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PERFORMANCE CONTROL STRATEGIES FOR OIL-FIRED RESIDENTIAL HEATING SYSTEMS

PROJECT REPORT

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ABSTRACT

Results are reported of a study of control system options which can be used to improve the combustion performance of residential, oil-fired heating equipment. Two basic control modes were considered in this program. The first is "service required" signals in which an indication is provided when the flame quality or heat exchanger cleanliness have degraded to the point that a service call is required. The second control mode is "excess-air trim" in which the burner would essentially tune itself continuously for maximum efficiency.

A key ingredient in any practical control system for this application is reliable, low-cost sensors and the identification of such sensors has been a primary emphasis of this project. An overview of current sensors used in commercial/industrial boilers and principles of operation is included.

To identify useful measurements, specific parametric studies related to control strategies were performed. These included:

- a) relationships between flue gas CO, smoke, and excess air with selected burners
- b) effects of excess air level, ambient air temperature, boiler water temperature, firing time, and furnace air flow rate on flue gas temperature.

It was found that evaluation of the rate of performance degradation due to heat exchanger fouling can be done very simply using the peak flue gas temperature during heating season firing cycles. Also, CO was not found to be a useful indication of flame quality.

Tests were performed with low cost, automotive type zirconium oxide oxygen sensors. This included units with and without integral electric heating elements. The unheated sensors were installed in the wall of the refractory combustion chamber liner where the steady state temperature was within the proper range for sensor operation. This provided a useful signal related to excess air but unacceptably slow response in cyclic operation. The heated oxygen sensor was installed in the flue and performed well. A small commercial oxygen analyzer system, also using a zirconium oxide sensor, was also found to work well in the flue.

Sensors based on measuring light emission from the flame were identified as a potentially very low cost approach to evaluating flame quality. Detailed spectral emission studies were done over the range 200-1100 nm (ultraviolet [UV] to near infrared [IR]) with conventional pressure atomized burners and one air atomized burner. Useful measures of flame quality include flame brightness, color, and brightness normalized to the OH spectral peak in the UV. A simple, three light flame quality indicator was developed using a photoresistor for input. This low cost system is shown to be very useful for monitoring changes in flame quality between service calls. Costs, and potential benefits of this and other control strategies, including active excess air trim are reviewed.

SUMMARY

Introduction

The goal of the work described in this report is to develop recommendations for control strategies which can be used to raise the efficiency of oil fired heating equipment in service.

The adjusted efficiency of oil-fired domestic heating systems in the home is lower than can be achieved with the same equipment under ideal conditions. Two factors are responsible. First, when burners are serviced excess air is set higher than necessary. This is done in the hope that it will prevent future sooting problems. Also, service personnel often do not use the instrumentation required to set the excess air properly. The second factor is fouling of heat exchanger surfaces over time with products of incomplete combustion, acids and corrosion products.

Two basic control modes can be considered for maintaining high efficiency operation:

- o Service-required signals - in this mode the homeowners or service company would be made aware that smoke production and/or efficiency have degraded to the point that service is required.
- o Steady-state excess-air trim - in this mode the burner would essentially tune itself continuously for maximum efficiency. Excess air would be changed in response to changes in fuel quality, draft, nozzle erosion, etc. to maintain "trace" smoke in steady state.

In implementing these control strategies an input is required which is related to air/fuel ratio and/or flame quality. This type of input could alternatively be used as a service tool. Instead of making excess air and smoke number measurements at a series of points and then selecting a setpoint, the excess air could simply be adjusted until a predetermined control signal is reached. The development of sensor inputs for advanced service tools, while not truly a "control" was considered as a part of the goals of this project.

Estimates of the magnitude of the annual degradation in thermal efficiency based on earlier published studies show considerable variation between units. The average is roughly 2% per year. Principle causes of deterioration are seen as fouling of the heat exchanger surfaces by soot, fouling of the oil nozzle, and changes in air/fuel ratio caused by dust accumulation on the air inlets. Sooting appears to be the key degradation process.

Generally, the introduction of advanced control systems could potentially reduce fuel consumption due to both high excess air and heat exchanger fouling.

Background

A wide variety of systems which control air/fuel ratio are commonly used on commercial and light industrial boilers. Current practice and experience in this area provide a base for considering such systems on a residential scale.

Boilers in this category are typically fully modulating and the control systems function to vary the air/fuel ratio over the load range, increasing excess air as firing rate decreases to avoid smoke. Control systems vary widely and can be roughly categorized with increasing complexity as follows:

1. Preset air/fuel ratio profile
2. Feed forward - O₂ trim
3. O₂ feedback
4. O₂ and CO feedback

A common component in commercial and industrial boiler control systems is the zirconium oxide oxygen sensor. This rugged sensor is heated and installed directly in the flue gas, eliminating the need for a flue gas extraction and conditioning system. Low cost versions of these sensors are also commonly used in automobiles. In this application, however, they are not used to accurately measure exhaust oxygen concentration. They are instead used to control the air/fuel ratio to be roughly near the stoichiometric ratio where there is a very steep slope in the sensor output/oxygen concentration relationship. The output voltage from zirconium oxide sensors is dependent upon both the oxygen content of the exhaust gas and the local temperature. Automotive sensors are commonly unheated, relying instead on the engine heat to raise the temperature to the correct operating range. This adds an additional approximation since the temperature would have to be either controlled or measured to enable accurate exhaust gas oxygen determinations. Newer cars use heated sensors primarily to reduce the warm up time required and to improve the system stability although the temperature control is too coarse for accurate oxygen measurements.

When the flame quality is poor burners emit higher levels of smoke and CO. Measurements of one or both of these parameters are often included in control systems in larger boilers. Smoke which is a good indicator of flame quality, is difficult to measure in residential equipment because of the low levels which are considered to be acceptable. Excessive smoke numbers can be realized even with optical opacities well under 1%. Any on-line smoke measuring system would have to be either extractive or use continuous air purging. Both would add considerable complexity. The use of CO, instead of smoke, as an indicator of flame quality was evaluated in the experimental portion of this project.

In another approach to burner control, light emitted from a burner flame is measured in one or more wavelength bands and this information is used as an indicator of excess air and/or flame quality. In a very rough sense it is an extension of the practical observation that rich flames are dull orange and lean flames are bright yellow. Several research and development groups have worked on this approach for a broad range of applications with promising results. The most difficult applications for optical methods are those which have variable firing rate and/or variable swirl settings. Home heating oil burners have fixed firing rates. As a part of this project detailed optical emission measurements were made in domestic oil-fired systems to evaluate the potential use of this method. Primary potential advantages were seen as low cost and simplicity.

Experimental Measurements and Results

The experimental portion of this project was conducted entirely in the Brookhaven National Laboratory (BNL) Combustion Equipment Technology (CET) Laboratory. All work was aimed at evaluating control options which could meet the goals of this program at low cost. This work specifically included:

1) CO/Smoke Relationship

The relationship between CO and smoke emissions and burner excess air was studied to evaluate the use of CO as an indicator of flame quality. In all cases a measurable increase in flue gas CO, with decreasing flame quality, was observed only after smoke had increased to unacceptably high levels. This result essentially precludes CO as a useful indicator of flame quality. It should be noted that all of these measurements were made in a conventional pressure atomized retention head burner. With air atomized burners, prevaporizing burners, and recirculating type blue flame burners, a preference towards CO has been observed in other studies.

2) Effect of Parameters on Flue Gas Exit Temperature

To monitor the condition of the heat exchanger surfaces the leading candidate is the temperature of the exiting flue gas. This temperature, however, is not constant but changes dramatically over each firing cycle. The steady state value can take five to ten minutes to reach. In addition, the flue temperature can be affected by the boiler water temperature, excess air, and the temperature of the surrounding room. During this project the effect of each of these parameters on the flue gas temperature was evaluated both experimentally and with the aid of a simple boiler model. This was a simple one-pass parallel-flow heat exchanger model and was found to simulate the effects of parameter changes quite well.

Large transients in flue gas exit temperature which occur during normal, cyclic burner operation could be a difficulty in the use of this parameter for monitoring efficiency changes over time. These transients can, however, be handled by monitoring only changes in the peak flue gas temperature which occurs during the heating cycle. A dial type thermometer with a maximum indicating hand could be used for this, for example.

In the case of boilers the flue gas exit temperature is affected by the water temperature. This effect could be reduced by monitoring the flue gas to boiler water differential temperature.

3) Longer Term Degraded Performance Tests

Test were done to determine changes in selected parameters as heating equipment fouls. The parameters examined are candidates for use in control strategies which would monitor efficiency changes over time. This includes flue gas exit temperature, combustion chamber to flue pressure drop, flue pipe surface temperature and flue gas oxygen. Two units, a boiler and a furnace were operated under forced cycles for a period of weeks, with unusually high smoke levels.

The boiler was operated with a 5 minute on- 10 minute off firing pattern and a steady state smoke number of 5. The test duration was 36 days and during this time the burner operated for a total of 289 hours and cycled 3,472 times. With a 1.0 gallon/hour firing rate 289 gallons of oil were consumed during this test. The rise in flue gas temperature observed during this test was 131 F which corresponds to a decrease in thermal efficiency of 2.9%.

In the furnace tests the burner operated 10 minutes on- 15 minutes off with a steady state smoke number of 8. The duration of the furnace test was 50 days. During this time the burner consumed 396 gallons of oil (1.0 gph) and cycled about 2400 times. During the test the flue gas temperature increased 74 F and the excess air decreased from 24% to 14%. At constant excess air this rise in flue gas temperature corresponds to a reduction in efficiency of 1.8%. With the reduced excess air this efficiency decrease is 1.2%.

These tests showed that the most consistent indicator of the efficiency degradation due to fouling is simply flue gas exit temperature. As a lower cost option the flue pipe surface temperature could also be measured. This was found to track the trend in flue gas temperature but the change was smaller in magnitude over time. Changes in the heat exchanger pressure drop were found to be too small to be practically useful.

4) Tests on Oxygen Sensors

Three zirconium-oxide oxygen sensors were tested during this project. This included a commercially available system produced by Nederlandse Philips Bedrijven, B.V. (Netherlands), a typical unheated automotive type sensor, and a heated automotive sensor. The Philips unit was of particular interest because the manufacturer has used it on small commercial boilers and has been pursuing the development of a low cost unit for domestic heating applications. The unit tested during this program is essentially the larger unit used in Europe modified for 60 cycles, 110 volt operation.

To utilize an unheated automotive type oxygen sensor in a residential system it must be located in a place where it will be heated to 900-1600 F. To achieve this the sensor was located in the upper region of the refractory combustion chamber of a dry base steel boiler. The heated automotive sensor which uses a positive temperature coefficient electrical heating element to maintain the zirconium oxide in its proper temperature range, was installed in the flue of the same boiler. The Philips oxygen analyzer was also installed in the flue.

The output signal from the two automotive sensors was simply a voltage which varies with both oxygen concentration and sensor temperature according to the Nernst relation (see Section 2.2). To calculate the oxygen concentration the temperature of the automotive sensor casings was measured with an attached thermocouple. Because this is only an estimate of the effective temperature of the zirconium oxide the calculated oxygen concentration will only be approximate. While this approach may not be acceptable in larger boilers it may be suitable for small residential units where the costs are more constrained. The primary demand on a dedicated

oxygen sensor is that it provide a repeatable and reliable indicator of the excess air, but not necessarily a very accurate one.

Both the heated and the unheated automotive oxygen sensors provided a repeatable signal which responded well to excess air changes. In the case of the unheated sensor, however, the difference between the calculated and measured oxygen concentration was very large and the response of the sensor in cyclic burner operation was unacceptably slow. The heated sensor produced much better time response and calculated excess air levels agreed to within about 15% of those measured independently. In quantity, the estimated costs of the unheated and heated automotive sensors are \$20, and \$30, respectively.

The output from the Philips unit is flue gas oxygen concentration directly. This unit preformed very well, accurately indicating oxygen concentration even at very high smoke numbers. No fouling of this sensor or change in its output was observed in 6 hours of cycling operation with the burner set for a steady state smoke number of 9.

5) Measurements of Flame Optical Emissions

Studies of flame optical emissions for control purposes evolved during the coarse of this program into a primary focus. This occurred because the preliminary results indicated good promise for low cost approaches toward indicating flame quality.

Measurements of the intensity of light emitted from oil burner flames were made as a function of wavelength ("spectral intensity") using an arrangement illustrated in Figure S-1. In this arrangement a liquid light guide is used to carry the light signal from the burner air tube area to an external monochromator which separates the light into narrow wavelength bands, and finally to a detector. Additionally, some measurements were made using simply a plain sensor located in the burner air tube just behind the retention head. These were "broadband" measurements because the sensors used responds to light over a wide wavelength range.

Figure S-1. Optical Arrangement for Spectral Intensity Measurements.

Figure S-2. Illustration of the spectral intensity of radiant energy emitted from an oil burner flame showing both "continuum" and narrow band peaks. [Note - This figure is for illustration only and is not derived from specific data. UV - ultraviolet; VIS - visible (400-700 nm); IR - infrared]

Figure S-3. Example of measured spectral intensity of radiant energy from an oil flame over the ultraviolet and part of the visible range.

The general nature of the light emitted from oil burner flames is illustrated in Figure S-2. The emission could be considered to have two basic parts. The first is the "continuum" emission which is like a black body curve and is due to emissions from soot particles in the flame. The second part is smaller peaks due to emissions from specific gas phase species in the flame. An example of the data obtained over the ultraviolet (UV) and part of the visible range is provided in Figure S-3. This clearly shows the peak centered at 310 nm wavelength which is due to emission from OH. The remainder of the emission is the continuum emission.

These optical studies were performed over a broad range of conditions. Parameters examined in this work included excess air, firing rate, nozzle spray pattern, nozzle condition, fuel quality, combustion chamber refractory liners, and transient effects during cyclic operation.

General conclusions include the following:

- 1) As burner excess air increases the continuum intensity decreases, the apparent flame color tends to increase, and the intensity of the OH peak in the UV is fairly constant.
- 2) Simply monitoring the intensity of the broadband emission from the flame was found to be a very useful indicator of the excess air. It is possible, for example, to set the excess air in the burner to produce a specific level of broadband intensity. This could be accomplished using a simple sensor like a cadmium sulfide photoconductor ("Cad Cell"). The setpoint established in this way was found to produce an acceptable setpoint with a wide range of nozzles from 0.5 to 1.0 gph. The setpoint was found, however, to be dependent on the details of the combustion chamber and refractory liner which the burner is fired into.
- 3) Monitoring of the "color" of the flame, which could be done through the ratio of the continuum intensity in two wavelength regions, was found to be useful only if the flame was viewed from the back end of the boiler. An advantage of using a ratio of two intensity signals is reduced sensitivity to fouling of the sensor heads. Viewing the flame from the back end of the boiler has the disadvantage of requiring an added penetration into the combustion chamber. In addition an air purge would be required to keep the sensors cool. When the flame is viewed from within the burner air tube normal combustion air flow serves to cool the sensors. Color was not found to be consistently useful from this viewpoint, however.
- 4) As an alternative to using simple continuum intensity for indicating flame condition the ratio of the continuum intensity to the intensity of the OH peak could be used. This should provide a system less sensitive to drift due to sensor fouling. The addition of the OH signal would add considerably to the cost, however.

