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Monitoring of Automatic Diagnostic Sensors for Oil-fired Heating Equipment

MONITORING OF AUTOMATIC DIAGNOSTIC SENSORS FOR OIL-FIRED HEATING EQUIPMENT

Final Report

Submitted to:

Canada Mortgage And Housing Corporation
National Office
682 Montreal Road
Ottawa, Ontario

Submitted by:

Buchan, Lawton, Parent Ltd.
5370 Canotek Road
Ottawa, Ontario
K1J 9E6

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EXECUTIVE SUMMARY

In 1989, Canada Mortgage and Housing Corporation entered into a joint venture initiative to field test three diagnostic devices for oil fired heating equipment. These devices include:

- o a Flame Quality Indicator
- o a net peak stack temperature sensor
- o an oxygen sensor

These devices have been under development by Brookhaven National Laboratories (BNL) for over two years and are intended to help improve efficiency, servicing and reliability of oil heating equipment. Diagnostic sensors can provide feedback to homeowners and service personnel regarding current state of burners so deviations from proper tune can be detected and corrected without prolonging the excessive fuel consumption

Five furnaces in Ottawa, Canada were retrofitted with a prototype burner which contained a flame quality indicator (FQI). The Flame Quality Indicator (FQI) is an optical performance sensor that reads the light intensity from the burner flame and signals deviations from initial tune based on changes in flame brightness.

A net stack temperature was also installed in the flue of each furnace. As the furnace heat exchanger surface becomes fouled by the normal accumulation of soot, less heat can be extracted from the combustion gases. This results in an increase in net stack temperature. By monitoring the steady state or peak temperature over time, increases provide an indication of furnace fouling.

A Zirconium oxide oxygen sensor was also installed in one furnace. By monitoring oxygen content directly, deviations in burner performance from perfect tune can be detected.

Field trials were conducted for a period of one year (two heating seasons), the purpose of which was to assess the practicality of these diagnostic sensors in actual field applications. A comprehensive monitoring program was implemented to track data generated from the diagnostic devices and correlate the outputs against actual field measurements.

Generally, the FQI was observed to perform very well. At all sites the FQI signal was seen to track CO_2 content, and generate valid alerts when the CO_2 excursions were large enough, when the burners actually required service. Despite the fact that the FQI was able to effectively signal deviations in burner tune, and burner failures, the FQI requires further evaluation with regards to initial dulling, overheating and effects of fuel oil deliveries. An initial burn-in may be required for each burner fitted with an FQI device.

The net stack temperature monitor does have the potential to signal heat exchanger fouling, but the high incidence of sensor failure

suggest a more rugged sensor may be required. More field testing of this diagnostic strategy needs to be conducted.

While only sporadic data was collected for this the O_2 sensor, both field and laboratory tests to date have indicated that it is too costly and difficult to implement correctly for residential heating applications at this time.

RÉSUMÉ

En 1989, la Société canadienne d'hypothèques et de logement a mis sur pied une coentreprise en vue de mettre à l'essai sur le terrain trois appareils de diagnostic pour appareils de chauffage à mazout, à savoir :

- o un indicateur de qualité de la flamme;
- o un thermomètre de conduit de fumée; et
- o un capteur d'oxygène.

Ces appareils ont été mis au point pendant plus de deux ans par Brookhaven National Laboratories (BNL) dans le but d'améliorer l'efficience, la fiabilité et l'entretien des appareils de chauffage à mazout. Ce genre de capteur renseigne les propriétaires-occupants et le personnel d'entretien sur l'état des brûleurs de sorte que d'éventuels dérèglages soient décelés et corrigés sans prolonger la consommation excessive de combustible.

Cinq générateurs de chaleur installés à Ottawa (Canada) ont reçu un brûleur expérimental muni d'un indicateur de qualité de la flamme (IQF). Cet indicateur consiste en un capteur de l'intensité lumineuse de la flamme du brûleur qui détermine, à partir de changements dans la luminosité de la flamme, si le brûleur est déréglé.

On a également posé un thermomètre indiquant la température nette du conduit de fumée de l'appareil de chauffage. À mesure que l'échangeur de chaleur du générateur s'encrasse par suite de l'accumulation normale de suie, il devient plus difficile d'extraire la chaleur dégagée par les gaz de combustion. Il en résulte une augmentation de la température nette du conduit de fumée. En contrôlant le régime établi ou la température optimale pendant une certaine période, les augmentations fournissent des indications sur l'encrassement du générateur.

Un générateur de chaleur a également été doté d'un capteur d'oxygène au zircone. En contrôlant la concentration d'oxygène directement, il est possible de déceler un dérèglage du brûleur.

Des essais en service ont été menés pendant un an (deux saisons de chauffage) en vue d'évaluer si ces dispositifs pouvaient être utiles sur le terrain. Un programme de contrôle complet a donc été élaboré pour observer les données engendrées par les capteurs et établir des corrélations entre les premiers résultats obtenus et les mesures prises sur le terrain.

En général, l'IQF s'est avéré très performant. Dans tous les cas, il a surveillé la concentration de CO_2 et a donné l'alerte chaque fois que les émanations de CO_2 étaient suffisamment importantes, donc lorsque le brûleur avait vraiment besoin d'entretien. En dépit du fait que l'IQF a pu signaler efficacement les problèmes

de réglage et les défaillances du brûleur, cet instrument nécessite de plus amples évaluations pour ce qui est de son ternissement initial, de sa surchauffe et des effets qu´entraînent les livraisons de combustible. Un rodage initial pourrait même s´imposer pour chaque brûleur recevant un IQF.

Le dispositif de contrôle de la température nette du conduit peut indiquer l´encrassement de l´échangeur de chaleur, mais la forte fréquence de défaillance de ce thermomètre semble indiquer qu´un capteur plus résistant serait sans doute de mise. De plus amples essais en service de cette stratégie diagnostique devront être menés.

Bien que seules des données sporadiques n´aient été recueillies pour le capteur d´oxygène, les essais sur le terrain et en laboratoire montrent qu´il serait, à l´heure actuelle, trop coûteux et compliqué de l´utiliser en milieu résidentiel.

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APPENDICES

1.0 INTRODUCTION

Much of the residential heating requirements in the colder, remote regions of Canada are met with oil-fired equipment. In such areas, fuel and service costs are high. Canada Mortgage and Housing Corporation is interested in strategies geared to minimizing heating costs, particularly in these remote areas. Inexpensive Burner performance diagnostic devices useable by the homeowner can reduce heating expenses in two ways: deviations from proper tune can be detected and corrected without prolonging the excessive fuel consumption characteristic of poor burner performance. Secondly, the use of skilled service could be implemented on an "as required" basis as opposed to the more traditional (and less economical) approach of periodic service.

Brookhaven National Laboratories (BNL) is currently exploring a range of diagnostic devices for oil burners. These include a Flame Quality Indicator (FQI), a net stack temperature monitor, and an oxygen sensor. BNL has developed the FQI, a simple diagnostic device that uses a cad cell to measure oil burner flame brightness as an indicator of burner tune. Net stack temperature sensors can be used to warn of heat exchanger fouling when monitored flue temperatures increase over time. Changes in oil burner tune usually result in changes in flue gas concentrations. Therefore oxygen sensors installed in furnace flues can also be used to monitor oil burner tune. CMHC has assisted BNL by providing extensive field testing for the FQI and net stack temperature sensor as diagnostic devices for residential oil heating. Some limited field testing of an oxygen sensor was also carried out.

The purpose of the project was to evaluate the ability of the three burner diagnostic sensors, mentioned above, with respect to their ability to signal poor performance and the market potential of these devices. This report presents the findings of the testing carried out by CMHC on fuel furnaces in and around Ottawa, Ontario. The work, which spanned the '89/'90 and '90/'91 heating seasons, included the first non-laboratory application of the FQI prototype developed by BNL.

2.0 DIAGNOSTIC SENSING STRATEGIES & TEST METHODOLOGY

Three diagnostic sensing strategies were tested:

- the Flame Quality Indicator (FQI),
- a net stack temperature monitor, and
- an oxygen sensor.

A test group of five furnaces were equipped with an FQI and a stack temperature monitor. In one of these houses an oxygen sensor was installed for the latter months of the project. The next three sections detail the sensors, the monitoring strategy and the test group of houses, respectively.

2.1 Sensing Strategies

The Flame Quality Indicator (FQI) is an optical performance sensor that reads the light intensity from the burner flame and signals deviations from initial tune based on changes in flame brightness. It has been the subject of several years development work by BNL. The device is the least expensive of the three devices, and was the focus of the project. The FQI is composed of a photo-sensitive resistor (a commercial CAD cell) connected to an electronic circuit equipped with three indicating lights: HIGH (red), OK (green), and LOW (red). The system is shown schematically in figure 2.1.

The FQIs were installed in the burners at BNL, and then calibrated at each site. The CAD cell was mounted behind the nozzle, aimed into the furnaces combustion chamber. The resistance across the CAD cell is a function of the light received from the flame. The light intensity itself varies with the amount of excess air delivered for combustion. By monitoring resistance of the CAD cell, the FQI circuitry produces an output DC voltage signal dependant on excess combustion air. At installation, the circuit is calibrated to a chosen voltage (usually 2.5 V) corresponding to perfect burner tune (see section 2.3). Also at installation, high and low trip voltages are established corresponding to too much and insufficient excess combustion air, respectively. Should the burner become over-aired to the extent that the FQI voltage exceeds the high trip, the red HIGH indicating light is illuminated, signalling that service is required. Over-airing can develop gradually overtime, and it can also be caused by oil nozzle constriction, oil pump failure and other malfunctions (see table 3.1). Conversely, a condition

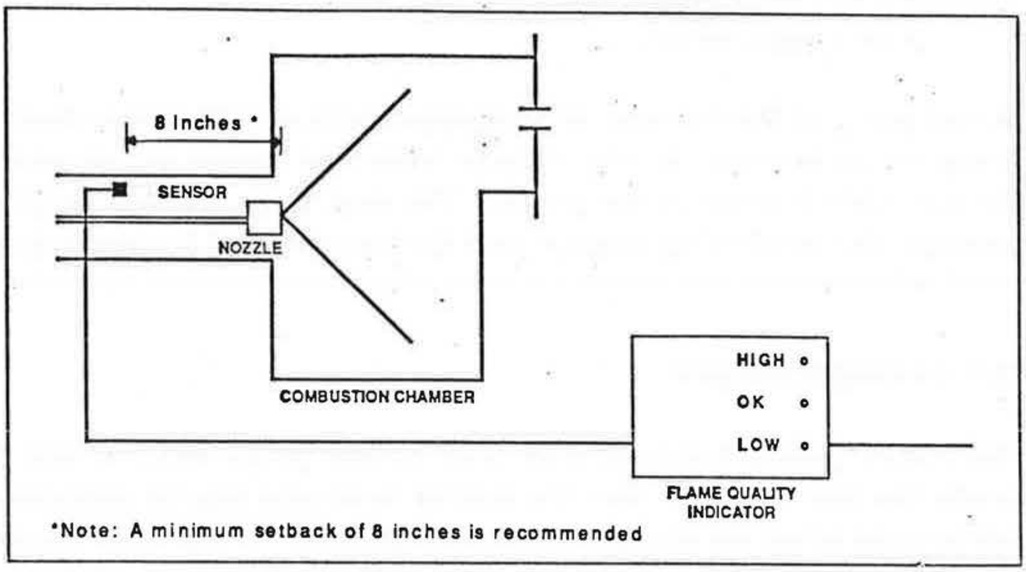


Figure 2.1 – FQI Schematic

of insufficient air will trip the LOW light (also red) if the FQI output voltage drops below the lower trip voltage. Under-airing could be caused changes in the properties of the oil being burned, increasing the flow of oil to the burner, or decreasing the air flow into the burner.

The second sensing strategy tested is the net-stack temperature sensor (see figure 2.2). As the furnace heat exchanger becomes fouled by the normal accumulation of soot, less heat is extracted from the combustion gases. This results in an increase in net stack temperature which is the difference in flue gas and intake combustion air temperatures. Net stack temperatures were monitored by E type thermocouples inserted in the flues. Amplifiers were used to force the thermocouple output into a useable range.

A temperature gauge with a peak hold dial was installed in each furnace flue. Homeowners were requested to read this dial on a weekly basis, and then reset the dial (so that it would record the high temperature for the next week). These readings could be used to check those from the net stack temperature monitor.

The third sensing strategy is to measure the oxygen content of the flue gases directly with a commercial oxygen sensor. Flue gas oxygen content varies in relation to conditions within the burner such as excess air and the rate of fuel being pumped into the burner. Therefore it can be used to show if the burner is in tune, under-aired, or over-aired, thus performing a similar diagnostic function to the FQI. The sensor used is a fairly expensive ($300) device which produces a 0 - 9 V output directly proportional to measured oxygen content. The device was designed for general measurement of oxygen content, and for use in furnace flues (see figure 2.2). The sensor is made of two zirconium dioxide discs, with porous platinum plate electrodes, separated by an annular platinum ring. The sensor works on the principle that a voltage is produced between the electrodes, and that this voltage is dependant on the partial pressures of oxygen inside and surrounding the sensor. The sensor requires a microprocessor driven circuit to monitor this voltage while cyclically reversing a current source used to ionize and recombine oxygen molecules. The platinum electrodes act as a catalyst during this process. The assembly is maintained at a temperature of 700°C by a heating coil which requires its own power supply. Further technical information on the oxygen sensor is given in Appendix J.

2.2 Test Methodology

The diagnostic sensors were tested by monitoring the sensor indicated burner performance parameters and the real burner performance.

The sensor outputs were monitored using a combination of digital data acquisition equipment and homeowner participation. All sensor outputs were connected to a digital data logger connected to a modem, as shown in figure 2.2.

With the logger configured for recording sensor values every minute, the logger had sufficient memory to store one week of data. It was necessary to install a leased phone line in every house to enable weekly remote data retrieval.

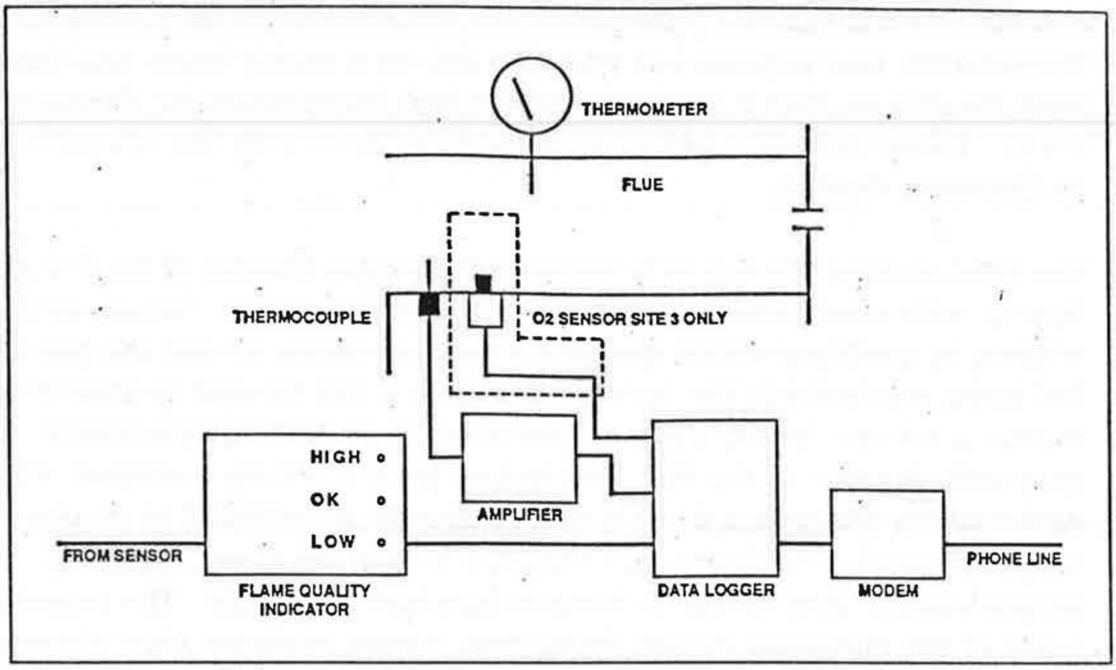


Figure 2.2 – Instrumentation Setup

In order to assess the validity of any FQI red light conditions (HIGH or LOW air trips), homeowners were asked to look at the FQI lights at least weekly. Data sheets were provided to the homeowners for recording weekly light status (see Appendix D). If a red light condition were to occur, they were instructed to notify Buchan, Lawton, Parent Ltd. It was essential that any burner in an alert condition not be serviced without CO2 measurements by Buchan, Lawton, Parent Ltd. The CO2 content was measured in order to determine the validity of the alert. If the CO2 reading correlated to an FQI voltage that was beyond the bounds of the green light condition when the FQI was calibrated, then a valid alert had been signalled and the burner needed servicing. Conversely, if the CO2 reading correlated to an FQI voltage that was within the bounds of the green light condition when the FQI was calibrated, then the alert was not valid and the FQI needed adjustment. For this reason Buchan, Lawton, Parent Ltd retained a service contractor to provide all service and sensor installation/removal for the entire test group. In addition to logging light status, the homeowners were provided with dial-type flue thermometers. The flue temperatures were also recorded on a weekly basis to provide a back-up to the datalogged thermocouple data.

Finally, the performance of the burner was measured by Buchan, Lawton, Parent Ltd periodically. This was done by measuring flue gas CO_2 content with an electronic flue gas analyzer on a monthly basis.

All installations were commissioned in late February, 1990 and monitored until removal in spring 1991. No annual service was provided prior to fall 1990 start-up, as it was desired to exacerbate the tendency of the furnaces to fail, or at least foul.

