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INFORMAL REPORT

DEVELOPMENT OF SELF-TUNING RESIDENTIAL OIL-BURNER

OXYGEN SENSOR ASSESSMENT AND EARLY PROTOTYPE SYSTEM OPERATING EXPERIENCE

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Prepared for:
Office of Building Technology, State and Community Programs
United States Department of Energy
Washington, DC 20585

Energy Efficiency and
Conservation Division

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Abstract

This document is the first topical report dealing with a new project leading towards the development of a self-tuning residential oil burner. It was initiated under the Statement of Work for the Oil Heat Research and Development Program, for Fiscal Year 1997 as defined in the Combustion Equipment Technology Program, under the management of Brookhaven National Laboratory (BNL). In part, this work is based on research reported by BNL in 1990, suggesting various options for developing control strategies in oil heat technology leading to the enhanced efficiency of oil-fired heating systems. BNL has been addressing these concepts in order of priority and technology readiness. The research described in this report is part of an ongoing project and additional work is planned for the future assuming adequate program funding is made available.

BNL has continued to investigate all types of sensor technologies associated with combustion systems including all forms of oxygen measurement techniques. In these studies the development of zirconium oxide oxygen sensors has been considered over the last decade. The development of these sensors for the automotive industry has allowed for cost reductions based on quantity of production that might not have occurred otherwise. This report relates BNL's experience in testing various zirconium oxide senors, and the results of tests intended to provide evaluation of the various designs with regard to performance in oil-fired systems. These tests included accuracy when installed on oil-fired heating appliances and response time in cyclic operating mode. An evaluation based on performance criteria and cost factors was performed. Cost factors in the oil heat industry are one of the most critical issues in introducing new technology.

One design of zirconium oxide sensor provided excellent results at a low production cost with fast response times in cycling which was selected by BNL for prototype development of a self-tuning oil burner design options. This sensor is unique in that one signal - the Nernst voltage across the sensing zirconium oxide disk is used both to control the sensor and to generate its output to the control system. The sensor acts as a oxygen pump and the frequency of pumping action is proportional to the partial pressure (concentration) of oxygen in the gas mixture of interest.

The sensor has been packaged along with air/fuel ratio control options with several different oil burners and tested in residential heating appliances with various levels of success. The most promising being in a Fan Atomized Burner (FAB) modified with a fuel feed control based on an automotive throttle body injector. The throttle body injector acts as a oil flow control which adjusts the burner's fuel firing (input) rate based on the control signal. The control signal is based on the burner's air/fuel performance (oxygen concentration in the combustion products) as determined by a zirconium oxide sensor located in the exhaust gases using a closed loop feed-back control system. Tests were also conducted using a conventional flame retention head burner, the current standard of the oil heat industry, using both speed control in one case, and a motor driven air control damper actuator in the other, both utilized the same oxygen sensor and closed loop controller as in the case of the modified FAB.

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Development of Self-Tuning Residential Oil Burner
Oxygen Sensor Assessment and Early Prototype System Operating Experience

1.0 Introduction and Background

BNL has initiated a project with the target of developing a self-tuning oil burner using an oxygen sensor technology similar to that used in automobile emission systems. In defining this project several approaches have been given consideration. The project has been restricted in scope by the over riding cost issues attached with the various concepts. Even in looking at the problem in this way, cost will ultimately be a major hurdle to any concept proposed in the price sensitive field of residential oil burner manufacture. The concept is not new, although to our knowledge, it has never been used in a residential sized oil burner. It has however been discussed by many members of the oil heat industry over the years. In part, this work is based on research reported by BNL in 1990, suggesting various options for developing control strategies in oil heat technology leading to the enhanced efficiency of oil-fired heating systems. BNL has been addressing these concepts in order of priority and technology readiness. The research described in this report is part of an ongoing project and additional work is planned for the future assuming adequate program funding is made available.

In larger systems, commercial and industrial scale, the idea has become a reality. The savings in satisfying emission requirements, as well as maintenance and fuel costs associated with combustion systems used in industrial manufacturing facilities, hospitals, and commercial buildings are such that systems designed for automated control are now practical and cost effective. In general, these concepts have taken the approach of monitoring the oxygen content of the combustion products and adjusting the burner by means of a electro-mechanical actuator to adjust the air-fuel ratio of the combustion process. Various sensors and systems have been designed by different manufacturers to measure the oxygen content in the exhaust stream. Likewise, different means are employed to adjust the burner to reach the desired air to fuel ratio. These oxygen measurement based systems require either a sampling system or an oxygen probe be placed into the exhaust gas stream. One manufacturer has very recently introduced a system that uses a unique optical scanner to monitor the flame using a controller that can interface with the burner via a linear linkage activator component. This system looks right into the flame through a sight port. It monitors two constituents in the targeted flame and the system maintains the efficiency ratio.

1.1 Oil Heat Equipment Manufacturer's Viewpoints

BNL has been gathering guidance and direction from the oil heat industry for over a decade including responses to an oil heat trade journal's survey of several leading oil heat equipment manufacturers regarding the self-adjusting system concept. The industry consensus is that yes, it can be accomplished. The benefits can be significant. The question remains: can it be done at reasonable cost and in a simple easy-to-implement design? There are reasons why it hasn't yet been done. If it was simple it would already be in the marketplace.

BNL has planned the project accordingly and will attempt to resolve these questions and issues in a logical sequence of smaller steps. First will be sensor technology. Second will be issues of mechanical actuators (servo systems). Third will be the question of controlling the process. Cost will be factored throughout the process. However, cost will not necessarily be a considered factor that will cause BNL to eliminate a concept prior to engineering developmental tests. An example would be the use of a prototype sensor technology that can't be had for a reasonable price because it has not yet been sold in sufficient quantities for quantity price reductions to have occurred.

This report will provide the results of the first step based on the initial assessment and comparison of low cost oxygen sensors. This has included actual testing of various candidate sensors in combustion and flue gases generated by residential oil burners and appliances, as well as long term testing of some of the most promising options in *breadboard* systems using a process controller in a closed feedback loop.

1.2 Oxygen Measurement System Selection

In selecting an oxygen measurement system BNL has, in the past, considered various sensor technologies including processes based on paramagnetic, electro-chemical, and zirconium oxide detection. The paramagnetic is the most accurate and dependable but not very practical due to the cost, sampling system, and complexity limiting it to only those types of applications where higher cost and sampling system maintenance are not at issue. The electro-chemical approach is quite accurate but requires periodic replacement of the sensor cell which is slowly consumed (oxidized) over its lifetime of about one year of intermittent use. Most portable flue gas analyzers use the electro-chemical type of oxygen sensing technology. The last category of common oxygen sensors are those based on zirconium oxide. This is the type used in the automotive industry and the technology of primary interest to this project.

2.0 Zirconium Oxide Oxygen Sensor Characteristics

A zirconium oxide oxygen sensor nominally consists of a pair of porous platinum electrodes separated by a layer of the zirconium oxide, see Figure 1. At high temperatures the solid zirconium ceramic becomes conductive to oxygen ions ($O^{=}$). When exposed to two different levels of oxygen concentration on either side of the cell (for example, ambient air and engine exhaust gases) a voltage is produced. The voltage output is dependent on the two partial pressures of oxygen in addition to temperature and can therefore be used to determine air/fuel ratio for an exhaust stream from a combustion system when referenced to the known ambient oxygen concentration in air.

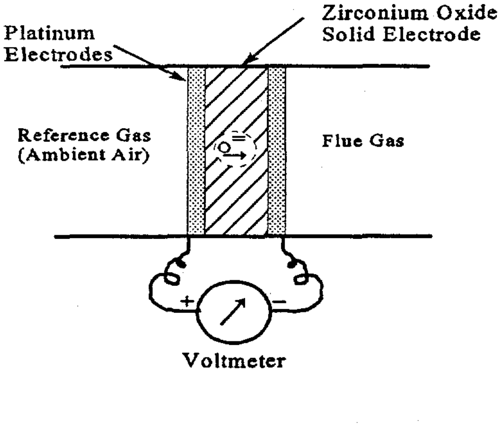


Figure 1.
Solid Electrolyte Oxygen Sensor

The basic characteristic output curve of voltage as a function of changes in the air/fuel ratio (lambda) for a typical zirconium oxide sensor is illustrated in Figure 2. This curve is different at different temperatures but will have the same characteristic shape and exhibit the same type of jump in output at stoichiometric conditions. The external voltage produced is related to the flue gas oxygen content, the reference gas oxygen constant, and the temperature by the Nernst equation. At stoichiometric conditions (fuel/air ratio equal to one, zero percent exhaust gas oxygen) the large change in the output voltage, termed the ***lambda jump***, is basically insensitive to sensor temperature. This behavior is used in automotive applications to control the air/fuel ratio near stoichiometric conditions in engines equipped with catalytic converters. These systems can be designed with heaters (used with lean burn engines) or without.

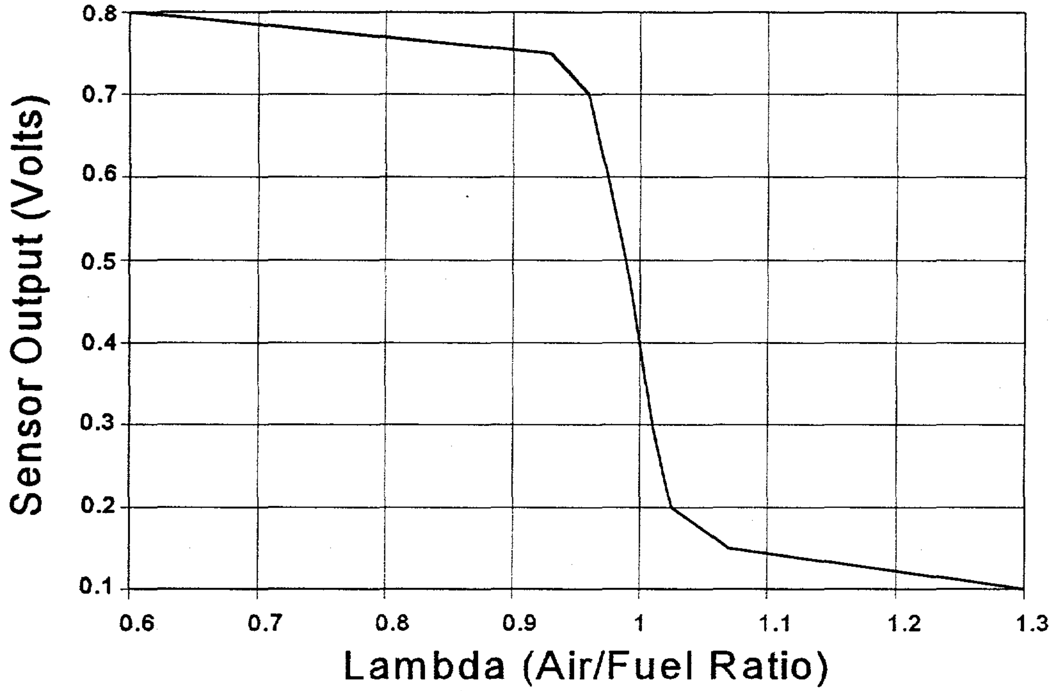


Figure 2. Typical Zirconium Oxide Oxygen Sensor Cell Voltage Characteristics

In considering the problem of developing a self-tuning burner BNL has recently investigated four candidate oxygen senors based on zirconium oxide technology. These included an unheated automotive lambda sensor, a heated automotive lambda sensor, a duel chambered Honeywell-Gasmodul heated sensor, and a simple unheated probe with an integral thermocouple made by Australian Oxytrol Systems Pty. Ltd..