Considering the results of these optical measurements one control system approach was selected for additional development. This is the use of a single, broadband sensor mounted within the burner air tube for

indicating flame brightness. If used in a specific burner mounted in a specific combustion chamber this system could be used to aid in the initial adjustment of the burner. For general retrofit in existing systems or arbitrary new units the system could be used to monitor performance changes between service calls. The setpoint in this general case would have to be established at each site. With this simple approach, the burners would be serviced before the efficiency has degraded due to soot fouling of the heat exchanger. Equipment reliability would be improved greatly. The cost associated with this system is estimated to be about \$20.

Control System Options

Experimental results from this project suggest a number of approaches for control systems. The simple optical system discussed above could be very useful for monitoring changes in flame quality between service calls. As a next step an approach of this type could be used for adjusting excess air. This would provide a rapid, accurate method of adjusting burners during servicing. Results of measurements with different equipment, however, have shown that the setpoint is dependent upon the combustion chamber. For this reason such a simple system would be most readily adapted in new matched boiler/burner units. As a further step, burners which have automatic excess air trim could be considered. For this purpose neither an optical sensor nor a flue gas oxygen sensor alone would provide a reliable input signal and both should be used. Implementation of excess air trim could be done using dampers, a variable speed burner pump motor, or, in the case of induced draft systems, a variable speed draft inducer. A burner system with automatic control of this type would roughly double the burner cost.

Four specific control approaches are listed below and compared with regard to cost and potential savings.

<u>Approaches</u>	<u>Cost</u>	<u>Potential</u>	
		<u>Savings (%)</u>	<u>Payback (Years)</u>
1. Peak Hold Dial Type Thermometer	\$ 35	2	2.2
2. Optical Flame Quality Monitor (single sensor)	\$ 20	2	1.3
3. Optical Service Tool	\$ 20	6	0.5
4. Automatic Feedback Air Trim	\$150	6	4.2

Because of the attractiveness of the simple optical flame monitor, work is continuing to establish the reliability of this system under actual field conditions, and its market potential.

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DEFINITIONS AND NOMENCLATURE

Some of the terms which are used in this report may not be familiar to all readers. To make the report generally more understandable and to ensure that the intended points are communicated, definitions for selected terms (primarily dealing with light emission studies) are provided below:

Adiabatic flame temperature -	the temperature that a flame would reach if there were no heat loss from the combustion zone.
Banded radiation -	radiant energy emitted from a body which is contained within one or more specific, narrow wavelength bands.
Broadband -	with a very wide wavelength band. In this report some sensors are referred to as broadband. This means that these sensors respond to light over a wavelength range. An example of this is the cadmium sulfide photoconductor ("cad cell") which responds to all visible light and also infrared light over a limited range.
Continuum -	light which varies in intensity smoothly as wavelength changes. Light from a black body is a continuum. Light from specific gas phase species in flames shows sharp peaks only at specific wavelengths. This type of light emission is not a continuum.
Emission spectra -	this refers to illustrations of emitted radiant energy as a function of wavelength.
IR -	infrared
Luminous -	emitting visible light. Oil burner flames are typically luminous because of the visible light emitted by incandescent particles.
mW/nm-cm ² -	unit used in this report to express spectral intensity. The light energy hitting the sensor per unit sensor surface area and per unit wavelength bandwidth.
Monochrometer -	an instrument which transmits light in a narrow wavelength band. The wavelength transmitted is adjustable. When used with a suitable detector a monochrometer can be used to study the spectral intensity of a light source.
nm -	nanometers (1000 nm = 1 micron); wavelength unit
Spectral intensity -	intensity of radiant energy as a function of wavelength.
Stoichiometric -	(air/fuel ratio) - the correct air/fuel ratio for a specific fuel. At the stoichiometric air fuel ratio there is exactly enough air available to completely burn all of the fuel.
UV -	ultraviolet

1. INTRODUCTION

The thermal efficiency of residential oil fired heating equipment in service is lower than the efficiencies which can be achieved under controlled conditions. Two primary factors contribute to this situation.

- o When equipment is installed and serviced, the burners are not adjusted for minimum excess air.
- o In continuous service, thermal performance deteriorates between tune-ups. This is due in part to soot accumulation on the heat exchanger surfaces.

For maximum thermal efficiency oil burners should have their air/fuel ratios adjusted to produce a "trace" smoke level in the flue. (A "trace" smoke is equivalent to a smoke number between 0 and 1 on the Shell/Bacharach Scale). A burner adjusted this way in steady state, however, will have significantly higher smoke levels during routine, cyclic operation. This is due to three factors: 1) an ignition pressure peak in the combustion chamber which has been shown to produce increasingly severe smoke peaks as excess air is reduced [1]; 2) immediately following ignition the average temperature in the chimney is lower than in steady state, leading to reduced draft and excess air; and 3) immediately following ignition the combustion chamber walls are still relatively cold, also leading to increased smoke. In addition, changes in fuel quality between service calls and excess air changes due to weather conditions might produce a soot problem for burners set with "marginal" excess air. Service personnel adjust burners to have generous excess air levels to prevent problems which might require a return visit to the home. Unfortunately, this results in a relatively poor operating efficiency compared with the maximum level that can be achieved.

Increasing excess air decreases efficiency by increasing the mass flow rate and temperature of the combustion products discarded to the outdoors. To illustrate the magnitude of the effect it is assumed that a burner is adjusted to 9% CO₂ instead of an optimal level, of 12%. This corresponds to 68% excess air vs. the optimal level of about 30%. Stack gas temperature would be about 70°F higher due to the unneeded excess air (Note - this is based on results in section 4.2 of this report). The steady state efficiency would be about 6% lower as a result of the two effects.

The above discussion assumes that the service personnel have the adequate instrumentation to properly set the air/fuel ratio and that they spend the time required to make these adjustments. In many cases burners are installed without proper adjustment leading to very high excess air settings with reduced efficiency and/or service problems.

Estimates of the magnitude of the annual degradation in thermal efficiency based on earlier published studies, show considerable variation between units. An average degradation of 2% per year has been used [2]. Some additional data on degradation rates is available from a recent study performed by the Alliance to Save Energy [3], on energy savings associated with the retrofit of flame retention head burners in low income housing. Initially, with the new burners, efficiency increased by an average of 20%. Over the five years following the retrofit one-third of that efficiency increase was lost. Principal

causes of deterioration are seen as fouling of the heat exchanger surfaces by soot, fouling of the oil nozzle, and changes in air/fuel ratio caused by dust accumulation on the air inlets. Sooting appears to be the key degradation process.

Generally, the introduction of advanced control systems could potentially reduce fuel consumption due to both high excess air and heat exchanger fouling.

1.1 Project Goal

The goal of this project is to develop recommendations for control strategies and systems for improved efficiency of oil-fired residential equipment, based on current technology.

Two basic control modes can be considered for maintaining high efficiency operation:

- o Service-required signals - in this mode the homeowners or service company would be made aware that smoke production and/or efficiency have degraded to the point that service is required.
- o Steady-state excess-air trim - in this mode the burner would essentially tune itself continuously for maximum efficiency. Excess air would be changed in response to changes in fuel quality, draft, nozzle erosion, etc. to maintain "trace" smoke in steady state.

In implementing these control strategies an input is required which is related to air/fuel ratio and/or flame quality. This type of input could alternatively be used as a service tool. Instead of making excess air and smoke number measurements at a series of points and then selecting a setpoint, the excess air could simply be adjusted until a predetermined control signal is reached. The development of sensor inputs for advanced service tools, while not truly a "control" is considered as a part of the goals of this project.

The service-required signal mode would reduce fuel consumption by reducing operating time in a degraded condition. The control approach might be as simple as monitoring stack temperature as an indicator of fouling. The simplicity of this approach is a great advantage. A disadvantage of this approach, however, is that the homeowner is alerted only after the heat exchanger surfaces have become fouled. A control system which alerts the homeowner when the burner has just started producing high smoke could eliminate the need for disassembly and cleaning of the unit. Potentially this mode could be achieved by measuring smoke, gaseous hydrocarbons, CO, or flame optical emissions ("color").

1.2 Report Organization

Control systems are routinely used in larger commercial-sector and industrial boiler applications. In Section 2.1 of this report, control practice in these systems and the relevance to smaller residential applications is reviewed.

In larger boiler systems, controls commonly use flue gas oxygen content, CO, combustibles or opacity. Technology for O₂, CO, and combustibles sensors, which has advanced significantly in the past ten years, is reviewed in Section 2.2 of this report.

Optical methods of flame diagnostics have received increasing attention in recent years. This approach has been applied to systems ranging from pulverized coal-fired utility boilers to kerosene-fired space heaters. In Section 2.3, progress in this area and its potential are discussed.

To monitor the condition of the heat exchanger surfaces the leading candidate is the temperature of the exiting flue gas. This temperature, however, is not constant but changes dramatically over each firing cycle. The steady state value can take five to ten minutes to reach. In addition, the flue temperature can be affected by the boiler water temperature, excess air, and the temperature of the surrounding room. During this project the effect of each of these parameters on the flue gas temperature was evaluated both experimentally and with the aid of a simple analytical model.

When a burner is operated without sufficient combustion air or has low-quality atomization the result is the emission of products of incomplete combustion: carbon monoxide, hydrocarbons and "soot." For control purposes any one of these three could be considered as an indicator of poor quality combustion and the need for either service or additional excess air. During this project the relationship between smoke and carbon monoxide was studied experimentally for typical residential heating equipment. CO was considered particularly important because of its use for this purpose in larger boilers. The relationship between smoke and gaseous hydrocarbons was not examined in this specific project although some information on this relationship is available from other BNL projects. Generally flue gas hydrocarbons are a poor indicator of smoke -- increasing significantly only at very high smoke levels.

Control systems for larger boilers frequently use zirconium oxide probes to measure flue gas oxygen concentration as an indicator of excess air. These probes are typically fairly large and expensive relative to the residential application. Experimental studies on low cost zirconium sensors which might be used for home heating systems have been performed during this project.

Because of their potential simplicity, optical measures of flame condition could be very useful for residential oil burners. Data on the spectral intensity of emitted radiation have been obtained over a broad range of conditions to evaluate this approach.

Details of the experimental methods are described in Section 3 of this report and results are described in Section 4. In selecting any control strategy an important consideration is the availability and cost of suitable sensors and indicators or actuators. In Section 5 methods of implementing the optical measurements, shown to be useful in Section 4, are discussed. Also discussed are the methods and costs for a local flame quality indicator, a telephone link system, and active excess air trim. In Section 6 integrated control strategies which are suggested by the work in this project are compared in cost, energy savings potential and practical factors. Conclusions are listed in Section 7 and in Section 8 specific recommendations for future control systems are discussed.

2. BACKGROUND

2.1 Control Practice in Commercial and Industrial Boilers

A wide variety of systems which control air/fuel ratio are commonly used on commercial and light industrial boilers. Current practice and experience in this area provide a base for considering such systems on a residential scale. Boilers in this category are typically fully modulating and the control systems function to vary the air/fuel ratio over the load range, increasing excess air as firing rate decreases to avoid smoke. Control systems vary widely and can be roughly categorized with increasing complexity as follows:

1. Preset air/fuel ratio profile
2. Feed forward - O₂ trim
3. O₂ feedback
4. O₂ and CO feedback

The most common method of implementing a preset air/fuel ratio profile over the load range is with a simple mechanical linkage or "jackshaft" controlling both fuel and air flow. An adjustable profile cam on the fuel valve allows for manual modification of the relationship between air/fuel ratio and load. Pneumatic or electrical actuators could also be used in place of the mechanical linkage.

In the next level of complexity, feed-forward control, fuel and air flow rate are measured and adjusted automatically to produce the desired air/fuel ratio over the load range. Relative to the preset air/fuel ratio method this mode can compensate for changes in atmospheric conditions, fuel pressure in systems firing gas and some changes in burner adjustment or performance.

With the third level of control, O₂ feedback, flue-gas oxygen is measured (typically with a zirconium probe) and this is fed back to trim the air/fuel ratio. A disadvantage of feedback systems based on O₂ only is a strong effect of air infiltration into the flue. Another limitation of trim systems based on O₂ alone is an inability to detect a burner which is operating badly because of some upset not related strictly to excess air (e.g. fouled nozzle or high viscosity oil).

This last consideration is addressed by the fourth mode in which a CO monitor is added. Hydrocarbons or opacity could replace or supplement CO but this is less common, particularly in small boilers. The advantage seen for CO is that it generally "leads" other parameters when excess air is decreased.

2.2 Methods of Analysis of Combustion Products

Oxygen Analyzers

Available oxygen measurement methods can be divided into the following four broad categories:

1. Paramagnetic
2. Wet Electrochemical
3. Solid Electrolyte (zirconium oxide)
4. Semiconductors

Paramagnetic analyzers take advantage of the magnetic susceptibility of O_2 . Details of the analyzer designs vary but the basic approach is similar in most systems. The extracted gas sample is dried and filtered and fed to the measurement chamber at a controlled temperature. A magnetic field is imposed which creates a "magnetic wind," the strength of which is dependent upon oxygen content. These analyzers are frequently used in laboratory applications but are generally not used in smaller boiler control applications.

Wet electrochemical sensors are very commonly used in low-cost, portable oxygen analyzers. The sensor is an electrochemical cell with an aqueous electrolyte solution. Cell life is typically 6 to 9 months and is limited by anode consumption. Wet electrochemical based systems are generally not intended for continuous service and must be fed flue gas which has been cleaned, cooled and dried.

Of the oxygen measuring methods, the solid electrolyte is perhaps the most important because of its widespread use for combustion control applications. Figure 1 illustrates a solid electrolyte sensor schematically. It consists of the electrolyte (zirconium oxide ceramic partially stabilized with yttrium) and porous platinum electrodes on the reference and flue-gas sides. At high temperatures the solid zirconium ceramic becomes conductive to oxygen ions (O^{2-}). An external voltage is produced which is related to the flue gas oxygen content, the reference gas oxygen content, and the temperature by the Nernst equation:

$$V = 0.0119 \cdot T \cdot \ln \frac{[O_2]_R}{[O_2]_F}$$

where

V = output voltage (mv)

T = temperature ($^{\circ}R$)

$[O_2]_R$ = oxygen partial pressure on the reference (ambient) side

$[O_2]_F$ = oxygen partial pressure on the flue gas side

Figure 2 illustrates the relationship between output voltage and excess air for a zirconium-oxide oxygen sensor over the range of O_2 concentrations typically found in the flue gas from residential oil-fired heating equipment. At the stoichiometric fuel/air ratio (0% flue gas O_2) there is a large change in the output voltage (termed the "lambda jump") which is somewhat insensitive to sensor temperature. This behavior is used in automotive applications to control the air/fuel ratio near stoichiometric in engines equipped with catalytic converters. These systems do not use heaters to control the sensor temperature and so cannot be used to accurately determine air/fuel ratio under lean conditions.

Figure 1. Solid Electrolyte Oxygen Sensor.

Figure 2. Output Voltage of Solid Electrolyte Oxygen Sensor.
(From Ref. 3).

Probes for measuring oxygen content in boilers for control purposes typically contain a thermostatically controlled chamber for the sensor and some means to ensure adequate flue-gas flow through this chamber. Details of commercially available probes vary. In some systems flue gas diffuses into the sensor chamber through a porous medium. Others use the difference between gas stagnation and static pressure ("velocity head") to drive flue gas through the chamber. In some cases an air driven aspirator is used to pull flue gas through the chamber, possibly through a coarse filter in dirty gas flows.