To summarize, the FQI/O_2 sensor test methodology was to measure real performance of the burner and compare this to sensor output. The field evaluation was designed to examine the degree (if any) and implications of sensor reading drift after initial adjustment, and to correlate any FQI alerts relayed by the homeowner with on site filed measurements to confirm the validity of the alert and (if required) the degree of service.

The net stack temperature methodology was more straightforward. Heat exchangers were inspected by the service technician at sensor installation and again at decommissioning. Datalogged flue gas temperatures were analyzed and compared with analog thermometer readings. A correlation between observed heat exchanger fouling and signal increase was attempted.

In order to assess the marketability of the FQI, a homeowner survey was issued. Out of the seven questions asked, five of them dealt directly with the homeowners opinion of the FQI and wether or not they would consider purchasing one. The two other questions were used to collect thermostat usage and oil delivery data. The service technician was also asked to comment on the FQI, and the extent of heat exchanger fouling at each site at the end of field testing.

2.3 Test Group and Calibration

A test group of four homes was chosen with furnaces of varying ages. The houses are numbered 1 through 5. House 2 does not exist because house 1 has two furnaces numbered 1A and 1B. Photographs of all field installations are presented in Appendix B.

In order to simplify the installation of the FQI sensor, the prototypes were shipped from BNL installed in new oil burners. All burners were Carlin Elite models, a modern, high efficiency retention-head design. During installation the burners were tuned by the service technician. At optimal tune, the FQI circuits were adjusted for the FQI set point (2.5 V for sites 1A, 1B, 3, 4 and 2.2 V for site 5). The CO_2 values for the optimal tune of each furnace were collected. For each house, the excess air was varied through five settings bordering the optimal tune. This generated an FQI voltage to CO_2 calibration. The calibration and various house data were collected for use by BNL (Appendix C). Figure 2.3 is an FQI vs. CO_2 curve generated from this calibration data for site 4.

House 4 CAD Cell Output vs. CO2

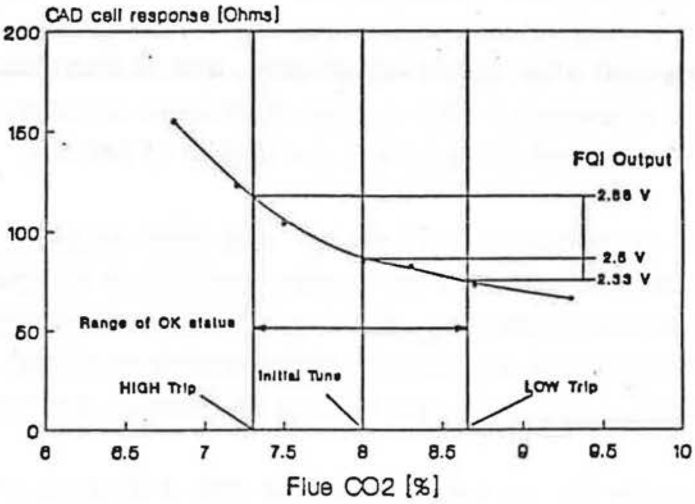


Figure 2.3 – Sample Calibration Curve

It is expected that if an FQI were to become commercially available, installation of the FQI in the oil burner would become part of the standard burner assembly procedure at the factory. Callibration would still be done on site during installation.

The net stack temperatures were monitored by standard E type thermocouples and thus did not require any on site calibration. The oxygen sensor had reset and recallibrate switches. Callibration was required at installation and after all power failures.

3.0 RESULTS

3.1 Overview

3.1.1 Monitoring

All field installations occurred between February 22, 1991 and March 1, 1990. The '89/'90 heating season ended in May, and the '90/'91 season spanned from October, 1990 through to the end of April, 1991. Throughout the nine months of monitoring, the Flame Quality Indicators in all installations were in continuous operation . No service was provided before the fall 1990 start up, as burner failures were desired.

The oxygen sensor was installed at site 3 on January 7, 1991. It was removed on April 26, 1991. Of the four months this sensor was monitored, only two months of useable data were obtained as the device lost its calibration twice.

The net-stack temperature sensors were problematic as well. Two of the five (sites 1A and 1B) were functional at installation. Faulty connections at the remaining sites were repaired prior to the end of the '89/'90 heating season, however three of the five failed at one point during the '90/'91 season. To compound this problem, only one of the three homeowners who collected flue thermometer data managed to consistently use his thermometer correctly. The analog dial-type thermometers were equipped with riding indicators that retain the peak temperatures. The homeowners were instructed to reset the rider after reading using another reset dial. As many readings appear low, it is suspected that the majority of the readings taken were from the instantaneous temperature dials instead of the riding indicators that held the peak temperature readings.

3.1.2 Signal Processing

To assist in the interpretation of the FQI/O2 sensor data to be presented in the following sub-section, consider the sample output of the FQI and thermocouple for one burner firing cycle presented in figure 3.1.

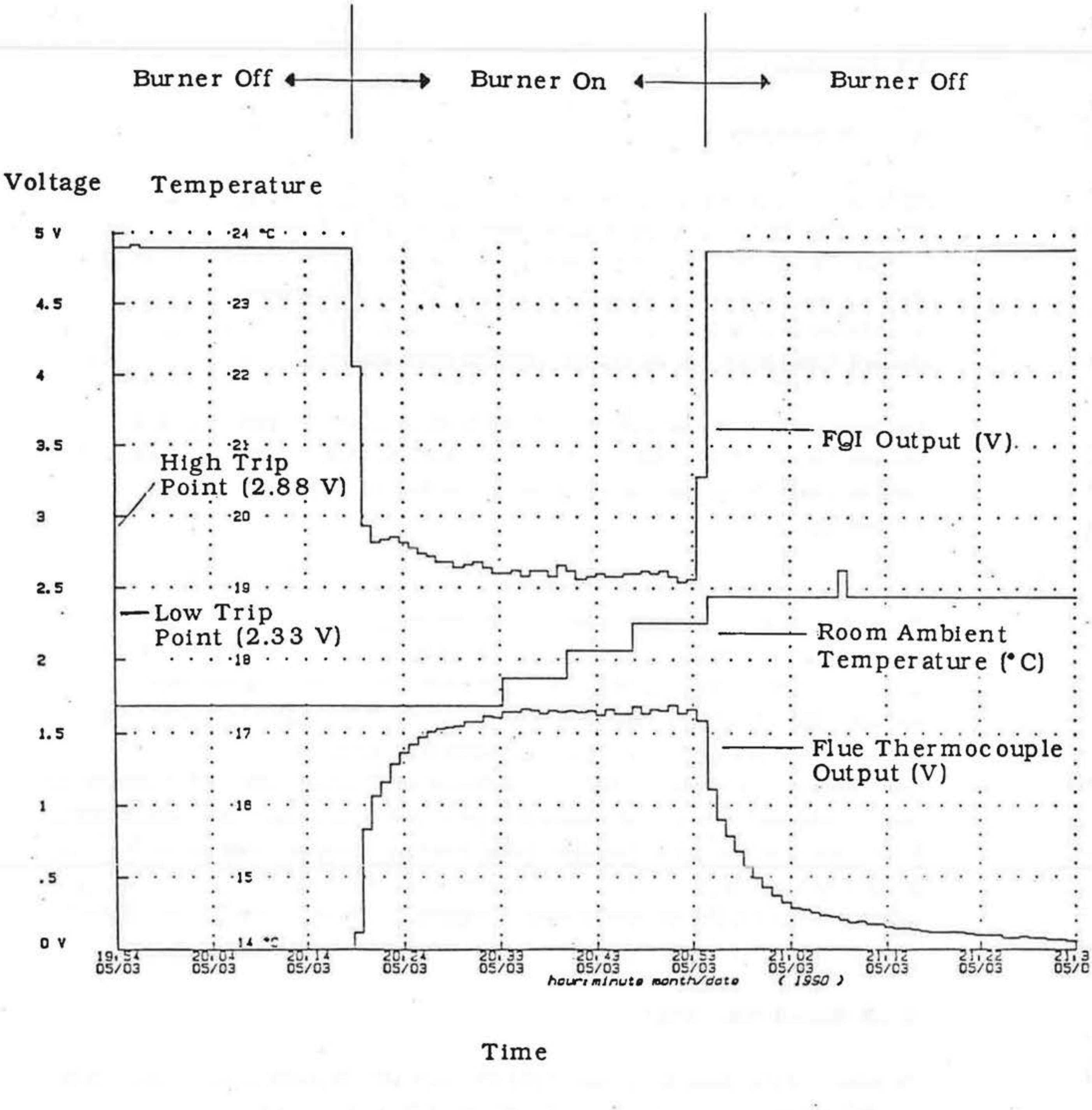


Figure 3.1 – Sample Firing Cycle

Note that the FQI output is 5 V when the burner is off. At 20:19 the burner ignites and the FQI signal approaches a steady state value. Between 20:19 and 20:21, the FQI output was above the HIGH trip of 2.88 V, causing an erroneous HIGH light condition. After 20:21 the FQI output falls below the HIGH trip and the OK light would have been illuminated. This initial erroneous HIGH alert is normal. It is a function of the refractory liner in the combustion chamber warming up and its effect on the light reaching the CAD cell. If the firing cycle gets interrupted, it is possible that an invalid HIGH alert would be generated. This is a very unlikely circumstance. It should be noted that future FQIs will have a timer that will keep the indicator light colour on the FQI from changing during startup. Therefore no erroneous HIGH alerts will result during startup or if a firing cycle is prematurely interrupted.

At 20:27, the voltage attains a steady state value of roughly 2.6 V indicating near perfect performance. The time required for the CAD cell to reach steady state (*response time*) is an important characteristic. The response time for this firing cycle is approximately six minutes. After 34 minutes the burner shuts off. The voltage just prior to 20:53 is the most reliable as the CAD cell has fully warmed-up. It is this value that was plotted and tracked in Section 3.2.1 and Appendix A.

The third plot on the graph is of the voltages recorded by the net stack temperature sensor. Towards the end of the firing cycle, a maximum reading of 1.55 V was recorded. This corresponds to a maximum net stack temperature of approximately 202° C. It is this value that was plotted and tracked in the graphs in Section 3.2.3 and Appendix B.

As the data logger stores each signal every minute, the data produced is comprised largely of periods when the burner is off, and also contains periods when the burner is on, but has not reached a steady state. The graphical data in the next section was produced by using a computer program to separate the cycle-end data from the rest. This worked by locating the FQI steady state output of each occurring firing cycle (the minimum for the cycle), then extracting the FQI signal value and the corresponding thermocouple and/or O_2 sensor signal. These extracted readings were retained and all other readings discarded. Before the FQI signal was stored, it was inverted by subtracting it from a constant value of 5 V (the base voltage output while the burner is off). Note that this inversion causes the lower trip voltage (burner under aired alert) and the upper trip voltage (burner over-aired) to have values of 2.67 V (5 - 2.33 V) and 2.12 V (5 - 2.88 V), respectively. On the graphs of the next subsection, the trip voltages are represented by two horizontal lines. The HIGH alert is the lower line, and the LOW alert is represented by the upper line. The inversion of the FQI signal produces a signal that is proportional to the intensity of light reading the CAD cell. Table 3.1 summarizes the meaning of variations in the plotted FQI signal.

The graphical data presented in the next section shows the occurrence of oil deliveries. This data as well as homeowner logged data is also available in Appendix G.

	FQI curve increasing	FQI curve decreasing
Excess Air	less air to burner	more air to burner
Fuel	more fuel to burner	less fuel to burner
Flue Gas CO_2	% CO_2 increasing	% CO_2 decreasing
Flue Gas O_2	% O_2 decreasing	% O_2 increasing
Light Reaching CAD cell	brighter	less bright

* Note: Changes in excess air and changes in the rate of fuel entering the burner cause changes in the remaining items listed above.

Table 3.1 – Interpretation of Plotted FQI Signal

3.2 Sample Field Results

This section looks at the results of the field data collected for the FQI at site 5, and for the FQI, oxygen sensor and net stack temperature sensor at site 3. Appendices A and B presents the results of the field data collected for the remaining sites in a similar way.

The FQI data at site 5 was particularly consistent and provides a good example of how the FQI is likely to work in future installations. Site 3 was particularly problematic. The data collected at this site provides a good forum to discuss problems with the diagnostic equipment and its installation, and how they were overcome. This data also shows how the diagnostic equipment responded when there were problems with the burner, and service was urgently needed.

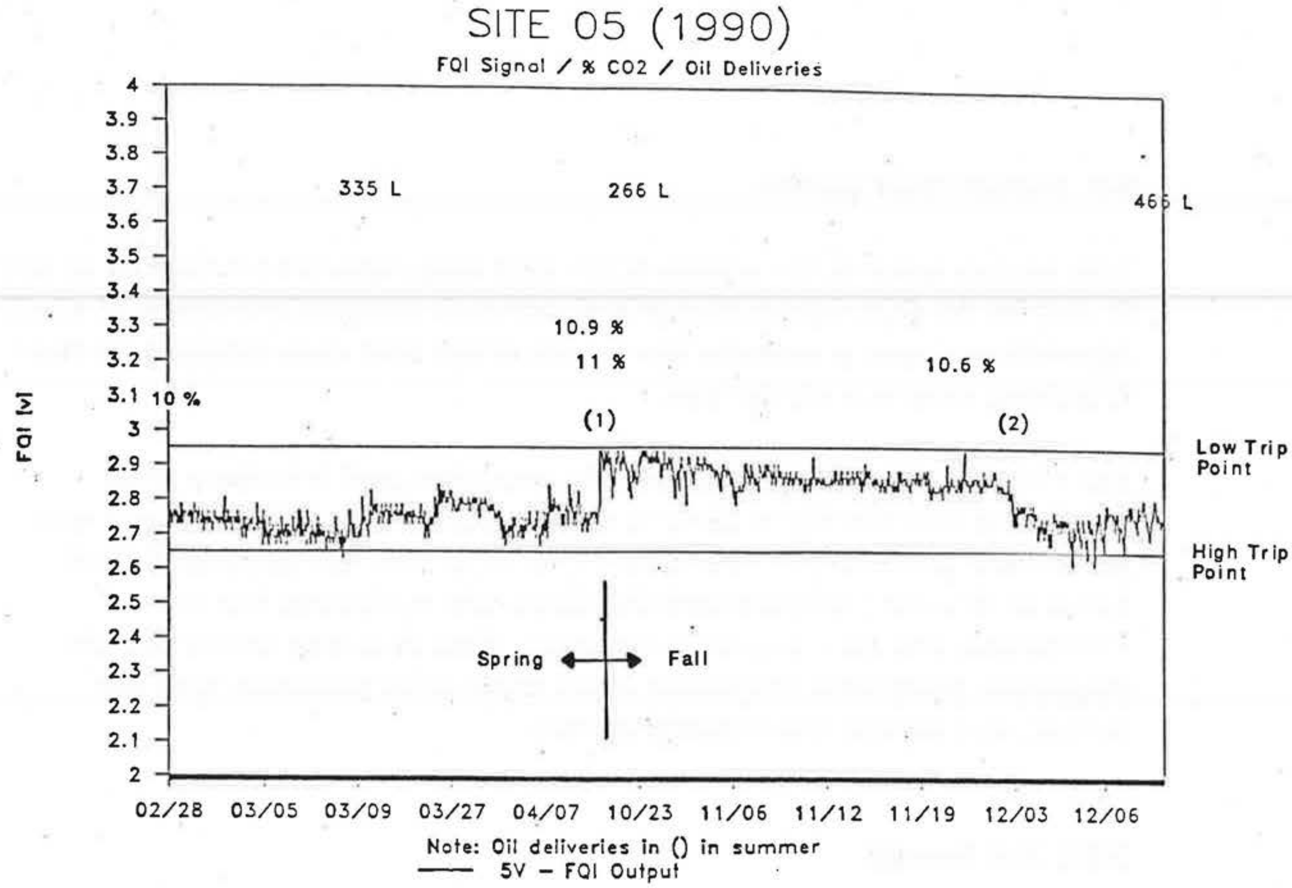
3.2.1 FQI Results

Site 5

The FQI installed at site 5 was the prototype. It was different from the others in that the HIGH and LOW trip voltages (2.35 and 2.05 V respectively) formed a more narrow band of OK status (other locations were typically 2.88 V and 2.33 V). It was suspected that this site would generate the most alerts. This was found not to be the case. Not only did the FQI signal remain flattest at this site (little drift), but the burner was very reliable despite the lack of service between seasons. The cycle durations are regular, at 5 minutes.

The FQI data for the entire project at site 5 is presented in figure 3.2. There are several features of the FQI curve worth noting.

A small amount of downward drift occurred for the first few weeks following installation. This is followed by a minor upward drift through March and April, 1990. A site visit on May 22, 1990 confirmed that at least the upward drift was a true indication of burner behavior as the CO_2 had increased from 10% (installation) to 10.9%. Note that the upward drift begins just following an oil delivery of 335 L on March 19, 1990. Smoke number readings were also taken in the furnace flues as a qualitative measure of soot concentration.