The oxygen sensors under examination are of a design applied to current automobile and combustion system emission controls. These take advantage of one of two electrochemical mechanisms of Zirconium Oxide (ZrO_2) when the material is heated or exposed to a gas stream at elevated temperatures. The automotive sensors are commonly provided in the unheated configuration but the addition of a heating element within the sensor provides faster response during cold starts. The gas stream temperatures range from below 300 C (572 F), with heat added to the cell material, to above 650 C (1202 F), without heat added to the material.

One of the characteristics is that at high temperature the material partly dissociates to produce mobile negative oxygen ions which normally move at random. When a DC voltage is then applied across the material, the ions can be transported through it, liberating oxygen at the anode. The application of this characteristic is as a pump to transfer oxygen ions within the sensor cell.

Another characteristic of ZrO_2 at high temperatures is that any difference in oxygen pressure across it generates an electrical potential, known as a Nernst voltage. The Nernst equation is:

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

where
V = output voltage,
T = temperature (° R),
$[O_2]_R$ = oxygen partial pressure on the reference (ambient) side,
$[O_2]_F$ = oxygen partial pressure on the flue gas side.

This voltage is proportional to the natural logarithm of the ratio of the oxygen partial pressures on either side of the material. The application of this characteristic is as a Nernst-concentration cell to measure the relative oxygen concentration of two gas mixtures, one normally is the ambient air (20.9 % O_2) and the other is the mixture of unknown oxygen content in question. In the case of a residential oil burner this will be somewhere in the range measured between 0% and 20.9% oxygen.

2.1 Unheated Lambda Sensor (Two Wire)

Whether unheated or heated these sensors have been called ***lambda type*** and used to measure the relative concentration of oxygen in combustion gases when compared to that of ambient air. Lambda (λ) is the fuel independent Air-Fuel (A/F) ratio. As is illustrated in Figure 1, an output voltage, called the Nernst voltage equal to about 0.8 volts, is generated by the sensor in a fuel rich exhaust stream where $\lambda = 0.6$. At about $\lambda = 0.95$ at 0.75 volts there is a downward knee in the (voltage versus λ) output and the voltage falls rapidly to about 0.4 volts at $\lambda = 1.0$ or stoichiometric conditions. The characteristic curve is similar but the voltage values measured on either side of the lambda jump will change depending on the temperature of the sensor. At the early fuel lean conditions, at about $\lambda = 1.05$ at 0.15 volts, the output again goes through a knee and begins to level off to a $\lambda = 1.3$ and a voltage of 0.1 volts. It is this fuel lean portion of the characteristic output curve which is of most interest with regard to designing a self-tuning control for residential oil burners. The design would be such that the oil burner would never be allowed to operate in a fuel rich condition due to the likely carbon monoxide formation and the potential for fouling due to soot formation.

In automobiles, unheated oxygen sensors are installed close to the engines exhaust manifold and rely on engine heat to bring the sensor temperature above the point at which the zirconium oxide has a reasonable conductivity. The temperature changes with engine load and the sensor can only be used in the ***lambda jump*** mode to control air/fuel ration very close to stoichiometric conditions. To be useful in the oil fired appliance the sensor would be required to be located in a zone of relatively constant high temperature if the fuel lean portion of the characteristic curve is proven to useful in control designs. In using an unheated lambda sensor the location of the sensor would most likely require it to be placed close to or in the combustion chamber of the appliance where it could be maintained within its functional temperature range between 900-1600F. A thermocouple or similar temperature measuring device would be required so that the temperature of the sensor could be used along with the voltage from the sensor to determine the oxygen concentration in the flue gases by use of the Nernst equation.

2.2 Heated Lambda Sensor (Three/Four Wire)

The heated automotive lambda sensor uses a positive temperature coefficient electrical heating element which is designed to maintain the zirconium oxide in its high conductivity temperature range. Reported advantages of using the heater include faster warmups, reduced difficulties due to upsets (such as water hitting the sensor), and the ability to use only one sensor with V-8 type engines. Like the unheated sensor the heated unit is used only in the ***lambda jump*** mode. In a residential oil fired system the heated sensor could be placed in the flue pipe or integrated with the appliance in a location where the flue gas temperature is higher.

2.3 Dynamic Oxygen Sensor (GMS-10, Honeywell-Gasmodul BV)

The unique sensor designed and developed by Nederlandse Philips Bedrijven, B.V. (Netherlands) was obtained in 1993 by Honeywell-Gasmodul BV which now owns the rights to this technology. Honeywell Gasmodul combines two Phillips development groups that specialize in burner controls and oxygen sensors. The intent was to develop a control system for appliance systems based on these two expertise. Current European appliance developments apply the sensor and control to gas fired residential equipment. To date, BNL is not aware of any private sector development plans centered on oil fired appliance system applications for the residential market.

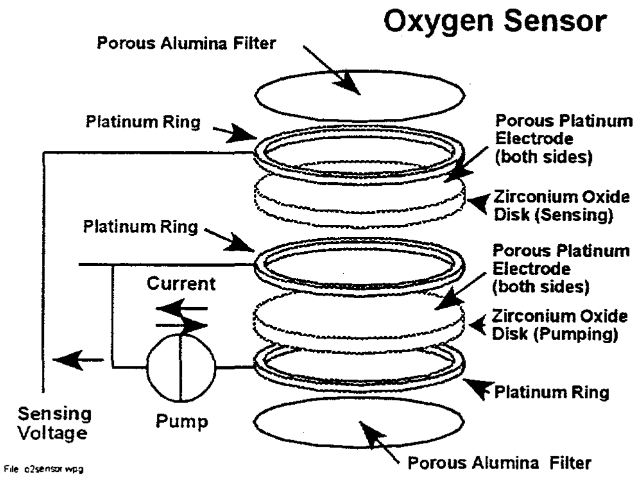
The sensor consists of two identical ZrO_2 disks with porous platinum electrodes and three platinum rings sandwiched alternately together, Figure 2. The outer platinum rings, which provide the sensors electrical contacts, are each covered by Al_2O_3 (alumina) filters, and the entire assembly, with a heating coil, is housed in a shell of porous stainless steel.

The sensors operation is cyclic. One of the two ZrO_2 disks is connected to a reversible current source. Working as an oxygen pump, it evacuates the oxygen from the chamber between the disks. This creates a difference in oxygen pressure across the other ZrO_2 disk, generating a Nernst voltage that is proportional to the difference between the oxygen pressure in the chamber and the oxygen pressure outside the sensor. The Nernst voltage increases as the electrochemical pump evacuates the chamber. When the voltage reaches a pre-set level, the current across the pumping disk is reversed. The chamber is re-pressurized, and the Nernst voltage decreases until it reaches its starting level, at which time the pumping action is reversed again, and the cycle repeats itself.

What makes the sensor unique is that one signal - the Nernst voltage across the sensing ZrO_2 disk - is used to both control the sensor and to generate its output to the control system. To control the sensor, the Nernst voltage is compared with two reference voltages, and the pump is reversed whenever one of the reference voltages is reached. The output to the control system is not based on voltage (which is never static) but on the duration of the pumping cycle, which is easy to measure. The duration of the cycle is a measure of the partial pressure of the ambient (combustion product) oxygen, which in turn is directly related to the oxygen content of the gas mixture.

The dynamic oxygen sensor is small, measuring 2 x 2 x 1.5 mm. It has no moving parts and does not require a mechanical dosing pump or a calibrated leak. As a result, it is expected to be rugged and reliable with a lifetime of more than 30,000 hours in continuous operation for gas applications and over 10,000 hours for oil applications equivalent to one year of continuous use or 3 years of cyclic operation based on the manufacturer's test data. The solid-state sensor is suitable for operation in oxygen pressures from 10 millibar to more than 3 bar. It will operate in temperatures up to 300C and at gas velocities of up to 10 meters per second, allowing the sensor to be mounted directly in the flue. In 1997 over 10,000 sensor units were produced mainly for industrial applications. The sensor had been used in several combination gas boiler control system prototype development project aimed at the small residential European gas fired boiler market.

Figure 3. Dynamic Pumping Dual Chamber Zirconium Oxide Oxygen Measurement Sensor Honeywell-Gasmodul BV



2.4 Temperature Compensated Sensor (Type DL, Australian Oxytrol Systems Pty. Ltd.)

The sensor consists of a ZrO_2 pellet with a Type-R, platinum-13% rhodium / platinum, high temperature thermocouple. The pellet is bonded permanently to an impervious alumina tube by a high temperature eutectic welding operation. The protruding portion of the ZrO_2 pellet is coated with porous platinum and carries circumferential grooves to facilitate the attachment of the external electrode. The pellet end within the sensor is also coated with porous platinum and connected to the inner electrode. The thermocouple is mounted inside the alumina tube with the tip spring loaded against the pellet for measurement of the sensor temperature. The sensor is designed for use at temperatures in the range 700-1300C. This sensor requires a source of clean ambient air at 10 cm^3 per minute which is fed to the inside surfaces of the sensor and is used as a reference level of oxygen.

2.5 Intended Application In Self-Tuning Oil Burner

The region of the lambda versus output voltage plot (Figure 2) of interest to this project is the right hand side of the cell characteristic curve, where lambda is greater than one. We never want to operate in the left hand region, lambda less than one, where combustion is incomplete and carbon monoxide generation becomes a real serious issue. The intention is to use the zirconium oxide sensor in a very different manner than they are used in automotive engines. In automotive engines the designers want to assure that they will optimize the operation of the catalytic converters which requires the engine to operate near stoichiometric conditions. With oil burners we want to design a system that burns fuel lean all the time, just close enough to stoichiometric conditions to minimize excess air but, not so close that smoke is formed in the combustion process. The oxygen sensor is just one part of the puzzle, the other part is a controller and actuator that will respond to the changes in oxygen content but not over respond such that the burner operates in the smoke forming region near stoichiometric conditions. In the initial development of the self-tuning oil burner BNL will examine four different design concepts based on actuator options as indicated in Figure 4.