As the temperature of the zirconium oxide electrolyte is decreased, the conductivity drops and as a result the response time increases. At sensor temperatures below 900°F in automotive applications deposits foul the zirconium sensors. Over 1600°F sensors can suffer physical damage. For boiler control applications sensors are typically heated to about 1200°F.

Under lean conditions (>3% O₂ i.e., greater than 16% excess air) the output voltage of solid electrolyte sensors is more sensitive to temperature changes than to changes in oxygen content. Several alternate approaches have been developed which increase the relative sensitivity to oxygen content. One such approach is termed "current mode" or Faraday type configuration. In this case an external voltage is imposed on the zirconium oxide cell, causing oxygen ions to be driven across the electrolyte. A diffusion barrier is placed between the flue-gas flow and the surface of the cell, which greatly limits the flow of oxygen to the surface. The driving voltage is maintained high enough so that the oxygen partial pressure at the surface is essentially zero. The current in the external circuit is dependent upon the rate of arrival of oxygen at the surface.

The output current is linearly related to oxygen concentration in the exhaust by:

$$I = 4FK_D P_e$$

where:

F = Faraday Constant

K_D = Diffusion Constant for Barrier

P_e = Partial Pressure of Oxygen in the Exhaust Gas.

Unfortunately, the value of K_D is not independent of temperature but increases as (T^{0.75}) [5]. The net result relative to voltage mode sensors is increased oxygen sensitivity and reduced (but not zero) temperature sensitivity. An oxygen sensor for small heating boilers using this approach was developed in a program conducted by Brown Boveri [6]. An orifice-type diffusion barrier was used in this design.

Another very interesting approach toward eliminating the temperature sensitivity has been developed by Franx [7,8,9] (Elcoma Division of Nederlandse Philips Bedrijven B.V., Netherlands). The system uses a pair of solid electrolyte cells and an involved cycle pumping method to eliminate the temperature sensitivity. Reportedly it is "ideal for... high efficiency self-controlling domestic oil fired and gas fired boilers" [8]. As discussed in the next sections of this report a prototype model of this sensor has been tested in this project.

In the fourth method, semiconducting oxides are used as the oxygen sensor. These have a resistance which is dependent on the oxygen content of the surrounding gas. Sensors are constructed with a high surface area (thin film or low density pellet) and are operated at fairly high temperatures (1300-1650°F). The relationship between oxygen and resistance is given by [10]:

$$R = R_0 \exp \left[\frac{E_A}{KT} \right] P_{e1/n}$$

where

- R = sensor resistance
- R₀ = a constant for the materials and geometry
- E_A = activation energy, a material constant
- K = the Boltzmann constant
- T = absolute temperature
- P_e = oxygen partial pressure
- n = constant

Like the zirconium oxide sensors this relationship also produces a large change near the stoichiometric ratio ("lambda jump"). Also, like the zirconium oxide sensors the semiconductor sensors have a strong temperature dependence.

Several metal oxides have been used for oxygen sensing, particularly in automotive applications. The most popular is apparently tin oxide. Relative to zirconium sensors they are considered to be less expensive and less durable.

Ihokura, Tanaka, and Murakami [11] (Figaro Engineering Co., Japan) have reported on the use of a tin oxide sensor in a domestic gas heater. A small piece of the oxide was mounted on a ceramic substrate and platinum electrodes were used to connect with the two lead wires. The entire sensor, which is not temperature controlled measures 40 mm x 6 mm x 2 mm. The sensor basically responds to the lambda jump and would shut off the heater in the event that a fuel rich condition occurred. The system was tested in a cyclic mode from 600 to 1800°F for 12,000 cycles and in a steady mode at 1750°F for 12,000 hours. No change in performance was noted.

Carbon Monoxide Analyzers

Carbon monoxide measurement techniques include the following three methods:

1. Infrared
2. Wet Electrochemical
3. Semiconductors

One of the most common methods of determining the carbon monoxide concentration in flue gas is by measuring the absorption of infrared light at a wavelength at which CO absorbs strongly. Extractive type infrared CO analyzers which must be fed clean, dry flue gas, are very widely used in laboratory

applications. In situ analyzers are also available which measure IR absorption across the stack. These systems are generally very expensive relative to the small boiler market. Wet electrochemical systems are similar to the wet electrochemical sensors used for oxygen determination. Like the oxygen sensors they have the advantage of low first cost and the disadvantages of expendable cells and requiring extractive sampling.

Semiconductor devices are being used increasingly for determination of CO and other reducing gases. When semiconducting oxides are heated to lower temperatures than used for oxygen determination they can be used for CO measurements. At these low temperatures, oxygen cannot come to equilibrium with the bulk solid. Resistance is then affected by adsorption of gas molecules on the surfaces of cracks [10]. These systems are very widely used to detect gas leaks in homes in Europe and Japan. A semiconductor based CO detector which shuts down gas appliances when ambient CO exceeds 50 ppm has recently received AGA approval. The manufacturer (Quantum Group Inc.) has recently reported on the development of a chemioptical device which might be used on heating equipment and cost less than current designs. An AC powered, ceiling mounted home detector for smoke and CO is also available which uses a semiconductor sensor (BDC Electronics). This sensor can give false alarms due to non-CO sources like paint thinners. Use of these semiconductor sensors for flue gas would require flue gas extraction and conditioning.

Smoke and Hydrocarbons Measurements

In large boilers carbon monoxide measurements are often supplemented with smoke measurements in evaluating performance for control purposes. This typically involves the extinction of light across the stack (opacity). Direct application of this approach to residential oil-fired systems is not practical because the opacity at smoke levels that are generally accepted as excessive is still well under 1%, which is difficult to detect accurately [1]. In reviewing alternative approaches for examining transient smoke, BNL has developed a multipass system for increased sensitivity [12]. A portable test set developed by Honeywell [13] for measuring smoke numbers in domestic oil-fired equipment used intensity of scattered light (as opposed to intensity of the main beam) measured with a photodiode detector. This approach was selected over other alternatives (e.g. ionization). An extractive sampling system was used.

Any optical system of this type which might be used must include a means for compensating for variations in the source light and fouling of optical windows. These considerations could be the greatest factor in the final cost. At present a suitable system is not available commercially although the basic technical feasibility is not at question.

For determining gaseous hydrocarbons, analyzers based on infrared light absorption are available. Like IR CO analyzers, these can be in situ or extractive and are likely to be prohibitively expensive. As a low-cost alternative, catalytic element sensors have also been developed. The sensor essentially consists of two resistance elements, often in a controlled temperature chamber. One of the elements is catalytic and experiences a temperature rise related to the combustibles content of the surrounding gas. These elements

are low in cost and are widely used for detecting combustible gases in confined spaces. These sensors have been reported to have limited sensitivity and stability and are not typically utilized in control applications.

2.3 Optical Flame Analysis for Control

In another approach the light emitted from a burner flame is measured in one or more fixed wavelength bands and this information is used for control. In a very rough sense it is an extension of the practical observation that rich flames are dull orange and lean flames are bright yellow. In this section, past work and commercial systems which have been developed are reviewed and their potential application to residential systems is discussed. This review serves as a background for some of the experimental studies described in subsequent report sections.

Radiant energy (light) emitted from luminous oil flames can be considered as the sum of two contributions - a continuum which is related to black body radiation at the flame temperature and banded radiation due to specific gas phase species. Figure 3, adapted from Reference 14 (see also [15]) illustrates the differences between a luminous oil flame, a gas flame, a "blue" oil flame, and a black body in the ultraviolet (UV), visible, and near infrared (IR). The bulk of the energy emitted from oil flames is due to infrared radiation at longer wavelengths than shown in this figure. For the luminous oil flame, typical of a pressure gun burner, the continuum emission dominates. For the blue oil flame and gas flame, which are not luminous, the relative importance of the banded radiation is increased.

Development work on an optically based air/fuel ratio controller was performed at the University of Sheffield [16]. The approach which was developed in this work was later commercialized by the Land Co. [17]. The method takes advantage of the observation that the intensity of infrared radiation peaks near the stoichiometric air/fuel ratio. Initial work done at the University of Sheffield involved gas burners. Only narrow band radiation at wavelengths around 4.3 and 2.7 microns was used for control. Note - 1 microm = 1000 nanometers (nm). The 4.3 micron band is primarily CO_2 radiation and the emission at 2.7 microns is due to both CO_2 and H_2O . In later tests with larger burners a very broad wavelength band in the infrared was used for control. This involved an unfiltered lead sulfide detector having a response in the range 1-3.5 microns. In the control application the burner air/fuel ratio is modulated continuously about 1-2% to ensure that the mean air/fuel ratio corresponds to the radiation peak. The University studies also included a domestic warm air furnace and small (75,000 Btu/Hr) kerosene heater. The system reportedly worked well although the data taken was not nearly adequate for the interest of this report. This system has reportedly been applied to larger boilers with success and is currently commercially available. Attempts to apply the system to smaller boilers were not successful because the peak emission was associated with excessive smoke and occurred over a wide air/fuel ratio range.

In a more recent program optical control of air/fuel ratio for residual oil flames was studied by MIT, sponsored by 5 utility companies [18]. As a part of this program the commercial Land "peak seeking" control system was tested. The sensor in this commercial system detects light in a wavelength

Figure 3. Comparison of Flame Emissions.
(Ref. 13).

band which is fuel dependent. For gas the sensor responds to radiation in the infrared while for oil a sensor which primarily responds in the visible is used. The peak seeking system was found to perform adequately in general but was adversely affected by a large change in flame pattern. As a part of the MIT program detailed emission spectra was obtained for 6 oil flames in the UV, visible, and IR. An emission peak due to the hydroxyl group, OH, in the UV (.310 microns or 309 nm) as measured from the flame front region was found to vary strongly with air/fuel ratio. It was concluded that broad band (i.e. peak seeking) methods might be improved by also examining some narrow band emissions from some gas phase species like OH.

An optical control system, which incorporates some of the conclusions of the MIT program has been developed by the Thermo Electron Corporation. This system has recently been tested on a 360 MW coal fired utility boiler [19]. Termed Spectral Fuel Analyzer (SFA) it is a modified version of an earlier system developed by Environmental Data Corp. (EDC), now a part of Thermo Electron. The older EDC system used as input two selected IR band signals. The SFA in contrast reads specific emissions from OH and CH in the UV and CO₂ and "background" in the IR. The utility boiler tests reportedly showed that the SFA could meet its measurement objectives. It was not apparently tested in a control mode. Presumably in a control mode the air/fuel ratio for each burner in a large boiler would be adjusted to give constant ratios of the specific gas species emissions to the background. Following these utility boiler tests additional development and further tests on a smaller package boiler were done under sponsorship of the U.S. Department of Energy. Generally it was concluded that the system was useful for burner diagnostics but could not be used for quantitative determination of air/fuel ratio under conditions of variable load and burner swirl [20].

The Babcock and Wilcox Co. has recently reported [21] on the development of an optical system for on-line monitoring of pulverized coal- and oil-fired utility boilers. The system uses the ratio of emitted light intensity at two specific wavelengths to determine flame temperature and intensity. Fiber optics are used to obtain this information at up to 30 locations throughout the furnace. An optical air/fuel ratio control system has recently been patented for internal combustion engines [22]. A fiber optic cable is used to transmit light from the combustion chamber to the detectors.

The "peak seeking" approach for control of industrial burners which fire natural gas has also been used in a recent project sponsored by the Gas Research Institute and performed by the United Technologies Research Center [23]. A lead selenide infrared detector was used in this project. While the basic control concept used in this work is not novel, the implementation details are.

3. EXPERIMENTAL APPARATUS AND MEASUREMENTS

3.1 Heating Equipment Used

Boiler tests for studies on flue gas temperature and CO/smoke relationships were done using a cast iron section-type boiler (Peerless Heater Co. Model NO-JOT-35-SPT) fired with a high-pressure retention-head burner (Beckett Model AFG). Furnace tests for these same studies were done using a conventional "low boy" warm-air furnace (Rheem Air Conditioning Division Model ROH2 120A) fired with a conventional retention head burner (Beckett Model AF).

Both units were installed in test stands at the BNL Combustion Equipment Technology Laboratory. The boiler water is circulated through a water-to-air heat exchanger which simulates a domestic heating load. The heat exchanger is equipped with a variable-speed air fan for load modulation, and heated air is discharged to the outdoors. Water temperature at the boiler inlet and outlet are accurately monitored. The burner can be operated in a fixed cycle mode or it can operate under the control of the boiler water temperature controller. The boiler, as installed for these tests did not have a domestic water coil.

In the furnace stand the standard blower is removed and air is supplied through a measurement/conditioning train. This set-up serves to heat the air to any desired temperature. Air mass flow rate is measured using a vortex shedding flowmeter. Thermocouple grids in the air inlet and outlet plenum are used to accurately measure these temperatures.

Some limited data were also obtained using a prototype condensing warm air furnace. This furnace is fired with a retention head burner and has a secondary air-to-air heat exchanger added to an otherwise conventional furnace to reduce the flue gas temperature to about 100°F.

Most of the experimental studies on oxygen sensors emissions were done using a conventional retention head burner (Beckett Corp., Model AF) firing into a dry base, steel boiler (Burnham BB0111.FR). Some additional tests of a zirconium oxide oxygen sensor were done using a prototype prevaporizing oil burner fired into a wet base, cast iron boiler (Peerless Heater Company Model JOT-35-SPT). The prevaporizing burner has been developed by Foster Miller Associates and a description can be found in reference 24. This burner was of interest because it can operate at excess air levels much closer to stoichiometric where zirconium oxide sensors are more sensitive.

Some of the optical studies were done using the conventional retention head burner fired into the dry base steel boiler described above. In addition, some data was taken using a wet base, two pass boiler with a horizontal, cylindrical combustion chamber (Thermodynamics Boiler Co. Model # 100). This unit, which is shown in cross section in Figure 4, is very well suited for the purposes of this project. It provides a water cooled combustion chamber with an easily removable refractory liner and a rear cover which can be easily modified for probe access to the combustion chamber. With this system optical measurements were made with viewpoints both ahead of and behind the flame.

Figure 4. Cross section illustrating wet base, two pass boiler used for optical studies.

In addition to the conventional retention head burners, optical emission measurements were made using one air atomized burner which is currently being marketed in Europe. (Airtronic Model - Bentone/Electro Oil, Sweden [25]). This is a very unique system which uses the externally atomized "Babington" nozzle [26,27].

3.2 Gas Analysis Equipment

Flue gas oxygen content, for excess air determination, was measured using a paramagnetic analyzer (Beckman Model 755). Flue gas carbon monoxide content was measured using an infrared analyzer (Beckman Model 865).

For most measurements flue gas samples were extracted from the stack using a stainless steel probe and heated sampling line. The gas sample was conditioned using a refrigeration drier before feeding to the analyzers. For some tests gas samples were extracted directly from the combustion chamber. The sampling train used for these measurements is illustrated in Figure 5. The sampling probe is water cooled to protect it from overheating and to inhibit gas phase reactions (specifically CO oxidation) from occurring in the sampling system.

3.3 Oxygen Sensors Tested

Three zirconium-oxide oxygen sensors were tested during this project, a commercially available system produced by Nederlandse Philips Bedrijven, B.V. (Netherlands), a typical unheated automotive type sensor, and a heated automotive sensor.

