

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2.0 INTRODUCTION

Over the past several years, the oil heating industry has shown growing interest in the current and future quality of home heating oil [2]. Many factors have contributed to this interest, and one of the most recent issues is related to the amendments of the Clean Air Act (1990). Changing refinery operations to meet stringent environmental regulations and the diminishing sweet crude stock challenge the petroleum industry to produce high quality fuels and, at the same time, meet the growing demands for distillate fuels [3].

The overall quality of distillate fuel is influenced by the nature of the fuel itself and the conditions in which it is stored. Earlier work at BNL looked at the effects of storage conditions, fuel contamination, sludge formation, and cold weather conditions on the operation of equipment [4]. This study concentrates on the effects of the inherent characteristics of the fuel on combustion performance. Our purpose was to address the concerns of the industry by reviewing fuel-quality parameters that are of importance and quantifying their effects on heating equipment.

The performance of heating systems typically is governed by the design and operations of the boiler or furnace and burner. However, the quality of the fuel also plays an essential role in combustion performance. The specific properties of the fuel can affect combustion performance and flue gas emissions. Combustion performance can be defined by the excess air required for a given Smoke No. (Bacharach scale), ignition quality, and emissions characteristics-carbon monoxide, oxides of nitrogen, and soot. In these studies, the effects of fuel viscosity, aromatic content, and sulfur content were evaluated. Performance was compared by measuring the differences that can be observed between a standard "typical" test fuel, and an "off-spec" test fuel.

Fuel properties are usually defined in terms of standards such as ASTM limits (ASTM D-396). For No. 2 heating oil, the ranges of typical or acceptable values are 1.9-3.4 cSt (at 40°C) for viscosity, and a maximum of 0.5% sulfur. The requirement for aromatic content is not explicitly defined in the ASTM; however, it is limited indirectly by other requirements, such as specific gravity. Aromatic components in the fuel are more dense and tend to increase the specific gravity. Typically, aromatic content varies from 30-35% by volume. As part of this work, blended fuels with properties extending beyond the ASTM limits also were used to determine the range within which performance is acceptable.

Both steady-state and transient behavior under typical cyclic operating conditions were evaluated. Fuel viscosity, which is strongly related to heavier compounds with lower API gravity, has a very significant effect on combustion. High viscous fuels are poorly atomized in burner nozzles, resulting in incomplete burning and higher stack emissions. Using several modern conventional types of burners, our tests show that there is a wide range in fuel viscosity within which burner performance is considered acceptable. Beyond this range, there is a considerable increase in flue gas emissions and smoke, and ignition is poor.

The strong interest in fuel quality was the basis for the studies conducted at Brookhaven National Laboratory within the Combustion Equipment Technology program. This work provides a technical basis for determining the impacts of some of these fuel properties on equipment performance, and their functional limits to ensure efficient and proper operation of oil-burning units.

3.0 BACKGROUND

The study of the effects of middle distillate properties on the combustion characteristics of residential heating oil has been looked at from many perspectives. In Canada, the increased use of Canadian distillate oils processed from synthetic crudes has caused concern about the deteriorated performance of oil burners. A strong correlation was established between fuel viscosity and aromatics content on emissions and burner performance [5,6].

The fuel's sulfur content affects combustion performance in terms of emissions and operation of equipment. Sulfur oxides emitted from oil-burning residential heating systems are typically very small compared to other sources, and are about 36 lb/1000 gal (roughly 1% in the form of sulfur trioxide, and the remainder as sulfur dioxide), assuming a typical sulfur content of 0.25% [7]. Sulfur trioxide, which is generated in small amounts, can be converted to sulfuric acid which contributes to the corrosion and fouling of heat exchangers in boilers and furnaces. Fouling and scale formation due to soot deposition (carbon and acid components) leads to reduced efficiency and an increased need for servicing. Brookhaven National Laboratory has an on-going program to study the causes of soot fouling to identify practical methods of minimizing these deposits [1].

In diesel engines, the fuel sulfur and aromatic content are the most important contributors to emissions of particulate and sulfur dioxide [8]. In an effort to improve ambient air quality, one of the new regulations under the Clean Air Act Amendments placed new restrictions on the limits for sulfur and aromatics content to reduce such emissions from engine exhausts. By October 1993, diesel fuel used for transportation will contain reduced sulfur, at 0.05% wt maximum (compared to the typical value of 0.25%), and aromatic levels will be held at or below the current average (approximately 34%). Both diesel and No. 2 heating oil are currently derived from the same pool and can be interchanged. As part of this study, we quantified the effects of sulfur and aromatics on emissions from residential heating equipment.

The properties of the fuel which are most affected by low-temperature operation - cloud and pour points, and their effects on equipment operation also have been studied at BNL. Cloud and pour-point temperatures were measured from field samples to determine their variability in commercial grade fuels. This information, along with other analytical measurements, helped to establish a database of information on the quality of current heating oils. In addition, fuel additives were evaluated as methods of controlling these fuel-quality parameters [2,3].