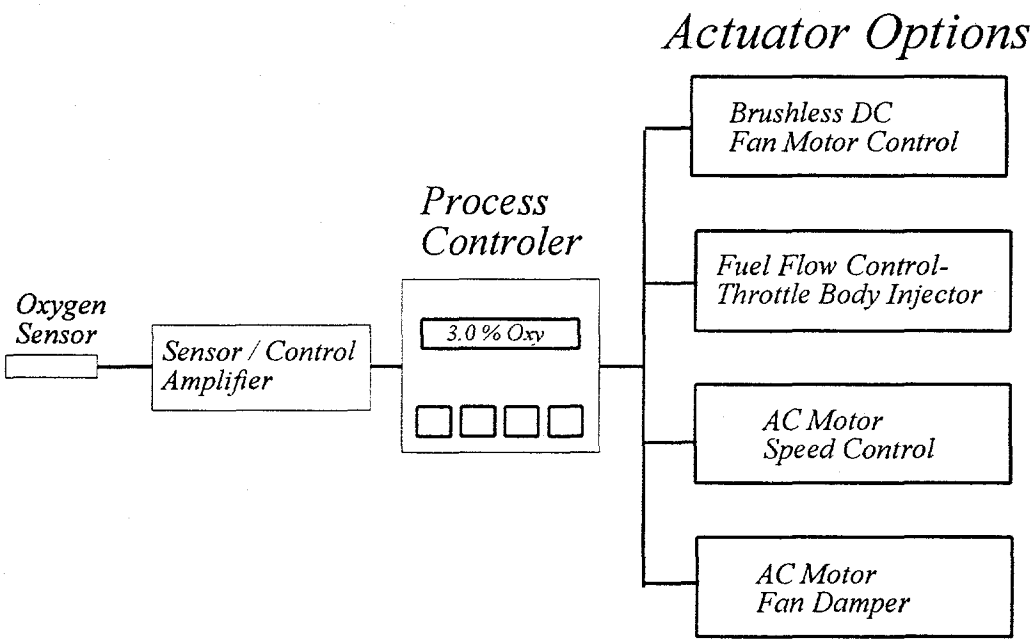


Figure 4. Diagram of Self-Tuning Residential Oil Burner Component Concepts

3.0 Oxygen Sensor Test Results

BNL has been looking at oxygen measurement technology for many years with regard to its combustion research related to residential oil burner performance and design. The first time BNL considered zirconium oxide sensors as a possibility for control technology was in 1990 when BNL had reported on its findings in ***Performance Control Strategies for Oil-Fired Residential Heating Systems*** (BNL Report 52250). At that time the self-tuning oil burner concept was not highly rated due to the need for more basic control concept development. The Flame Quality Indicator (U.S. Patent Issued to DOE) is one example of such controls. There has however been a continued interest in the possible application of zirconium oxide sensor technology to oil heat technology. The results presented in this section are therefor a compendium of results which include tests conducted over a considerable period of time dating back as far as 1990.

3.1 Unheated Lambda Oxygen Sensor (Two Wire)

In testing an unheated automotive type oxygen sensor the device must be located in a position where the probe will attain a temperature in the range of 700-1600F. The higher the zirconium oxide temperature the faster the response time will be to changes in oxygen level. In 1990 tests at BNL this was accomplished by installing it in the upper region of the refractory combustion chamber of a dry base steel boiler. The sensor was mounted into a refractory disk 0.5 inches thick and 3.5 inches in diameter. This disk was then placed in the *view port* location in the combustion chamber of the boiler. The end result was that the sensor was 6 inches above and 6 inches to the right of the center-line of the oil burner's retention head. This geometry produced a sensor temperature of 1200F which was ideal for the zirconium sensor when the oil burner was operating. This was determined by a type-K thermocouple installed to monitor the approximate sensor temperature by mounting it on the outside of the sensor housing.

The output voltage was measured along with the thermocouple temperature and are illustrated in Figure 5. The excess air levels as calculated based on these measurements, using the Nernst equation, are plotted in Figure 6 against the excess air levels as determined for the same test run using an independent paramagnetic oxygen measurement in the flue. There is a tremendous difference observed between the two different methods. This may be a result of not actually measuring the internal temperature of the probe, the zirconium oxide itself, and thus producing an error in calculating excess air levels based on the measured data and the Nernst equation where both voltage and temperature must be known accurately. The output of the unheated sensor along with measured temperature is plotted against time from burner start in Figure 7 over a firing cycle. This plot indicated one of the problems with the unheated sensor in that it requires approximately five minutes to settle down to reasonable output levels.

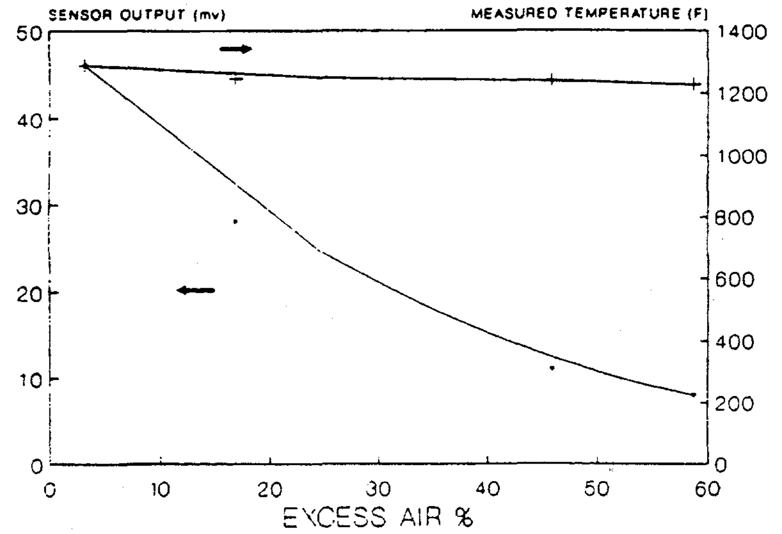


Figure 5. Unheated Automotive Zirconium Oxide Sensor --- Voltage Signal and Temperature as a Function of Excess Air

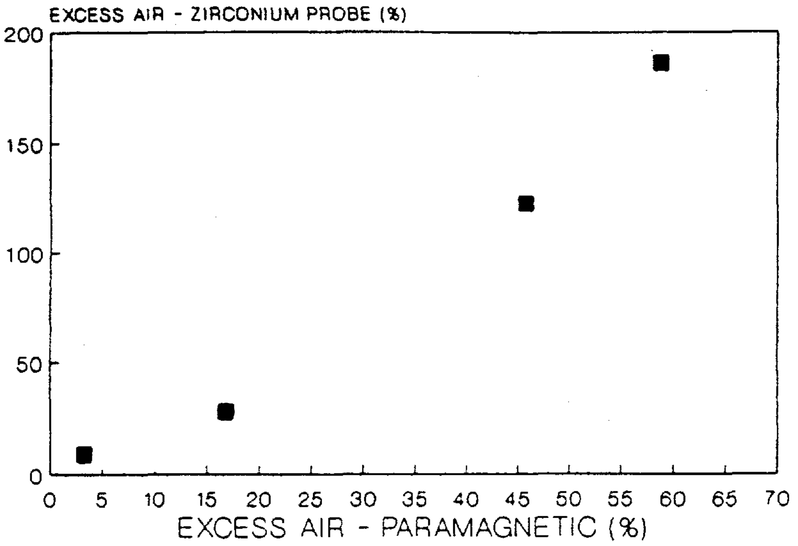


Figure 6. Excess Air Based on Unheated Automotive Sensor Compared To Paramagnetic Oxygen Analyzer

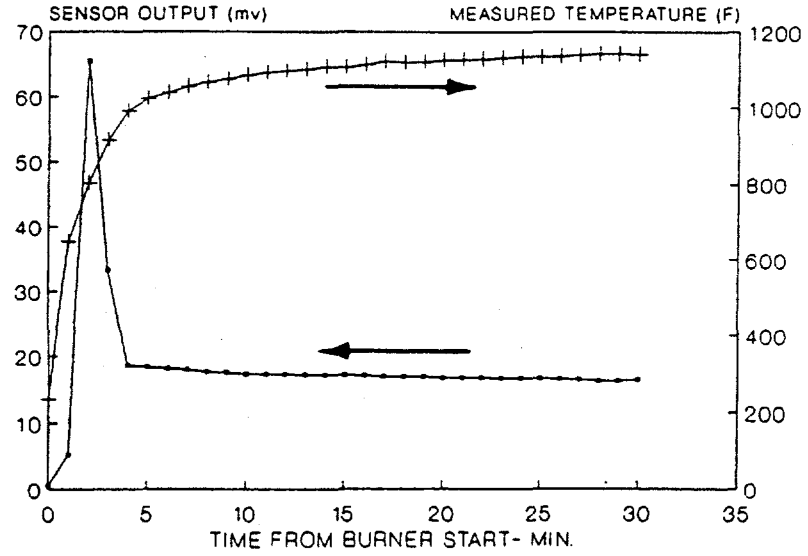


Figure 7. Unheated Automotive Sensor --- Output Signal Over A Firing Cycle

BNL has conducted tests of an unheated automotive oxygen sensor in a conventional three section cast iron wet base boiler with the sensor installed in a plug mounted and sealed in the view port opening of the front burner mounting plate. Also installed through this plug were a thermocouple for measuring gas temperature in the region around the sensor, a separate thermocouple for measuring gas temperature within the casing of the sensor, and a stainless steel sampling probe for measurement of the oxygen content in the surroundings of the sensor. The stainless steel probe could then be used of the laboratory sampling system and calibrated paramagnetic oxygen measurement system for direct comparison.

Tests were conducted at a firing rate of 0.65 gallons per hour (90,000 Btu/h) the resulting temperature at the point where the sensor was mounted was in the 750-800F range depending on oxygen level (excess air) which was varied from 2-6 percent during different tests. Figure 8 shows the measured gas temperature within the casing over the range of oxygen levels tested. These temperatures are at the low end of the operating range of the zirconium oxide sensor. At lower temperatures the internal resistance of the zirconium oxide becomes excessive. Figure 9 shows the measured sensor output in millivolts. This is directly measured at the sensor and not amplified or conditioned. Given the sensor temperature and the output the corresponding oxygen content can be calculated using the Nernst equation. Using this the calculated oxygen content was determined in two ways. First, using the measured temperature within the casing. Second, it was assumed that the temperature was higher and fixed at 850F. This was based on the readings of the second thermocouple installed to read the nearby gas temperature. Figure 10 shows the comparison of the measured oxygen content and the oxygen calculated in these two ways. The agreement is interesting particularly at the low oxygen end which is of most interest for the intended application.

3.2 Heated Lambda Oxygen Sensor (Three/four Wire)

In the case of the heated automotive sensor mounting location was much simpler. The probe was located in the flue pipe of the boiler for testing. The power to the sensor heater could be varied between 0 and 24 volts to control its casing temperature between the boiler flue temperature (about 500F) and 1100F. Tests were conducted at different temperatures with the best response obtained at the highest temperature. When the casing temperature drops below 700F the output is not useable. Figure 11 shows the excess air levels calculated using the sensor output and the Nernst equation in comparison to the paramagnetic oxygen measurement system results. While the agreement is not excellent it is better than that of the unheated sensor in early tests conducted at the same time. As in the case of the unheated probe it is likely that the measured casing temperature is different than the temperature of the zirconium oxide. Figure 12 illustrates the response of the heated sensor over a firing cycle. Relative to using the low-cost unheated sensor in the combustion chamber, the heated sensor in the flue has a much shorter response time. When considering the heated sensor for the intended use the response time is quite acceptable. However, the cost of this sensor is almost three times that of an unheated sensor and would suggest that it is unacceptable for use in self tuning oil burners at this time.