The Philips unit was loaned to BNL for this project by Amperex Electronic Corp., a North American Philips Company. Relative to other zirconium oxygen analyzers which are commercially available, this unit was of particular interest because the manufacturer has used it on small commercial boilers and has been pursuing the development of a low cost unit for domestic heating applications [8]. The unit tested during this program is essentially the larger unit used in Europe modified for 60 cycles, 110v operation. The tested sensor system consists of two parts, a stack probe and a control/readout unit. The sensor is located in the tip of the electrically heated stack probe and consists of two zirconium oxide disks separated by a small hermetically sealed chamber. As discussed in Section 2 of this report, this analyzer uses a unique cyclic pumping method to eliminate the temperature effect on the signal. The control/readout unit displays the partial pressure of oxygen in the flue gas.

The sensor which has been developed by Philips for residential applications is significantly smaller than the one tested (17.5mm x 10mm) [8] and reportedly could market for less than \$75.00 in large quantities, including the control circuitry for the sensor [28].

In automobiles, unheated-type oxygen sensors, are installed close to the engine's exhaust manifold and rely on exhaust heat to bring the sensor temperature above the point at which the zirconium oxide has a reasonable conductivity. The temperature of the unit changes with engine load and the sensor can only be used in the "lambda jump" mode to control air/fuel ratio very close to stoichiometric.

Figure 5. Sampling Train for Combustion Chamber Gas Analysis.

In the case of the newer heated type unit the positive temperature coefficient electrical heating element maintains the zirconium oxide in its high conductivity temperature range. Reported advantages of using the heater include faster warmups, reduced difficulties due to upsets (e.g. water hitting sensor), and the ability to use only one sensor with a V-8 type engine. Like the unheated sensor the heated unit is used only in the "lambda jump" mode.

To utilize an unheated type oxygen sensor in a residential system it must be located in a place where it will be heated to 900-1600°F. To achieve this the sensor was located in the upper region of the refractory combustion chamber of a dry base steel boiler. The sensor was mounted through the center of a refractory disk 0.5" thick and 3.5" in diameter. This disk was then placed in the "view port" cut out of the boiler's combustion chamber. Figure 6 illustrates the location of the sensor in the chamber and Figure 7 illustrates the sensor in the refractory disk. The center line of the oxygen sensor was 6" to the right and 6" above the burner centerline. A thermocouple ($1/16$ ", type K, inconel sheath) was also passed through the refractory disk to measure the gas temperature adjacent to the sensor. Firing at 0.75 gph the temperature was measured to be about 1200°F, which is ideal for the zirconium sensor. The heated type automotive sensor was located directly in the flue pipe for testing. A thermocouple was attached to the outer sheath of the sensor and temperature was controlled by varying the heater supply voltage over a range from 8 to 22 volts.

3.4 Optical Emission Measurements

In this program detailed flame optical emissions were measured, primarily from a line-of-site within the burner air tube close to the centerline. This was done, as opposed to adding separate viewports through the combustion chamber because of two practical considerations. First, optical sensors in the burner housing are cooled and kept clean by combustion air while separate ports would require an additional purge air system. Second, in the residential heating equipment industry, burners and boilers or furnaces are not integrated but are produced by separate manufacturers. A burner control system, which requires access ports in the boiler or furnace in which the burner is fired would be less practical than one incorporated in the burner package.

Optical measurements made during this program included 1) spectral intensities over the range 200 to 1100 nm and 2) broadband emissions. In spectral measurements intensity is measured at many different wavelengths, with a narrow bandpass monochromator. The broadband measurements, in contrast, are made with a sensor which responds over a broad spectral range and a monochromator was not used. To implement the spectral measurements, a fiberoptic cable or liquid light guide was used to bring the light signal to an external monochromator and detector. This arrangement is illustrated in Figure 8. The broadband emission measurements involved placing the optical sensors directly in the combustion tube. These sensors then responded to light over their entire wavelength response range.

The glass fiber optic cables used have a bundle diameter of $1/8$ inch and a length of 24 inches. These have good transmission over the wavelength range 380-1300 nm. The liquid light guide was used in place of the glass fiber optic cable to extend the spectral measurements further into the ultraviolet. The light guide has a case diameter of 0.197 inches, a length of 39.4 inches and good transmission over the range from 200-720 nm. The grating monochromator used is a $1/8$ meter, in-line off axis Ebert configuration with a maximum

Figure 6. Illustration of the location of the unheated automotive type oxygen sensor in the combustion chamber.

Figure 7. Details of the installation of the unheated automotive oxygen sensor in the combustion chamber.

Figure 8. Optical Arrangement for Spectral Intensity Measurements.

resolution of 0.5 nm (Oriel Corporation, model 77250). The monochromator slit width was generally adjusted to give the maximum resolution possible for each grating consistent with the detector sensitivity. Gratings were used with groove spacings of 2400, 1200 and 600 lines/mm. These have useable wavelengths of 175-500 nm, 175-700 nm, and 600-2000 nm, respectively. Two detectors were used alternatively at the monochromator outlet, a silicon photodiode (Oriel Corporation Model 7182) and a photomultiplier (Oriel Corporation Model 77340). The range of spectral response is 300 to 1100 nm for the photodiode and 200 to 700 nm for the photomultiplier.

Sensors used for broadband emissions include a cadmium sulfide photoconductor ("cad cell"), a lead selenide (PbSe) photoconductor, and a simple thin foil thermocouple. The cad cell used is the type commonly used for flame proving in oil burners and for the purposes of these studies was located in its normal position, adjacent to the transformer. The PbSe cell (Hamamatsu Corp. - P791) responds to infrared radiation primarily in the wavelength range from 1500 to 6000 nm. The thin foil thermocouple was installed as a very low cost pyroelectric type sensor and will respond primarily to IR radiation. Figure 9 illustrates the location of the PbSe sensor in the burner air tube. This sensor was simply mounted through the support plate which is 2 3/8 inches from the nozzle tip. The centerline of the PbSe sensor was 3/4 inches from the nozzle centerline. At this position the sensors view of the flame is partially blocked by the slotted retention ring. The thin foil thermocouple and the end of the fiber optic cable (or light guide) were essentially adjacent to the PbSe sensor and also 3/4 inches from the nozzle centerline (note - these sensors are not shown in Figure 9).

In optical systems as used in these studies each system component has a unique wavelength dependent transmission or sensitivity. To allow output signals from the spectral intensity measurements to be converted to a meaningful numerical scale, calibration of complete systems was done using a "standard" tungsten-halogen light source. Detailed calibration of the broadband sensor was not done and results are reported in terms of resistance for the photoconductors and temperature for the thin foil thermocouple. An approximate calibration done using the tungsten-halogen light and the cad cell indicates that resistance is roughly related to intensity (over the range of interest) by:

$$\text{Resistance} \propto (\text{intensity})^{-1/2}$$

It is this relationship that allows relative intensity to be inferred from measured resistance.

3.5 Suction Pyrometer

To compliment the measurements of flame optical emissions some measurements of temperatures along the center line of the combustion chamber of the boiler illustrated in Figure 4 were made using a radiation shielded suction pyrometer. This was constructed using an uncooled ceramic tube with a radiation shield attached to the front. This shield is a ceramic tube and small ceramic spacers held the two tubes concentric. Temperature was

Figure 9. Location of PbSe sensor in burner air tube.

measured using an exposed junction, type S thermocouple (AWG 30) located in the center tube within the radiation shield. Outside of the boiler the probe was connected to an air cooler, a condensate trap, and a sampling pump. The gas flow rate through the pyrometer was about 1.0 standard cubic feet per minute. At this rate the measured temperature is estimated to be 40°F (or less) lower than the actual gas temperature. This is based on comparison with calibrations for pyrometers of similar design [29].

4. RESULTS

4.1 CO/Smoke Relationship

In Figures 10 and 11, measured smoke numbers and flue gas CO contents over a range of excess air levels are shown for the cast iron boiler at two firing rates. Comparison of these figures shows that smoke is produced at higher excess air levels with the lower firing rate. This is a very typical behavior resulting from reduced head pressure drop and turbulence with the lower air flows at the lower firing rates.

The data at 0.65 gph was taken up to very high excess air levels. It is interesting to note that there was no significant CO at these high air flow levels. This is in contrast to earlier studies which indicated high CO at both very low and very high excess air levels. In none of the tests performed during this program was CO produced at high excess air. It is expected that at some extremely high excess air level, CO would be produced because of flame quenching, but these results indicate that this excess air level may be too high to be practically reached. High excess air CO could be a concern in CO based control. A system which senses CO and increases excess air in response would fail if that CO was being produced in the high-air-flow limit.

The data in Figures 10 and 11 indicate a reasonably good agreement between smoke and CO. In Figure 12, CO and smoke data obtained over a range of excess air levels is shown for the condensing warm air furnace. In this case smoke clearly "leads" CO as the excess air is reduced. A control system which relies on high CO to indicate poor combustion would not be practical in this system. Results with the conventional (non-condensing) furnace are shown in Figure 13. In this case smoke again leads CO.

Carbon monoxide and smoke are both products of incomplete combustion, and so it is expected that a low quality flame could generate both species. Available information on the kinetics of CO oxidation, however, indicates that it oxidizes rapidly relative to soot in flue gas with typical residual oxygen levels. A flame which is producing high smoke may also be producing high CO but the CO may be oxidized before reaching the flue pipe. Carbon monoxide measured closer to the flame zone, then, may be a better indicator of a poor quality flame. To evaluate this, CO measurements were made inside of the combustion chamber of the boiler. The water cooled sampling probe used for these measurements was described in Section 3.

Figure 14 illustrates the approximate location of the two sampling points. One location was in the upper portion of the combustion chamber well beyond the flame zone. The other sampling point was just beyond the visible flame zone. Figures 15 and 16 show the sampling results for both locations. In all cases the smoke number was measured at the flue. In general, as the sampling point is moved closer to the flame, the CO levels rise and the excess air level at which CO begins to become significant increases. It should be noted that the excess air level corresponding to a number one smoke is not significantly different with the cooled probe in the chamber. The probe, then, is not affecting the flame quality greatly. Figure 17 shows the CO

Figure 10. Measured smoke number and CO emissions over a range of excess air levels. Hot water boiler, 0.65 gph.

Figure 11. Measured smoke number and CO emissions over a range of excess air levels. Hot water boiler, 1.00 gph.

Figure 12. Measured smoke number and CO emissions over a range of excess air levels. Condensing warm air furnace, 0.5 gph.

Figure 13. Measured smoke number and CO emissions over a range of excess air levels. Warm air furnace, 1.00 gph.

Figure 14. Location of Sampling Points in Combustion Chamber.

Figure 15. Measured smoke number and CO emissions over a range of excess air levels. Hot water boiler, 0.65 gph. Sampling location for CO - A in Figure 14.

Figure 16. Measured smoke number and CO emissions over a range of excess air levels. Hot water boiler, 0.65 gph. Sampling location for CO - B in Figure 14.

plotted versus the steady state smoke number for the three different sampling locations. This figure very clearly indicates that CO measured closer to the flame zone would provide a better indicator of flame quality than stack measurements.

Tests were also performed in the boiler using a fouled nozzle. The nozzle used had a nominal rating of 0.65 gph and had fairly heavy coke deposits on the front tip from prior use. Examination of the spray pattern showed the spray cone to be partially blocked. Measurements indicated that the fouling resulted in a reduction in fuel flow of about 17% at the rated pressure. Figure 18 shows the smoke number/excess air relationship for this nozzle. Comparison with Figures 10 and 11 indicates much greater smoke levels with the fouled nozzle as expected. Measurements indicated very low CO concentration in the stack over the entire excess air range examined. A stack CO measurement would not have indicated that the nozzle condition had degraded. Measurement made in the combustion chamber indicated higher CO levels than in the stack, but these measurements also could not be used to signal a poor quality flame condition.

4.2 Effect of Parameters on Flue Gas Exit Temperature

In interpreting the results of these parametric tests on gas exit temperature it is useful to compare the measurements with a simple heat exchanger model. A model of this type serves as a check on the reasonableness of experimental results and can be used to extrapolate experimental results to other cases. In the next few paragraphs the model assumptions are presented.

Figure 19 illustrates a simple one-pass parallel-flow heat exchanger model which could be used for a boiler or furnace. The "hot fluid" entering is assumed to be the combustion products at the adiabatic flame temperature. For this case the total heat transfer rate will be:

$$Q = UA \cdot \text{LMDT} \quad (1)$$

where

- Q = heat transfer rate (Btu/hr)
- U = overall heat transfer coefficient (Btu/Ft²Hr°F)
- A = heat exchanger surface area (Ft²)
- LMDT = log mean temperature difference between the combustion products and the circulating water.

The product U·A in equation 1 can be determined using experimental data at one condition termed the "baseline." The model would then be useful for predicting changes from that baseline condition.

While such a simple model could be expected to approximately describe the effects of changing inlet conditions on heat transfer, its accuracy will be limited for several reasons. These include 1) the LMTD assumes heat transfer by conduction and convection while radiation also plays a role in oil fired boilers and furnaces, and 2) the constant U in equation 1 is expected to be constant when in fact it will be dependent on flow rate.

Figure 17. Relationship between CO and smoke number with three sampling locations for CO. Hot water boiler, 0.65 gph.

Figure 18. Smoke number vs excess air with a fouled nozzle. Hot water boiler. Nominal nozzle rating - 0.65 gph.

Figure 19. Illustration of a boiler (or furnace) as a simple, parallel flow heat exchanger.

Figure 20. Effect of excess air on flue gas temperature. Hot water boiler, 0.65 gph. Data (•) and trend predicted by simple heat exchanger model (-).

For a change from the baseline condition the heat transferred from the combustion products to the boiler water can be expressed as:

$$Q = Q_B - M_g C_{pg}(T_{go} - T_{gob}) \quad (2)$$

where

Q_B = Heat given up by the gas in the baseline case (Btu/hr)
 M_g = Mass flow rate of combustion products (Lb/hr)
 C_{pg} = Mean specific heat of the combustion products (Btu/Lb°F)
 T_{gob} = Gas outlet temperature in the baseline case (°F)
 T_{go} = Gas outlet temperature (°F)

Also, the heat gained by the boiler water can be expressed as:

$$Q = M_w C_{pw}(T_{wo} - T_{wi}) \quad (3)$$

where

M_w = Mass flow of water (lb/hr)
 C_{pw} = Specific heat of water (Btu/lb°F)
 T_{wo} = Water outlet temperature (°F)
 T_{wi} = Water inlet temperature (°F)

By solving equations 1, 2, and 3 simultaneously, the effect of changing conditions on flue gas exit temperature can be predicted. The equations are non-linear and an iterative procedure must be used. At the baseline condition used for the boiler U·A was found to be 84.22 Btu/°F hr.

Figure 20 shows the variation of flue gas exit temperature with excess air for the boiler fired at 0.65 gph (constant water temp.). Also shown is the trend predicted by the simple heat exchanger model. The model predicts a greater change in flue gas temperature with excess air than the data.

For changes in the boiler water temperature the model predicts about an 11°F rise in stack temperature for a 10° rise in boiler water temperature (10.7° at 20% excess air; 11.6° at 100% excess air). This is roughly equivalent to a constant differential between stack temperature and boiler water temperature. Figure 21 shows data on the difference between stack temperature and boiler water temperature over a range of boiler water temperatures at constant excess air. As this figure shows, the temperature differential decreases with increasing boiler water temperature. Over the range from 130 to 220°F boiler water temperature, which is the maximum expected range over a typical heating season, the temperature differential changes by about 16°F. The model assumptions in this case as well as the experimental data are based on constant water flow rate, as would occur for example in the winter, when the house is calling for heat.