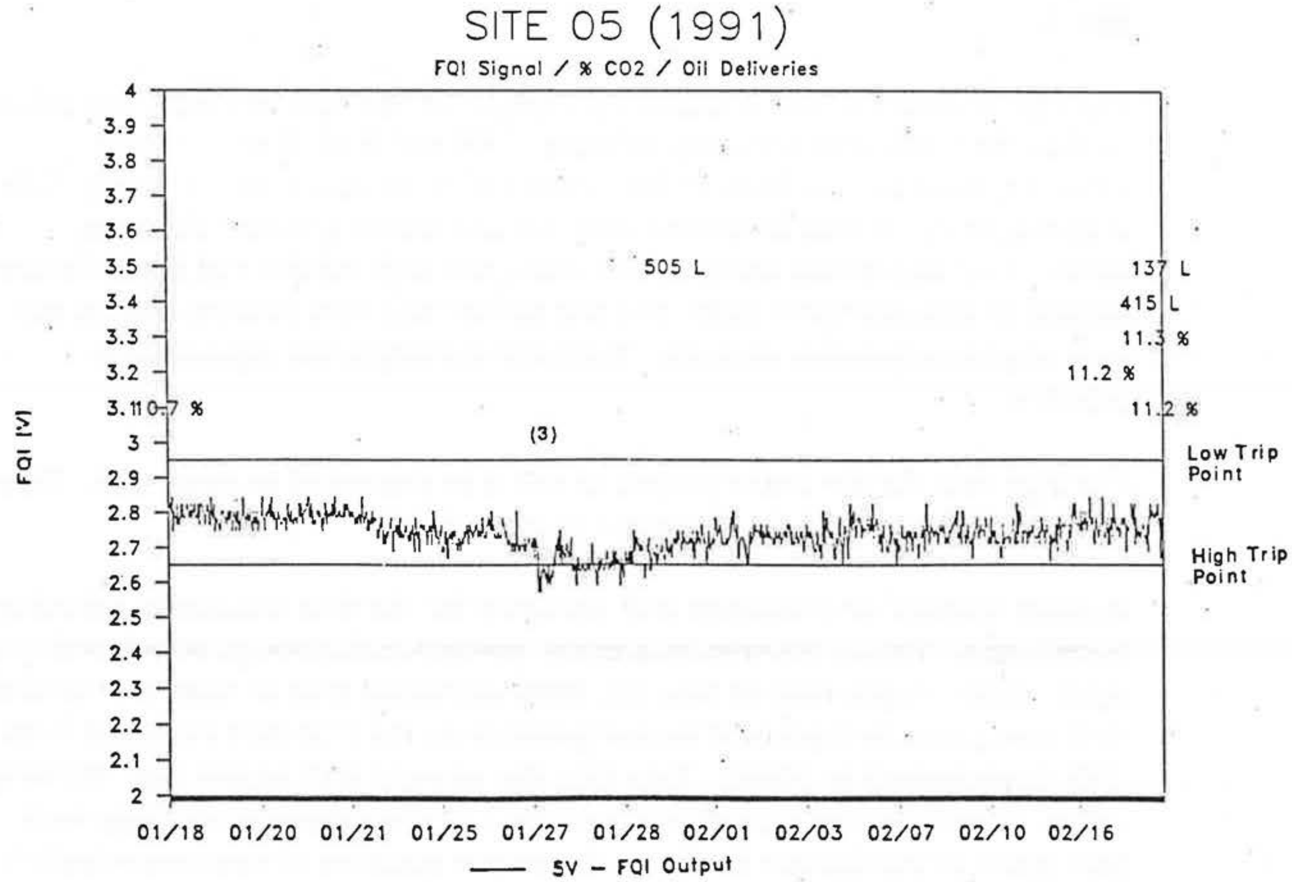


Figure 3.2– Site 5 FQI Results

The smoke number was measured at optimal burner tune at installation so that later results could have a point of comparison. Increases in smoke number (increases in flue soot content) would be expected to occur at the same time as increases in CO_2 content. This was the case as the smoke number readings of 0 and 1 were recorded when the CO_2 content readings were recorded as 10% and 10.9% respectively.

A small jump occurred (item 1) during the burner start-up in the fall, 1990. Note that the jump is consistent with measurements taken at 14:20h on October 5, 1991, which yielded a CO_2 content of 11% and smoke number of 1. A slight downward drift over the fall was confirmed as consistent with measurements taken at 12:05h on November 23, 1990, which produced a CO_2 reading of 10.6% and a smoke number reading of 1.

In early December (item 2) a dip in the FQI signal caused a HIGH alert. As the occupant did not report these alerts, site confirmation was not performed. During the January visit, the CAD cell was cleaned and replaced without resetting the FQI. This produced a short-lived increase in FQI signal (not shown), followed by a fairly rapid return to the FQI value prior to cleaning. Measurements taken during this visit revealed a CO_2 content of 10.6% and trace smoke. This slight downward drift resulted in a HIGH alert in late February (item 3). The FQI status must have been borderline as the alert was not logged by the occupant. After an oil delivery on January 29, 1990, the FQI signal increased and remained stable for the duration of the project. CO_2 measurement taken on February 20, March 19 and April 24, 1991, were consistent with observed stability over this period with values of 11.2%, 11.3% and 11.3%, respectively. The February and March figures were accompanied by trace smoke values, and the final smoke number was 1.

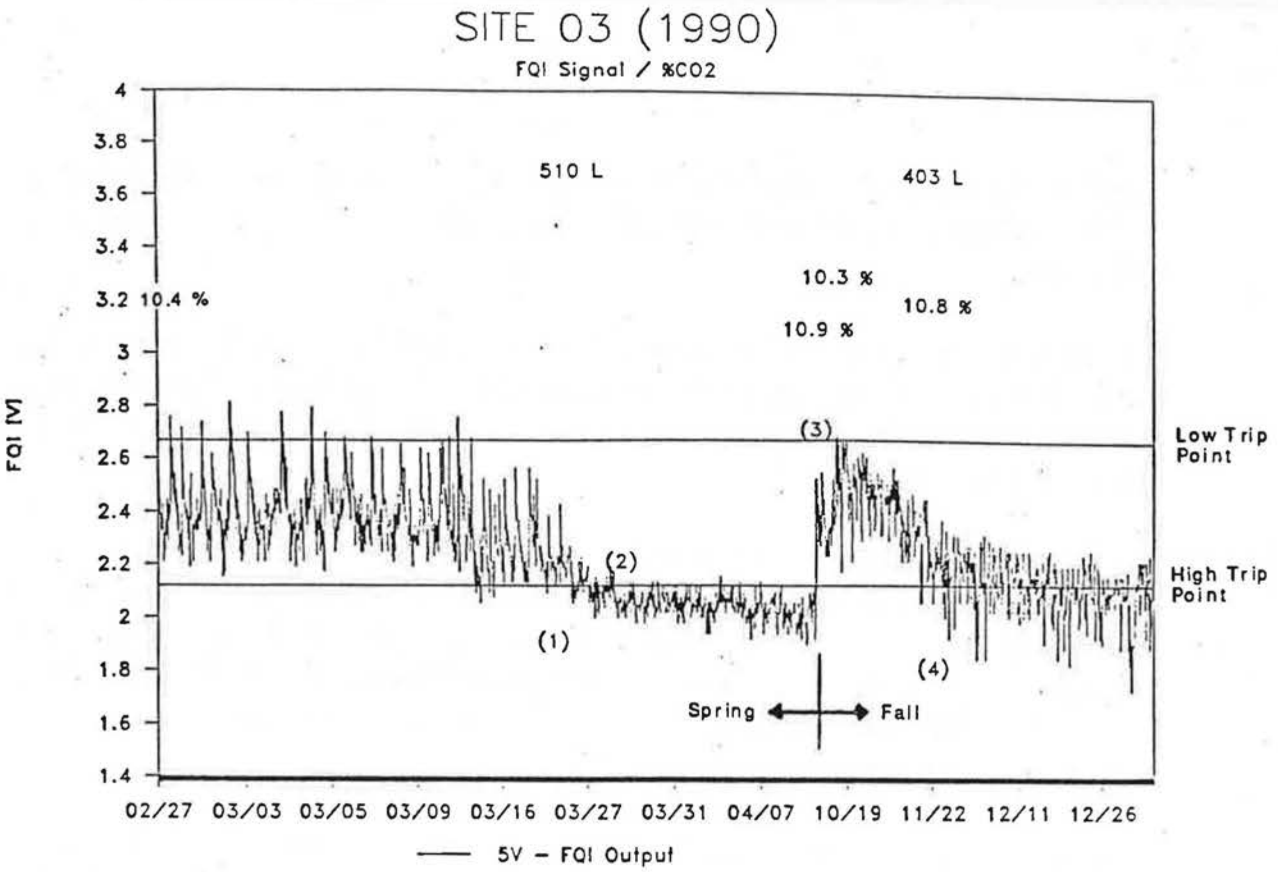
Site 3

The occupants at site 3 adjusted the thermostat to 23°C between 6:00 and 7:30h, and between 16:30h and 22:30h. The remainder of the day the thermostat was set back to 18°C. Therefore durations of firing cycles at this site are somewhat erratic. Most of the time, the burner would fire between 10 and 20 minutes. Less frequently, very long firing cycles lasting from 1 to 2 hours would occur. This was caused by sporadic thermostat adjustments by the occupants. Although this has not had a significant effect on the FQI data (the shorter cycles produced steady state responses similar to the longer cycles), the CAD cell may have been affected by low overheating due to this type of service.

The FQI signal results for site 3 are presented in figure 3.3. Note that an O_2 sensor was commissioned in January, 1991. The highlight of the site 3 monitoring is the pump failure that occurred at the end of January, 1991.

At site 3 the FQI signal drifts steadily downwards from installation to the signal jump indicated as item (3). As with most sites, the thermocouple was removed temporarily for repairs. Item (1) points to the thermocouple removal (approximately March 19, 1990). Based on similar results of a thermocouple failure at site 4, it is suspected that the ripple in the FQI signal prior to item (1) is a result of the thermocouple signal over-ranging the data logger. Item (2) points to the HIGH alert caused by the gradual drift. On April 26, 1990 at 11:30h, the flue gas CO_2 content was measured at 10.9%, and the FQI reset to 2.5 V (item 3). As the drift was contrary to the CO_2 content change from installation (10.4%), this was a false alert. The signal continued its downward trend following the fall start-up, contrary to an increase in flue CO_2 content from 10.3% to 10.9% measured on October 5, 1990 at 10:48h, and November 23, 1990 at 9:20h, respectively. The continued drift triggered another false HIGH alert (item 4) in late November 1990.

At four of the five sites, HIGH alerts (increases in excess air) were recorded between the first and eighth week following installation. During this period, field inspections did not reveal a corresponding decrease in CO_2. These false alerts are thought to be caused by the dulling of new shiny burner components. As a result of this dulling, less light was reflected to the CAD



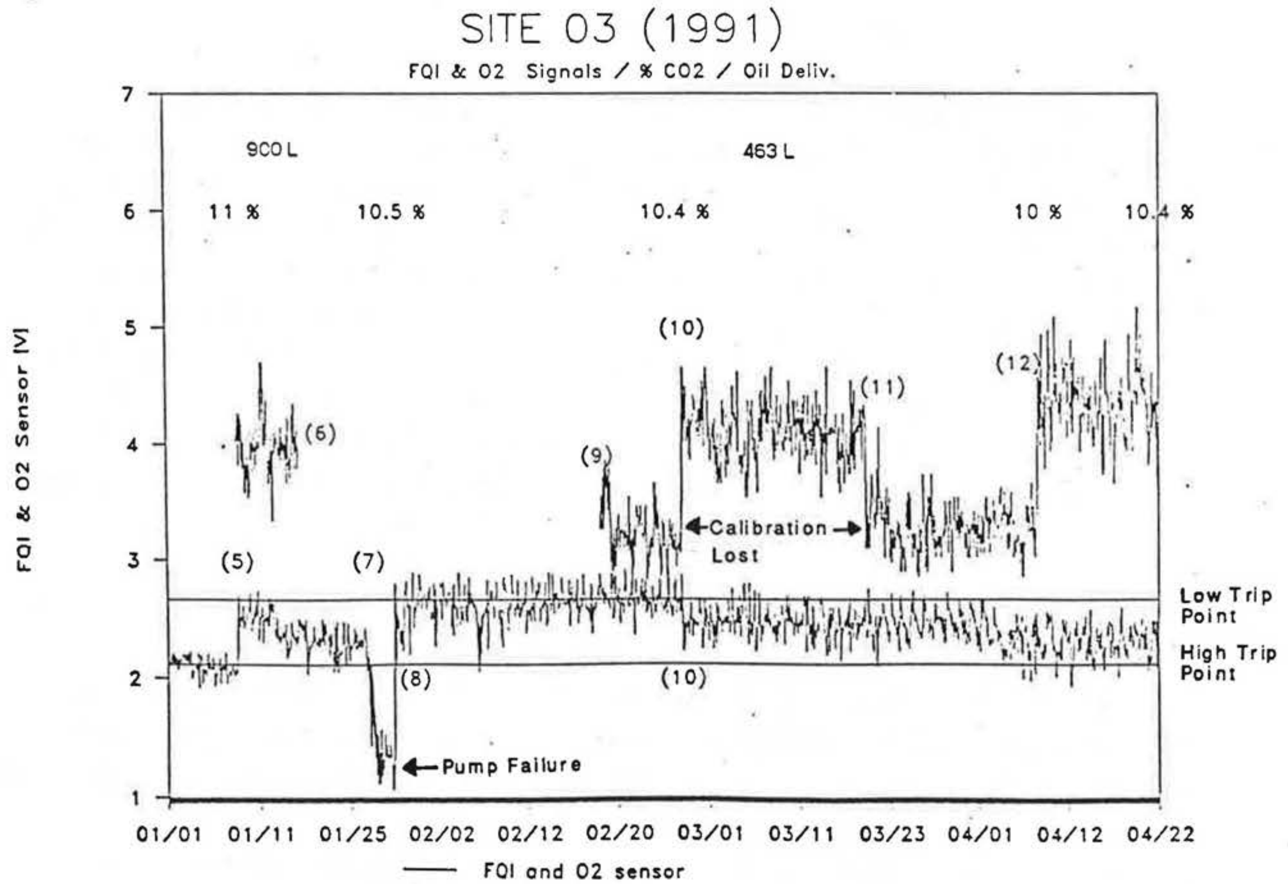


Figure 3.3 – Site 3 FQI Results

cell producing an increase in FQI voltage. At other sites, much more stable FQI readings were observed after this initial period of boiler component dulling.

During the January 7, 1991 site visit (item 5), the flue gas CO_2 content was measured at 11% with a smoke number of 0 (optimal tune). This confirmed that the HIGH alert pointed to by item 4 was invalid, and that the FQI drift was still occurring.

It was suspected that much of the downward drift was a result of the CAD cell being too close to the combustion chamber and that this was causing the CAD cell to be overheated. Overheating the CAD cell rendered it less sensitive. This was equivalent to the CAD cell recieving less light. The long term drift reflected the degradation of the CAD cell over time as its sensitivity was being reduced.

The CAD cell was cleaned and re-positioned 50 mm further back from the combustion chamber and then recalibrated during the January visit. The FQI was reset for green light (OK status) and an output of 2.5 V.

Item (7) indicates a sudden drop in FQI signal and a HIGH alert on January 26, 1991. Follow-up to the alert revealed that a fuel pump seal had failed, and that fuel was leaking from the pump. The pump and motor were replaced and the FQI pot reset on January 28,1991 (item 8). Note that the drop in FQI signal was consistent with how the FQI signal should have responded to a burner starved of fuel (see table 3.1). It is clear that this incident actually produced a fuel deficiency and this was exactly as indicated by the FQI. At site 1A two separate failures were recorded, once a fuel pump and motor had to be replaced, and then the fuel pump had to be replaced again. In these situations the FQI voltage output changed in a similar manner to warn of impending failure.

Following the pump replacement, the CO_2 content was measured at 10.5%. The next two visits (items 9 and 10 at 18:00h on February 18, 1991, and at 19:00h on February 26, 1991, respectively) produced CO_2 content values of 10.5% and 10.4%. Correspondingly, the FQI signal was very flat at this site as would be expected. During the second visit the FQI was reset because the previous adjustment was incorrectly set to produce too high a signal, producing meaningless LOW alerts. The remaining data shows a small amount of downward FQI signal drift. Note that the lack of drift after CAD cell repositioning appears to confirm that overheating of the CAD cell was likely to be the cause of the drift problem.

3.2.2 Oxygen Sensor Results

Site 3

Site 3 was the only site at which an oxygen sensor was installed. This was done during the January 7, 1991 site visit (item 5). It produced an output signal of about 4 V, corresponding to an O_2 content of 10.1%. The data collected is presented in figure 3.3 with the 1991 FQI data.

The actual O_2 sensor failed due to a faulty connection (not a fault of the sensor). The connection was repaired on February 18, 1991 (item 9), but was not re-calibrated until February 26, 1991 (item 10). Item (11) points to an O_2 sensor failure (due to power interruption and subsequent calibration loss) March 20, 1991. As the site was not accessible, the sensor was not re-calibrated until April 10, 1991 (item 12). The useable O_2 sensor data occurred between items (5) and (6), (10) and (11), and after item (12). When the re-calibration was performed (item 10), the CO_2 content was measured at 10.4%. Converting, this corresponds to an O_2 reading of 6.1%. Although the O_2 sensor readings were incorrect, note the correct trending of this sensor (O_2 increasing) between the January 7, 1991, site visit (actual O_2 5.6%, indicated O_2 10.1%) and the February 20, 1991 site visit (actual O_2 6.1%, indicated O_2 10.4%). The change is in the correct direction, consistent with a decrease in CO_2 content. This points to a possible calibration problem. Similarly, from item 12 through to the end of the season, the indicated O_2 content decreased, consistent with an increase in the actual CO_2 content.

3.2.3 Net Stack Temperature Results

The temperature data collected during this project is incomplete. This was due to failures of the thermocouple amplifiers, and generally incorrect use of the thermometers by the homeowners. Despite this, the data that was collected is workable.

At installation time the furnaces were cleaned and inspected by the service technician. When the instrumentation was decommissioned, the same technician inspected the heat exchangers. His comments were recorded.

Site 3

For site 3 the net stack temperature results are shown in figure 3.4. A sharp jump in stack temperature appears to coincide with the fall 1990 start-up. From this point onwards, the trend is towards decreasing temperature from about 210°C. The reasons for these changes are unclear.