The viscosity of the fuel can significantly affect oil-burner operation. Although other fuel characteristics remain constant and are predetermined by the refining and blending practices, viscosity can fluctuate markedly with variations in the fuel's temperature. The effects are most

prominent during winter when a decrease in temperature outdoors can cause a rise in viscosity; associated operational problems which can occur include a loss in the fluidity of the fuel, poor atomization, and inefficient burning, requiring additional excess air.

4.0 EXPERIMENTAL

A series of combustion tests using several different burners were performed to look at the effects of fuel sulfur content, aromatic content, and viscosity on steady state and cyclic operating conditions.

Studies of the effects of changes in fuel properties on a burner's performance and emissions are complicated by the fact that few changes in the properties of a fuel can be made independently. For example, varying the aromatic content will change other properties, such as density and distillation end points. For this study, fuel samples were purchased from Phillips Petroleum Refinery that were blended specifically to enhance those properties of interest while maintaining the other properties relatively constant to within an acceptable range, as dictated by the ASTM D-376 for heating oil. The characteristics of performance considered include flue gas analysis (gross and measurable effects) and equipment operation.

Emission measurements included:

- Particulate (filterable)
- Carbon Monoxide (CO)
- Nitrous Oxides (NO_x)
- Transient smoke (startup and shutdown)

4.1 Fuel Analyses

The test fuels were purchased from Philtex/Phillips 66 Corporation, and were custom-blended and analyzed. Most of the properties of each test fuel meet the criteria under ASTM limits for No. 2 heating oil, except those that we were interested in, which may exceed the ASTM limits. The fuel's properties are shown in Table 1. The baseline fuel is considered to be the "typical" heating fuel, with all of its properties meeting No. 2 distillate requirements, against which any effects observed with the other test fuels were compared.

Distillate fuels typically contain an average level of 30-35 vol% aromatics. Although, generally, there are no specifications for aromatic content, its value is usually limited by other related properties, such as specific gravity and density. Increased amounts of aromatic compounds tend to result in an increase in density and, therefore, a lower API gravity. The low aromatic fuel (16.6 vo. %) technically meets the ASTM specifications, although this fuel would typically not be found in the market.

The viscosity of commercial fuels typically ranges between 2.0 - 2.5 cSt at 40°C; however, it can significantly change with storage and operating conditions. Under cold storage viscosity can increase dramatically, making it more difficult to move or transfer the fuel. For our test

fuels, viscosities ranged between 1.6 to 8.0 cSt at 40°C. In order to obtain an intermediate level at approximately 3.3 cSt (at 40°C), an in-house blend was prepared with the baseline fuel (2.3 cSt) and the highly viscous fuel (5.0 cSt) in a 40/60 % by volume mixture. The other properties were not analyzed for this particular fuel mixture.

A few exploratory tests were done with a sample of light cycle oil (LCO). Most middle distillate fuels contain light cycle oil as blending stock. The properties of LCO are very similar to the No. 2 distillate in terms of the distillation range, viscosity and sulfur level. The aromatics content is very high (86%) and consequently, the API gravity is low (19.7), below the ASTM limit. The carbon residue, which is sometimes used to evaluate the carbonaceous depositing characteristics of the fuel, exceeds the ASTM limit.

FUEL PROPERTIES - ASTM LIMITS

Fuel Type Lot No.	Sulfur 0.5 wt% max	Viscosity, (at 40C) 1.9 - 3.4 cSt	Aromatics v% no limit	API grav 30 min	sp.gr. 0.876 max	Flash pt 100 F min	Dist.90% 540-640 F	Carbon R 0.35%,ma x	Nitrogen no limit
Baseline K-848	0.26	2.3	33.6	35.6	0.8468	152	571	ND	0.05% (1)
High Sulfur HOWELL	0.7	2.1	ND	34.8	0.851	216	565	0.06	0.08% (1)
Low Sulfur K-955	0.037	2.8	33.5	36	0.8448	161	592	ND	ND
Low Aromatic R-676	0.271	2.6	16.6	42.7	0.8123	175	561	0.06	< 2.5 ppm (2)
High Aromatic R-598	0.25	2.3	55.5	30.9	0.8713	144	614	0.30	44 ppm (2)
All Aromatic R-471	0.0035	2.36	100	14	0.9723	211	550	0.44	0.05% (1)
Low Viscosity R-585	0.25	1.6	33.2	38.4	0.8328	140	541	0.07	56 ppm (2)
High Viscosity R-711	0.31	5.0	38	35.2	0.8488	136	656	0	0.04% (1)
Hi Arom/Visc R-472	0.12	8.0	76.7	27.6	0.8894	230	657	ND	0.05% (1)
LCO	0.387	2.66	86.1	19.74	0.9356	ND	570	1.2	ND
Interm Visc (3)	ND	3.3	ND	ND	ND	ND	ND	ND	ND

ND - No Data

(1) Detection limit-14 ppm

(2) Detection limit - 2.5 ppm

(3) In-house blend 40/60 vol% of K-848 and R-711, respectively.