These results on the variation of stack temperature with boiler water temperature have several implications for control strategies. Certainly, one

Figure 21. Temperature difference between the stack and the boiler water over a range of water temperatures, 0.65 gph.

Figure 22. Effect of excess air on flue gas temperature. Warm air furnace, 1.0 gph. Data (.) and trend predicted by simple heat exchanger model, (—).

very simple control approach involves monitoring stack temperature alone, although this will vary significantly with the water temperature. For a fixed setting on the controls, however, the burner typically shuts off at a fixed water temperature. Monitoring of the maximum temperature realized during normal heating season cycling is one method of eliminating the water temperature effect. An alternative, but a more complicated approach, would involve measuring the flue gas to water differential temperature. This would permit monitoring of efficiency changes essentially continuously during cyclic operation. The variation in this temperature difference over a normal cycle could be compared with the rise in stack temperature with degradation. At typical excess air levels and stack temperatures (non-condensing) a 1% reduction in efficiency corresponds to a 36°F rise in stack temperature. Considering the typical variation in this differential a 1% change is about the minimum which might be reliably indicated.

Studies were also done on the effects of changes in ambient air temperature on stack temperature. The simple heat exchanger model predicts an increase in stack gas temperature of 4.1°F for a reduction in ambient temperature from 70 to 30°F. Laboratory tests were conducted with ambients ranging from 72.5°F to 43.7°F. Over this range stack temperature did increase about 2 to 5°F, although this could be considered within the normal variation range. The relevant conclusion is that variations in ambient air temperature will not significantly affect a control strategy which uses stack temperature as an input.

A similar series of tests were also performed using the warm air furnace. Again, a simple heat exchanger model similar to that described for the boiler was used to compare with the trends observed experimentally. Figure 22 shows the effect of excess air on flue gas temperature and the trend predicted by the simple model. As in the case of the boiler, the model predicts a somewhat greater change with excess air than the data indicate.

In Figure 23 the effect of changing furnace air flow on the measured stack temperature is shown along with the trend predicted by the model. While the fixed value of $U \cdot A$ used in this case predicts stack temperatures 10-15°F lower than those measured, the trend is certainly similar. The range of air flow rates studied produced an air temperature rise from 70 to 90°F.

The simple model was used to predict the effect of changing ambient temperature on flue gas temperature. As in the case of the boiler, the effect is fairly small. A change in ambient from 70 to 30°F produced only a 10°F change in stack temperature.

In normal heating season operation, a furnace would typically have a nearly constant return air temperature and warm air flow rate. Under this condition, the stack temperature will depend only on firing time and excess air. The time for the stack gas to approach its steady state temperature varies. In the system tested the time was about three minutes, which could be considered typical. Based upon the results available to date, simple measurement of the peak stack temperature may be the most reliable indicator of performance degradation. During the warm up transient the difference between the flue gas temperature and the warm air exit temperature is not constant,

Figure 23. Effect of changing furnace air flow on stack temperature. Data (·) and simple heat exchanger model, trend (—).

eliminating this as an approach to continuously monitoring performance during the burner on-cycle.

4.3 Longer Term Degraded Performance Tests

Both the previously described boiler and the warm air furnace were operated with high smoke numbers for an extended period of time. The purpose of this test was to measure changes in flue gas temperature, flue pipe surface temperature, gas side pressure drop, air flow rate and CO emissions as the systems fouled.

The boiler test stand was arranged with the burner cycling under control of the aquastat, the circulator ran constantly, and the thermal load was adjusted (by adjusting heat dump fan speed) to produce a cycling pattern of 5 min. on- 10 min. off. The burner was adjusted to 11% excess air (2.2% O₂ or 14% CO₂).

Figure 24 shows the variation in measured smoke numbers during a typical cycle. These smoke numbers were obtained with a constant rate sampling system and represent averages over 15 sec. It is interesting to note the low startup smoke level with this burner. This is likely a combined result of the high static pressure fan in the burner and the fairly rapid cycling pattern. Under rapid cycling the flue and refractory remain warm during the off cycle.

The boiler test duration was 36 days, 4 hours. During this time the burner operated for a total of 289 hours and cycled 3,472 times. With a 1.0 gallons/hours nozzle, 289 gallons of oil were consumed during this test.

Figure 25 shows the measured trend in flue gas temperature during the test. This temperature was measured at the center of the flue pipe, and represents the maximum observed during the firing cycle. As this figure shows, the rate of increase in flue temperature was steady until about day number 26, at which time it increased notably. At this point a small increase in smoke number was also observed indicating a deteriorated nozzle condition. The rise in flue gas temperature observed during this test (131°F) corresponds to a decrease in thermal efficiency of 2.9%.

In Figure 26 the trend in flue pipe surface temperature during the test period is shown. Comparison with Figure 25 shows that the flue pipe surface temperature followed the gas temperature trend. The overall rise in the pipe temperature, however, was lower than for the gas (91°F vs 131°F). This trend is not unexpected. As soot deposits collect on the inner wall of the flue pipe, the temperature difference between the gas and the pipe will rise.

Following the termination of the boiler test the unit was disassembled for a detailed inspection and cleaning. The thickness of the soot coating varied significantly with location, but averaged about 1-1/2 mm. The thickest deposits were located around the extended surface in the convective section and blocked some of the flow area. The total mass of soot removed from the boiler surfaces was 250 grams.

In the furnace tests the burner operated 10 min. on/15 min. off with a steady state excess air level of 23% (4.1% O₂ or 12.5% CO₂). The furnace was

Figure 24. Measured smoke numbers over a typical firing cycle - Boiler longer term performance test.

Figure 25. Flue gas exit temperature. Cycle maximum - Boiler longer term performance test.

Figure 26. Flue pipe surface temperature - Cycle maximum-boiler longer term performance test.

Figure 27. Measured smoke numbers over a typical firing cycle - Furnace longer term performance test.

configured to have significantly higher smoke numbers than the boiler. Figure 27 shows the variation in measured smoke numbers over a typical firing cycle. At equal smoke levels the fouling rate of a furnace would be expected to be lower than for a boiler. This, presumably, is due to higher heat exchanger surface temperatures with the furnace and a more complex heat exchanger geometry in the boiler. In the furnace the heat transfer surface is essentially a smooth steel drum with air on one side and gas on the other. In the boiler there are many fins on the gas side of the cast iron sections.

The duration of the furnace test was 50 days. During this time the burner ran for 396 cumulative hours and cycled on/off about 2400 times. At a firing rate of 1 gph, 396 gallons of oil were consumed during this test.

Over the period of the test excess air decreased from 24% to 14% and flue gas CO content increased from roughly 35 ppm to 55-100 ppm. Smoke numbers, which were greater than 7 Bacharach over the entire firing cycle, were found to increase slightly over the test period.

During the test the steady state flue gas temperature rose from 552 to 626°F, a 74°F rise. At constant excess air this rise in flue gas temperature corresponds to a reduction in efficiency of 1.8%. With the reduced excess air this efficiency decrease is 1.2%.

It is interesting to note that the rise in flue gas temperature with the furnace was about 1/2 of the rise observed in the boiler test (131°F vs. 74°F). This occurred even though the steady state smoke numbers were significantly higher in the furnace test and the burner ran longer in the furnace test (396 hours vs. 289 hours).

After termination of the test the furnace was disassembled for inspection of the heat exchanger surfaces. As with the boiler, the soot deposits varied significantly with location. Thickness ranged from 1 to as much as 6 mm. The total mass of soot removed from the heat exchanger surfaces was 175 g.

Generally, the furnace deposits and boiler deposits were comparable in magnitude. It seems likely that the greater rise in flue gas exit temperature with the boiler was due to the heat exchanger configuration. In the furnace soot deposits simply coat the surface of the steel heat exchanger drum. In the boiler, however, soot deposit bridging occurs around the extended surface. This can significantly modify gas flow, leading to channeling.

4.4 Tests on Oxygen Sensors

Stack Probe Zirconium Sensor

Tests using the commercial zirconium oxide probe, (Philips) were done both in steady state, with varied excess air and over cyclic operation. For comparison purposes the flue gas oxygen content was also measured using a paramagnetic analyzer (Beckman-Model 755). The paramagnetic analyzer, which is fed clean, dried flue gas, indicates oxygen concentration on a "dry" basis. The zirconium oxide probe, however, indicates oxygen partial pressure in the total flue gas, including water vapor. To put both on an equivalent

basis these oxygen contents can be converted to % excess air using the following equations for a typical number 2 oil:

O₂ on a dry basis:

$$\% \text{ EA} = \frac{4620 \cdot \text{OD}}{(1037.5 - \text{OD} \cdot 49.375)}$$

O₂ on a wet basis:

$$\% \text{ EA} = \frac{\text{OW} \cdot 100 (52.55 + \text{W} \cdot 78.85)}{(1037.5 - 49.375 \cdot \text{OW} - \text{W} \cdot 78.85)}$$

where:

% EA = % Excess Air.

OD = Oxygen concentration in flue gas with water vapor removed - % molar (volume) basis.

OW = Oxygen concentration in flue gas (including water vapor) - % molar (volume) basis.

W = Ambient air moisture content, lbs/lb dry air.

Figure 28 shows a comparison of the excess air determined from the zirconium oxide and the paramagnetic analyzers. Agreement is reasonably good over the range examined. Figure 29 shows the smoke number/excess air (based on the paramagnetic analyzer) curve for the system tested. The in-stack zirconium probe performed well even at smoke numbers well in excess of normal values. With the burner set to produce a number 9 smoke in steady state the burner was operated with 5 minutes on/15 minutes off cycles for 6 hours cumulative on-time. No change in the zirconium sensor output or soot fouling of the probe tip was observed. At the probes operating temperature any deposited soot would simply be burned off. In Figure 30, the response of this zirconium probe over cyclic operation is illustrated. Response time in this case is about 1/2 min.

Unheated Automotive Sensor

As discussed in Section 3, the unheated zirconium oxide sensor was located in the upper region of the combustion chamber of a dry base steel boiler for testing. Figure 31 shows the output voltage from the sensor and the measured temperature near the sensor casing as a function of excess air at a burner firing rate of 0.75 gph. The sensor output voltage/excess air relationship was found to be very repeatable even over a number of firing cycles. Excess air levels calculated using the sensor output voltage, the measured temperature, and the Nernst equation (see Section 2.2) did not agree with excess air levels based on measured flue gas oxygen concentration. This comparison is illustrated in Figure 32. Several factors could be responsible for this lack of agreement but perhaps the most significant is the assumption that the measured temperature matches the temperature of the zirconium oxide.

In Figure 33, the measured temperature and output voltage from this sensor are shown as a function of time following a startup. From this figure at

Figure 28. Excess air based on commercial zirconium probe - comparison with paramagnetic analyzer.

Figure 29. Smoke number vs. excess air for test illustrated in Figure 28.

Figure 30. Commercial zirconium probe - indicated flue gas O_2 over a firing cycle.

Figure 31. Unheated automotive type oxygen sensor - output signal and measured temperature as a function of excess air.

Figure 32. Excess air based on unheated automotive type sensor - comparison with paramagnetic analyzer.

Figure 33. Unheated automotive type oxygen sensor - output signal and measured temperature over a firing cycle.

least four minutes of firing are required before a useful signal is available from the sensor. This slow response would be a major impediment to the use of unheated sensors in this application.

Heated Automotive Sensor

As discussed in Section 3 the heated type automotive oxygen sensor was located in the flue pipe for testing. By varying the voltage of the supply power to the sensor heater from 0 to 24 volts its casing temperature could be controlled between the flue gas temperature (about 500°F) and 1100°F. In Figure 34 the output signal from the sensor is shown, as a function of measured casing temperature at three excess air levels in steady state. The best response to changes in flue gas oxygen is at the highest temperature. Below about 700°F the casing temperature is too low and the output is not useable. Figure 35 shows the excess air levels calculated using the sensor output voltage, the measured casing temperature and the Nernst equation. While the agreement is not very good it is significantly better than for the unheated sensor in the combustion chamber (see Figure 32). As in the case of the unheated sensor it is likely that the measured casing temperature is different than the temperature of the zirconium oxide.

Figure 36 illustrates the response of the heated sensor over a firing cycle. Relative to the lower cost, unheated sensor in the combustion chamber the heated sensor in the flue has a much shorter response time. For control purposes this response would certainly be acceptable.

Some tests using the heated automotive oxygen sensor were also performed using the prototype vaporizing oil burner described in Section 3. Relative to conventional retention head burners this burner is capable of operating at very low excess air levels without producing smoke. In Figure 37 the smoke number/excess air and CO/excess air relationship for this burner are illustrated. Figure 38 shows the variation in sensor output over the same excess air range. For this burner there is a very significant change in output as the "smoke limit" is passed. In Figure 39 the excess air calculated from the zirconium oxide sensor output (heated to 1100°F) is compared with that determined from the paramagnetic analyzer O₂ reading. At O₂ levels below about 14%, which is the point at which smoke and CO begins to become excessive, the zirconium sensor indicates much less O₂ than the paramagnetic. At this condition the oxygen concentration at the surface of the zirconium sensor is lower than for the bulk flue gas because of oxidation of the products of incomplete combustion on the hot sensor surface. For control purposes this is an advantage, amplifying the change in output when the smoke limit has been passed.

4.5 Measurements of Flame Optical Emissions

4.5.1 Conventional Retention Head Burner Flame, Viewed from the Burner Housing.

Figure 40 shows emission spectra measured with a 1200 lines/mm grating covering the visible range (450-700 nanometers (nm)) and a part of the UV for a retention head burner. The system was fired at 1.0 gph with excess air levels ranging from 17% to 54% (smoke numbers 9 to 0). The emission spectra shown are essentially like a black body emission from a luminous flame. Decreasing excess air increases flame emissivity and results in increased intensity of emitted radiation.

Figure 34. Heated automotive type oxygen sensor - output signal as a function of sensor temperature and O₂ (paramagnetic analyzer).

Figure 35. Excess air based on heated automotive type oxygen sensor at 1100°F - comparison with paramagnetic analyzer.

Figure 36. Heated automotive type oxygen sensor - output signal and measured temperature over a firing cycle.

Figure 37. Measured smoke number and CO emissions over a range of excess air levels. Prototype vaporizing oil burner.

Figure 38. Heated automotive type oxygen sensor - output signal as a function of excess air in prototype vaporizing oil burner.

Figure 39. Excess air based on heated automotive type oxygen sensor in prototype vaporizing oil burner - comparison with paramagnetic analyzer.

Figure 40. Flame optical emission spectra over the visible range (450-700 nm) and a part of the UV-retention head burner at four excess air levels.

In Figure 41 the emission intensity at selected wavelengths is plotted as a function of excess air. The decrease in intensity with increasing excess air is more significant at higher wavelengths. This is further illustrated in Figure 42 which shows the ratio of intensity at 600 nm to intensity at 400 nm as a function of excess air. This trend would be consistent with an increase of source temperature with excess air (black body assumption). The two wavelengths chosen (600/400) are near opposite ends of the visible wavelength range and so their ratio is roughly an indicator of "color."