The graph of the 1991 high stack temperature during burner cycles has a minimum value just prior to the fuel pump replacement on January 28, 1991. This would be expected as less oil was fueling the burner and therefore temperatures in the burner and flue should decrease.

Observed condition of heat exchanger

- overall condition good

Technician comments

- "Amount of soot collected is typical of what one would expect for one year service, not two."

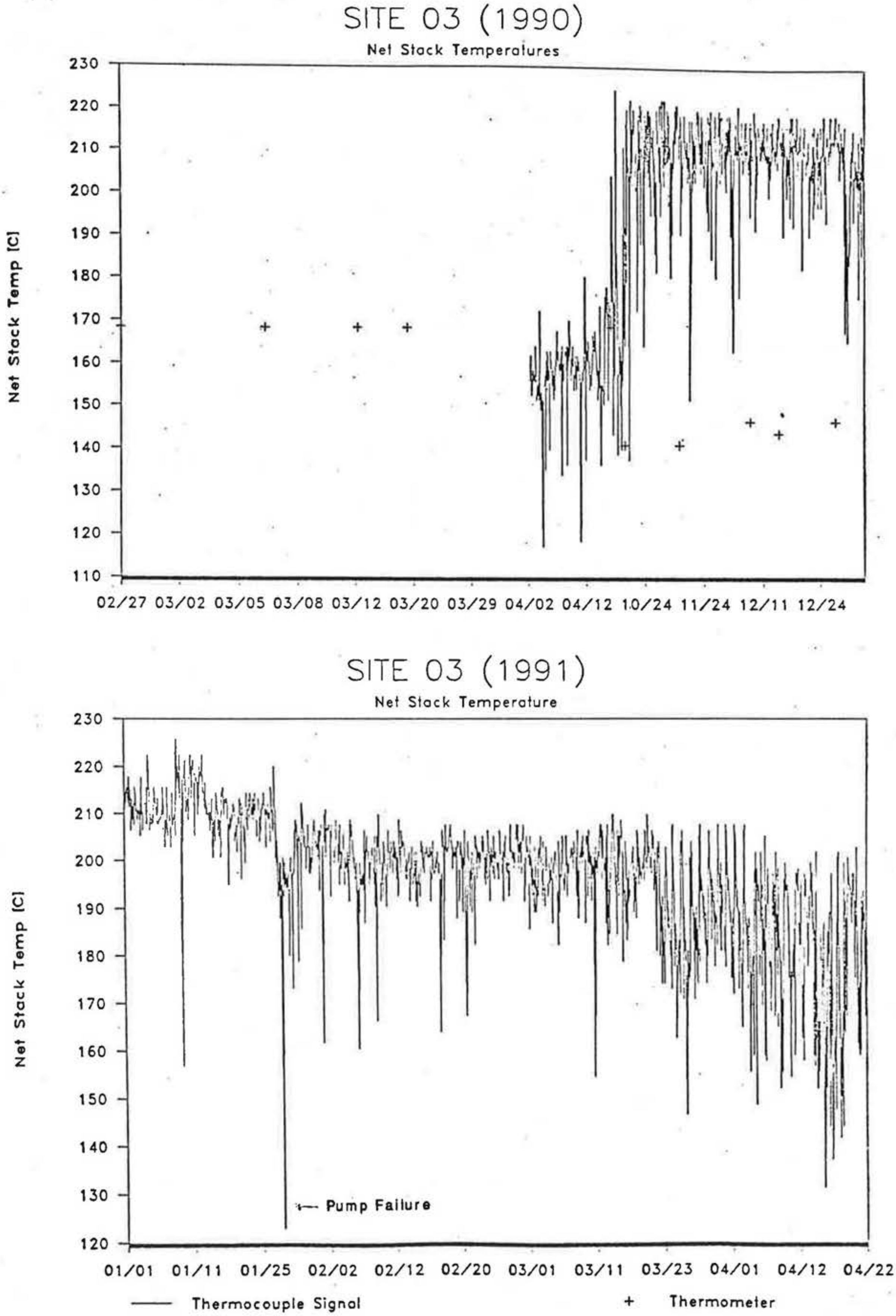


Figure 3.4– Site 3 Stack Temperature

4.0 DISCUSSION

4.1 FQI Performance

Generally, the FQI was observed to perform very well. At all sites the FQI signal was seen to track CO_2 content, and generate valid alerts when the CO_2 excursions were large enough, when the burners actually required service. At sites 3 and 1A, pump failures were detected and signalled. Similarly, the FQI correctly signalled a clogged nozzle at site 4.

Overall, the concensus of the homeowners involved was that that they felt the FQI was a useful device worth buying. (The Homeowner Survey Results are presented in Appendix C)

Despite the foregoing, the monitoring program did reveal some areas where the FQI requires improvement. These are initial drift, long term drift and handling of short cycles.

With the exception of site 5, a large rapid drift occurred after installation. BNL has identified this effect as a result of new shiny burner components becoming less shiny with break-in and thus reflecting less light to the CAD cell. None of the field installations in this project were retrofits. Retrofitting an older burner would have possibly confirmed break-in initial dulling as the cause of early drift.

All of the invalid alerts were caused by long term downward drift and by short cycle durations that interrupted the FQI signal approach to steady state. Of the two causes, only the long term drift is a concern. The worst cases of drift observed were during 1990 at site 3 and in 1991 at site 4. The FQI at site 3 began to function properly only after the CAD cell was moved back from the combustion chamber. This indicates that the likely cause for the drift is CAD cell over-heating. At site 4 the long term drift was not corrected by moving the CAD cell back (in fact, the drift occurred after retracting the cell by 50 mm). However, there was no false alert associated with this drift.

Overheating the CAD cell renders it less sensitive. This is equivalent to the cell receiving less light. The long term drift downwards reflects the degradation of the CAD cell over time as it losses sensitivity. It is possible that not only the long term drift, but also the initial rapid drift are both caused by impairment of CAD cell sensitivity. If this is the case, both problems would be corrected with the implementation of more robust CAD cells (currently under examination by BNL). It may well be that the best solution of all is to simply eliminate the CAD cell altogether, and use the CAD cell in the primary control (used for flame proving). This eliminates the proximity problem, and reduces the entire FQI to a simple bit of circuitry with negligible cost.

The electronic problems at site 1A were likely unrelated to the CAD cell, and likely an effect of bad field installation practise.

Initially it was thought that short cycles would cause HIGH alerts in shoulder seasons. All of the FQI data in section 3.2.1 and appendix A failed to substantiate this. Short cycle invalid HIGH alerts can be caused only by firing cycle interruption, which in most cases is caused by thermostat adjustment during firing. The best defence against this problem is to correctly set the thermostat anticipator for 10-20 minute cycle durations at FQI installation.

Within the context of CMHC's interest in the FQI – fuel efficiency in remote northern communities, it would appear that the FQI could reduce heating costs if the above problems were resolved.

4.2 O2 Sensor Performance

The O2 sensor performance was not very well tested by the monitoring program. The data that was collected has about 100% error, but shows that the sensor output did correctly track trends in flue gas O2 content.

The error was likely due to the fact that the sensors were not calibrated according to a complex (optional) procedure outlined by the manufacturer. Although it is expected that the accuracy of the sensor is quite good, the high initial and calibration cost of this device makes it unsuitable for residential diagnostic application.

The loss of calibration experienced occurs whenever power to the sensor is interrupted. The monitoring program did reveal that this causes the sensor to be unreliable. In the remote communities of the North, this would be unacceptable.

4.3 Net Stack Temperature Monitor Performance

The results presented in section 3.2.3 and appendix B pointed out that four of the five of the test installations finished the program with heat exchangers with less than normal fouling. In all of these four cases, the trend over time in net stack temperature was predominantly decreasing. The only site where the heat exchanger was significantly fouled did show a sharp increase in stack temperature.

It would appear from the observed results that the stack temperature monitor is an effective means of signaling fouling.

Although in principal the strategy appears effective, the data suggests that implementation of the sensor could be a problem. The high incidence of sensor failures in this project is a non-issue, as inexpensive and rugged temperature sensors are abundant. The difficulty is with the apparent variation in the parameter itself, stack temperature.

All of the thermocouple data collected showed a high degree of scatter. Recall from section 3.1 that the temperature values correspond identically to the instant in time that the burner was firing under steady-state conditions. One would expect the stack temperatures to fall along a more stable trend line.

A diagnostic fouling sensor based on stack temperature would require that the burner was on for a certain length of time prior to any results being shown. This would prevent false alerts due to reduced flue temperatures during short burner on cycles. Individual (singular) low and high maximum temperatures during each burner cycle that do not reflect the trend in maximum temperature might still cause false alerts. Prevention of these false alerts may well require that the diagnostic aquipment consider more than one maximum burner on cycle temperature at a time before signalling an alert. This could possibly lead to two potential problems: high cost and/or slow or delayed detection of fouling.

4.4 Market Acceptance

The homeowner survey results (presented in Appendix C) look very promising for the FQI. The first question showed that three of the four homeowners understood what the FQI did. The fourth understood the basic concept of having a service alert, but thought that the burner itself was being examined.

The second question revealed that all except one homeowner thought the FQI was useful. Note that one of these individuals was the one with a limited understanding. The fifth homeowner did not say that the FQI was not useful, but rather that few homeowners would be assisted by it.

Although the homeowner who was not entirely convinced that the FQI was useful would not buy one if he could, he would be prepared to spend $20.00 at the time purchasing a furnace or burner. Two homeowners were willing to spend any amount if it were justified with a sufficiently short payback period. The fourth homeowner would spend $100.00 but the meaning of this is unclear, as this was the individual who did not fully understand the product. It is worth noting that two of the four homeowners mentioned that the manufacturer of the device would have to be reputable, or at least a familiar household name.

Considering that the commercial product would be priced at a value on significantly less than $20.00, it would appear that all the homeowners involved would buy an FQI it they were given the opportunity.

There is considerable interest in the FQI from industry. A few manufacturers are looking into the possibility of installing the FQI as part of their standard burner assembly. One possibility is to connect the FQI circuitry to the cad cell that is already in place in the standard burner design. The FQI can be incorporated very cheaply in oil burners that already have microprocessors as part of their standard assembly.

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

- The FQI has been demonstrated to effectively signal deviations in burner tune, and burner failures.
- The FQI requires refinement in that tendency to drift towards under-aired indication must be corrected.
- The majority of homeowners who tried the FQI reacted favourably.
- The ZrO_2 O_2 sensor is too costly and difficult to implement correctly for residential heating diagnostic application.
- The net stack temperature monitor does signal heat exchanger fouling, but is not easily applied to residential heating diagnostics.

5.2 Recommendations

- Perform FQI testing in retrofit application to attempt to decouple the initial and long term drift problems. This could easily be done by BNL.
- Acquire the next version of prototype FQI device, and conduct actual tests in remote northern communities. The test program should incorporate similar data collection, but focus on heating and service costs.

APPENDIX A

FQI Sensor Results

Sites 1 and 4

FQI Sensor Results

The FQI sensor results for Sites 3 and 5 are presented in section 3.2.1. Therefore the results given in this appendix are for Sites 1A, 1B, and 4 only.

Site 1

Two identical furnaces are used at this site. Site 1A refers to the furnace which supplies most of the heating requirements of the building. The other unit is referred to as site 1B. The occupants of this building reduce the temperature setting of both furnaces at night. Unit 1A is fired during the day, while 1B is only fired for a short period every morning.

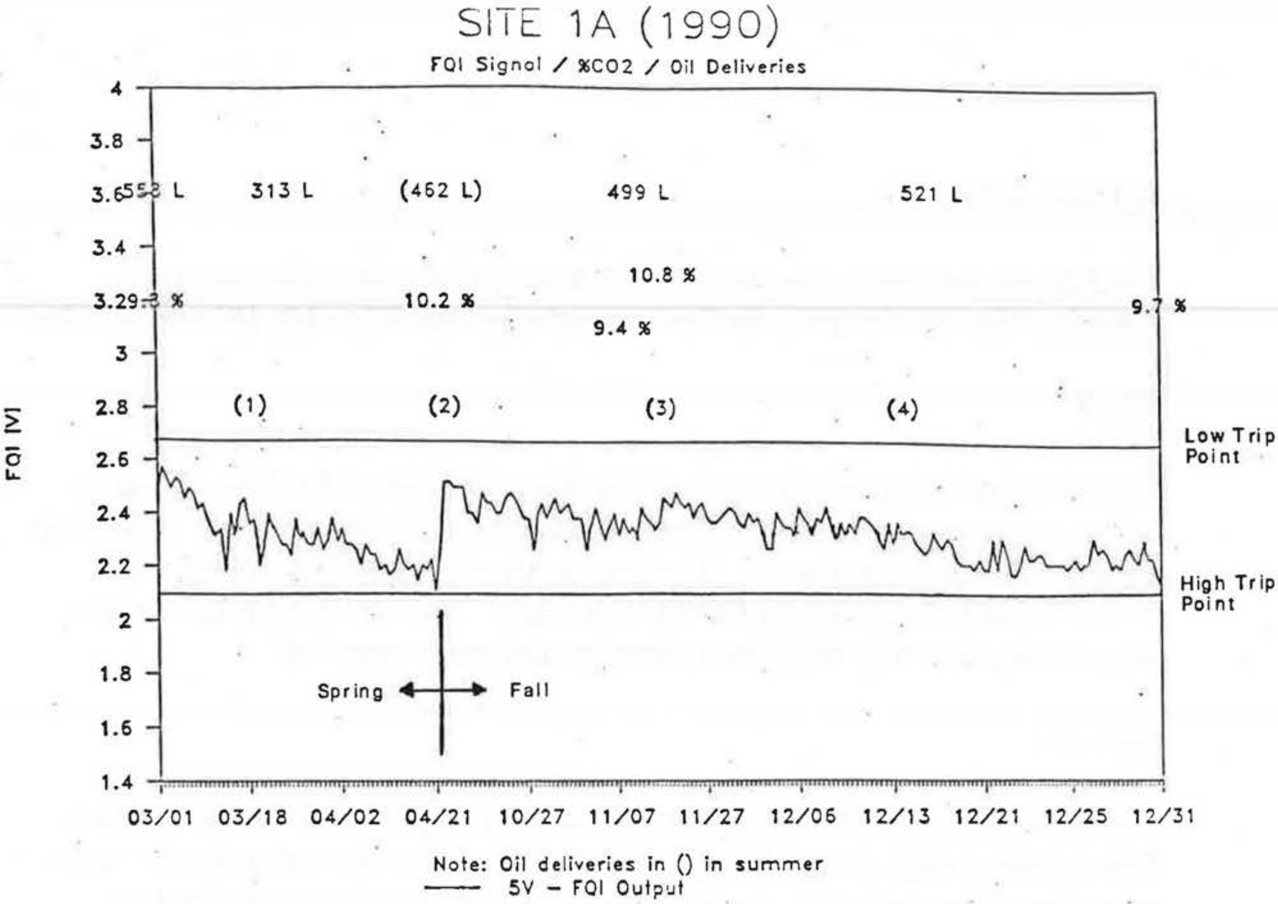
Site 1A

The furnace at site 1A functioned normally throughout the '89/'90 season. The collected data revealed early in the project that the firing cycles were very short (approximately 3 min). This was long enough for the FQI to closely approach a steady state condition. Early in the '90/'91 season both the homeowner and service contractor were notified and warned that the excessive cycling could be harmful to the burner and furnace. No corrective action was taken and the oil pump failed in February.

The FQI data for the entire project is presented in figure A.1. There are several features of the FQI curve worth noting.

Very shortly after installation the FQI signal drifted rapidly downwards producing a false HIGH alert after 48 days (item 1). This initial drift was observed at most sites. During a field visit at 10:00h on April 26, 1990, the CO_2 was measured at 10.2% (originally tuned at 9.8%). The FQI voltage was re-adjusted to its original value of 2.5 V.