Table 1. Test Fuels

4.2 Equipment and Setup

Three burners were used in these tests: a conventional flame-retention head burner (AF), a high static-pressure-retention head burner (RL), and an air-atomizing burner (BB). Conventional retention head burners have dominated the oil heat market in the U.S. for the past 15 years. The fans on these burners produce a maximum static pressure of about 1" of water column. Recently several "high static" burners have become available. These produce a maximum static pressure of about 3" of water column. This higher pressure gives cleaner starts and enables the burner to operate with some chamber back pressure. The high static burners also have improved head designs which also give some performance improvements. The air-atomizing burner is currently marketed in Europe and has a very different method of atomizing and combusting the fuel compared to that of the conventional pressure atomized retention head burner. In the air-atomized system, the fuel is supplied to the outside of a hollow spherical surface which contains a narrow slit. The liquid fuel spreads out over the surface in a thin film; compressed air exits the narrow slit under this film and atomizes the fuel. The resulting dispersion of fine liquid drops are mixed with primary combustion air and ignited. The test bed boiler was a Peerless Model with a nominal firing rate for each test set at 0.5 gal/hr. The actual firing rate varied slightly depending on the type of burner, the nozzle, and the burner's pump pressure.

With all cyclic tests, certain operating conditions for each burner with each test fuel were preset initially under steady-state conditions. The draft was adjusted to a low level (less than 0.005 in. w.c.) to minimize air leakage around the shell of the boiler. The excess air level for each test was set 10% higher than that required to obtain a Smoke No. 1 on the Bacharach Scale, and was adjusted by monitoring the oxygen (O_2) level of the flue gas. For these tests, the excess air setpoint for each fuel and burner type was considered the "optimum" operating condition (Figure 1).

Under cyclic operations, the burner is set to turn on for 5 minutes and shut off for 15 minutes. The temperature of the fuel oil supply, the room, and the boiler water were recorded. Emissions of nitrogen oxides (NO_x) and carbon monoxide (CO) were recorded on a chart recorder for several cycles. Oxygen was measured using the Beckman Model 755 paramagnetic O_2 analyzer. With this system, volume magnetic susceptibility of the flowing gas sample is sensed in the detector/magnet assembly and gives a linear response. Nitrogen oxides were measured with a Beckman Model 955 analyzer with the chemiluminescent method for detecting nitric oxide. Carbon monoxide was measured with a Beckman Model 865 non-dispersive infrared analyzer in which the percentage of infrared radiation absorbed is proportional to the concentration of carbon monoxide.

Figure 1. Excess Air Requirement for Test Operation

Transient smoke was measured with the Bacharach smoke spot test using the standard procedure, ASTM D2156. A manually operated suction pump draws a specific volume of sample gas from the flue gas stream through a standard filter paper. The darkness of the spot produced on the filter indicates smoke emissions, and was compared to a 0-9 smoke spot reference scale (Bacharach scale).

Chamber pressure transients during startup and shutdown were measured using a pressure transducer and monitored on an oscilloscope. The pressure is measured with a transducer in volts, which is then converted to inches of water column; the values represented are the average of peak values for several cycles.

4.3 Emissions Testing

During steady-state operation when the oil burner stays on continuously, there are negligible flue gas emissions, such as carbon monoxide (CO) and particulates; elevated concentrations are observed only during startup and shutdown in cyclic operation. During these transient periods, the emissions of nitrogen oxides (NOx),

CO, and smoke number were recorded over several cycles. The peak values or concentrations were averaged and are reported in the next section.

For the low sulfur, low aromatics, and baseline fuels, the total particulate matter emitted as soot was determined by gravimetric analysis. Duplicate tests were conducted with the flame-retention head burner. Figure 2 is a schematic of the collection train that we used which resembles the EPA Method 5 train. The sampling train consists of several major components: a primary filter which collects the soot particles for analysis, condenser impingers which dry the gas before it enters the flowmeter, a backup filter which prevents breakthrough if the primary filter is ruptured (prevents contamination of the pump), and a flowmeter which measures the total volume of dry gas sampled.

Figure 2. Sampling System

During cyclic operation, filterable particulates emitted during the "on" period were collected and weighed. To collect enough material for weighing, each test required about a minimum of 24 hours of operation (71 cycles). A timed relay circuit to the automatic sampling equipment was set up so that sampling started 15 seconds before the "on" period and ended 15 seconds after the burner shut off, ensuring that all the particulates during the entire 5 min "on" period were collected. The primary filter was maintained at $248 \pm 25^\circ \text{F}$ with heating tape to prevent condensation. The filter was predried and preweighed before each test, then, at the end of the test, removed, dried, and weighed again. The probe was rinsed with acetone into a

preweighted dish to catch any remaining soot, allowed to dry, and added to that collected on the filter to give the total amount of particulate.