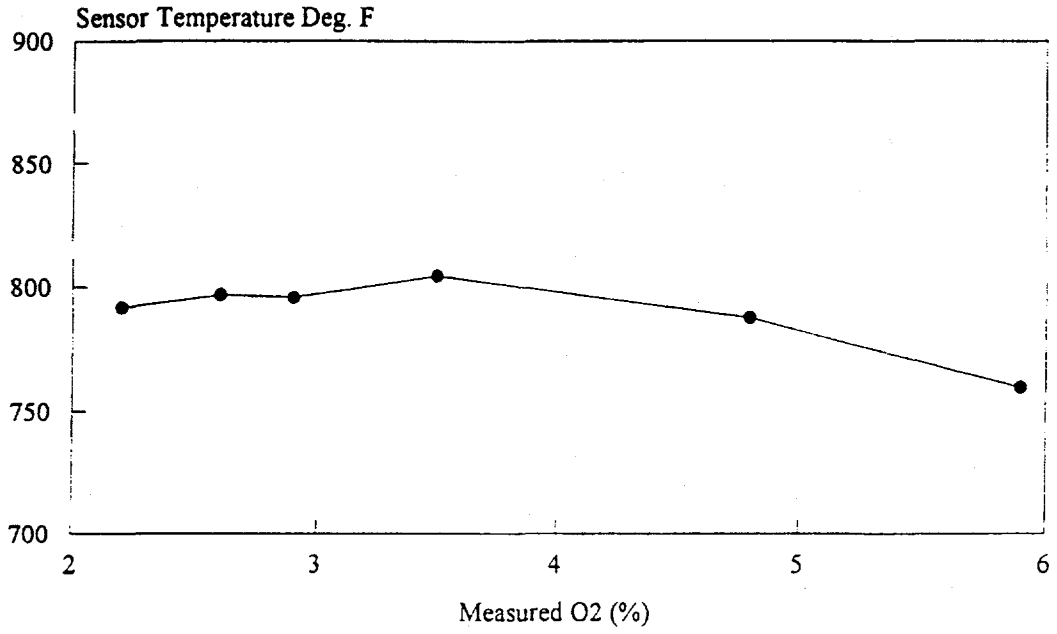


Figure 8. Automotive Oxygen Sensor In Combustion Chamber Wet Base Cast Iron Boiler Temperature of Sensor Casing Over a Range of Excess Air --- 0.65 GPH

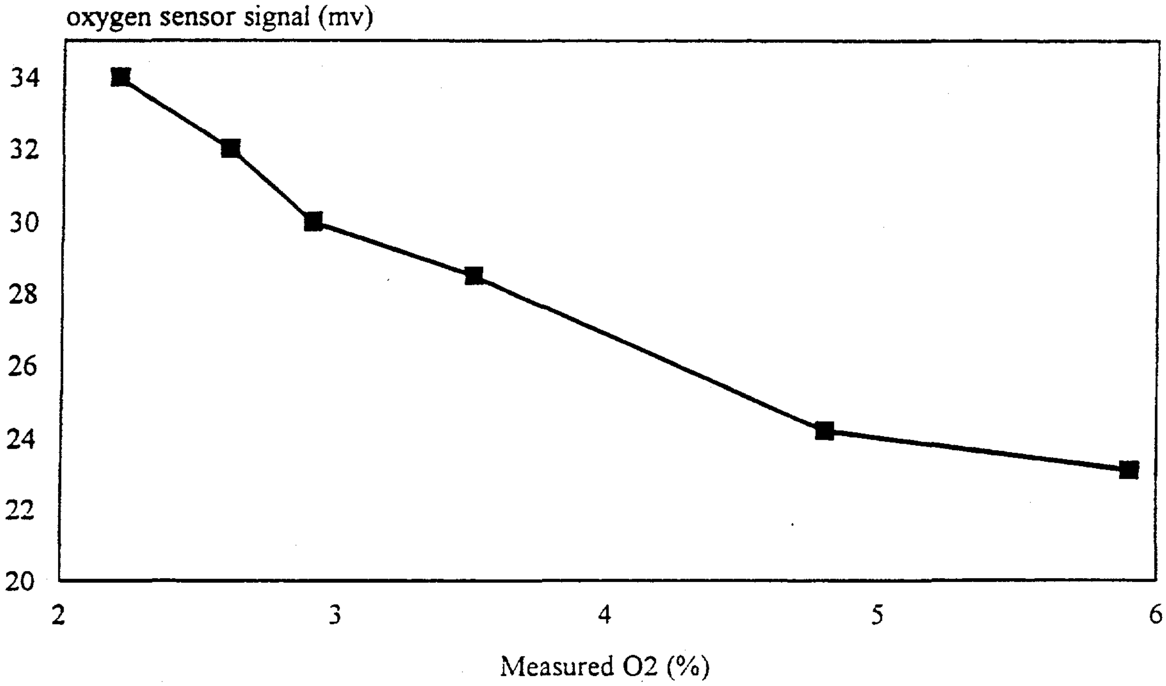


Figure 9. Automotive Oxygen Sensor In Combustion Chamber Wet Base Cast Iron Boiler Sensor Output Over a Range of Excess Air --- 0.65 GPH

Figure 10. Unheated Oxygen Sensor Flue Gas Oxygen Based On Casing Temperature and Assumed Average Temperature

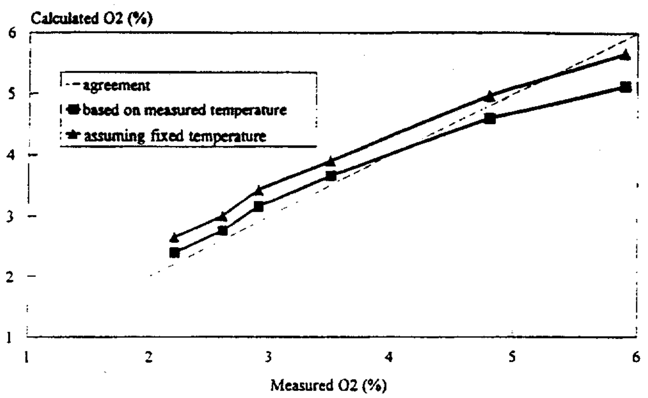


Figure 11. Excess Air Based On Heated Sensor Compared To Paramagnetic Analyzer

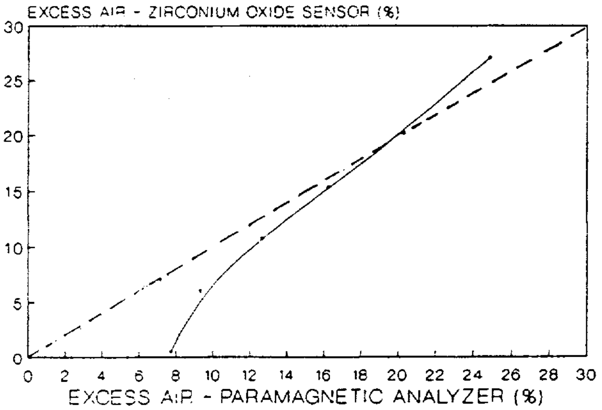
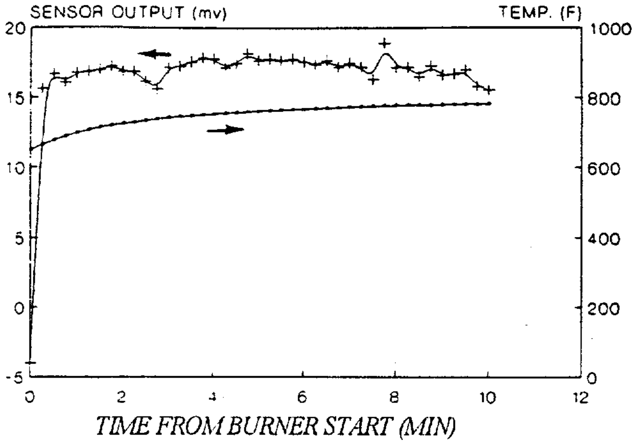


Figure 12. Heated Sensor Output Signal And Measured Temperature Over A Firing Cycle



3.3 Dynamic Oxygen Sensor (GMS-10, Honeywell-Gasmodul BV)

The dual chamber zirconium oxide device is designed for a maximum ambient temperature of 530F. It contains an internal heater which maintains its inner working temperature at a constant level (1290F) well above the minimum required for stable fast response of the zirconium oxide. Given the ambient temperature limit the sensor was mounted in the flue pipe of a boiler for testing at BNL. A control circuit serves to pump oxygen in and out of the chamber at periodic intervals. The time period depends upon the oxygen content of the flue gas and the control circuit produces a linear voltage signal in the range 0.0-8.3 volts for oxygen content between 0% and 20.9% for atmospheric pressure. Tests were conducted on the Honeywell Gasmodul BV, GMS-10 probe and control system starting in June of 1997 and are still continuing.

Relative to the simple zirconium oxide sensor this approach gives much better sensitivity at oxygen concentrations typical of oil heat systems. Figure 13 shows the results obtained of a comparison of the oxygen content based on the output of this sensor and the output from the laboratory paramagnetic oxygen measurement system. Based on this test accuracy is clearly adequate for the purposes of the self-tuning oil burner system being considered. The sensor has continued to be evaluated in the laboratory and in the field.

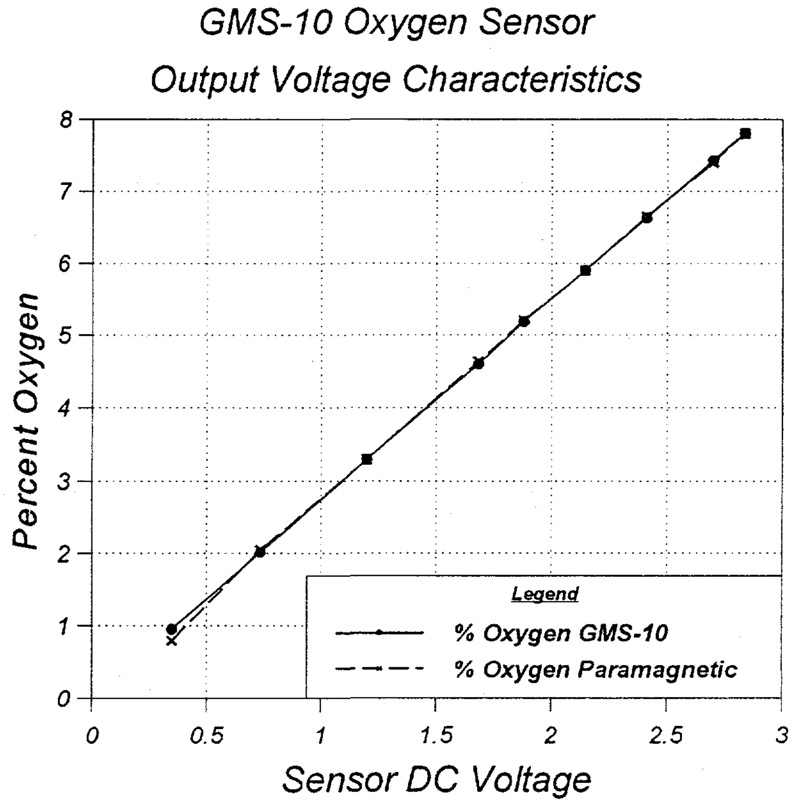


Figure 13. Oxygen Measured With GMS-10 Compared to Laboratory Paramagnetic System

Tests have been conducted to evaluate response to upset conditions. The sensor output was directed to a rapid response chart recorder and the flue or burner air inlet was suddenly restricted to change the excess air in a step-wise fashion. The measurements indicated that the sensor responded in under ten seconds in all cases, typically in less than eight seconds.