On November 19, 1990, 499 L of oil were delivered. Two bordering CO_2 measurements of 9.4% and 10.8% (made on November 8 at 9:40h and on November 23 at 10:40h) indicate that the delivery coincided with a jump in CO_2 content. Note that the FQI signal shortly after the delivery increased slightly. This increase is consistent with the increase in CO_2 content (see table 3.1). Note as well that the trend between items (2) and (3) is downward, again consistent with a decrease in CO_2 content from the



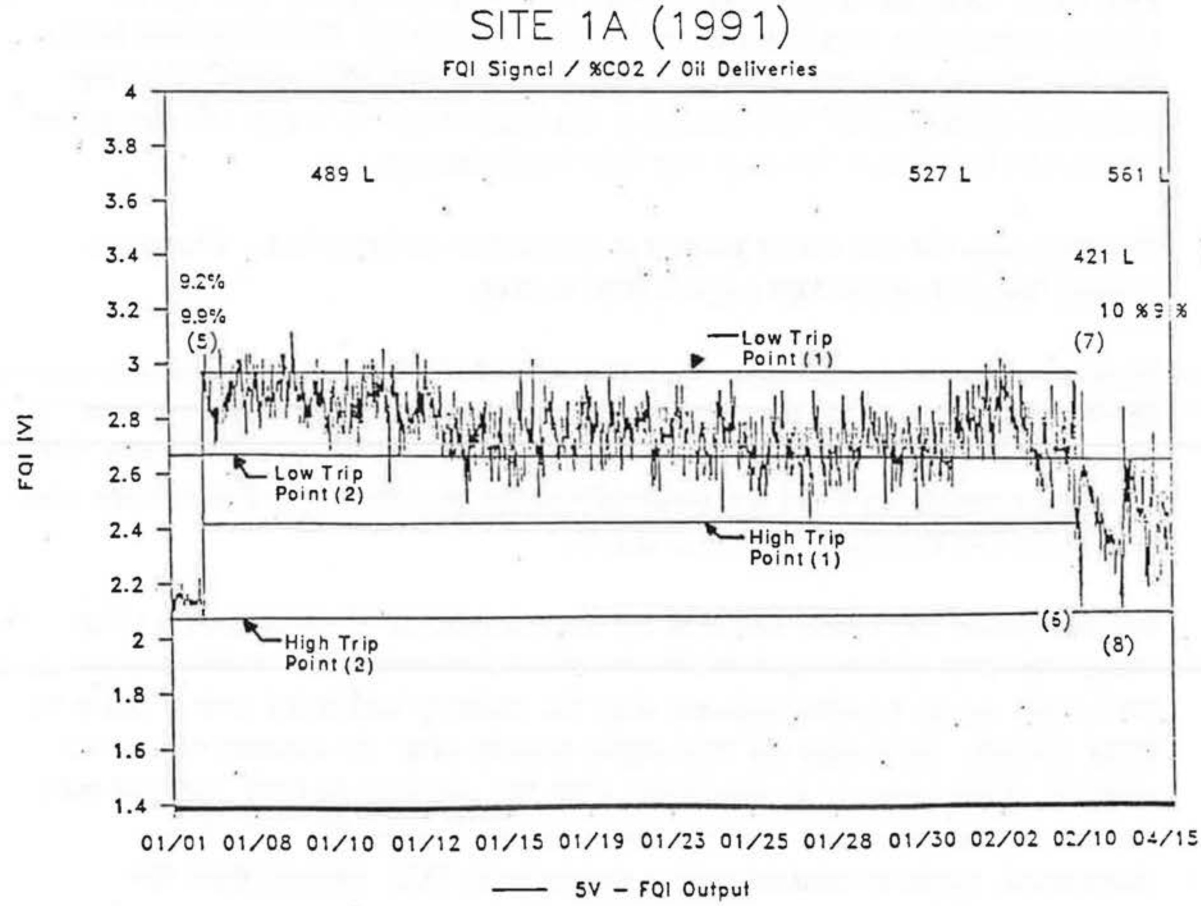


Figure A.1 – Site 1A FQI Results

previous spring as the CO_2 content was measured to be 10.2% on April 26, 1990 at 10:00h.

Item (4) shows that a steady downward trend in FQI signal from the previous spring eventually caused a HIGH alert condition on December 11, 1990. The next CO_2 measurement was taken at 15:20h on January 4, 1991, and produced a value of 9.7%. Recalling the CO_2 value at item (3) was 10.8%, the FQI was tracking CO_2 content correctly and this alert was valid.

At 8:30h on January 7,1990, a site visit was made, and the CO_2 content was measured at 9.2%. The CO_2 content had changed from the optimum of 9.8% significantly enough that the excess air was decreased. The CO_2 content was then measured at 9.9%. During the same site visit, the FQI circuit changed electronically (see Appendix H, figure H.1). The effect of this change is that the burner-off and steady-state burner-on voltages became equally biased downwards by roughly 0.5 V. For this reason the item (5) jump appears larger than it would have been for the decrease in excess air alone.

Note: Inspection of the log sheet (Appendix D) shows that no alerts were recorded between items (5) and (6). These readings may be incorrect in which case the trip voltage remained the same throughout the field testing. However, if the log sheet readings were recorded correctly, then the trip voltages between item(5) and item (6) may also have been biased downwards. Both possible pairs of trip voltages for this time period are shown on the graph.

On February 8, 1991, a site visit was made due to reports of the furnace firing indiscriminately. The problem was diagnosed as a failing fuel pump. Although no corrective action was taken, some activity (unknown) during inspection caused a reverse voltage bias, returning the electronic characteristics of the FQI to the normal state prior to the occurrence explained under item (5). Item (6) points to the reversing bias (see Appendix H, figure H-2). The light status during this visit indicated a HIGH alert.

On February 9, 1991, the service technician replaced the fuel pump and motor. Item (7) shows that this caused an upward shift in the FQI signal. As indicated on the next site visit on February 12, 1991, the pump replacement had caused the HIGH alert status to return to OK.

Following the pump replacement the FQI drifted downwards, until a HIGH alert was initiated on March 3, 1991 (item 8). A site visit was performed on March 20, 1991 at 8:45h, the FQI was showing OK status, but was close to a HIGH alert. The CO_2 content was measured at 10%. Again, during this visit some inspection caused yet another voltage bias downwards, by about 0.9 V (see Appendix H, figure H-3). Item (8) points to the upward shift in the plotted signal produced by this bias.

The electronic problems at this site, render the data less useful. What is known is that the pump failure was detected (item 6), and that a downward drift occurred following the replacement. On April 13, 1991, the service technician replaced the fuel pump again. During the decommissioning visit, oil leakage was detected around the burner. It was not certain if this was a result of the previous failure or a new pump failure. There was a high alert recorded at this time. The downward drift from item (7) onwards is valid tracking of the second pump failure.

Site 1B

The furnace at site 1B fired normally throughout the entire monitoring period. Firing cycles at this site were approximately 7 minutes in duration. The FQI data for this installation is presented in figure A.2.

Generally, the FQI signal for site 1B is flat. The FQI voltage was readjusted only once during a site visit on April 26, 1990 at 11:30h. The effect of this adjustment is not noticeable in the figure as the adjustment moved the FQI voltage from 2.6 V to 2.5 V. Item (1) shows a jump in FQI signal that was associated with the start-up of the furnace in the fall.

Note that the fall start-up FQI bump and another upward bump coincide with oil deliveries of 462 L (summer) and 499 L. At site 1A where the oil deliveries are of course identical, similar effects were observed. Also at these sites, the 489 L delivery in January produced downward excursions on the FQI curve.

CO_2 measurements taken at the time of the installation and coincident with item (1) (9.8% and 9.9%) were in agreement with the lack of drift over the '89-'90 season. Over the course of the '90-'91 heating season there is a small amount of downward drift. With the exception of one CO_2 reading of 10.4%, taken on January 4, 1990 at 15:20h, this drift tracks the measured CO2 content. There were no alerts at site 1B.

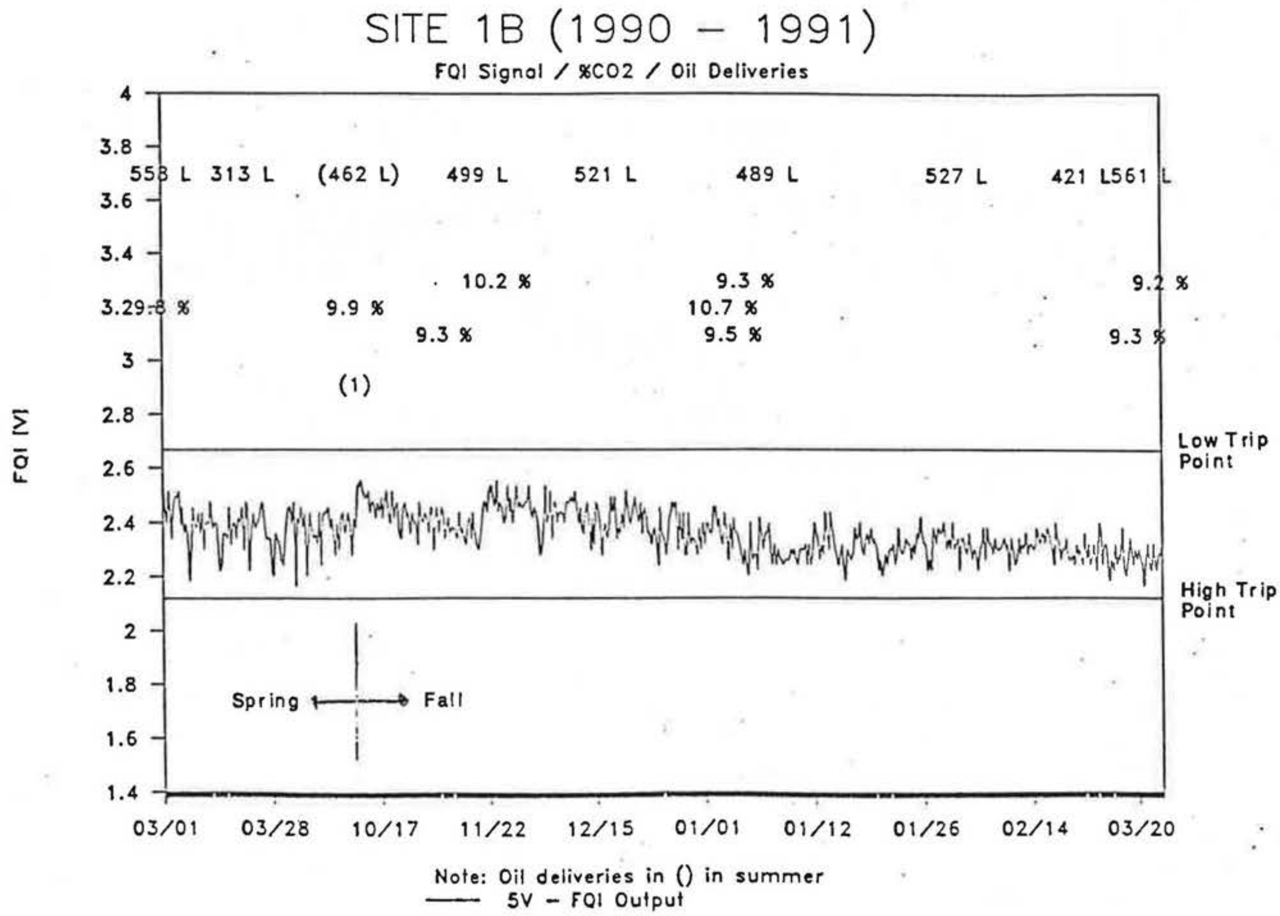
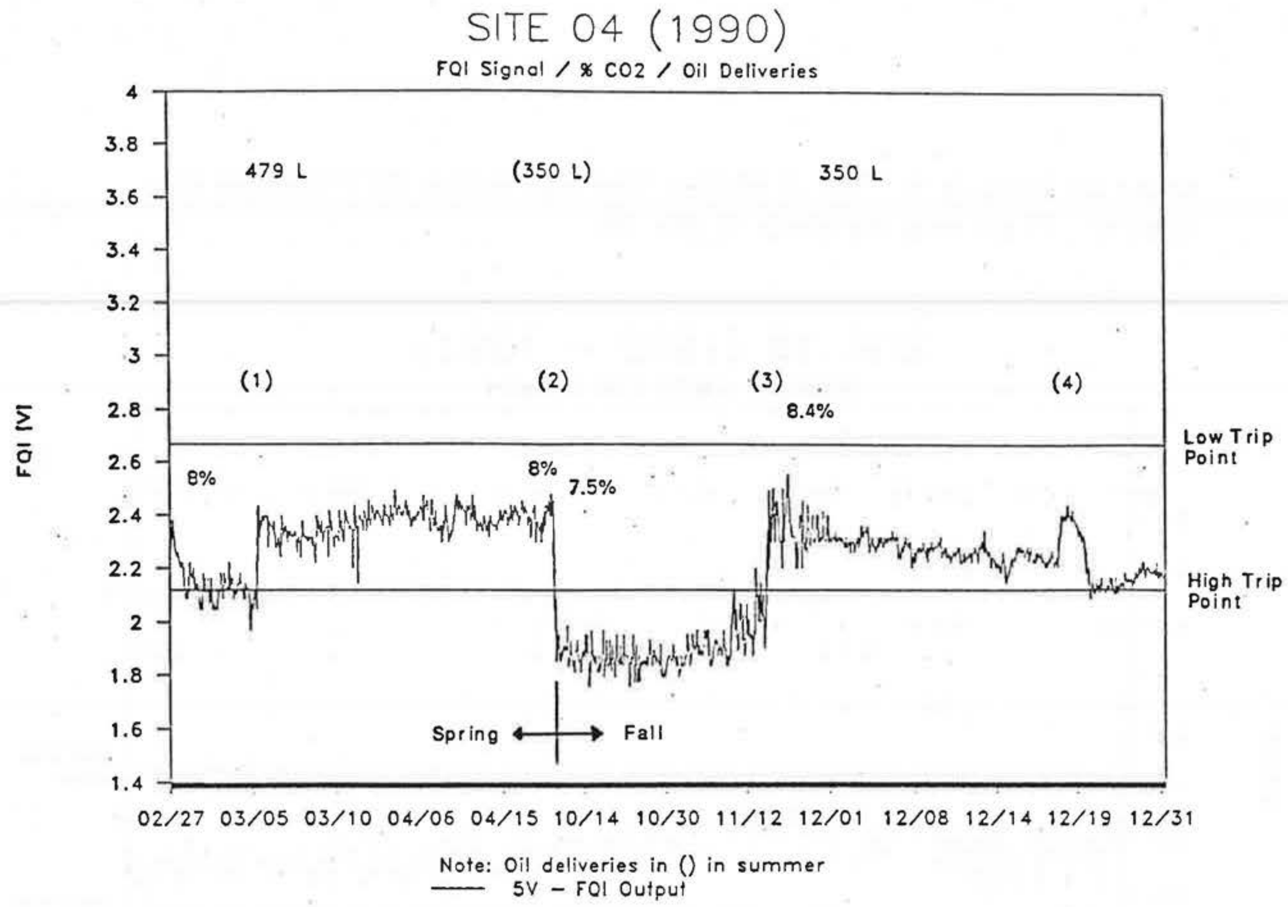


Figure A.2 – Site 1B FQI Results

Site 4

At the fourth test installation, the homeowner would set the thermostat at 20°C at 16:30h until 23:00h at which time it was set to 14°C. The firing cycles were fairly regular at this site, ranging from 20 to 30 minutes. The FQI signal results for site 4 are presented in figure 3.4. The highlight of the project at this site was a clogged nozzle, which occurred during the fall 1990 start-up.



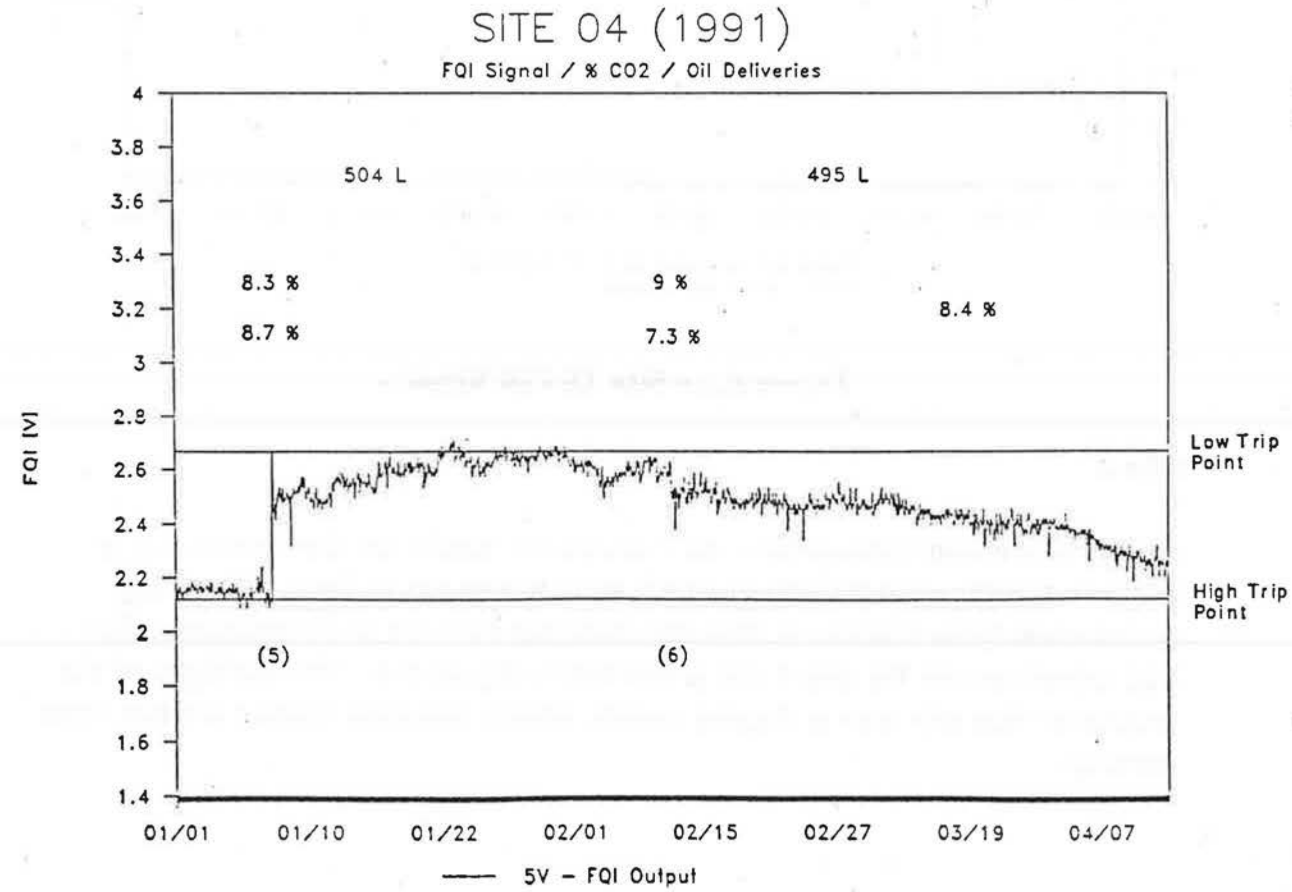


Figure A.4 – Site 4 FQI Results

After installation (CO_2 content 8.0%), the FQI signal drifted very rapidly downwards causing a false HIGH alert within about 1 week. This change in FQI signal cccurred much more quickly than at the other sites. The reason for this has not been determined. The FQI was reset by adjusting the FQI voltage so that the FQI voltage was 2.5 V when the burner approached steady state conditions at 10:49h on March 5, 1990 (item 1). During a site visit on May 22, 1990 at 19:30h, the CO_2 content was determined to be 8%. This was reflected by the essentially flat FQI signal following item (1) before the fall start-up. When the burner started up in the fall of 1990, a HIGH alert was initiated, and confirmed with a CO_2 measurement of 7.5% taken on October 5, 1990 at 12:00h (item 2). As the FQI had functioned well the previous season, it was decided not to change anything, but to observe site 4. A service visit was made on November 22, 1990 at 12:50h, the nozzle was changed, and the excess air reduced. The CAD cell was noted to be in good condition. The service was correctly reflected by an increase in FQI signal, as the changes had brought the CO_2 content back up to 8.4%.