The purpose of these measurements was to determine if any benefits can be realized by using fuel with reduced sulfur (0.05 % wt.), and low aromatic content (17 % vol). The aromatic content selected is roughly half that of typical distillate oil. All emissions data are compared with the baseline fuel.

Emission factors for filterable particulate are usually expressed as the total weight of soot collected per unit of fuel consumed, either as pounds per 1000 gallons (lbs./1000 gal) or pounds per million Btu (lbs/MBtu). Gas phase emissions are measured in parts per million by volume (ppm) and the results are reported for 3% oxygen in the flue gas. The emissions calculations are detailed in the Appendix.

5.0 RESULTS

The results are based on cyclic operating conditions with preset levels of excess air optimal for the particular burner unit and fuel type (Section 4.2).

5.1 Transient Smoke

The simplest measurement that can be made is the smoke number, which evaluates the smoke density of the flue gas. Figure 3 illustrates the effects of fuel characteristics on the smoke generated upon startup and shutdown during cyclic operating conditions for each burner type. For the flame-retention head burner, more smoke is generated during startup than during shutdown. Higher startup smoke is evident with the test fuels containing all aromatic compounds, and the light cycle oil (LCO). The effects of sulfur content (up to 0.7%, high sulfur), and aromatic effects up to 56% by volume (high arom.) were small.

The most significant effects observed were for fuels with high viscosities when burned in the flame-retention head burner. During startup, the smoke number for the high viscosity fuel (5.0 cSt) measured #8 on the Bacharach scale; the smoke number for the fuel with viscosity 8.0 cSt (and also, a high aromatic content) was exceedingly high (beyond the scale range) and could not be adjusted for clean burning conditions even with high excess air. Under these circumstances, other emissions could not be measured because the flame burned erratically and periodically went out. Similarly, excessive smoke beyond the scale range was observed for the high viscosity/high aromatic fuel when introduced into the high static-flame retention head burner.

In terms of fuel properties, the data for the air atomized burner show a similar trend for the shutdown condition; however, its overall effects are relatively smaller than those for the flame-retention head burners. Higher smoke was observed for the

Smoke No.

Figure 3. Smoke Number - Cyclic Operation

100% aromatic fuel as well as with the high viscosity/high aromatic fuel. This particular type of burner can operate with relatively low excess air and is tolerant of a wide range in fuel viscosity. The fuel with viscosity of 5.0 cSt and LCO showed little change in smoke from the baseline fuel.

For fuels within small ranges, such as ASTM standards, the differences in properties in terms of sulfur and aromatics content, and viscosity, do not significantly affect smoke number. Viscosity effects become important at approximately 5.0 cSt which is beyond the upper ASTM limit of 3.4 cSt.

5.2 Gas Phase Emissions

Carbon monoxide (CO) exhausted with the flue gas results from incomplete combustion which can be caused by insufficient fuel-air mixing or insufficiently high temperatures within the combustion zone. These conditions generally occur for very short times (about 30 seconds or less) during startup and shutdown, and result in higher CO emissions compared to the steady periods during the on-cycle. Figure 4 shows the average peak CO emissions, expressed in ppm for each fuel and burner type. For the flame-retention head burner and the high static-flame retention head burner, CO emissions are important during startup; the opposite is observed for the air-atomized burner. The most significant effects occur with highly viscous fuels. In fact, data was not obtainable for the fuel with viscosity 8.0 cSt (also containing high aromatics), for reasons discussed in Section 5.1. Elevated CO was observed for one of the high sulfur fuels, but when repeated, the concentration dropped back to near baseline levels. Generally, CO levels change more dramatically with the differences in burner design than in fuel characteristics.

Nitrogen oxides, NO_x, (a combination of nitrogen oxide, NO, and nitrogen dioxide, NO₂) in the flue gas are formed when No. 2 oil is burned in air. The major constituent, NO, is formed from the high temperature reaction with atmospheric nitrogen and oxygen, and from the burning of nitrogen contained in the fuel. NO_x concentrations increase after the burner starts up and reach a steady level; when the burner is shut off, levels drop. The average concentrations during the steady on-period are shown in Figure 5. By convention, emissions are generally reported as though the compound emitted were NO₂, in pounds per million Btu (lbs/MBtu). NO_x concentrations do not vary much with a particular burner for various fuel types, and the small fluctuations observed can be attributed to the different amounts of nitrogen in the fuel. When comparing NO_x compounds emitted by the various burners, on average the air-atomized burner yields slightly higher levels.

CO Emissions

Figure 4. Carbon Monoxide Emissions - Cyclic Operation

Figure 5. Nitrogen Oxides Emissions

We did not measure hydrocarbon emissions because they are expected to be generally very low for residential heating systems. Earlier studies at BNL for modern burners indicate that the value is about 10^{-3} lbs/million Btu [9]. In fact, all gas phase emissions measured agree fairly well with this reported data.