Figure 43 shows emission spectra over the ultraviolet range from 200 to 450 nm. In addition to an extension of the continuum emission observed in the visible (Fig. 40) there is a clear peak due to emission from OH at about 310 nm. Figure 44 shows the variation of the emission at selected wavelengths in the UV with excess air. Because of the very wide spread in values over this range, three intensity scales are used. Unlike the continuum emission the OH emission does not decrease significantly with increasing excess air. This suggests that the ratio of a continuum signal to the OH signal would be a useful indicator of air/fuel ratio. Relative to simple continuum intensity this would have the advantage of a reduced sensitivity to partial sightpath blockage and sensor misalignment.

An ideal system for monitoring flame quality would give an output dependent only on smoke emissions and at least somewhat independent of other parameters. A system which has a different set point depending upon firing rate or which is affected by small variations in fuel quality would be less interesting than one which is universal. Towards evaluating the usefulness of an optical flame quality signal, emission spectra were obtained over the UV and visible ranges as a function of excess air for a wide variety of conditions. This includes:

- o firing with new 0.75 and 0.50 gph nozzles
- o firing with a 0.85 nozzle which had been removed from a home and was apparently fouled.
- o firing with a 1.25 gph nozzle with oil pump pressure reduced to 70 psi.
- o a 1 gph nozzle fired with No. 4 oil.
- o a 1 gph nozzle fired with blends of No. 2 and No. 4 oils.

The nozzles used in these tests were not optimized for this burner/chamber situation but were selected at random. The fouled nozzle was rated at 0.85 but actually delivered 0.65 gph due to interference from the heavy coke deposits. The #4 oil was tested as an extreme case of degraded fuel quality. In the case of the 1.25 gph nozzle at reduced pressure the intention was to have poor atomization without a severely misshaped flame.

In tests with the #4 oil the smoke number changed from 1 to 6 with the introduction of the lower grade oil and excess air changed slightly. Optical

Figure 41. Flame optical emission intensity as a function of excess air at selected wavelengths in the visible-retention head burner.

Figure 42. Ratio of optical emission intensities at 600 and 400 nm as a function of excess air - retention head burner.

Figure 43. Flame optical emission spectra over the ultraviolet range (200-450 nm) - retention head burner at four excess air levels.

Figure 44. Flame optical emission intensity as a function of excess air at selected wavelengths in the ultraviolet (note - three scales used for intensity).

emission measurements were made over the range 200-450 nm. The continuum signal intensity decreased by $1/2$ indicating a very significant change in flame position. No significant change in the shape of the optical emission curve was observed.

As Table 1 shows, the fuel blend with the lowest content of No. 4 oil (10% #4/90% #2) had a carbon residue only slightly greater than the ASTM limit while API gravity and viscosity are within the specified limits. The blend with the highest content of No. 4 oil (30% #4/70% #2) was outside of the ASTM limits for carbon residue, API gravity and viscosity of No. 2 oil. In tests, the oil burner pump suction was changed to each blend in turn and the burner excess air setting was unchanged. Relative to operation with 100% No. 2 oil, the smoke numbers increased only slightly (from "trace" to about No. 1 Bacharach) with the lowest quality blend (30% #4/70% #2). No significant optical changes were observed.

The 1.25 gph nozzle operated at reduce pressure was found to have a smoke/excess air curve and optical emissions essentially identical to those from the 1.0 gph nozzle.

Table 1. Fuel Properties

Fuel	Carbon Residue-wt%	API Gravity at 60° F	Viscosity, Centistokes at 100° F
No. 2 Oil	<0.05	34.0	2.5
No. 4 Oil	4.00	19.2	108.2
<u>Fuel Blends:</u>			
10% #4, 90% #2	0.40	32.4	2.9
20% #4, 80% #2	0.80	31.0	3.4
30% #4, 70% #2	1.20	29.3	3.9
ASTM Limits for No. 2 oil	.35 max	30 min	2.0-3.6

Figure 45 shows the smoke number/excess air relationship for the 0.5, 0.75 and 1.0 gal/hr nozzles and the fouled 0.85 gph nozzle and indicates that the range in performance was very broad. In Figure 46 intensity at 450 nm for the four nozzles is shown plotted against excess air. This certainly shows that this intensity is a poor indicator of the absolute excess air level. Figure 47 shows the intensity at 450 nm against smoke number and Figure 48 shows the ratio of intensities at 450 and 310 nm against smoke number. As discussed previously the signal at 450 nm is indicative of the continuum intensity and the 310 nm signal is due to OH and fairly independent of excess air and smoke number.

Figure 45. Smoke number over a range of excess air levels - retention head burner with four nozzles.

Figure 46. Flame optical emission intensity at 450 nm as a function of excess air - retention head burner with four nozzles.

The results in Figures 47 and 48 can be used to illustrate two possible control schemes. A control system might have a set point at a fixed value of continuum intensity. Based on Figure 47 this might be 0.1 mW/nm-cm^2 at 450 nm for example (note - in practice a much broader wavelength indicator of continuum intensity would likely be used). As an alternative, a fixed ratio of continuum to OH intensity might be used. A value of the 450/310 ratio of 8 might be used for this based on Figure 48. In Figure 49 the smoke number/excess air relationship for these burners is again plotted with markers added to show the setpoint which would result from both of these control approaches. Both methods produce a setpoint reasonably close to the excess air which gives "trace" smoke. No point is shown for the 0.85 gph nozzle with the 450 nm intensity only because the setpoint signal chosen for this example was not reached over the air/fuel ratio explored.

In Figure 42 it was shown that, for a given nozzle, the ratio of intensities at 500 and 400 nm varies smoothly with excess air. For the four nozzles it was attempted to use this ratio as an indicator of smoke. Unlike the intensity at 450 nm and the 450/310 nm intensity ratio, the 600/400 nm intensity ratio was found not to be consistent or at all useful.

As discussed in Section 3 some broadband measurements were also made using a cadmium sulfide photoconductor, a lead selenide photoconductor and a simple thin foil thermocouple target. Results at a firing rate of 0.75 gph are shown in Figure 50. In this case any of these measures shows a good sensitivity to excess air.

Measurements using both the 1200 and the 600 lines/mm gratings at the same combustion condition were made using the conventional retention head burner fired into the boiler illustrated in Figure 4. This provided results which cover a broader spectral range in the visible and near infrared (500 to 1100 microns). With these results apparent flame temperatures were estimated based on the ratio of intensities at 1000 and 600 nm. This temperature estimate assumes that the flame emission follows the black body laws.

Results are shown for different excess air levels in Figure 51 with the stock combustion chamber in place and in Figure 52 with chamber removed. For each case the intensity ratio (1/.6 micron) and corresponding apparent flame temperatures are shown. These results do not show a consistent trend of apparent flame temperature (or color) with excess air over this range which could be used for control purposes. As expected, removal of the chamber reduces the apparent flame temperature.

In Figure 53 the results of temperature measurements along the chamber axis with and without the refractory liner are shown. These were made using the suction pyrometer described in section 3.5. The temperatures shown in this figure are significantly lower than those calculated based on the optical emissions. To a large degree this is due to the black body law assumption which was used in calculating the apparent optical flame temperatures. In using the black body law, it is assumed that the emissivity of the oil flame is independent of wavelength. Actually emissivity decreases with increasing wavelength over this range [28]. Both methods, however, show the reduced flame temperature with the removal of the refractory liner. It is

Figure 47. Flame optical emission intensity at 450 nm as a function of smoke number - retention head burner with four nozzles.

Figure 48. Ratio of optical emission intensities at 450 and 310 nm as a function of smoke number - retention head burner with four nozzles.

Figure 49. Excess air setpoints based on continuum emission at 410 nm (▲) and ratio of intensities at 410 and 310 nm (▼) - retention head burner with four nozzles.

Figure 50. Smoke number and response of broad band sensors vs. excess air - retention head burner.

Figure 51. Optical Emission Spectra With a Combustion Chamber.

Note - Temperatures in parenthesis indicate "apparent" flame temperatures using black body assumption and ratio of intensities at 1000 and 600 nm.

* = 1200 lines/mm grating

□ = 600 lines/mm grating

Figure 52. Optical Emission Spectra Without a Combustion Chamber.

Note - Temperatures in parenthesis indicate "apparent" flame temperatures using black body assumption and ratio of intensities at 1000 and 600 nm.

Figure 53. Measured Flame Temperatures Along Combustion Chamber Axis.

interesting to note the sharp reduction in temperature near the nozzle in the cold wall case. This is likely due to an increased flame standoff distance.

During this project an effort was made to measure centerline temperature profiles with the suction pyrometer as a function of excess air. Generally, over the range of excess air examined (25 to 60%) no consistent trend was found. Measured temperatures were found to be independent of excess air to within about 50°F.

The use of a very simple optical sensor like the cad cell or PbSe photoconductor to indicate flame quality is obviously very attractive from a cost perspective. As in the case of the narrow wavelength measurements discussed earlier, however, the possible effects of changes in firing rate and spray pattern on this signal have to be established. For this purpose a series of measurements were compared for eight selected nozzle cases. These include:

- A. 0.75 gph, 70° solid
- B. 0.85 gph, 70° hollow
- C. 1.0 gph, 70° hollow
- D. 0.5 gph, 70° hollow
- E. 0.65 gph, 80° hollow
- F. 0.65 gph, 80° solid
- G. 0.65 gph, 60° hollow
- H. 0.65 gph, 60° solid

Figure 54 shows the cad cell resistance/smoke number relationships for all eight nozzles. Figure 55 shows the same relationships for the PbSe photoconductor. All of these data were taken using the retention head burner firing into the hot water boiler. Note that for these tests the cad cell was mounted in its conventional location (below the transformer) but the PbSe cell was mounted further forward, close to the retention head.

In an ideal case all of the resistance/smoke number points might fall on a single curve and the photoconductors would be universal indicators of flame quality. This certainly did not occur, although most of the data do fall within a reasonably narrow band. A very notable exception to this is the case of the very low firing rate (0.5 gph nozzle D) and the cad cell (Fig. 54). Because of the low firing rate the intensity reaching the cad cell is significantly lower than for the other nozzles. With the PbSe cell, which views the flame essentially from the centerline, the loss in intensity (increase in resistance) with the low firing rate is not as pronounced.

If either photoconductor were to be used as a "universal" flame quality sensor, then the burner excess air would be adjusted to give a fixed value of resistance in steady state. To illustrate the consequences of doing this with these eight nozzles, resistance values of 190 ohms and 55 kohms were chosen for the cad cell and PbSe photoconductors, respectively. Resulting setpoints are shown on the smoke number/excess air curves for the burner fired with each of the eight nozzles in Figure 56 (over two pages). The case of the cad cell with the 0.5 gph nozzle is not shown as this control approach would simply not work at that firing rate. For all other cases either sensor would cause the burner to be set fairly close to the ideal trace smoke point. Of the two sensors the PbSe sensor gives a better setpoint. This may be simply a result of the placement of that sensor rather than the wavelength response range.

Nozzle:

• A	+ B	* C	□ D
x F	◇ G	△ H	x E

Figure 54. Resistance of cadmium sulfide photoconductor as a function of steady state smoke number for eight nozzles - retention head burner.

Nozzle:

• A	+ B	* C	□ D
x F	◇ G	△ H	⊗ E

Figure 55. Resistance of lead selenide photoconductor as a function of steady state smoke number for eight nozzles - retention head burner.

Figure 56. Excess air setpoints based on resistance of cadmium sulfide (∇) and lead selenide ($\blacktriangledown$) photoconductors - retention head burner with eight nozzles.

Figure 56. Excess air setpoints based on resistance of cadmium sulfide (∇) and lead selenide ($\blacktriangledown$) photoconductors - retention head burner with eight nozzles.
(cont.)

To evaluate the effect of location of the cad cell some additional tests were performed with the cell moved closer to the retention head, near the PbSe cell. In the first test set at this location the cad cell was set to view the flame directly, through the center opening of the retention head with a very narrow view angle. At this location the results were found to be strongly affected by nozzle spray angle and not generally useful. The sensor was then moved forward to view the flame through a much wider angle, again through the center hole in the retention head. Results at this location in the form of cad cell resistance as a function of smoke number for the eight nozzle sets are shown in Figure 57. In Figure 58 (over two pages) the setpoints which would result from two different choices of resistance of the cad cell at the forward location are illustrated for the eight nozzles. In all cases an acceptable excess air setting is realized.

4.5.2 Conventional Retention Head Burner, Viewed from the Back End

Measurements of the flame optical emissions were made from a viewpoint at the back end of the boiler illustrated in Figure 4. A fiber optic cable was used to collect the light from the access port and transmit it to the monochrometer. The port is located on the centerline of the combustion chamber and the fiber optic cable tip is cooled by air, drawn in by chamber draft.

In Figure 59 optical intensity at 550 nm (center of the visible) is plotted as a function of smoke number for three different firing rates. This data indicates some increase in intensity with firing rate. In addition and particularly for the 0.6 and 0.7 gallon per hour nozzles a peak in the emission intensity near a smoke number of 0 to 1 and a decrease in intensity as the smoke number increases over the range 2-6 is observed. This result is markedly different from previous results obtained with the optical sensors located within the burner housing, which indicated much better agreement between the intensity/smoke curves for different firing rates. In addition, intensity measured from within the burner housing showed a continuous increase with smoke number over the range 0-10.

In Figure 60 the ratio of the intensities at 600 and 400 nm is shown as a function of the smoke number for the three firing rates. As discussed in the previous section, this ratio is a rough measure of flame "color" or effective flame temperature. In this case the relationship is very similar for all three nozzles, which suggests that flame color measured from the back end could be a very useful indicator of flame quality. Measurements made from a viewpoint within the burner housing (previous report section) did not indicate a consistent relationship between "color" and flame quality with different nozzles.

4.5.3 Air Atomized Burner

Optical emission measurements were made with the air atomizing burner (Airtronic/Babington) firing into the boiler illustrated in Figure 4. Due to the unique geometry of this burner, measurement of optical emissions from a viewpoint within the burner housing are very difficult. For this reason, measurements were made only from a backend viewpoint as in section 4.5.2.

Figure 57. Resistance of cadmium sulfide photoconductor in forward position as a function of steady state smoke number for eight nozzles -- retention head burner.

Figure 58. Excess air setpoints based on the resistance of the cadmium sulfide photoconductor at the forward location (∇ - 38 ohms; $\blacktriangledown$ - 41 ohms).

Figure 58. Excess air setpoints based on the resistance of the cadmium sulfide photoconductor at the forward location (▽ - 38 ohms; ▼ - 41 ohms).

Figure 59. Viewpoint at the end of the combustion chamber. Intensity at 550 nm, three nozzles.

Figure 60. Viewpoint at the end of the combustion chamber. Intensity ratio vs. smoke number, three nozzles.

Tests were performed at a firing rate of 0.5 gallons per hour and Figure 61 shows the smoke/excess air relationship at this condition. Figure 62 shows the measured intensity at 550 nm (center of visible) as a function of excess air. The trend shown by this data is very similar to that with conventional pressure atomized burners with a viewpoint within the burner housing. Compared with data taken with pressure atomized burners with a backend viewpoint, the intensities with the air atomized burners are about half. In Figure 63 the ratio of intensities at 600 and 400 nm is shown as a function of excess air. As with conventional pressure atomized burners (viewpoint in burner housing) the trend is toward lower ratios of intensities at 600 to 400 nm (higher flame temp) with increasing excess air. With the air atomized burner, however, the apparent flame temperatures are significantly higher (lower 600/400 intensity ratio) across the excess air range.