Note the ripple in the FQI signal bordering item (3). The FQI signal had been very erratic, and the nozzle change was an attempt to correct the problem. Although the nozzle had actually been clogged, this was signalled only by the drop in FQI signal. The erratic behavior persisted until the thermocouple amplifier was finally determined to be malfunctioning and over-ranging the data logger, it was then disconnected. The bump in the FQI curve (item 4) cannot be explained. Close examination of the data shows that the jump in FQI signal occurred on December 18, 1990 at 3:18h, on the first firing cycle following a nightly setback (the last cycle ended at 24:00h). This change in FQI signal did not initiate an alert.

During the site visit on January 7, 1991 (item 5), the CO_2 content was measured at 8.3%. Although this is a small deviation from the previous value of 8.4%, the FQI was indicating a HIGH alert. The alert cannot be interpreted as false because following the nozzle change (item 3). the FQI had not been reset. Upon inspection, the CAD cell showed signs of overheating and it was moved back 50 mm. The FQI voltage was reset. Some air leaks associated with the burner installation were corrected and the excess air decreased. This brought the CO_2 content to 8.7% with trace smoke. Site 4 received an oil delivery on January 15, 1990. The FQI signal appears to increase over time as a result. The occupant logged a LOW alert on Jamuary 22, 1991 at 17:25h. A service visit was made (item 6) and a CO_2 measurement of 9.0% and a number 6 smoke confirmed a valid alert.

Although the signal had by then drifted to the green side, the burner was adjusted for increased excess air. This brought the CO_2 content to 7.4%. The FQI was reset.

Subsequent to item 6, the FQI signal drifted downwards substantially for the remainder of the monitoring program, but without generating an alert. A CO_2 measurement of 8.4% with a number 1 smoke on March 19, 1991, indicates that this drift is incorrect and contrary to what the FQI should have signalled.

APPENDIX B

Net Stack Temperature Results

Sites 1, 4 and 5

Net Stack Temperature Results

The temperature data collected during this project is incomplete. This was due to failures of the thermocouple amplifiers, and generally incorrect use of the thermometers by the homeowners. Despite this, the data that was collected is workable.

The results for site 3 are presented in section 3.2.3. The results for the remaining sites are given in this appendix.

Site 1A

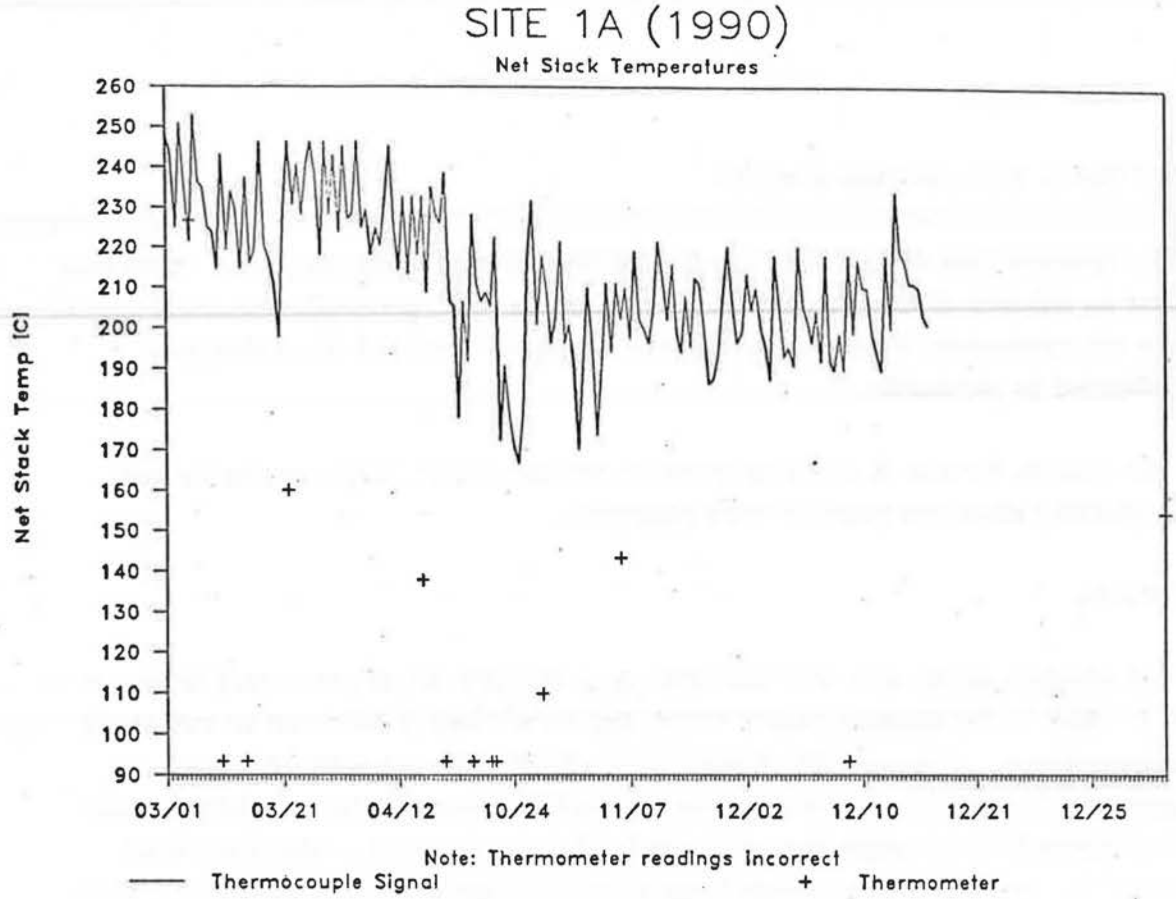
The thermocouple and thermometer data for site 1A is presented in figure A.1. Before the thermocouple failed, the trend was a decrease in net stack temperature. Although the homeowner clearly did not take the flue temperature readings correctly, as he read the instantaneous temperature dial instead of the peak temperature hold dial, there is a sharp upward trend in temperature readings from about February 7, 1991 onwards. This coincides with the timing of the pump failure.

Observed condition of heat exchanger

- large amount of soot buildup

Technician comments

- "to be expected given the number of problems with the burner involving leaks and replacement of parts"



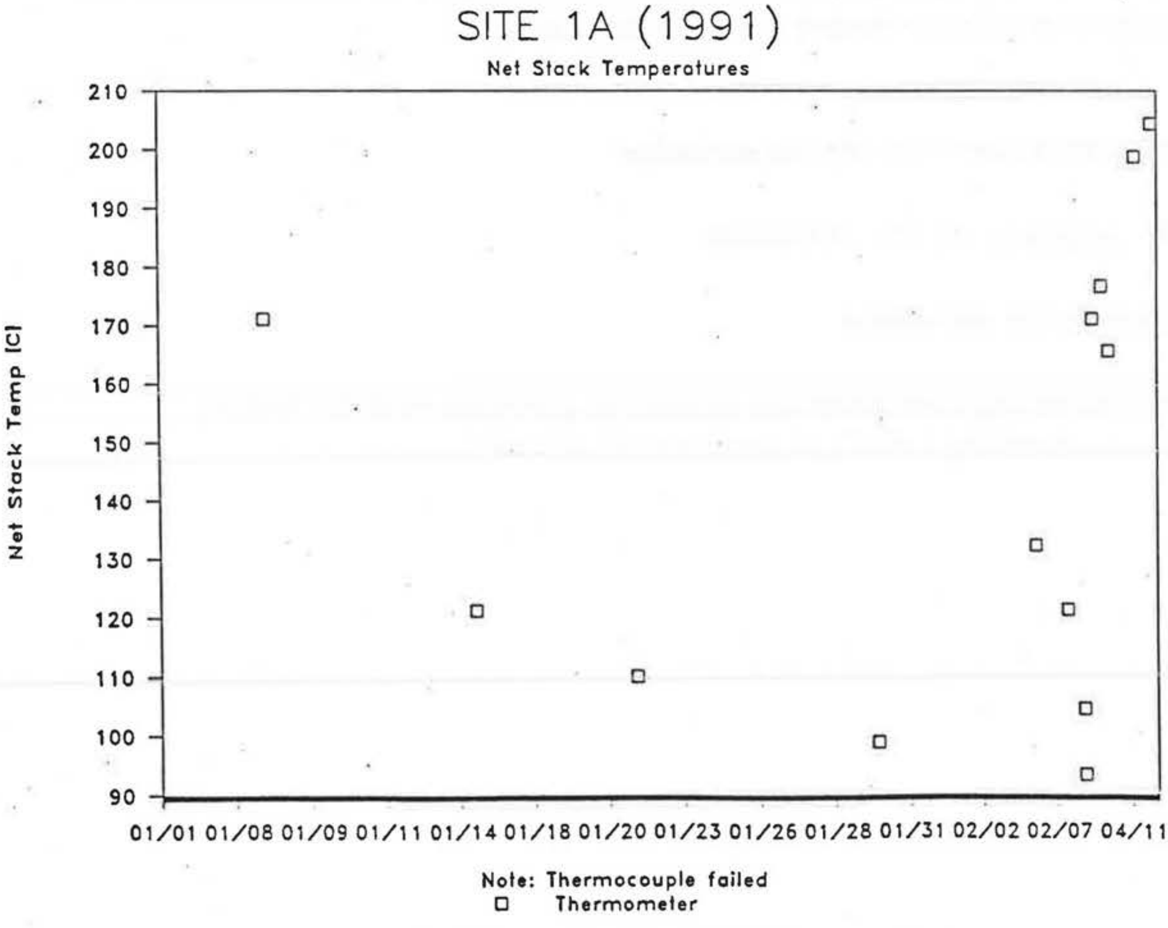


Figure B.1- Site 1A Stack Temperature

Site 1B

The net-stack temperature results for site 1B are presented in figure B.2. Initially, the trend is towards decreased temperature and then the signal becomes steady at approximately 150°C for the entire project.

Observed condition of heat exchanger

- very little accumulation of soot

Technicians comments

- none

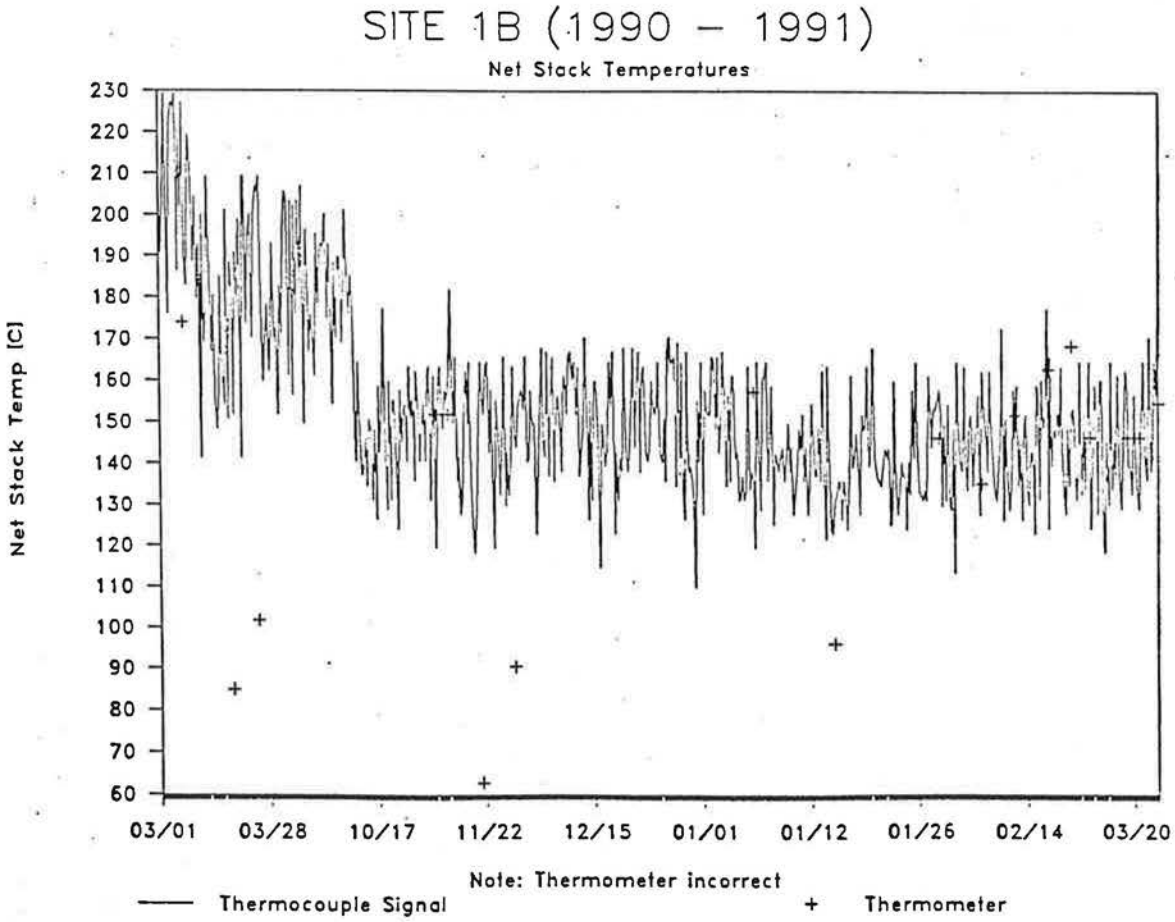


Figure B.2 – Site 1B Stack Temperature

Site 4

The net stack temperature data for site 4 is presented in figure B.3. From the data that was salvaged, it appears that the initial trend after installation was to reduced temperature. Late December 1990, and January 1991 seem to show an increase, then a final downward trend developed through March 1991.

The downward drop in flue temperature from the spring to the fall of 1990 corresponds to the change in FQI readings toward a high alert. Both are a result of the reduced flow of oil to the burner due to nozzle restriction.

Observed condition of heat exchanger

- overall condition good

Technician comments

- "Less soot buildup than would be expected over a 2 year period"