3.4 Temperature Compensated Sensor (Type DL, Australian Oxytrol Systems Pty. Ltd.)

A series of laboratory tests were also completed in June of 1997 with another zirconium oxide sensor manufactured by Ceramic Oxide Fabricators Pty. in Australia. The sensor tested was custom built for BNL and was much shorter than those normally produced by the company for use in determining and or controlling oxygen levels in gas mixtures and molten metals. Their normal applications involve large industrial furnaces and the probe must be considerably longer to penetrate jacket insulation. The nominal operating temperature range for use of the sensor is 1300 to 2370F. As tested this sensor was installed at the back end of a Thermodynamics test boiler in the BNL facility. To achieve temperatures in the range specified a retention head burner was used and the firing rate was 0.6 gallons per hour. The result of a comparison of oxygen levels, as calculated based on the sensor temperatures and millivolt signals, with the oxygen as measured with the laboratory paramagnetic oxygen measurement system is shown in Figure 14. Over the entire range the oxygen levels obtained using the output from the zirconium sensor was low relative to the oxygen levels determined by the calibrated paramagnetic measurement system. Reasons for the difference are not clear. Testing was conducted to see if the effects of the sensor temperature or forced flow rate of the required clean ambient reference air into the sensor had any measurable effect. No resolution was determined for the difference.

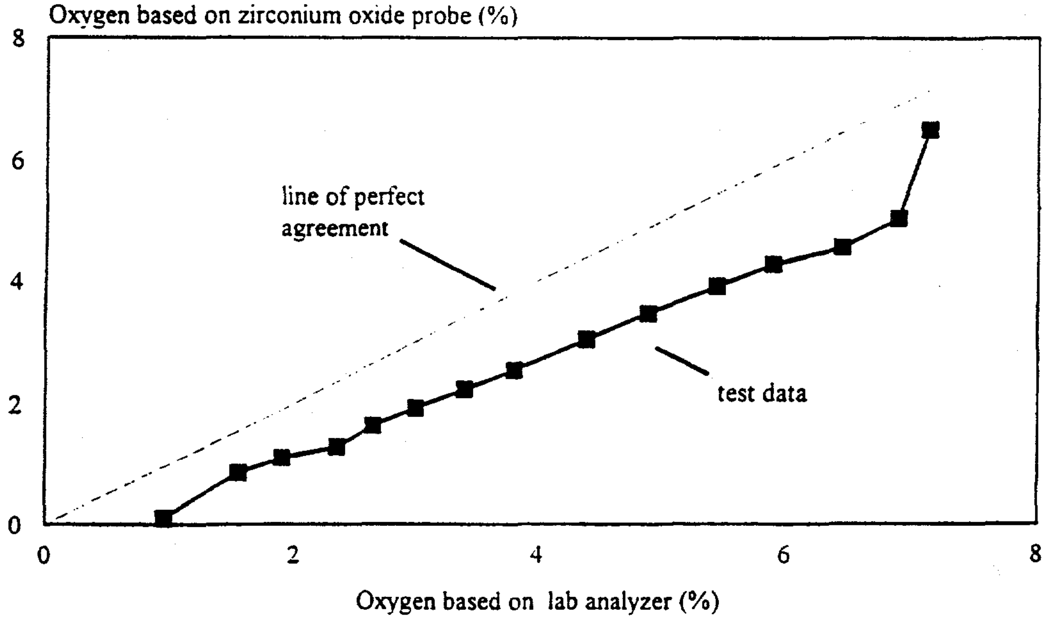


Figure 14.Comparison of Australian Zirconium Oxide Sensor Versus Paramagnetic System

3.5 Discussion of Tests results

The unheated automotive lambda oxygen sensor is very desirable from the stand point of unit cost at about $25 per sensor. The problems associated with locating the sensor in a hot location within or very near the combustion chamber present real problems when considering the variety of oil fired furnace and boiler designs on the marketplace today. The results of testing indicate that the unheated sensor could be useful in steady state applications but that relatively long burn times, more than five minutes, would be required for good results. Even though the accuracy of the sensor is relatively good, in many installations there is a real problem due to the frequency of the burn cycle and the relatively short duration which is often less than five minute. The heated automotive lambda sensor resolves the issue of burn duration but the cost factor is almost triple at about $75 per unit. With the same type of relatively accuracy the cost per sensor is much too high for use in a self-tuning oil burner application. The heated sensor which is already in mass production for use in automobiles so that further cost reductions based on additional volume can not be considered probable when dealing with the oil heat industry which only produces about 400-500,000 unit per year. The temperature compensated sensor manufactured in Australia does not have the high level of accuracy BNL had hoped it would exhibit. This probe is not currently produced in quantity.

This leaves the dynamic oxygen sensor developed by Phillips and now produced by Honeywell Gasmodul BV which shows excellent potential for application in the design of a self-tuning oil burner. This sensor almost duplicates the performance and accuracy of the calibrated laboratory oxygen measurement system which BNL uses as a standard for comparison. The one issue which must be considered with this sensor as with any sensor located in the flue is that of leakage of air into the appliance or flue pipe and may be unsteady in nature. Any such unpredictable leakage variations could easily upset the set point of a oxygen based control using a sensor located in the flue pipe. This is similar to what would expected for a heated lambda type probe. Care must be used in locating the sensor to minimize the potential for such problems.

The dynamic (GMS-10) sensor is projected to be in the same price range as an unheated automotive lambda oxygen sensor, about $25 per sensor. It is already in production with approximately 10,000 unit per year made mainly for industrial applications (efficiency meters, industrial boilers, ceramic ovens, composting, etc.). Life time testing of the sensor has been the subject of research by the manufacturer with over 30,000 hours in gas fired units and over 8,000 hours in oil fired units when the tests were stopped. Based on these tests, the manufacturer expects a minimum of three years continuous service, or seven year cyclic service when used with gas systems, and one year continuous, or three years cyclic service with used with oil systems.

The sensor is intended for use in applications in heating systems and is currently being considered by several gas boiler manufacturers along with a micro-processor gas boiler controller also made by Honeywell-Gasmodul. The electronic circuit and control unit used by BNL in the tests described above can be reduced to a few dollars in cost when incorporated along with a micro-processor based oil burner primary flame safety control which are currently emerging in the marketplace in the United States. Most of the major U.S. control manufacturers currently offer this type of control in their product lines and they are becoming more common place in the field with newer oil fired appliances.

These are the reasons that BNL has chosen to pursue the self-tuning oil burner concept using this particular type of oxygen sensor at this time. At this point in our research this is the most promising option for an affordable and durable oxygen sensor to base the control system of the oil burner design on.

4.0 Preliminary Experiments in Development of a Self-Tuning Oil Burner

During the later half of August of 1997 a very quick experiment setup was assembled using a BNL (direct current) powered fan atomized oil burner, a fan speed control circuit, a proportional, integral, derivative (PID) control, and a dynamic zirconium oxide oxygen sensor (GMS-10) and control circuit (Oxymac 20) purchased from Honeywell Gasmodul in the Netherlands. This was used during the 1997 Oil Heat R&D Technical Advisory Group meeting to demonstrate the feasibility of the concept of a self-tuning oil burner. The results clearly illustrated the concept, but there was a great deal of instability in the control loop at times while at other times it behaved quite nicely as we expected. Not having the scheduled time for detailed experiments during FY 1997, work was halted until the next fiscal year as discussed below.

4.1 Self-Tuning Oil Burner With Fan Speed Controller For Air/Fuel Ratio Adjustment

In October of 1997 experiments continued bread boarding a prototype self-tuning oil burner using the dynamic zirconium oxide oxygen sensor. This time it was combined with a high static pressure flame retention head burner, the programmable PID controller, and a commercially available speed (fan) control designed for a PSC type electric motor as indicated in Figure 15.

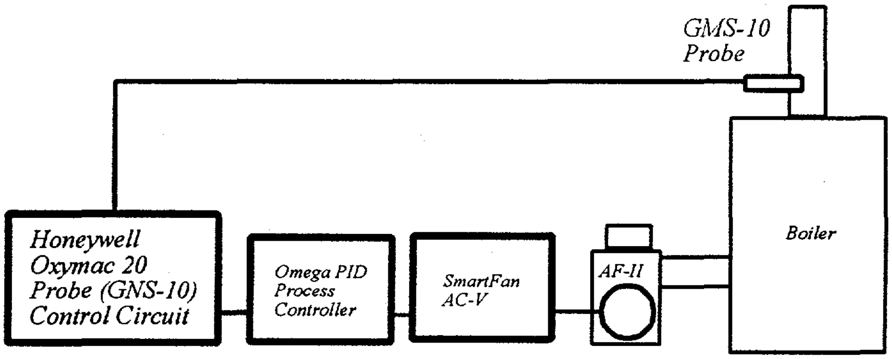


Figure 15. Schematic of Self-Tuning Residential Flame Retention Head Oil Burner

The first step was to determine the characteristics of the fan control (SmartFan AC-V) when coupled with the burner. Figure 16 is a plot of the AC voltage supplied to the oil burners PSC motor plotted on the Y1 axis and also the corresponding flue gas percent oxygen plotted on the Y2 axis. This data was obtained as a function of input DC voltage to the controller using a regulated variable DC voltage source. This test was conducted with the burner properly adjusted within the output voltage range of 77 to 120 volts AC. At a voltage output of 60 volts AC the smoke level was measured between a trace to number one on the Bacharach scale and at 50 volts AC the smoke was measured to be a Bacharach number 1. When a voltage below 2.65 DC volts was input there was an insufficient AC output, less than 50 volts, from the AC-V controller to keep the oil burners motor operating.

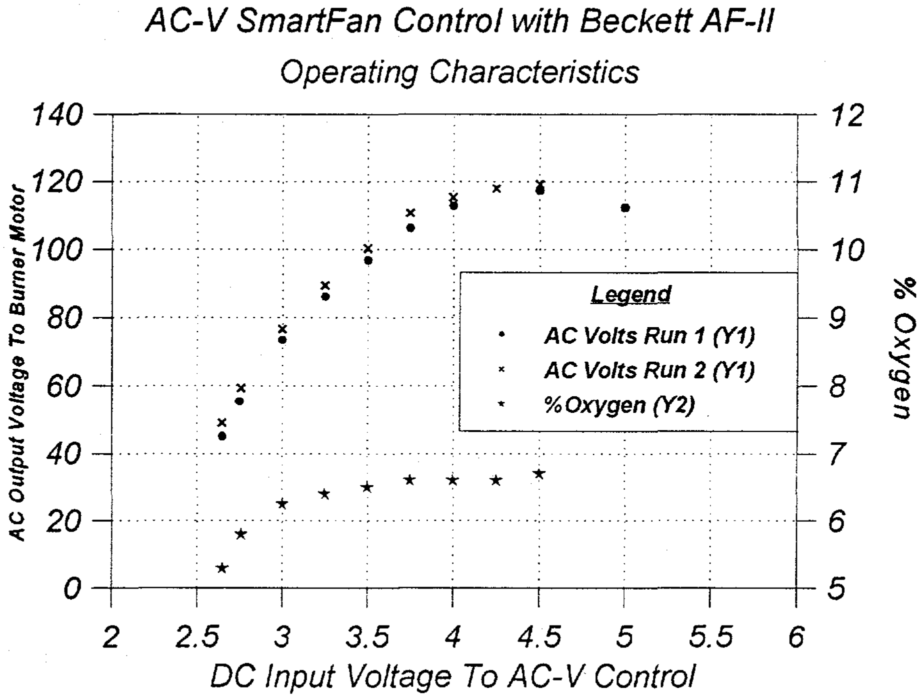


Figure 16. DC Input Voltage Versus AC Voltage and Resulting Oxygen Levels In Stack

The process controller provided for inputs of a process variable, in this case the % oxygen signal from the GMS-10/Oxymac 20 system, a reference set point variable, and a control output, the DC voltage signal which was used as an input to motor speed controller. The output of the controller is a function of the error which is the deviation between the process signal (%oxygen voltage signal) and the set point value. The PID controller was one that could be used in any of three basic functions. The proportional controller could be used with the integral and derivative functions either turned on or off. Along with many other functions which could be turned on or off, the main variables of the controller, the proportional band value, integral reset value, and derivative rate value could all be varied over a wide rand of settings.