5.3 Particulate Emissions

Total particulate matter (soot) was collected during startup and shutdown. The maximum amount of soot is generated during these transient periods and concentrations decay quite rapidly afterwards. While the burner is firing steadily, very little soot is produced. Table 2 shows the data and the calculations used to determine soot emissions; the results are presented on the graph below. Two measurements were made for each fuel type - baseline, low sulfur and low aromatic. Particulates were measured to evaluate the benefits of low aromatic and low sulfur fuels.

PARTICULATE EMISSION CALCULATIONS						
OPERATING CONDITIONS	Base1	Base2	Fuel Lo Sulfur1	Type Lo Sulfur2	Lo Arom1	Lo Arom2
%O ₂	6.10	6.10	6.00	6.00	6.80	6.80
%Excess Air	38.28	38.28	37.40	37.40	44.77	44.77
Mol. Wt. of dry gas, lb dry gas/ mol dry gas	30.02	30.02	30.03	30.03	29.97	29.97
Specific volume of dry flue gas, dscf/lb dry gas	12.84	12.84	12.83	12.83	12.86	12.86
lb dry gas/lb fuel	19.63	19.63	19.50	19.50	20.56	20.56
Total particulate collected, mg	5.00	6.40	8.60	6.80	5.50	5.50
Total volume of dry sample collected, cu. ft.	167.99	168.06	165.25	160.15	168.87	167.51
Sample temperature, F	83.48	83.66	80.24	80.06	80.06	80.40
Sample pressure, psi	14.41	14.41	14.41	14.41	14.41	14.41
Total volume of dry sample collected, dscf	159.99	160.00	158.32	153.48	161.84	160.43
Fuel flow rate, gal/hr	0.391	0.391	0.4	0.4	0.396	0.396
Measured particulate concentration, mg/dscf	0.0312528	0.0400002	0.05432042	0.044304	0.0339838	0.03428228
Particulate emissions, lb/million Btu (lb/MBtu)	0.0008918	0.0011414	0.00153967	0.0012558	0.0010174	0.00102636
Particulate emissions, lb/1000 gal	0.12	0.16	0.22	0.18	0.14	0.14

Particulate Emissions

There were very small differences in the amount of particulate matter emitted in the flue gas for low sulfur and low aromatic fuels compared to the baseline fuel, with an overall average of roughly 0.16 lbs/1000 gallons. Emissions from an improperly adjusted burner can fluctuate up to ten times this amount. In general, these emissions are extremely low in comparison with other types of combustion sources.

5.4 Startup Characteristics

The variation of static pressure within the combustion chamber during startup was investigated to determine the ignition characteristics. Upon ignition, there is a surge in pressure caused by the rapid expansion of high temperature combustion gases. Figure 6 illustrates a typical measurement as observed on an oscilloscope. The pressure in the chamber is measured with a transducer and a voltage signal is obtained, which is shown on the curve as the amplitude. This value can be expressed in inches of water pressure. Ignition does not necessarily occur simultaneously when the burner starts ($t=0$). Some burners, such as the flame-retention head burners (AF and RL) have solenoid valves that delay the delivery of fuel to the nozzle until after the burner fan has started. Figure 7 shows peak pressure values for the various burner and fuel types ranging from less than 0.5 in. to almost 3.0 in., depending on the type of burner. Differences in peak pressures upon ignition are dominated by differences in the design of the burner. The transition period of high amplitude lasts up to about 0.1 seconds, then the oscillations decay to much smaller fluctuations.

The high static-pressure retention head burner had the lowest startup peak pressures, and therefore, had the greatest stability. Other studies have shown that the maximum static pressure of the burner fan and the initial pressure peak in the combustion chamber is an important design parameter that influences startup stability in small oil-fired boilers [10].

In general, the variations between fuel types for a particular burner are small. However, the peak pressure for the high viscous fuel (5.0 cSt) showed a large spike at 4 in. with the flame-retention head burner compared to the average value of 1.5 in. This sudden rise in pressure indicates that a greater amount of fuel vaporized and may result from larger droplets forming from the viscous fuel. Even after the startup, the pressure continued to fluctuate due to nonuniform combustion. These results are consistent with smoke number measurements which were very high at startup (Smoke #8) and lower but still significant during the entire on-cycle (Smoke #3).

Figure 6. Example of static pressure variation at burner startup

Figure 7. Transient Pressure during Startup

6.0 CONCLUSIONS

The type of burner, how it is setup, and the operating conditions of the system are important factors to consider when evaluating combustion performance. Based on this study, these factors outweigh the effects of variations in fuel property, especially if the properties do not exceed such ranges as those established in the ASTM limits. These findings are fairly consistent with studies conducted in the early 1970s of emissions from burning domestic heating oil. In the range of practical operating conditions, there is no significant effect of fuel composition on the emissions of carbon monoxide, total hydrocarbons, nitrogen oxides, and mass particulates [11].