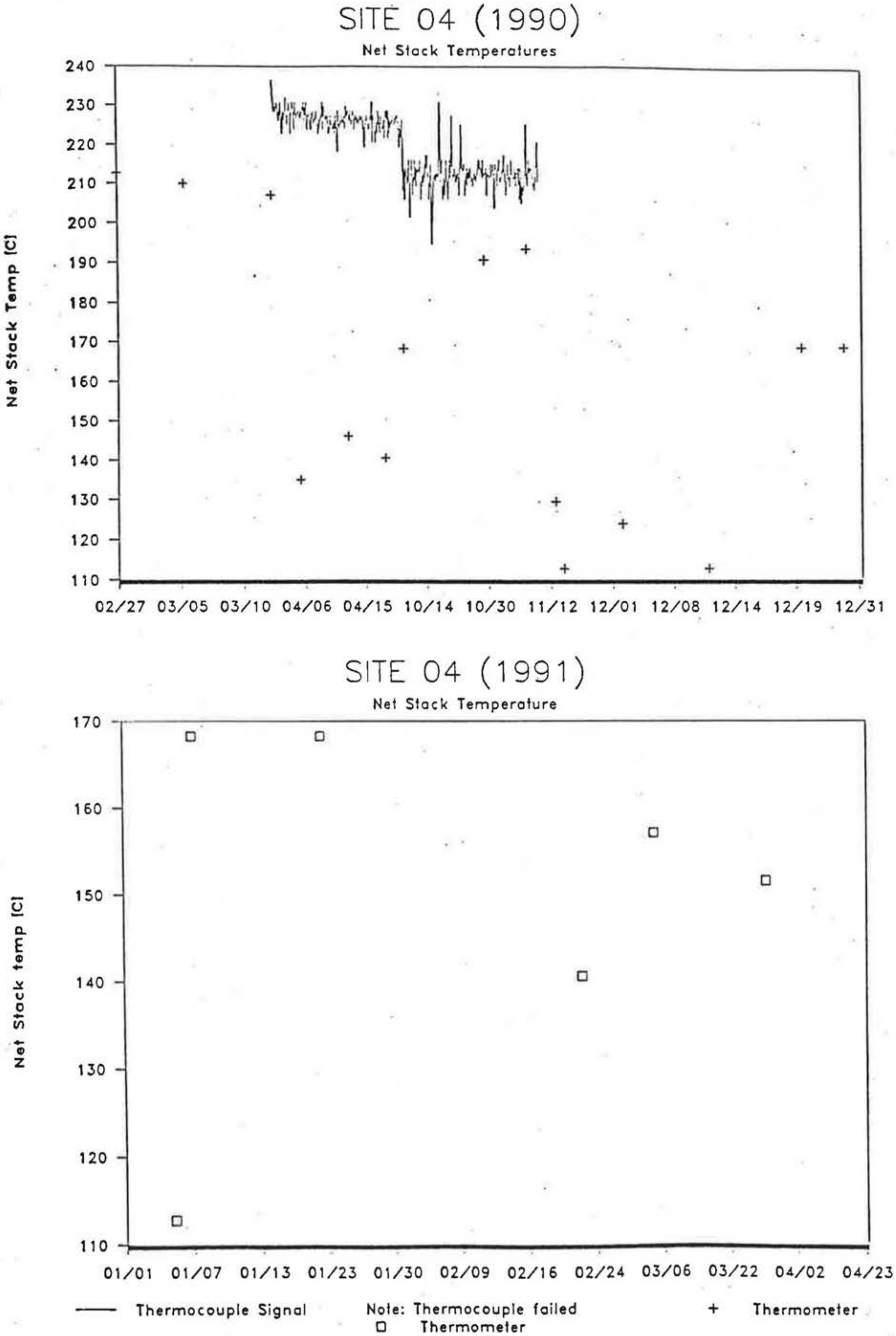


Figure B.3 – Site 4 Stack Temperature

Site 5

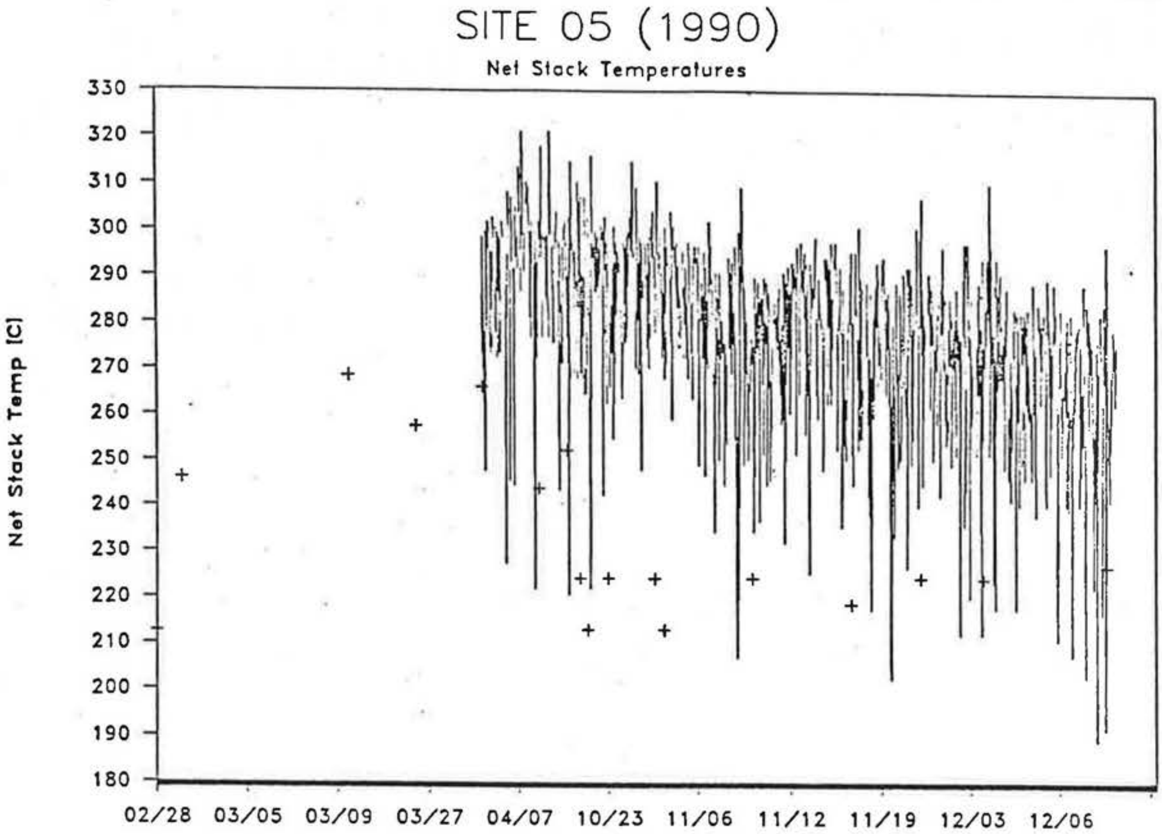
The temperature monitoring results for site 5 are shown in figure B.4. As with all other installations, an initial trend downward occurred after installation. Subsequently, the observed trend disappeared, and the temperature became stable.

Observed condition of heat exchanger

- very good

Technicians comments

- "The heat exchanger is in better condition than would normally be expected over a 2 year time frame."



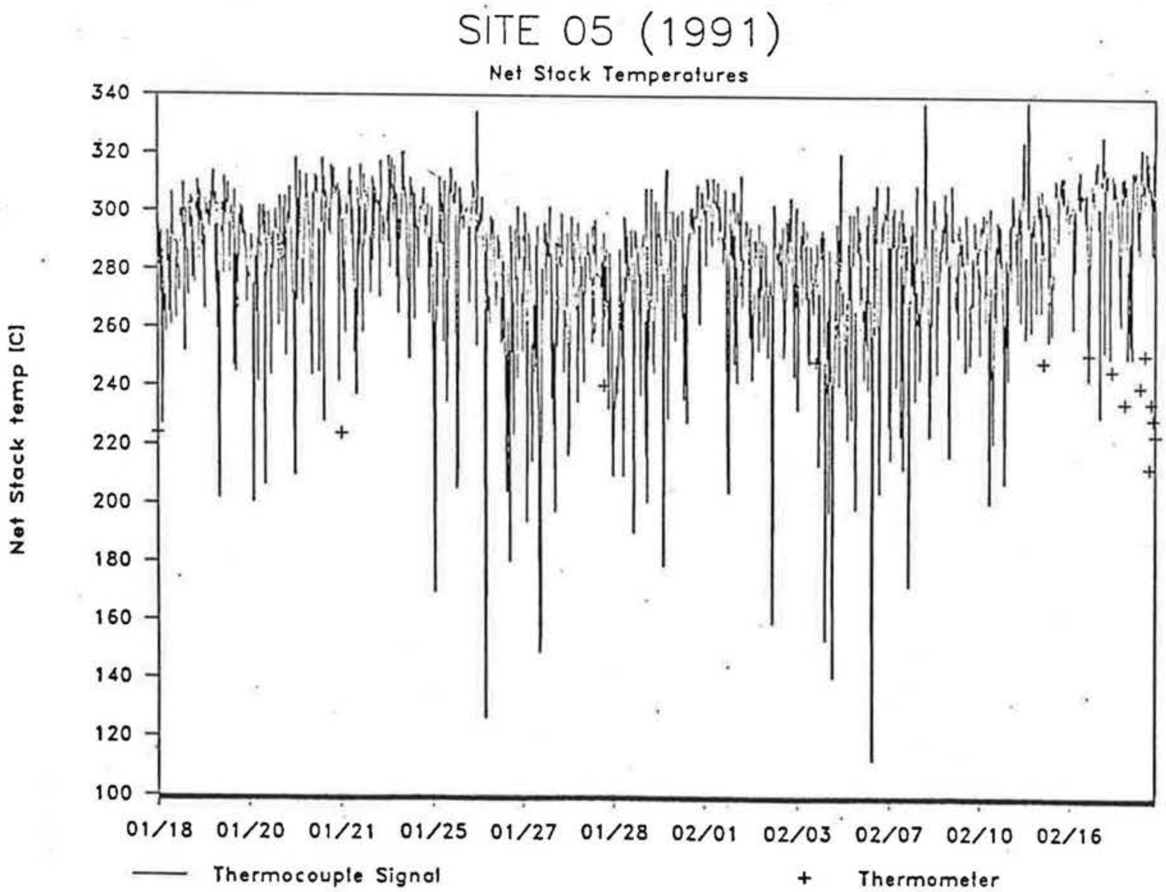


Figure B.4 – Site 5 Stack Temperature

APPENDIX C

Homeowner Survey Results

Homeowner Survey Results

Five questions dealt directly with the homeowners impressions of the FQI and whether or not they would purchase one if they could. The first question asked the homeowner what the purpose of the FQI is. This was deemed necessary as not all homeowners seemed to understand. It was felt a lack of understanding might impair the validity of the responses.

Q1

In your own words, briefly describe what you understand to be the purpose of the FQI?

A 1A/B

"To measure the performance of furnace and flag problems."

A 3

"An aid to inform if the furnace is in tune."

A 4

"I understand it to be an experimental, highly efficient oil burner designed for use in the far north where winters are severe and service difficult to obtain quickly."

A 5

"To indicate to the homeowner/layman when the furnace needed service to ensure maximum efficiency at all times."

Q2

Do you think the FQI is useful to homeowners?

A 1A/B

"Perhaps."

A 3

"Few."

A 4

"Yes."

A 5

"Probably"

Q3

Consider a refined commercial version of the FQI, with one light - 'SERVICE REQUIRED'. Such a device would be unobtrusive and perhaps mounted on the furnace or wall mounted near the thermostat. Would you buy one? Explain.

A 1A/B

"Probably, if it would result in improved efficiency, and thus, fuel economy, and the price was reasonable. and life of unit was, say, 10 years or more."

A 3

"No. We would rely on annual service."

A 4

"Yes if it were reasonable and a reputable firm were to do the servicing."

A 5

"Most likely, it it were a mainstream feature."

Q4

How much money would you be willing to pay providing you were convinced that the device performed well?

A 1A/B

"2-3 times annual savings"

A 3

N/A

A 4

"$100.00."

A 5

"Depends on potential dollars saved."

Q5

If you answered no in question 5, would you consider adding the FQI as an option at the time of changing you furnace or oil burner? If so, how much would you pay for the option?

1A/B

N/A

A 3

"$20.00"

A 4

"I don't think this is pertinent because if I were to change my furnace, I would look at gas, not oil considering the gulf war and subsequent gouging by the oil companies."

A 5

N/A

APPENDIX D

Homeowner Log Sheets

		Burner Performance Indicator					Notes:	Read lights only when Hold light is on
House 1a			Weekly Log Sheet					Please reset Thermometer after reading
								Enter comments only if something unusual is noted
	Date	Time	Light Status (check = on)				Flue	**Notify BLP If High or Low is on a while**
Week Of	(mm/dd)	24 hrs	High	OK	Low	Hold	Temp.	**Hold is on BLP:748-3762**
14-Jan-90								
21-Jan-90								
28-Jan-90								
4-Feb-90								
11-Feb-90								
18-Feb-90								
25-Feb-90								
4-Mar-90	5-Mar	9:30		√		√	440	
11-Mar-90	12-Mar	21:30		√		√	200	
18-Mar-90	18-Mar	16:30	√			√	200	
25-Mar-90	26-Mar	22:45	√			√	320	
1-Apr-90	2-Apr	13:15	√			√		
8-Apr-90	9-Apr	16:55	√			√		
15-Apr-90	15-Apr	12:35	√				280	
22-Apr-90	25-Apr	17:30	√			√		
29-Apr-90								
6-May-90								
13-May-90								
6-Oct-90	10-Oct	21:57		√		√	200	
13-Oct-90	17-Oct	21:19		√		√		
20-Oct-90	23-Oct	20:52		√		√	200	
27-Oct-90	30-Oct	21:17		√			230	
3-Nov-90	6-Nov	21:06		√		√		
10-Nov-90	12-Nov	17:34		√			290	
17-Nov-90	20-Nov	21:05		√		√		
24-Nov-90	27-Nov	21:40		√		√		
1-Dec-90	4-Dec	18:07		√		√		
8-Dec-90	11-Dec	19:44	√				200	
15-Dec-90	17-Dec	22:06		√		√		
22-Dec-90								
29-Dec-90	31-Dec	10:31	√				310	
5-Jan-91	8-Jan	21:41		√		√	340	
12-Jan-91	14-Jan	15:27		√		√	250	
19-Jan-91	21-Jan	12:15		√		√	230	
26-Jan-91	29-Jan	21:51		√		√	210	
2-Feb-91	5-Feb	17:12		√			270	
9-Feb-91	12-Feb	11:03		√			250	
16-Feb-91	18-Feb	20:03		√		√	220	
23-Feb-91	24-Feb	11:40		√		√	200	
2-Mar-91	3-Mar	14:04		v		√	240	
9-Mar-91	10-Mar	22:36		√			350	
16-Mar-91	18-Mar	21:13	√	√		√	330	
23-Mar-91								
30-Mar-91								
6-Apr-91	11-Apr	17:28	√				390	
13-Apr-91								
20-Apr-91	21-Apr	20:30	√			√	400	
27-Apr-91								
4-May-91								
11-May-91								

		Burner Performance Indicator					Notes:	Read lights only when Hold light is on
House 1b			Weekly Log Sheet					Please reset Thermometer after reading
								Enter comments only if something unusual is noted
	Date	Time	Light Status (check = on)				Flue	**Notify BLP if High or Low is on a while**
Week Of	(mm/dd)	24 hrs	High	OK	Low	Hold	Temp.	**Hold is on BLP:748-3762**
14-Jan-90								
21-Jan-90								
28-Jan-90								
4-Feb-90								
11-Feb-90								
18-Feb-90								
25-Feb-90								
4-Mar-90	5-Mar	9:30		√		√	410	
11-Mar-90	12-Mar	21:30		√		√		
18-Mar-90	18-Mar	16:30		√			250	
25-Mar-90	26-Mar	22:45		√		√	280	
1-Apr-90	2-Apr	13:15		√		√		
8-Apr-90	9-Apr	16:55		√		√		
15-Apr-90	15-Apr	12:35		√		√		
22-Apr-90	25-Apr	17:30		√		√		
29-Apr-90								
6-May-90								
13-May-90								
6-Oct-90	10-Oct	21:57		√		√		
13-Oct-90	17-Oct	21:19		√		√		
20-Oct-90	23-Oct	20:52		√		√		
27-Oct-90	30-Oct	21:17		√		√		
3-Nov-90	6-Nov	21:06		√		√	370	
10-Nov-90	12-Nov	17:34		√		√	370	
17-Nov-90	20-Nov	21:05		√		√	210	
24-Nov-90	27-Nov	21:40		√			260	
1-Dec-90	4-Dec	18:07		√		√		
8-Dec-90	11-Dec	19:44				√		
15-Dec-90	17-Dec	22:06		√		√		
22-Dec-90								
29-Dec-90	31-Dec	10:31		√		√		
5-Jan-91	8-Jan	21:41		√			380	
12-Jan-91	14-Jan	15:27		√			270	
19-Jan-91	21-Jan	12:15		√		√	250	
26-Jan-91	29-Jan	21:51		√		√	260	
2-Feb-91	5-Feb	17:12		√		√	340	
9-Feb-91	12-Feb	11:03		√		√	370	
16-Feb-91	18-Feb	20:03		√		√	360	
23-Feb-91	24-Feb	11:40		√		√	370	
2-Mar-91	3-Mar	14:04		v		√	360	
9-Mar-91	10-Mar	22:36		√		√	360	
16-Mar-91	18-Mar	21:13		√		√	370	
23-Mar-91								
30-Mar-91								
6-Apr-91	11-Apr	17:28		√		√	360	
13-Apr-91								
20-Apr-91	21-Apr	20:30		√		√	375	
27-Apr-91								
4-May-91								
11-May-91								

		Burner Performance Indicator					Notes:	Read lights only when Hold light is on
House 03			Weekly Log Sheet					Please reset Thermometer after reading
								Enter comments only if something unusual is noted
	Date	Time	Light Status (check = on)				Flue	**Notify BLP if High or Low is on a while**
Week Of	(mm/dd)	24 hrs	High	OK	Low	Hold	Temp.	**Hold is on BLP:748-3762**
14-Jan-90								
21-Jan-90								
28-Jan-90								
4-Feb-90								
11-Feb-90								
18-Feb-90								
25-Feb-90	27-Feb	14:00		√		√	400	
4-Mar-90	6-Mar	16:30		√		√	400	
11-Mar-90	13-Mar	14:30		√		√	400	
18-Mar-90	19-Mar	15:00		√		√	400	
25-Mar-90								
1-Apr-90								
8-Apr-90								
15-Apr-90								
22-Apr-90	23-Apr	17:00		√		√	400	
29-Apr-90	29-Apr	18:00		√		√	220	
6-May-90	7-May	18:00		√		√	250	
13-May-90								
6-Oct-90								
13-Oct-90								
20-Oct-90								
27-Oct-90								
3-Nov-90								
10-Nov-90								
17-Nov-90								
24-Nov-90								
1-Dec-90	29-Nov	18:00		√		√	350	
8-Dec-90	7-Dec	18:50		√		√	360	
15-Dec-90	14-Dec	18:00		√		√	355	
22-Dec-90								
29-Dec-90	27-Dec	9:00		√		√	360	
5-Jan-91								
12-Jan-91	12-Jan		√				380	
19-Jan-91								
26-Jan-91								
2-Feb-91								
9-Feb-91								
16-Feb-91								
23-Feb-91								
2-Mar-91								
9-Mar-91								
16-Mar-91								
23-Mar-91								
30-Mar-91								
6-Apr-91								
13-Apr-91								
20-Apr-91								
27-Apr-91								
4-May-91								
11-May-91								