Once the entire system was assembled the major issue was one of gaining a level of understanding the PID controller. This self tuning burner prototype system tended to result in either a saturated control mode or a unstable operating condition. In the saturated mode the system could not reach the set point value because it is either too high or too low. The result being the oil burner motor remained at a constant high or low speed. In the unstable mode the motor speed cycled rather quickly between the full and minimum speed conditions. The major part of the problem was the very narrow oxygen range that could be obtained with the motor/control range. Tests were suspended for several months due to other priorities in the overall statement of work for FY 1998.

4.2 Self-Tuning Oil Burner Using A Fan Atomized Burner With Throttle Body Control

In January 1998 a decision was made to temporarily set aside the investigation of controlling the fan speed (combustion air) with an output signal for a oxygen sensor and control system. Instead an effort was launched to investigate an earlier concept employing a pulse width modulation (PWM) driver using an automotive type fuel injector as a fuel flow control valve to control an oil burner. The original concept was that of developing a variable firing rate oil burner.

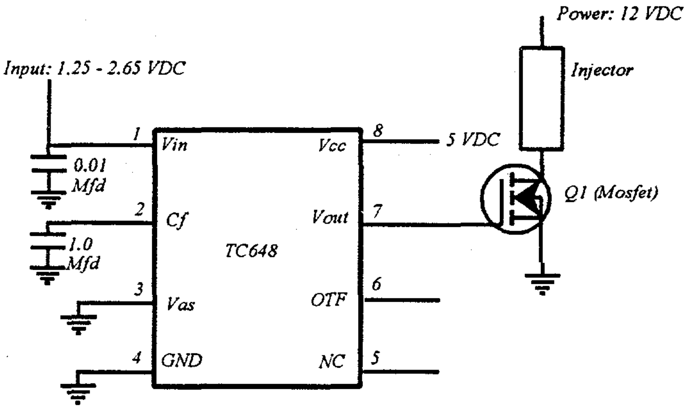
In this case we would utilize the controlled variation of fuel flow to correct for any variation in oxygen that might occur as a result of a system upset to control a self-tuning oil burner. With the proper orifice sizing the injector can be used to modulate the fuel flow rate to a Fan Atomized Burner (FAB) or a High-flow Fan Atomized Burner (HFAB) nozzle assembly. The initial set up of the driver and injector was successful in yielding a pulse width duty cycle (injector open) of 0.05 to 0.43 gallons per minute, more than enough range for what was needed for designing the self-tuning burner.

In a parallel effort an investigation of available PWM integrated circuits resulted in some engineering samples provided to BNL at no cost. The integrated circuit (IC chips) provided us with output characteristics that were an excellent match to the input range required by the PID control and input characteristics that matched our oxygen sensor's outputs for the range of oxygen concentrations we were most interested in from a combustion control standpoint. This chip would when combined with some timing control and power switching circuits provide us with a compact and simple fuel flow modulation control for a self-tuning oil burner. Relative to the fan speed control this offered a much wider control range.

Two samples of a TC648 PWM controller chip were obtained from Telcom Semiconductor, Inc. One of these chips was integrated into a circuit which provided switching for the automotive fuel injector through a Mosfet (transistor) switching device. The control (driver) input for the system ranges 1.25 - 2.65 volts dc. This is well within the expected operational range for the oxygen sensor and controller system. Figure 17 represents the controller circuit as it was initially tested.

Figure 17.

Schematic of the PWM Controller Chip Serving To Switch An Automotive Fuel Injector Through a Mosfet Transistor.



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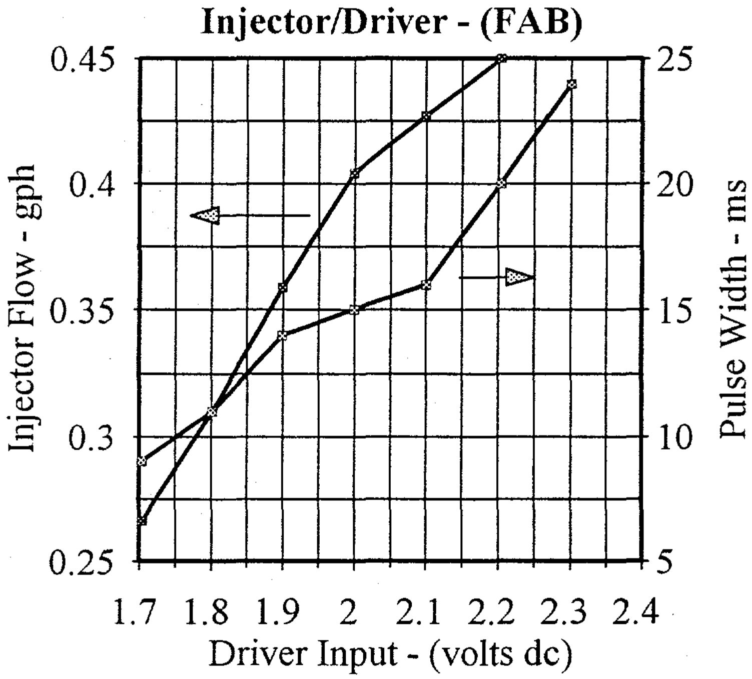
The circuit was then evaluated in breadboard form as a fuel control for the FAB burner. The injector assembly was integrated into the fuel supply system of the burner, located between the fuel pump and the nozzle. Preliminary combustion tests were conducted in the BNL quartz cylinder combustion chamber test rig. These early results were good and are presented in Figure 18. The apparent non-linear appearance of the output pulse width versus input voltage shown in the plot is due to observational recording errors of the timing width as taken from the oscilloscope face and not to the control circuit. The PWM output runs at a constant frequency of 30 Hz, so that a pulse width of 33 ms corresponds to the injector valve open 100% of the time. At a pulse width of 10 ms the injector is open 30.3% of the time. Apparently the pulsing fuel flow does not cause an obvious pulsation in the flame.

Figure 18.

Performance of the PWM Controller Modulating the Fuel Flow in a FAB Burner.



The flow rate of interest is about 0.4 gallons per hour which occurs initially at an input of 2.0 volts dc. Under steady firing the flow rate dropped as the injector warmed up. Over a period of 1.5 hours, the input voltage had to be gradually increased to a maximum of 2.3 volts dc to maintain the flow through the injector at about 0.4 gallons per hour. This may be due to physical expansion of the injector parts under heating from the electrical power dissipated within the solenoid coil windings. Some of the heating may be due to exposure to hot boiler parts. The implication of all this is that steady state firing rates at a given level may not be achieved in practice. Some variation from nominal may always exist. This is basically consistent with our prior results. In the planned use of the injector, the flue gas oxygen measurement and control system will correct for any drift in injector characteristics.

Assuming that the burner is set at an initial 5% oxygen (equivalent to excess-air of 29%) at 0.4 gallons per hour, the variation of flow from 0.35 to 0.45 gallons per hour will result in an excess-air variation of about 48% down to 15%. The intent is to eventually work the set-point down to 3% oxygen (equivalent to an excess-air of 16%) so that the burner achieves a truly low excess-air operation in the field.

The complete control circuit in breadboard form was integrated with the FAB, see Figure 19, and this system was installed in a two-section cast-iron boiler. The conditioned signal from an oxygen sensor placed in the flue was fed to the PID controller. The output from the controller was then sent to the injector in the FAB burner through the PWM circuit shown above in Figure 17. Preliminary exploratory tests were conducted and the initial operating parameters for the PID controller were identified.

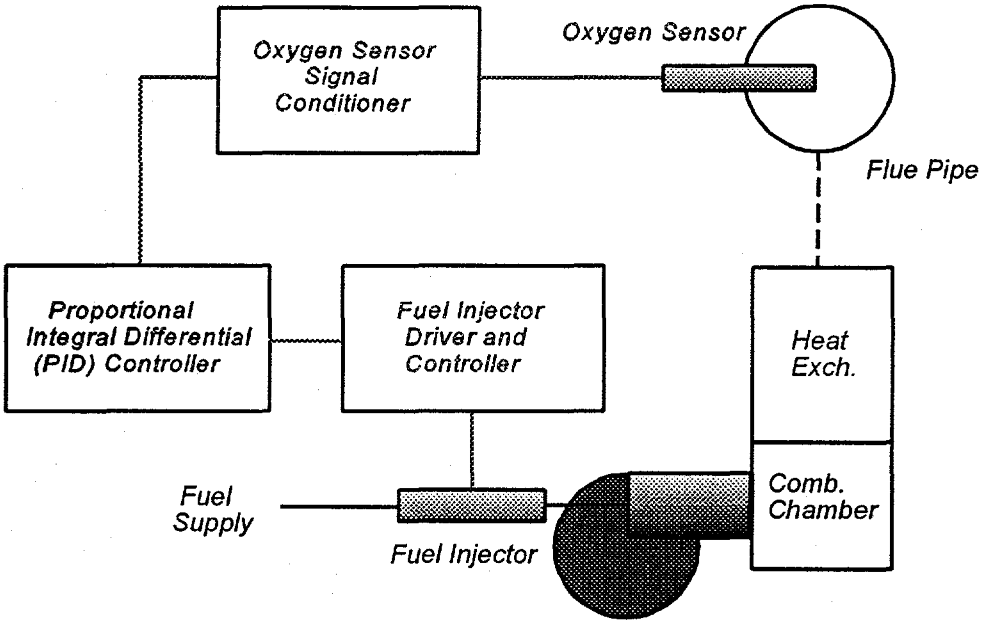


Figure 19.Schematic of Self-Tuning Fan Atomized Oil Burner

With fine tuning the PID the initial promising results of tests of the FAB burner were confirmed by repetitive placement and removal of air inlet restrictions. These restrictions consisted 0.25 and 0.5 inch diameter orifice plates applied to the inlet opening of the air blower. With the burner operating steadily at a nominal 3.0% oxygen in the flue gas, the air restriction was applied to the fan inlet. Within several seconds the flue gas oxygen was seen, on the PID controller, to have dropped to about 1.5%. During a subsequent period of about 3 minutes the flue gas oxygen was observed to gradually recover to 3.0% under a downward fuel adjustment of the PID controller. The restriction was removed and the burner's air flow returned to normal. The oxygen content of the flue gas was seen to climb to about 4.1%. Again over a period of about 3 minutes the PID controller gradually adjusted the fuel flow upward and the flue gas oxygen set point of 3.0% was restored as shown in Figure 20. The test was performed several times and this self-tuning concept was demonstrated during the Oil Heat Conference conducted on April 7-8,1998