The viscosity of the fuel is one of the most important properties affecting performance because it varies to a great extent with fuel temperature, and affects the atomization of the oil. Much larger effects are found with fuels with varying viscosities. Viscosity can fluctuate slightly from one batch of fuel to the next, but overall changes are dominated by the effects of temperature. For these tests, fuels were specifically blended to obtain a broad range of viscosities. During steady-state operation, burner performance varies slightly with viscosity (up to 5 cSt). However, more dramatic changes are observed during cyclic operation. As fuel viscosity increases substantially, poor atomization can occur. At high viscosities (approximately 5 cSt) smoky conditions will occur during cyclic operation. When the boiler unit is running continuously during steady state, the combustion chamber and the oil recirculating within the burner housing remains warm, thereby minimizing the effects of highly viscous fuels.

These results show that burner performance does not vary much with sulfur content (up to .70%) or aromatics (up to 56%). Slight degradation in terms of elevated smoke emissions occur for the flame-retention head burner at the aromatic concentration of 100%, which is a level that would not be found with typical No. 2 oil. It is likely that a burner which is out of tune, or operating conditions that are unfavorable would cause this same degree of degradation or worse. In other words, changes to equipment and operating conditions have a bigger effect on burner performance than the effect of fuel type.

7.0 DISCUSSION

At the end of 1993, low sulfur distillate fuel will become available for use in transportation. Although this study shows very small differences in the performance of heating systems with fuels of varying sulfur content, in terms of particulate, CO, and NO_x emissions, other benefits can be realized with a low sulfur fuel. Sulfur oxides (SO_x) emitted to the atmosphere will be reduced because the amount of SO_x in the flue gas is directly related to the amount of sulfur in the oil. A small portion of the sulfur oxides (less than 5%) is converted to sulfuric acid in ambient conditions.

BNL has started a long-term study to correlate fuel sulfur content with the degradation of equipment. It was found that sulfur levels do correlate well with corrosion and fouling rates of the heat exchanger; the lower the sulfur content, the lower the rates of oxide scale formation and

deposition. This work is part of the ongoing BNL program to minimize soot formation in oil-fired heating systems.

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9.0 APPENDIX

Example Calculation - Pollutant Emission Rates

EXAMPLE CALCULATION - POLLUTANT EMISSION RATES

This section provides the raw data on the flue gas analysis and the derived concentrations of gaseous emissions corrected on a standard basis of 3% oxygen in the duct. Complete burning of No. 2 oil is assumed (with constant composition) to obtain the products of combustion.

I. The products of combustion are calculated as follows:

Given-		Flue Gas	
Fuel Analysis		O ₂ := 6	%oxygen, dry basis
%Carbon	C := 87.3	CO := 96	ppm, dry basis
%Hydrogen	H := 12.5	NO _x := 112	ppm, dry basis
%Sulfur	S := 0.21		

$$(1) \quad \beta := \frac{C}{12} + \frac{H}{4} \quad \text{where } \beta \text{ is a convenient collection of terms}$$

$$(2) \quad \alpha := O_2 \cdot \frac{\frac{C}{12} + 3.76 \cdot \beta + \frac{S}{32}}{100 \cdot \beta - 4.76 \cdot O_2 \cdot \beta} \quad \text{where } \alpha \text{ is the excess air coefficient}$$

$$\alpha = 0.375 \quad (37.5\% \text{ excess air})$$

$$(3) \quad CO_2 := \frac{C}{12} \quad CO_2 = 7.275 \text{ moles}$$

$$(4) \quad N_2 := \left(\frac{C}{12} + \frac{S}{32} + \frac{H}{4} \right) \cdot (1 + \alpha) \cdot 3.76 \quad N_2 = 53.786 \text{ moles}$$

$$(5) \quad O_2 := \left(\frac{C}{12} + \frac{H}{4} + \frac{S}{32} \right) \cdot \alpha \quad O_2 = 3.898 \text{ moles}$$

$$(6) \quad SO_2 := \frac{S}{32} \quad SO_2 = 0.007 \text{ moles}$$

$$(7) \quad H_2O := \frac{H}{2} + \left(\frac{C}{12} + \frac{H}{4} + \frac{S}{32} \right) \cdot (1 + \alpha) \cdot 0.01 \cdot 7.61$$

$$H_2O = 7.339 \text{ moles}$$

where 0.01 is the assumed ambient moisture content (lb/lb dry air)

$$\text{Total moles of dry gas (as fired)} \quad CO_2 + N_2 + O_2 + SO_2 = 64.966$$

$$\text{Total moles of dry gas (3\%)} \quad = 54.142$$

$$\text{lbs dry gas/100 lb fuel} \quad CO_2 \cdot 44 + N_2 \cdot 28 + O_2 \cdot 32 + SO_2 \cdot 32 = 1.951 \cdot 10^3$$