4.5.4 Transient Optical Emissions

Results which have been reported in previous sections include data taken with burners operating in steady state. While this is important, residential oil burners always operate cyclically. A typical boiler, for example, may realize 6 to 8 thousand firing cycles per year and the average on-times range from 5-10 minutes. It is important, then, to consider the effect of these transients on optical indicators of flame quality.

For this purpose the warm-up period is the time required to heat the combustion chamber refractory insert to its steady state temperature. During the warm-up period flame temperature is lower than in steady state because of the cooler chamber walls. This reduced flame temperature would reduce the intensity of the optical emissions and move the apparent flame color to longer wavelengths. During the warm-up period the reduced flame temperature leads to increased soot emissions. This would act opposite to the reduced flame temperature and increase the total optical emission intensity. Increasing soot would not, by itself, affect flame color very strongly during the warm-up period.

Transient measurements were made using the three broad band sensors installed in the retention head burner mounted in the dry base steel boiler as discussed in section 4.5.1. Results are shown in Figure 64. During the first few minutes of operation the smoke number is quite high. In steady state such high smoke levels would give increased levels of emissions throughout the spectrum. Apparently, during startup the cold walls of the combustion chamber are reducing flame temperature and optical emission intensities. The effect of the cold walls dominates over the effect of increased emissivity from the flame due to the increased soot. During the warm-up period the cad cell approaches its steady state value (on a relative basis) sooner than the IR or thermocouple sensor. The cad cell requires about 10 minutes of firing to approach its steady state value. During the time period from 1 to 10 minutes, however, the change in excess air associated with the changing resistance is only about 10% (roughly 45 to 34% excess air in this specific case).

The duration of the warm-up transient is dependent upon the combustion chamber arrangement. To illustrate this, Figure 65 shows the trend in cad

Figure 61. Air Atomized Burner. Smoke Number/Excess Air Relation.

Figure 62. Air atomized burner. Intensity at 550 nm vs. excess air. Viewpoint at end of the combustion chamber.

Figure 63. Air atomized burner. Intensity ratio vs. excess air. Viewpoint at end of the combustion chamber.

Figure 64. Smoke number and response of broadband sensors over a firing cycle - retention head burner.

Figure 65. Cad cell resistance over a firing cycle-wet base boiler.

cell resistance after startup for a retention head burner mounted in a wet-base cast iron boiler. This boiler has a "bucket" type combustion chamber with a fairly thin wall ($\sim 3/8$ "). Some additional data of this type was taken with two other wet base boilers with and without combustion chambers. Generally, the warm-up time is related to the combustion chamber refractory mass. Wet base boilers with no combustion chamber have warm-up times on the order of a few seconds.

5. CONTROL SYSTEM OPTIONS

Results presented in the previous section suggest a number of approaches for control systems. The practical aspects of the implementation of these are discussed in this section. A critical factor for any control system which is discussed in this section is the availability of suitable sensor system components and the cost of these components. As discussed in Section 1.1 two basic control modes are considered, 1) service required signals, and 2) steady state excess air trim. All of the cost estimates discussed in this section are "O.E.M." or wholesale costs. In most cases these estimates have been obtained from manufacturers. In some cases estimates of O.E.M. costs are based on retail costs.

5.1 Optical Sensors

Table 2 lists the common types of optical sensors which could be considered for use in control applications. Photoconductors are made from semiconductor materials and experience a bulk decrease in resistance with increasing light intensity. A photodiode consists of a PN junction arranged so that light can strike the junction area. The response characteristics of a photodiode depend upon the way in which the diode is biased. Connected to a high impedance sensor circuit (no diode current), the diode operates as a photovoltaic device with output voltage increasing with the logarithm of light intensity. If connected to a very low input impedance sensor circuit, the output current has a linear relationship with light intensity. Relative to photoconductors, photodiodes are less sensitive because they respond only at the junction while the photoconductor responds throughout the material. The photodiode, however, has much faster response times which is important in some applications. Junction type detectors can be configured in different ways to amplify the output signal. Examples of this include the phototransistor and photodarlington transistor.

For measuring intensity over the entire visible range Cadmium Sulfide (CdS) photoconductors are the sensors of choice. These sensors, which are commonly used for flame proving in oil burners, are inexpensive (\$1.00 to \$2.00 each). Silicon photodiodes, which respond over a similar wavelength range, are similar in cost but not as sensitive.

Figure 66 illustrates the relationship between resistance and light intensity for CdS photoresistors. Over a small intensity range this curve can be approximated by a straight line and relationship between resistance and intensity expressed as:

$$R \propto I^{-n}$$

The value of n approaches 1 at low levels of light intensity and decreases toward zero at high levels. A high value of n means high sensitivity. With most of the measurement made during this project the intensity was in a range which produced an n value of about 0.5. In an optical control system sensitivity could be improved by reducing the intensity of light at the cell. The best method of achieving this is with the addition of a filter between the

CELL RESISTANCE

INTENSITY

Figure 66. Illustration of the Relationship Between Light Intensity and Resistance of a Cad Cell.

sensor and the flame. A plastic filter could be used with very roughly constant transmission over the visible and the cost would be insignificant.

In section 4 the use of the ratio of continuum (broad band) intensity to the intensity at the OH peak (310 nm) as a flame quality signal was discussed. The primary advantage of the use of this ratio, as opposed to simply the continuum intensity is reduced sensitivity to sensor surface fouling. Implementation of the measurement at the OH peak would require the addition of a narrow band pass filter. In addition, a sensor more sensitive than a photoconductor would be required because of the reduced intensities generally in the ultraviolet range and the narrow wavelength involved. Narrow bandpass filters are available for this purpose. These are glass filters with depositions of selected nonconductive materials. The minimum cost involved would be about \$10.00. To achieve the required detector sensitivity a vacuum photodiode or (better) a photomultiplier could be used. Complete with high voltage power supply this would involve a minimum cost of \$40.00. Considering that the wholesale cost of a residential oil burner is less than \$200, it seems clear that the added cost required to measure the intensity at 310 nm would greatly reduce the attractiveness of the optical flame quality indicator. Some cost reduction could be realized using a semiconductor photodiode (GaAsP) and a filter with a broader band pass. A filtered sensor of this type is available (for example, from Hamamatsu Corp., Model G3614) for about \$14.00. This would measure more than just the OH peak and an additional filter may be required.

Another approach discussed in section 4 involved the measurement of flame color. This could be achieved using two CdS photoconductors, each with a different broad band filter. This could be realized at very low cost, again using colored plastic filters. Unlike the narrow bandpass filter required for the measurements at 310 nm these transmit over a very broad range in the visible (several hundred nm) and would add an insignificant cost.

In section 4 it was shown that flame quality sensors based on color are most effective if the viewpoint is at the back end. This would involve several complicating factors. First, the optical sensor system could not be supplied integral with the burner but would have to be integrated with the complete boiler/burner system. In dry base, steel boilers, or other systems with an uncooled back wall, a penetration through the refractory wall and outer casing would be required. With cast-iron, section boilers or other boilers with water cooled rear walls a penetration through the pressure section would also be required, adding significantly to the cost. In addition, since the sensors are not located within the burner air tube, an additional fan for cooling and purging the sensors would be required. The minimum added cost for the fan is estimated to be \$5.00. Generally the flame color approach appears reasonable from a cost perspective. Because it requires integration of the sensor with the boiler and burner, however, this approach would be most attractive on new, matched systems.

In section 4 it was shown that the broad band intensity of light as sensed by a CdS photoconductor located within the burner airtube could be a useful measure of flame quality. One circuit for implementing this is illustrated schematically in Figure 67. This provides three LED lights to

Figure 67. Schematic of a Simple Comparator Circuit for Indicating Cad Cell Resistance.

indicate the resistance of the CdS photoconductor. When the cell resistance is at the setpoint a green light comes on. Red lights indicate a high or low resistance. This circuit was assembled and tested during this project. Three integrated circuits were used including a quad comparator amplifier, a quad "NAND" gate and a quad LED driver. The total cost of the components is about \$9.00 including the CdS photocell but not including the 5 V DC power supply. In an actual installation the power supply might be adapted from the existing burner safety control. Otherwise, if a dedicated power supply were used, the added cost would be under \$5.00.

In a laboratory test this optical system was used to adjust the burner air/fuel ratio with a repeatability of about ± 1 percent of excess air. In cyclic operation (5 min on/15 min off) the system operated reliably for a period of two months after which the test was stopped. It should be noted that longer term field tests are planned for the future.

One of the disadvantages of the simple broad band intensity signal is that the setpoint is dependent on the boiler or furnace into which it is fired. If the system were used in a burner intended for general use, the setpoint would have to be established as part of the installation procedure. The sensor system would then be useful in indicating when subsequent changes in flame quality and/or excess air occur. If, however, this optical system were used in new matched burner/boiler units, a setpoint could be established by the manufacturer. The initial excess air adjustment could then be easily done based on the lights.

Another potential disadvantage of the system illustrated in Figure 67 is that the system only indicates flame quality accurately when the burner is on and the combustion chamber is close to steady state. As discussed in section 4 of this report, the chamber warmup period is long in systems which have large refractory liners in the combustion chamber. This situation could be improved by adding a sample-and-hold function in the circuit which would hold the lights in their condition at burner shut-down through the off cycle. This would enable the homeowner to "inspect" the burner condition at any time.

5.2 Telephone Link for "Service Required"

Over the last few years systems have become available which allow service companies to monitor home oil tank levels remotely. A low oil tank level is communicated through the existing telephone service to a central computer. Manufacturers of these systems include Scully Signal Company (Wilmington, MA) and STS Systems, Inc. (Canada). These systems are also currently capable of indicating when a burner control lockout has occurred and when the indoor air temperature has dropped below a setpoint indicating a heating system failure.

The optical systems discussed in section 5.2, or other service required signals as discussed in section 4 could be integrated with these telephone link systems fairly easily, and at minimal additional cost. The current cost, however, of the telephone link systems will limit the penetration to the more affluent homeowner market. The cost of the base computer system at the service company is \$2,000-\$3,000. The cost of the equipment required at each

home ranges \$80 - \$140. While integration of the sensors discussed in this report with telephone link systems offers obvious advantages, the use of sensors with simple, local condition indicators may achieve greater market penetration, at least in the near term.

5.3 Implementation of Active Excess Air Trim

Much of the discussion in previous sections involved methods of indicating burner condition for service purposes. As an extension of this, oil burners which self-tune excess air based on selected control system inputs might be considered. Control systems of this type are commonly used in larger commercial and industrial boilers (see section 2.1). Self-tuning, gas-fired residential heating units have also been built although there has been essentially no market penetration by these units to date.

For such control systems one or more inputs are required which indicate air/fuel ratio and/or flame quality. For excess air a zirconium oxide sensor is the most promising candidate. A very small sensor of this type (manufactured by Nederlandse Philips Bedrijven) has been used in a prototype self-tuning gas burner developed by a Dutch Gas Research Group. It seems likely that the quantity cost for sensors of this type, with heater controls, will be \$40-\$80.

To implement active excess air control it is necessary to modulate either burner air flow or oil flow. With conventional pressure atomized nozzles oil flow modulation could only be done by varying oil pressure. Currently, nozzles are rated at 100 psi and oil flow varies with the square root of this pressure. A reduction of oil pressure much below 100 psi would lead to larger drop sizes in the spray and increased smoke. Assuming a set point pressure of 144 psi and maximum and minimum pressures of 200 and 100 psi, respectively, gives a control range of $\pm 18\%$ on air/fuel ratio. Because of the high pressures involved and the limited control range, it seems more reasonable to consider air modulation instead of oil modulation.

In a conventional oil burner, air flow could be controlled either by throttling burner fan inlet air or by modulating the fan motor speed. For the first approach a very small damper actuator would be required. Systems of this type are very common in larger boiler controls and actuators may be either pneumatic or electrical. Damper actuators of this type are also commonly used in warm air heating systems to provide zoning. Because current residential oil heating systems do not already have a supply of compressed air available, electrically operated actuators would be more reasonable. These can be one of two basic types - proportional control actuators and directly operated. Proportional actuators would receive an input signal from a control circuit (e.g., 2-15 volts dc) and would produce a proportional damper position. A directly operated actuator would move the damper at a fixed rate in response to an input signal which is either on or off (or reverse). Cost estimates for these actuators range from \$25 to \$50. In any case, an added control circuit would be required with an additional cost of about \$15.

In modern retention head burners, both the fuel pump and the combustion air fan are driven by single electric motor typically rated at 1/8 - 1/7

horsepower. Combustion air flow could be controlled simply by modulation of this drive. The oil pump discharge pressure is regulated by an adjustable back pressure relief valve integral with the pump creating an internal (or external) recirculation of the excess oil flow. Modulation of the motor speed over a limited range would change only the relief valve flow rate but not the pressure. Since the flow of oil through the nozzle is driven by pressure, the burner firing rate would not change. Fuel pumps are commonly available which are rated for service at either 1750 RPM, typical of older burner designs, or 3600 RPM, for currently made burners. A 2:1 range of motor speeds could then be used without changing fuel flow. This would produce roughly a 2:1 range in burner air flow.

Variable speed motor drives are becoming increasingly popular for fan and pumping applications particularly in larger sizes (1 HP and up). There is a considerable improvement in efficiency in using variable speed motors in place of throttling for flow control [31]. At 1/7 horsepower an oil burner motor draws about 270 watts which is equivalent to 920 Btu/hr. Assuming a factor of 3 for the power production, the primary oil energy use due to the motor is 2800 Btu/hr. For a burner with a firing rate of .5 gal./hr (72,000 Btu/hr), the motor energy is 3.9% of the total consumption. For a typical air flow at 0.5 gph firing rate, the theoretical fan horsepower is small - less than .01 HP. Assuming even very poor fan efficiency (10%), the fan's contribution to the required motor horsepower is about 1/3. The purpose of this discussion on power is to point out that the energy savings which might be realized by using a variable speed drive in place of throttling to control burner air flow are small (under 1/2%) and should not be considered as a primary factor in comparing alternatives.

Oil burner motors are typically split phase (resistance start). These have auxiliary windings which are powered from start to about 85% of the rated speed. These motors cannot be operated at variable speed. Continuous operation with the auxiliary windings powered would lead to excessive current draw and motor failure. A better option for variable speed operation would be a permanent split capacitor (PSC) motor in which the auxiliary windings are powered continuously. This type of motor is commonly used for small fan applications and can have its speed changed either with an adjustable frequency inverter or with varied input voltage. The primary disadvantage of the PSC motor is low starting torque. A split phase motor has a starting torque about equal to the full speed rated load torque while a PSC motor has a starting torque about half (or less) of the full speed torque. The high torque requirement is imposed by the oil pump. The low starting torque disadvantage of the PSC motor could be overcome by using a two-value capacitor motor ("capacitor start - capacitor run"), although this is less common. As an alternative the oil pump and combustion fan could be driven by separate motors, although this would require a substantial change in system design.