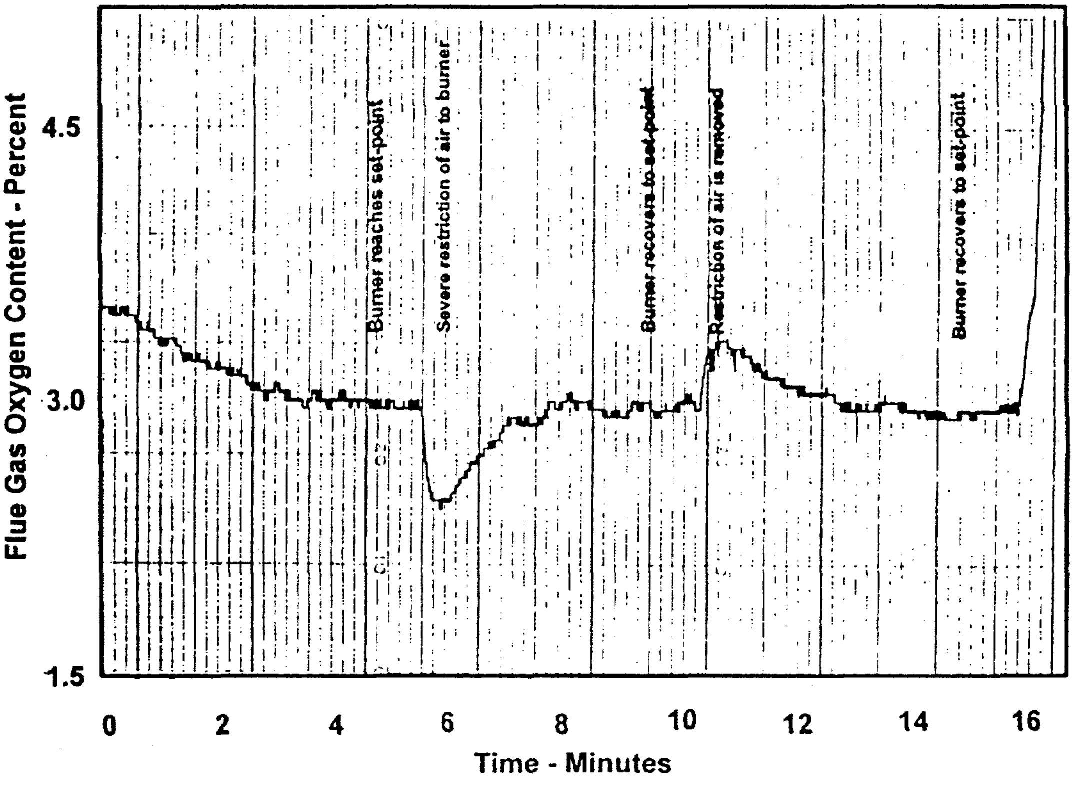


Figure 20. Chart Trace of FAB Under Self-Tuning Operation With/Without Severe Air Restriction

4.3 Self-Tuning Oil Burner With Air Damper Actuator For Air/Fuel Ratio Adjustment

During June of 1998 various actuator control components were obtained which were then assembled with components and various other parts to create a burner system as illustrated schematically in Figure 21. This embodiment of the self-tuning concept is of particular interest because it could conceivably work with most of the oil burners in use today.

In this configuration BNL has incorporated an inlet air damper driven by a non-spring return direct coupled damper actuator (which was donated to BNL by the Home and Building Group, Honeywell Inc.). The particular actuator was selected based on its availability and its 2-10 volt DC control signal feature which works very nicely with our PID process controller which can be programed with an output signal between 0 - 10 volt DC. The actuator varies its rotational position between 0 and 90 degrees as a function of the control signal voltage.

BNL staff built a damper assembly and mounted it on the intake of an outside air adaptor kit which in turn was installed on a flame retention head oil burner. In this way the damper controls the amount of combustion air going to the burner. Then the actuator was added to the assembly to drive the damper according to the control signal from the PID process controller which is a function of the oxygen concentration in the stack as compared to a set value stored in the memory of the PID unit. As oxygen concentration goes up the damper is closed, as it goes down the damper opens. The PID control algorithms have programmable coefficients and provide for smooth transitions during burner starts and stability during the operation of the burner when properly tuned. The oxygen concentration in the flue gas was again measured using the dynamic oxygen sensor (GMS-10) and control circuit and was used as the process signal for the PID control.

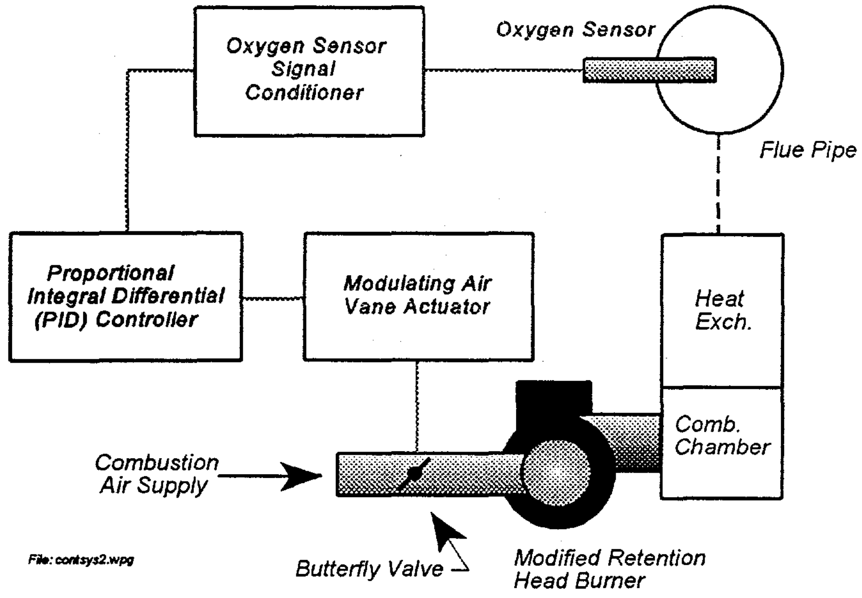


Figure 21. Schematic of Self-Tuning Flame Retention Head Burner with Air Control Valve

Shake down experiments were conducted in a modified Peerless boiler fired at 0.75 GPH where operating temperatures were close to the maximum limit for the oxygen sensor. The burner was then installed in a Utica Starfire boiler firing at 0.75 GPH. Table 4.1 contains some of the data obtained prior to installing the PID control and illustrates the control of the burner using a regulated DC voltage variable power supply as a control signal source. BNL then began the process of tuning the PID coefficients prior to test and evaluation of the concept.

Table 4.1 Burner Control Using A Regulated Voltage Supply Without Self-Tune Feature

Control Voltage	Stack Temperature	Boiler Temperature	Oxygen Percentage	Smoke Number	Draft Inches H_2O
2.00	456	120	3.6	5	-0.025
2.25	488	150	3.8-4	4	-0.035
2.50	488	150	3.8	4	-0.035
2.75	497	155	4.3	1.5	-0.035
3.00	505	160	4.3	1.5	-0.035
2.63	503	160	4.2	2	-0.035
2.83	517	172	5.0	0+	-0.04
3.25	517	172	5.0-5.1	0+	-0.04
3.5	524	175	5.7	0	-0.4

Table 4-2 shows the results of this control scheme under different firing rates of the burner. The variation in firing rate was induced by varying the fuel pump pressure in steps from 100 to 130 psi. Using a nozzle with a nominal 0.65 GPH delivery at 100 psi we were able to vary the flow from 0.65 to about 0.74 GPH or about 14%. The PID Controller set-point for the test was 4.0% oxygen in the flue gas. Over the range of firing rate variation the smoke number remained at or below number 1.

Table 4-2 Utica Boiler/Carlin Burner Preliminary Results With Air Damper Under PID Control

Fuel Pump Pressure	Flue Gas Temperature	Boiler Water Temperature	Flue Gas O_2 Percent*	Smoke Number
100 psi	435 F	168 F	4.2 %	0-trace
110 psi	442 F	172 F	3.9 %	1
120 psi	460 F	174 F	4.0 %	1
130 psi	469 F	178 F	4.0 %	1

*Converted to wet-basis O_2 valves for comparison purposes.

The results of this work, as applied to a retention head burner firing into a three-section cast-iron boiler at about 0.65 GPH, was demonstrated during the BNL Oil Heat Technical Advisory Group meeting held on August 19, 1998. This demonstration included the introduction of an air-side blockage intended to simulate an accumulation of fibers or hair. The system was able to recover to the set-point even under a sudden application of the blockage which would otherwise slowly accumulate over a much longer period of time.

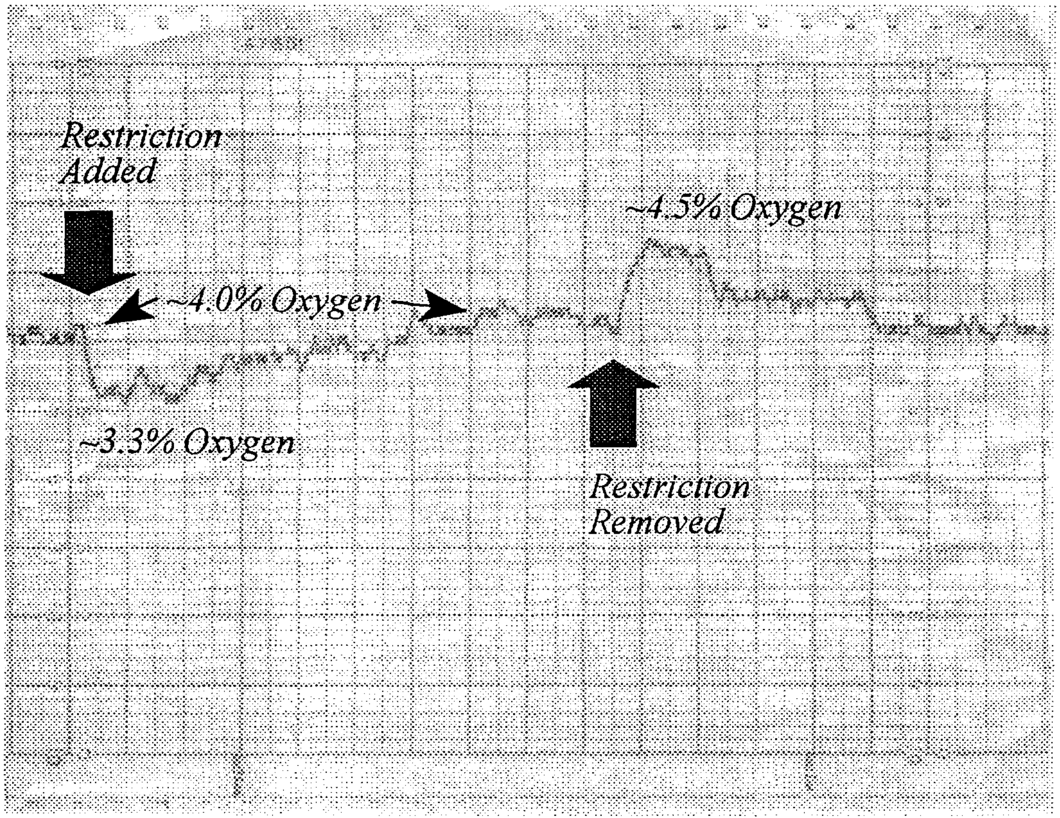


Figure 22. Chart of Transient Flue Gas O2 % During Application and Removal of the Air Blockage

The flue gas set-point programed into the PID controller was 4.0% $O_{2..}$ Based on a signal from the flue gas O_2 sensor, the burner's combustion air inlet flow was modulated to maintain the set-point in the flue gas. As can be seen from Figure 22, upon application of the restriction, the flue gas O_2 dropped to about 3.3% O_2 in about 20 seconds. Under the control of the PID the O_2 recovered to the set-point or about 4.0% within 4.5 minutes from the initial application of the restriction. The restriction was then removed and again in about 20 seconds the flue gas O_2 rose to about 4.5%. The flue gas O_2 then recovered to the set-point in under 3 minutes once the restriction was removed.