II. Emissions at 3% O₂ basis:

$$(8) \quad NO_x \text{ (at 3\%)} = NO_x \cdot \frac{64.966}{54.142} = 134.391 \quad \text{or} \quad NO_x \cdot \frac{46}{10^6 \cdot 30.035} \cdot 19.51 \cdot \frac{7.2}{0.14} = 0.172 \quad (\text{lbs/MBtu})$$

where 30.035 is the molecular wt. of dry gas, lb/mol; and 46 is the molecular wt. of NO₂

$$(9) \quad CO \text{ (at 3\%)} = CO \cdot \frac{64.966}{54.142} = 115.192 \quad \text{or} \quad CO \cdot \frac{28}{10^6 \cdot 30.035} \cdot 19.51 \cdot \frac{7.2}{.14} = 0.09 \quad (\text{lbs/MBtu})$$

EMISSIONS CALCULATIONS

	A	B	C	D	E	F	G	H
1	COMBUSTION CALCULATIONS - FIRING No. 2 HEATING OIL							
2	INPUT VARIABLES : %O2, Measured emissions							
3	Assumed typical fuel analysis for No.2 heating oil, 87.3%C, 12.5%H, Ambient moisture cont 0.01 lb/ lb dry air, Stack temperature 345F							
4	Flame retention head burner (AF); air atomized burner (BB); high static flame retention head burner (RL)							
5	Burner	AF	AF	AF	AF	AF	AF	AF
6	Fuel Type	Base	Hi Sulfur	Lo Sulfur	Lo Arom	Hi Arom	All Arom	Lo Visc
7	%O2	6.00	6.30	6.50	5.80	6.10	6.70	6.90
8	%Excess Air	37.39932	40.07024	41.91222	35.67724	38.27768	43.80569	45.75285
9								
10	PRODUCTS OF COMBUSTION							
11	CO2 , moles	7.275	7.275	7.275	7.275	7.275	7.275	7.275
12	N2, moles	53.76253	54.80763	55.52837	53.08871	54.10622	56.26926	57.03116
13	O2, moles	3.891983	4.169934	4.361621	3.712775	3.983391	4.558667	4.761299
14	SO2, moles	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563
15	Water, moles	7.338119	7.359271	7.373859	7.324482	7.345075	7.388854	7.404274
16	moles dry gas/100 lb fuel	64.93608	66.25913	67.17155	64.08304	65.37118	68.10949	69.07402
17	lb dry gas/ 100 lb fuel (CO2,N2,O2,SO2)	1950.204	1988.362	2014.676	1925.603	1962.753	2041.727	2069.544
18	lb water/100 lb fuel	132.0861	132.4669	132.7295	131.8407	132.2114	132.9994	133.2769
19	Mol. Wt. of dry gas, lb/mol	30.03571	30.01184	29.99593	30.05163	30.02776	29.98001	29.9641
20	At 3% O2:							
21	N2, moles	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668
22	O2, moles	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811
23	moles dry gas/100 lb fuel (CO2,N2,O2,SO2)	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006
24								
25	FLUE GAS ANALYSIS							
26	NOx concentration (ppm), dry basis	112	94	113	105	101	88	77
27	CO concentration (ppm) dry basis, startup	96	45	94	81	104	160	81.5
28	CO concentration (ppm) dry basis, shutdown	19	11	19	23	22	30	16.5
29	Smoke No. - startup peak	2	2.5	1.5	1.5	2.25	5.25	3
30	Smoke No. - shutdown peak	0.5	0.75	0.25	0.25	0.25	0.25	0.25
31	Pressure - startup peak	1.45	1.6	1.8	1.5	1.35	0.9	1.1
32								
33	Concentration corrected for 3% O2							
34	NOx concentration (ppm)	134.3586	115.0628	140.225	124.3065	121.9745	110.7266	98.25778
35	CO concent (ppm) - startup	115.1645	55.08327	116.6473	95.89361	125.5975	201.321	104.0001
36	CO concent (ppm) - shutdown	22.79298	13.4648	23.57765	27.22905	26.56871	37.74769	21.05524