In the oil heat industry, the use of induced draft, powered venting is starting to become accepted. In this case combustion air is driven both by a conventional burner fan and an added induced draft fan. Modest changes in excess air could be easily achieved in these systems by modulating only the draft inducers which are typically driven with a PSC motor. This would reduce the speed controller power requirements to about 100 watts and this could be met with a simple triac controller. The cost of such a simple controller

Table 2. Common Types of Optical Sensors

<u>SENSOR TYPE</u>	<u>RANGE</u>
<u>Photoconductors</u>	
CdS	visible (515 nm peak)
CdSe	visible to near IR (735 nm peak)
PbS	infrared (1000 to 3000 nm)
PbSe	infrared (1000 to 4200 nm)
<u>Junction Detectors (Photodiodes)</u>	
Silicon	UV to near IR (about 200 to 1100 nm)
Germanium	near IR (700 to 1900 nm)
GaAsP	UV to visible (190 to 760 nm)
GaP	UV to visible (190 to 520 nm)
InAs	infrared (1500 to 4000 nm)
<u>Photoemissive Detectors</u>	
Vacuum Photodiode	UV to near IR
Photomultiplier	UV to near IR
<u>Thermal Detectors</u>	UV to far IR

would be about \$15.00. A potential disadvantage of controls of this type is that they tend to be fairly noisy.

For modulation of the speed of the combined burner oil pump and combustion air fan, another option is a brushless DC, electronically commutated motor (ECM) [32]. These long-life motors have high starting torque and are available in the required horsepower range. One advanced gas fired furnace uses an ECM to drive an induced draft fan and another to drive the furnace warm air blower [33]. These motors, with the required DC control electronics, are fairly expensive. For oil burner service the cost would likely be \$50 - \$100. Using the ECM, the speed could be easily controlled over a wide range. In addition, a feedback motor speed signal could be readily provided by the ECM control circuit. This could be used in the overall burner control system.

6. DISCUSSION OF CONTROL STRATEGIES

Four specific control approaches are compared in this section with regard to cost, potential energy savings, and practical factors. In each of the four cases assumptions are made about the components which might be used and the type of output indications. Other options, however, could certainly be used. In no case, for example, is the use of a telephone link considered specifically. This is done only because it would add substantial cost with the primary benefit being convenience and not substantial energy savings. In homes in which the telephone links are being used, these should certainly be considered for communicating information on the burner and heating unit condition. This technology holds great promise for improving the efficiency of service organization operations and heating equipment reliability. In addition, future control sensors are likely to be integrated with heating system primary controls, effectively reducing costs. A resistance temperature detector integrated with the primary control could replace a peak hold dial thermometer, for example.

Stack Thermometer with Peak Hold

For evaluating fouling of the heat exchanger, the peak cycle flue gas temperature is the simplest and most effective measurement parameter. The use of a dial type thermometer with a maximum indicating arm would enable the homeowner to monitor system efficiency changes over the heating season and schedule a cleaning when performance degrades. The wholesale cost of this thermometer is about \$35. The average annual efficiency degradation due to fouling is about 2% which corresponds to a rise in peak flue gas temperature of 65°F. A stack thermometer would provide the greatest benefit in cases where a burner problem has occurred and the heat exchanger fouling rate is unusually high. Another important application is those systems which are not cleaned on a regular basis. The stack thermometer would prompt the homeowner to arrange for a cleaning when he might otherwise let the system run in a degraded condition for years. Assuming a reduction in annual fuel use of 2% with cleanings indicated by stack temperature and an annual oil bill of \$800, the simple payback would be 2.2 years. In some cases, however, particularly those in which burner problems do not develop over the heating season and which are cleaned properly on a regular basis, there would be no measurable benefit of a stack thermometer.

In the fall, as the load of a boiler with a domestic coil changes from hot water only to hot water plus heating, a jump in the cycle peak reading should be expected. In the next level of complexity, thermocouples arranged to indicate the differential between the flue gas and the boiler water temperature would be very useful. Such a system would reduce variations over cycles and seasons.

Flame Quality Indicator Light

In the general case, flue-gas CO measurements were not found to be useful indicators of smoke. CO levels become high only at very high smoke levels. A

very important exception to this is the case of the prevaporizing burner. For burners of this type and blue-flame burners, CO often leads smoke and so could be a very useful control system input. For the prevaporizing burner tested, the output of the zirconium probe increased significantly at the point at which CO and smoke began to increase. This was a result of reduced flue-gas O_2 as well as increased combustibles on the sensor surface. The use of zirconium sensors could be a very attractive control approach for high performance burners of this type.

The optical-emission measurements which were made during this study show that this approach may be very useful in providing a measure of the flame quality. The variation in continuum intensity with smoke number could be very simply measured using, for example, the familiar cad cell. The addition of a sensor to measure emissions in a narrow band about the OH peak in the UV and the use of the continuum/OH ratio for control offers a significant advantage. This dual sensor system would be much less sensitive to small shifts in sensor position, coke deposits on the burner tip, and the buildup of dirt or oil film on the sensor. A disadvantage of the dual sensor approach is, of course, the additional cost.

The optical approach generally has the disadvantage of not being totally independent of firing rate and nozzle characteristics and of being subject to possible blockage problems. As a service tool, however, the optical approach could be very useful. Service personnel could adjust excess air until a given intensity or intensity ratio is obtained and then simply check the steady-state smoke number and excess air to ensure that the setting is reasonable. A substantial change in firing rate would require a setpoint change but the setpoint would not need to be changed if a slightly different spray pattern were used.

Based upon the simple comparator circuit for the cad cell described in section 5, the cost of a local flame quality indicator will certainly be less than \$20. This system will save energy simply by triggering a burner service call before service efficiency degradation has occurred. Assuming a 2% annual savings, a simple payback period of 1.3 years results (again \$800 annual fuel bill assumed). As in the case of the stack thermometer, an energy savings would be realized only in cases where burner problems develop between regular service. In light of this, it would be worthwhile to consider the relative frequency of occurrence of burner problems. In a recent oil heat industry workshop [34] participants were polled about the most significant service problems. Three items made up 70% of their responses:

1. sooting
2. burner setup and service diagnostics
3. oil quality

Also a recent analysis of the oil heating service industry listed the quantities of replacement parts required for servicing existing burners [35]. The most common are listed below:

<u>Item</u>	<u>Annual Usage</u>
oil filters	7,972,540
nozzles	7,775,573
controls	762,063
transformers	500,845
motors	450,682
circulators	200,769

These two examples simply serve to point out the importance of fuel and nozzle related problems. Both the flame quality indicator and the stack thermometer are relevant to these problems.

In addition to the simple cad cell, the results in section 4 and the discussion in section 5 indicate that optical intensity ratios could also be used. The primary disadvantage of these is increased cost and the primary advantage is reduced sensitivity to sensor fouling. Based upon the data currently available, the simple cad cell approach appears to be most attractive. The long term reliability of this approach, however, has not been evaluated. If sensor fouling proves to be a serious problem then further consideration should be given to the two color approach.

Local Oxygen Indicator

The addition of a zirconium oxide oxygen sensor with local output would be a great aid in burner tuning and diagnostics. Continuous monitoring of oxygen would indicate when excess air has changed due to fouling of the burner air inlet, flue blockage, or other burner upset. As discussed in section 2, however, the oxygen sensor may not indicate that service is required, in the case of a fouled nozzle. In many cases, when a nozzle fouls the oil flow rate drops (and flue gas oxygen increases), the spray pattern becomes skewed and the smoke level increases. A service required signal which is triggered by low flue gas oxygen would not indicate that this has occurred. At a cost of \$50-\$100 the oxygen sensor is expensive, and considering that it would be most useful as a service tool it is best carried by the serviceman rather than permanently installed on each boiler.

Feedback Excess Air Trim

One of the control modes under consideration in this project is automatic excess air control. While either optical or flue gas oxygen sensor inputs might be considered, both have serious limitations. The difficulty with the oxygen probe, as discussed above, is related to the occurrence of a fouled nozzle. An oxygen based control system would function to reduce excess air in the case of a fouled nozzle and so further increase smoke.

Similarly, a control system based on optical intensity could have serious problems in the case of partial blockage or fouling of the sensor. For example, a case could be considered in which a burner is adjusted to give constant continuum intensity at a sensor in the combustion tube. As that sensor gets dirty, the burner would be adjusted for higher smoke numbers and greater emission intensity to compensate, an unacceptable result.

For the automatic excess-air control mode, the potential difficulties of the oxygen system and the optical system could be largely eliminated by including both as inputs into the system. The air controller would then function to keep both signals within bounds or, if unable to do that, indicate "service required" and possibly lockout. Any system for automatic excess air control should be a "trim" system only, able to adjust air flow only within a limited range. This would prevent the system from operating under fuel-rich conditions and producing high levels of carbon monoxide.

For implementing excess air control in conventional oil fired systems, either a modulating damper or a variable speed drive could be considered. Because of the potential for mechanical failure with the damper, the variable speed motor would seem preferable. In either case, the addition of the oxygen sensor, optical sensor, controller, and actuator would add about \$200 to the cost of the burner. This at least doubles the burner cost. Potential energy savings with automatic excess air trim, as in other cases, are strongly dependent upon the current service practice. If the burner would normally be adjusted for very high excess air, the savings with an automatic trim system could be about 6% (see section 1). In this case the payback period, based on an annual oil bill of \$800, would be 9.2 years. If, on the other hand, the burner was serviced properly and regularly, the energy savings with automatic excess air trim could be negligible.

Summary

Four specific control approaches are listed below and compared with regard to cost and potential savings.

<u>Approaches</u>	<u>Cost</u>	<u>Potential Savings (%)</u>	<u>Payback (Years)</u>
1. Peak Hold Dial Type Thermometer	\$ 35	2	2.2
2. Optical Flame Quality Monitor (single sensor)	\$ 20	2	1.3
3. Optical Service Tool	\$ 20	6	0.5
4. Automatic Feedback Air Trim	\$150	6	4.2

7. CONCLUSIONS

Based upon the work performed during this program the following conclusions can be made:

- o Evaluation of the rate of performance degradation due to heat exchanger fouling can be done very simply using the peak flue gas temperature during heating season firing cycles.
- o Zirconium oxide oxygen sensors work well in oil-fired residential equipment and would be a very attractive part of an advanced control system. Based on current technology likely sensor cost is estimated to be \$50-\$75.
- o Measurement of flame optical emissions has been shown to be a very useful method of evaluating flame quality. Potentially this could be done using a low cost photoconductor sensor (e.g., a cad cell). Additional evaluation of the behavior of this type of sensor in extended service is needed.
- o Measures of the intensity of the continuum emission ("flame brightness") were found to be fairly good indicators of flame quality in tests with a broad variety of nozzles. An intensity "setpoint" for excess air adjustment for a specific nozzle could be used without resetting if a nozzle with a moderately different firing rate or spray angle were substituted. The measure of the continuum intensity could be in a narrow wavelength band or it could be made over a very wide band using, for example, an unfiltered cadmium sulfide photoconductor (cad cell).
- o A three light flame quality indicator, using a cad cell could be produced at a cost of about \$20 which would indicate "service required". Assuming an annual savings of 2% resulting from improved maintenance a simple payback of 1.3 years would result.
- o An improvement over the simple continuum intensity measure of flame quality would be realized if the ratio of continuum intensity to the intensity at the OH peak (310 nm) were used. The primary advantage of the use of this ratio is reduced sensitivity to moderate misalignment and fouling of the sensor.
- o As another approach flame "color" measurements could be made using two broad band sensors with different spectral response ranges. This type of measurement is particularly useful if made from a viewpoint at the rear of the combustion chamber. Such a measurement would be extremely difficult to implement in "wet base" boilers, requiring the addition of an air purged opening through the water passages. This approach should be considered in new designs.
- o Three uses could be considered for oxygen or optical sensors including 1) service tools to make excess air adjustment easier and more accurate, 2) "service required" signals, and 3) active excess air trim. For the first and second application either O_2 or intensity

inputs could be used. The oxygen sensor will require a different setpoint for each nozzle, firing rate and combustion chamber configuration. The optical method may also require setpoint readjustment with substantial changes in firing conditions or with different combustion chambers. With either control input, a final check of smoke number and possibly small excess air readjustments in the field is still recommended.

- o In the active excess air control mode situations could occur in which the control system creates a high smoke situation with either optical or oxygen input. This negative situation could be improved by using both oxygen and optical inputs and by limiting the controllable range for excess air.
- o The cost of implementing active excess air trim is about \$200. A substantial energy savings would be realized in those cases in which burners are not properly serviced.

8. RECOMMENDATIONS FOR FUTURE CONTROL SYSTEMS

8.1 Technical Recommendations

In this project a number of varied control inputs and approaches were considered. The results could be used in control systems which range from very simple with immediate application to sophisticated systems for the future. In this section recommended concepts for near term and far term controls are discussed.

The simplest case is the use of the flue gas cycle peak temperature to monitor degradation of the heat exchanger thermal performance. Dial type thermometers with a peak indicating arm are currently available. As a simplification of this a "dirty heat exchanger" warning light could be used to clearly indicate to the homeowner that a predetermined rise in flue gas exit temperature has occurred. The next step in the implementation of either of these approaches is the collection of data in a number of actual operating boilers and furnaces over a heating season. This would serve to demonstrate sensitivity and identify any practical factors which would influence selection of measurement methods and/or temperature sensor location.

The next level of complexity which should be considered is the optical flame quality indicator with local, three light output, as developed during this project. A major question remaining with this attractive optical approach is reliability over extended use. Long-term performance evaluation and, if required, optimization of the sensor location within the burner air tube to minimize fouling effects are specifically recommended. If the reliability of the simple optical sensor approach is not found to be acceptable, then dual wavelength sensors should be considered. This should include both the continuum to OH ratio and two broad band sensors (flame color). The latter approach should use a viewpoint at the back of the flame.

The simple optical system could be considered for refit to existing burners. In this case it would be very useful for indicating changes in flame condition after the burner has been properly adjusted by the service personnel. As a tool for adjusting the air/fuel ratio of a burner during initial installation and servicing, any of the optical approaches discussed in this report could be considered. The best application for this purpose, however, is in new, matched systems. This would be a boiler or furnace designed to operate with only one brand of burner, at a fixed firing rate, with a specified nozzle. Under such a carefully controlled situation, a single control setpoint could be established, greatly improving the accuracy and simplicity of installation and routine service.

The next approach which should be considered is control systems which actively adjust burner excess air for optimal performance. The primary advantage of considering the "three light" (or related approach) system before the active control system is that it is essentially failsafe. A failure of the three light system might produce an unnecessary service call or, in the worst case, would simply not indicate a burner which needs service. This latter case is essentially equivalent to the present uncontrolled situation. The active control system, however, could create an air fuel ratio which is too

lean or, worse, too rich. For this reason implementation of active controls should be considered after the reliability of the sensors has been established. A system which actively trims excess air has some very significant advantages and should be considered as the eventual goal of controls development, in spite of the presently estimated costs for such systems. Such a system would make service very simple and accurate. In addition, it would permit variation in excess air over the firing cycle to reduce transient smoke and ensure that the equipment operated at maximum efficiency over the entire heating season. For maximum reliability both oxygen and optical sensors should be used in active control systems.

8.2 Programmatic Recommendations

The use of advanced control systems would lead to maintaining a higher level of efficiency and reliability of oil fired home heating systems than would result by current practices of service personnel. The following two planned follow-on activities will help the commercialization by establishing reliability under realistic field conditions and by evaluating market potential.

1. Field Tests on the Optical Flame Quality Indicator

Testing is continuing to evaluate the reliability of the three light optical flame quality indicator under actual field conditions.

2. Evaluation of Market Potential

A presentation and brief report describing the optical flame quality indicator will be prepared for discussions with industry groups. Based on discussions with controls manufacturers, primary equipment manufacturers, and service organizations the level of commercial interest as well as any concerns will be identified. The physical configurations for this concept which are most interesting commercially will also be identified.

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