One of the concerns for residential application of this system is the inadvertent dislodging of the O_2 sensor out of it's flue pipe location. This was simulated twice by manual removal of the sensor from the connector. Each time the measured O_2 quickly rose to above 11%. At this point replacement of the sensor restored the control of the burner but with induced oscillations about the set-point of

3.7 to 4.3% O_2. The apparent accumulation of error within the PID during periods of sensor exposure to ambient conditions was enough to induce instability of control. The next burner off-cycle would allow the PID to start without accumulated error.

Some additional tests were conducted to get an estimate of the time required to reset an accumulated error within the PID controller. It was found that after shutting the burner and PID off for periods less than 5 minutes oscillations in control were again induced upon burner restart. This appears to be due to some electronic retention of accumulated error within the control after it was shut off. Given a time period greater than 5 minutes the accumulated error in the PID appeared to be eliminated as evidenced by steady burner operation under set point control. Any PID control used with an oil burner would have to reset accumulated error immediately upon burner shut down. It should be noted that the PID used for these experiments was an off the self component intended for temperature control. Its features were not optimized for use as a self-tuning residential oil burner control.

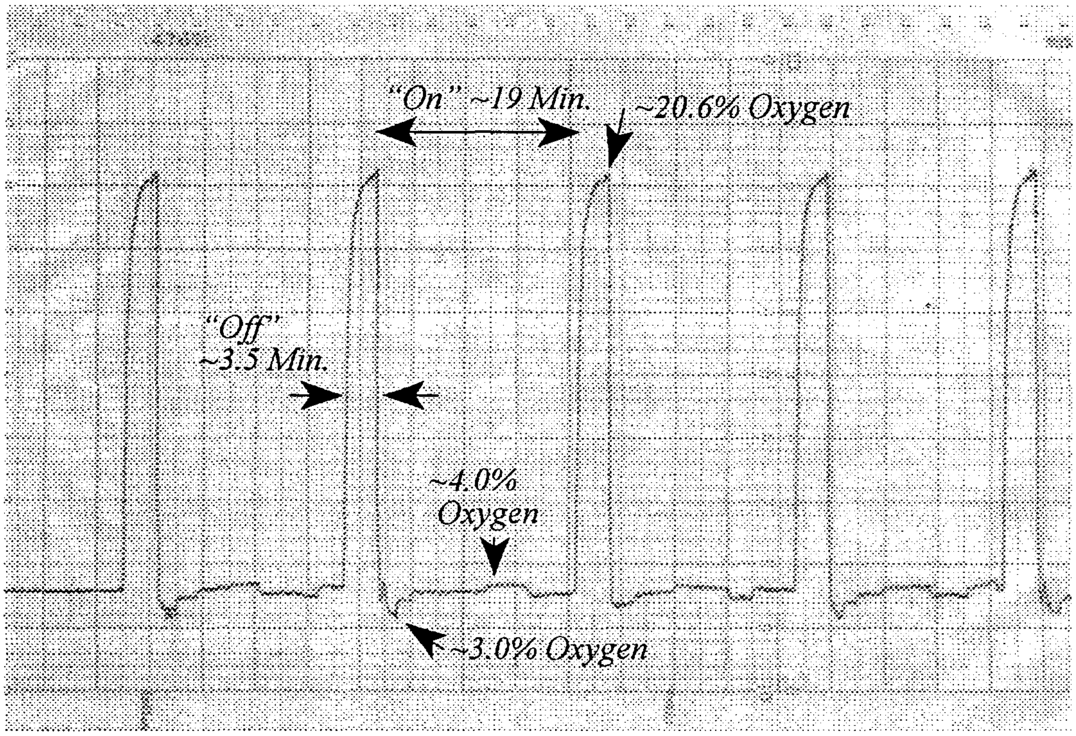


Figure 23. Chart Showing Transient Flue Gas O_2 % During Burner Cyclic Operation

Using the same configuration described above, the burner/boiler combination was allowed to cycle under control of the PID for burner combustion air and the high limit (180 F) of the boiler set-point for water temperature. The results of this test are shown in Figure 23. The configuration reached steady cycling with burner-on and burner-off periods of about 19 and 3.5 minutes respectively. The burner-off period was unfortunately less than the 5 minutes required for elimination of error accumulation in the PID found in the previous experiment. This off period was dictated by the choice of cooling flow rate to the boiler. Typically, with the burner-off, the flue gas O_2 rose to about 20.6% just before the on period. When the burner came on after the pre-purge period (opening of the fuel solenoid valve) the PID was held inoperative for 15 seconds with a time-delay circuit. This was to allow time for the flue gas O_2 to drop to about 5-6% and avoid excessive additional error accumulation within the PID. Despite this effort the flue gas O_2 still under-shot the set-point to a level of 3.0%. Recovery to the set-point occurred in about 2 minutes.

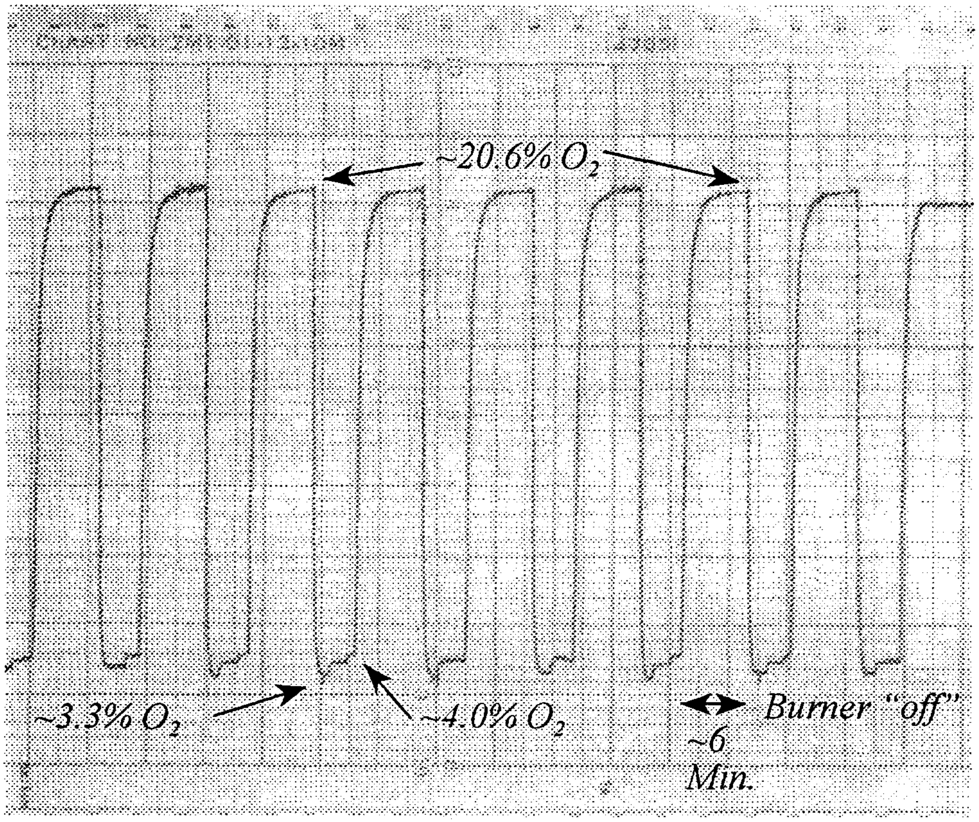


Figure 24. Chart of Flue Gas O_2 % with Cooling Flow Adjusted to Achieve Greater Than Five Minute Period of Burner-Off

Additional delay time had to be added for PID activation after the fuel solenoid valve opened. The delay was increased to 20 seconds. Figure 24 reveals that even with this additional delay and a prolonged burner-off period the flue gas O_2 under-shot the set-point to a level of 3.3% O_2. During the relatively short burner-on period the flue gas O_2 reached the set-point in about 2 minutes.

5.0 Summary of Progress

The results of the study of oxygen sensors and their operating characteristics resulted in the selection of a dynamic zirconium oxide sensor (Honeywell-Gasmodul BV, Model GMS-10) for use in bread board experiments to validate the concept of small residential self-tuning oil burners. Three different burner systems were assembled from available off-the-shelf components for experimental bread board engineering development tests. Two concepts proven interesting and merit additional work in the future. These were the self-tuning version of the FAB which used a throttle body fuel injector as a dynamic fuel flow control and the standard flame retention head burner equipped with a motorized variable position inlet combustion air damper. In either case the actuator, the throttle body injector (fuel-side), or inlet damper (air-side), was used to regulate the air/fuel ratio. In both cases the process signal (O_2%) was measured with the zirconium oxide sensor, then input to a programmable PID controller and a control signal was output from the PID to the burner system.

The eventual product(s) envisioned would incorporate the PID function, or an alternative control approach with a micro-processor based primary oil burner control. Faster response in some of the individual components will improve the performance in terms of set-point recovery during transients and steady cycling. The control would be programed to be compatible with the oil burner and its starting and stopping sequencing so that the PID error accumulation problems we encountered would not be a factor. The signal conditioning of the oxygen sensor could also be programed into this same type of oil burner control. The issues of both sensor and actuator reliability must be proven for long term field operation. The sensor mounting would have to designed to ensure against its physical dislodgment and air leakage variations into or out of the vent system must be controlled. Component costs must be carefully accessed and kept with in design constraints. Considerable development in many areas is required before a practical system can be manufactured for the oil heat marketplace.

The residential self-tuning oil burner has been proven, in concept, to work. This technology can be applied to new and existing burner systems. The current complexity and cost of the conceptual operating system can be engineered downward. The manufacturing community which will ultimately judge the cost restrictions consistent with the benefits that can be derived from a self-tuning system.

6.0 Acknowledgments

The authors wish jointly to acknowledge the significant and important contributions of our laboratory staff: Yusuf Celebi (Staff Engineer and Laboratory Manager) and Gang Wei (Associate Staff Engineer). In addition, the support of Honeywell Inc. through the donation of control actuators and components for use in the experiments was most helpful.