EMISSIONS CALCULATIONS

	I	J	K	L	M	N	O	P	Q	R	S
1											
2											
3											
4											
5	AF	AF	AF	BB	BB	BB	BB	BB	BB	BB	BB
6	Interm Visc	Hi Visc	LCO	Base	Base	Base	Hi Sulfur 1	Hi Sulfur 2	Lo Sulfur	Lo Arom	Hi Arom
7	5.00	4.80	5.60	3.20	3.90	3.80	3.20	6.35	3.20	3.50	4.00
8	29.21924	27.70435	33.99987	16.81016	21.32564	20.65808	16.81016	40.52602	16.81016	18.70115	22.00105
9											
10											
11	7.275	7.275	7.275	7.275	7.275	7.275	7.275	7.275	7.275	7.275	7.275
12	50.56178	49.96902	52.43238	45.70627	47.47311	47.21191	45.70627	54.98597	45.70627	46.44619	47.73739
13	3.040718	2.88307	3.538218	1.74936	2.219266	2.149796	1.74936	4.217366	1.74936	1.946147	2.289553
14	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563
15	7.273338	7.261341	7.311198	7.175066	7.210826	7.205539	7.175066	7.362881	7.175066	7.190041	7.216174
16	60.88406	60.13365	63.25216	54.73719	56.97394	56.64327	54.73719	66.4849	54.73719	55.6739	57.30851
17	1833.343	1811.701	1901.639	1656.065	1720.574	1711.037	1656.065	1994.873	1656.065	1683.08	1730.223
18	130.9201	130.7041	131.6016	129.1512	129.7949	129.6997	129.1512	132.5319	129.1512	129.4207	129.8911
19	30.11528	30.13119	30.06754	30.25847	30.20279	30.21074	30.25847	30.00786	30.25847	30.23461	30.19483
20											
21	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668
22	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811
23	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006
24											
25											
26	125	100	122	94	187	142	122	118	141	122	155
27	85	145	166	31	79	59	43	46	38	59	79
28	13	115	16	80	112	136	302	72	146	100	163
29	2.5	8	7.5	0.25	0.25		0.25	1	0.25	0.25	1.25
30	0.25	3	0.25	1	0.25		1	1	0.5	0.25	0.25
31	1.1	4	2	2.7	1.6	1.9	2.4	2.2	2	2.8	2.1
32											
33											
34	140.5967	111.0911	142.5597	95.05432	196.8246	148.5929	123.3684	144.9327	142.5815	125.4796	164.1014
35	95.60575	161.082	193.9746	31.3477	83.1505	61.73931	43.4823	56.49921	38.42622	60.68274	83.63878
36	14.62206	127.7547	18.69635	80.8973	117.8843	142.3144	305.3873	88.43354	147.6376	102.8521	172.5712

EMISSIONS CALCULATIONS

	T	U	V	W	X	Y	Z	AA	AB	AC	AD
1											
2											
3											
4											
5	BB	BB	BB	BB	BB	RL	RL	RL	RL	RL	
6	All Arom	Lo Visc	Hi Visc	Hi Arom/Vis	LCO	Base	Hi Sulfur	Lo Sulfur	Lo Visc	Hi Visc	
7	4.70	3.80	3.90	4.70	4.00	5.80	6.40	6.10	5.90	5.20	
8	26.96083	20.65808	21.32564	26.96083	22.00105	35.67724	40.98492	38.27768	36.53258	30.77246	
9											
10											
11	7.275	7.275	7.275	7.275	7.275	7.275	7.275	7.275	7.275	7.275	7.275
12	49.67809	47.21131	47.47311	49.67809	47.73739	53.08871	55.16553	54.10622	53.42339	51.16953	39.12868
13	2.805696	2.149796	2.219266	2.805696	2.289553	3.712775	4.265122	3.983391	3.801786	3.202356	0
14	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563	0.006563
15	7.255453	7.205539	7.210826	7.255453	7.216174	7.324482	7.366515	7.345075	7.331255	7.285639	7.041939
16	59.76535	56.64327	56.97394	59.76535	57.30851	64.08304	66.71222	65.37118	64.50674	61.65345	46.41024
17	1801.079	1711.037	1720.574	1801.079	1730.223	1925.603	2001.429	1962.753	1937.822	1855.532	1415.913
18	130.5982	129.6997	129.7949	130.5982	129.8911	131.8407	132.5973	132.2114	131.9626	131.1415	126.7549
19	30.13915	30.21074	30.20279	30.13915	30.19483	30.05163	30.00389	30.02776	30.04367	30.09937	30.51295
20											
21	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668	45.22668
22	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811	1.621811
23	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006	54.13006
24											
25											
26	135	142	146	170	150	91	83	99	78	104	
27	57	93	48	30	52	95	90	75	137	208	
28	162	188	153	271	258	24	29	23	14	21	
29	1	0.75	1.25	7	1.25	2.25	2.25	2.5	3.5	4	
30	3.25	0.75	0.25	6	1	2	1.75	1.75	1.5	3.75	
31	2.7	2	2.5		2	0.43	0.37	0.46	1.3	1.9	
32											
33											
34	149.0544	148.5929	153.6705	187.6981	158.8078	107.7323	102.2928	119.5592	92.95253	118.4547	
35	62.93407	97.3179	50.52182	33.1232	55.05338	112.4678	110.9199	90.57515	163.2628	236.9094	
36	178.8653	196.7287	161.0383	299.2129	273.1494	28.41292	35.74085	27.77638	16.68379	23.91873	

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