		Burner Performance Indicator					Notes:	Read lights only when Hold light is on
House 04			Weekly Log Sheet					Please reset Thermometer after reading
								Enter comments only if something unusual is noted
	Date	Time	Light Status (check = on)				Flue	**Notify BLP if High or Low is on a while**
Week Of	(mm/dd)	24 hrs	High	OK	Low	Hold	Temp.	**Hold is on BLP:748-3762**
14-Jan-90								
21-Jan-90								
28-Jan-90								
4-Feb-90								
11-Feb-90								
18-Feb-90								
25-Feb-90	26-Feb	21:38		√			480	
4-Mar-90	5-Mar	10:49		√		√	475	
11-Mar-90	15-Mar	11:10		√		√	470	
18-Mar-90	23-Mar	19:50		√		√	350	
25-Mar-90	29-Mar	19:26		√		√	340	
1-Apr-90	6-Apr	18:59		√		√	340	
8-Apr-90	12-Apr	18:55		√		√	360	
15-Apr-90	18-Apr			√		√	330	
22-Apr-90								
29-Apr-90								
6-May-90								
13-May-90								
6-Oct-90	5-Oct	12:07	√			√	400	
13-Oct-90	29-Oct	18:00	√			√	440	
20-Oct-90								
27-Oct-90								
3-Nov-90	6-Nov	18:00	√			√	445	
10-Nov-90	14-Nov	19:27	√			√	330	
17-Nov-90	21-Nov	18:35	√			√	300	
24-Nov-90								
1-Dec-90	2-Dec	21:10	√			√	320	
8-Dec-90	11-Dec	18:52		√		√	300	
15-Dec-90	21-Dec	10:55		√		√	400	
22-Dec-90	29-Dec	13:55		√		√	400	
29-Dec-90								
5-Jan-91	5-Jan	13:50	√			√	300	
12-Jan-91	7-Jan	19:00		√		√	400	
19-Jan-91	22-Jan	17:25			√	√	400	
26-Jan-91	1-Feb	12:57		√		√		
2-Feb-91								
9-Feb-91	9-Feb	11:50		√		√		
16-Feb-91								
23-Feb-91	22-Feb	21:30		√		√	350	
2-Mar-91	4-Mar	17:40		√		√	380	
9-Mar-91	9-Mar	14:20		√		√		
16-Mar-91	18-Mar	16:59		√		√		
23-Mar-91	27-Mar	17:50		√		√	370	
30-Mar-91								
6-Apr-91	7-Apr	13:55		√		√		
13-Apr-91	14-Apr	12:20		√		√		
20-Apr-91								
27-Apr-91								
4-May-91								
11-May-91								

		Burner Performance Indicator					Notes:	Read lights only when Hold light is on
House 05			Weekly Log Sheet					Please reset Thermometer after reading
								Enter comments only if something unusual is noted
	Date	Time	Light Status (check = on)				Flue	**Notify BLP If High or Low is on a while**
Week Of	(mm/dd)	24 hrs	High	OK	Low	Hold	Temp.	**Hold is on BLP:748-3762**
14-Jan-90								
21-Jan-90								
28-Jan-90								
4-Feb-90								
11-Feb-90								
18-Feb-90	23-Feb	15:00		√		√	480	
25-Feb-90	27-Feb	10:00	√			√	540	
4-Mar-90	1-Mar	14:40		√		√	550	
11-Mar-90	14-Mar	8:30		√		√	580	
18-Mar-90	19-Mar	8:00		√		√	580	
25-Mar-90	26-Mar	14:15		√		√	560	
1-Apr-90	3-Apr	13:30		v		√	575	
8-Apr-90	10-Apr	7:45		√		√	535	
15-Apr-90	15-Apr	13:00		√		√	550	
22-Apr-90	25-Apr	10:40		√		√	535	
29-Apr-90	4-May	22:25		√		√	530	
6-May-90	10-May	7:00		√		√	550	
13-May-90	13-May	10:30		√		√	500	
5-Oct-90	5-Oct	14:20		√		√	480	
6-Oct-90	10-Oct	23:40		√		√	500	
13-Oct-90	oct 15]	16:00		√		√	480	
20-Oct-90	23-Oct	17:30		√		√	500	
27-Oct-90	30-Oct	10:30		√		√	500	
3-Nov-90	3-Nov	11:00		√		√	480	
10-Nov-90	10-Nov	12:25		√		√	500	
17-Nov-90	17-Nov	11:15		√		√	490	
24-Nov-90	24-Nov	14:30		√		√	500	
1-Dec-90	3-Dec	1:00		√		√	500	
8-Dec-90	9-Dec	16:00		√		√	505	
15-Dec-90	15-Dec	14:10	√			√	520	
22-Dec-90	2-Jan	5:00		√		√	490	
29-Dec-90	7-Jan	5:00		√		√	490	
5-Jan-91	14-Jan	5:00				√	500	
12-Jan-91								
19-Jan-91	21-Jan	14:00		√		√	500	
26-Jan-91	28-Jan	10:00		√		√	530	
2-Feb-91	3-Feb	17:00		√		√	545	
9-Feb-91	11-Feb	9:05		√		√	545	
16-Feb-91	18-Feb	11:00		√		√	550	
23-Feb-91	25-Feb	13:00		√		√	540	
2-Mar-91	2-Mar	9:25		√		√	520	
9-Mar-91	9-Mar	14:40		√		√	530	
16-Mar-91	16-Mar	20:30		√		√	550	
23-Mar-91	22-Mar	11:45		√		√	480	
30-Mar-91	27-Mar	13:29		√		√	520	
6-Apr-91	6-Apr	9:45	√			√	500	
13-Apr-91	14-Apr	17:00		√		√	510	
20-Apr-91	23-Apr	16:00		√		√	500	
27-Apr-91								
4-May-91								
11-May-91								

		Burner Performance Indicator					Notes:	Read lights only when Hold light is on
House 1a			Weekly Log Sheet					Please reset Thermometer after reading
								Enter comments only if something unusual is noted
	Date	Time	Light Status (check = on)				Flue	Notify BLP If High or Low is on a while
Week Of	(mm/dd)	24 hrs	High	OK	Low	Hold	Temp.	Hold is on BLP:748-3762
14-Jan-90								
21-Jan-90								
28-Jan-90								
4-Feb-90								
11-Feb-90								
18-Feb-90								
25-Feb-90								
4-Mar-90								
11-Mar-90								
18-Mar-90								
25-Mar-90								
1-Apr-90								
8-Apr-90								
15-Apr-90								
22-Apr-90								
29-Apr-90								
6-May-90								
13-May-90								
6-Oct-90								
13-Oct-90								
20-Oct-90								
27-Oct-90								
3-Nov-90								
10-Nov-90								
17-Nov-90								
24-Nov-90								
1-Dec-90								
8-Dec-90								
15-Dec-90								
22-Dec-90								
29-Dec-90								
5-Jan-91								
12-Jan-91								
19-Jan-91								
26-Jan-91								
2-Feb-91								
9-Feb-91								
16-Feb-91								
23-Feb-91								
2-Mar-91								
9-Mar-91								
16-Mar-91								
23-Mar-91								
30-Mar-91								
6-Apr-91								
13-Apr-91								
20-Apr-91								
27-Apr-91								
4-May-91								
11-May-91								

APPENDIX E

Site Photographs

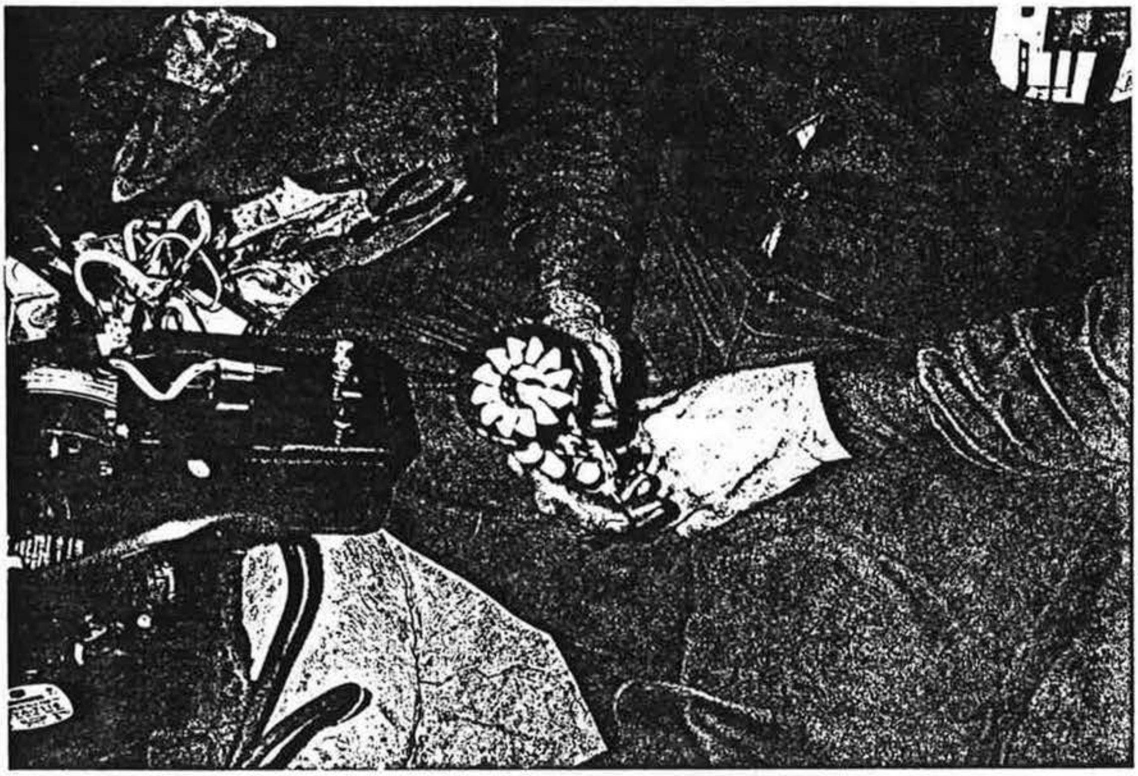


Photo E.1 - Site 1A
Burner Assembly (April 29, 1991)

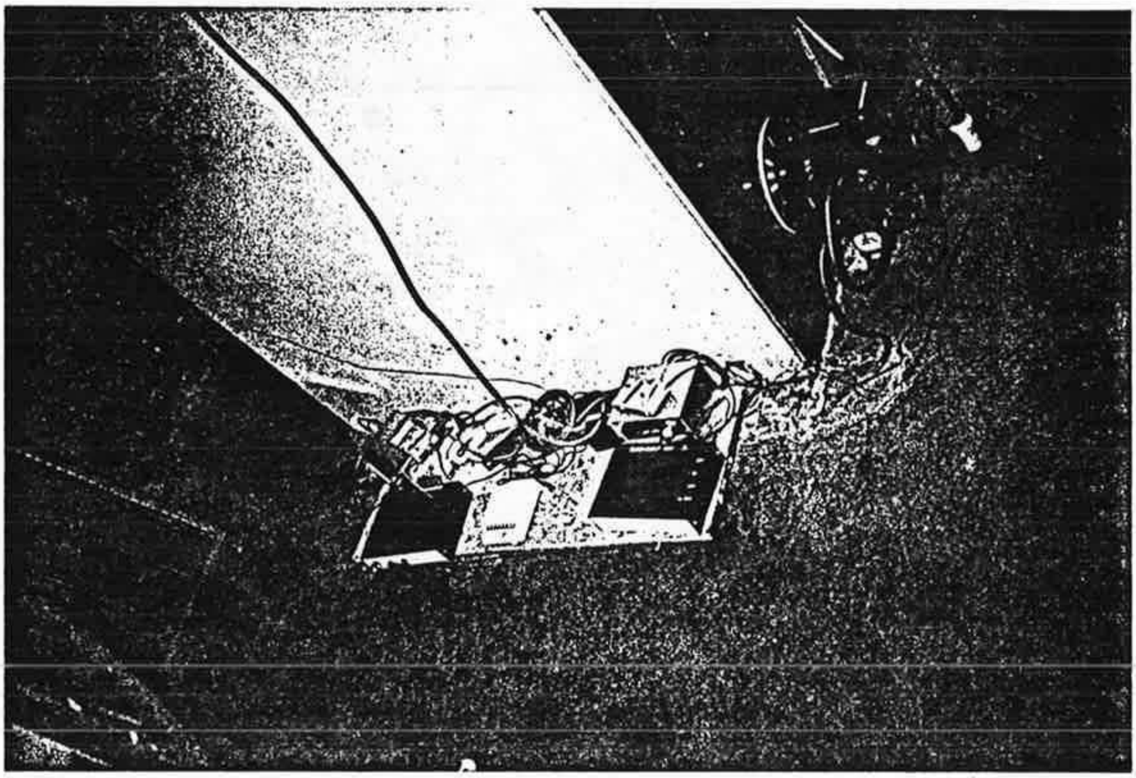


Photo E.2 - Site 1B
Monitoring Equipment Installation

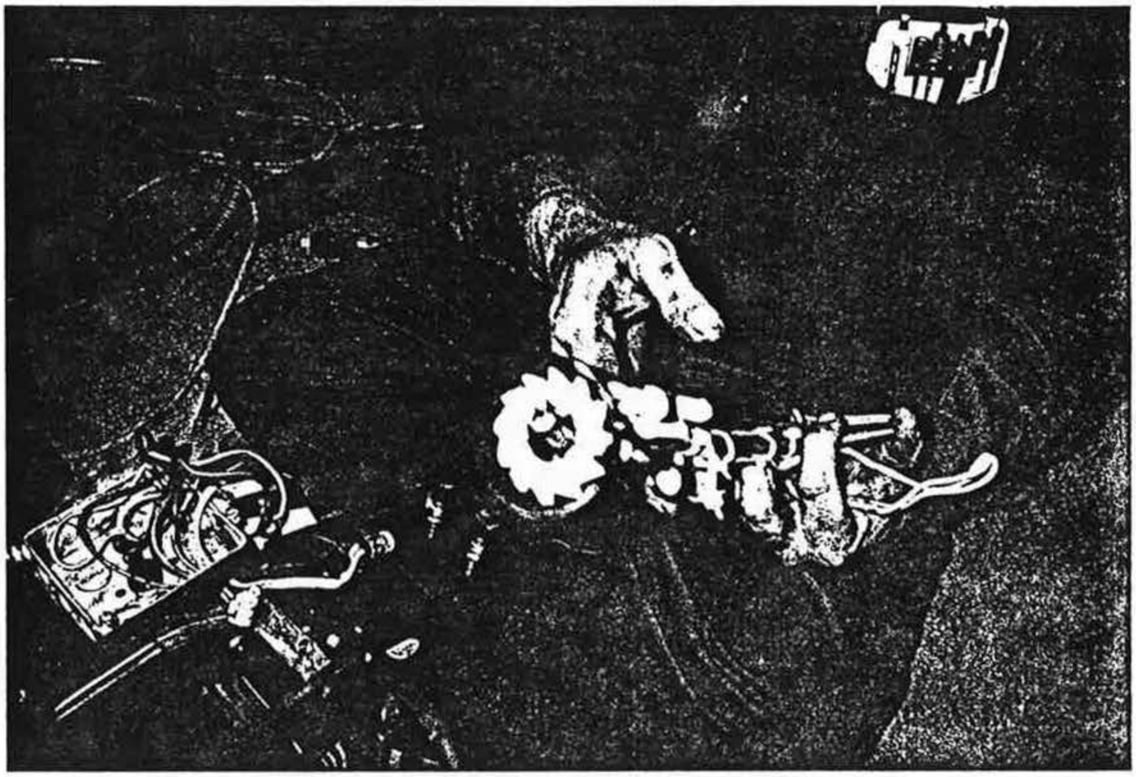


Photo E.3 - Site 1B
Burner Assembly (April 29, 1991

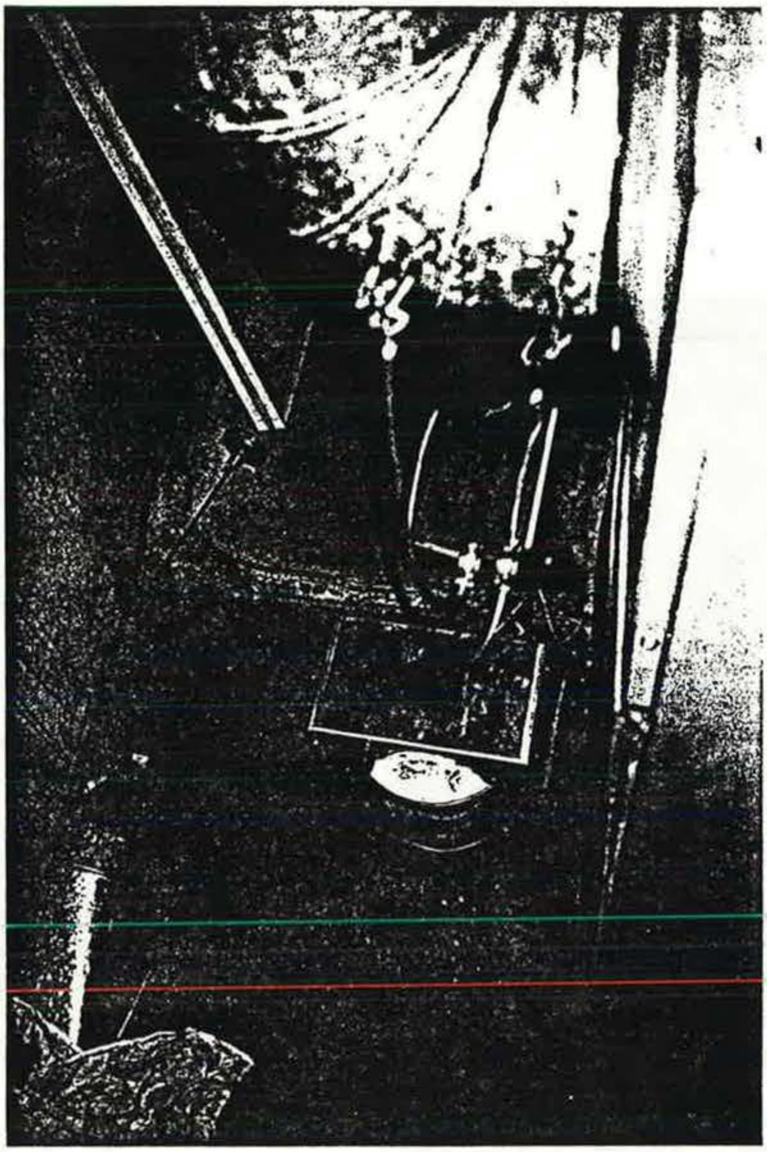


Photo E.4 - Site 3
Oxygen Sensor Installation

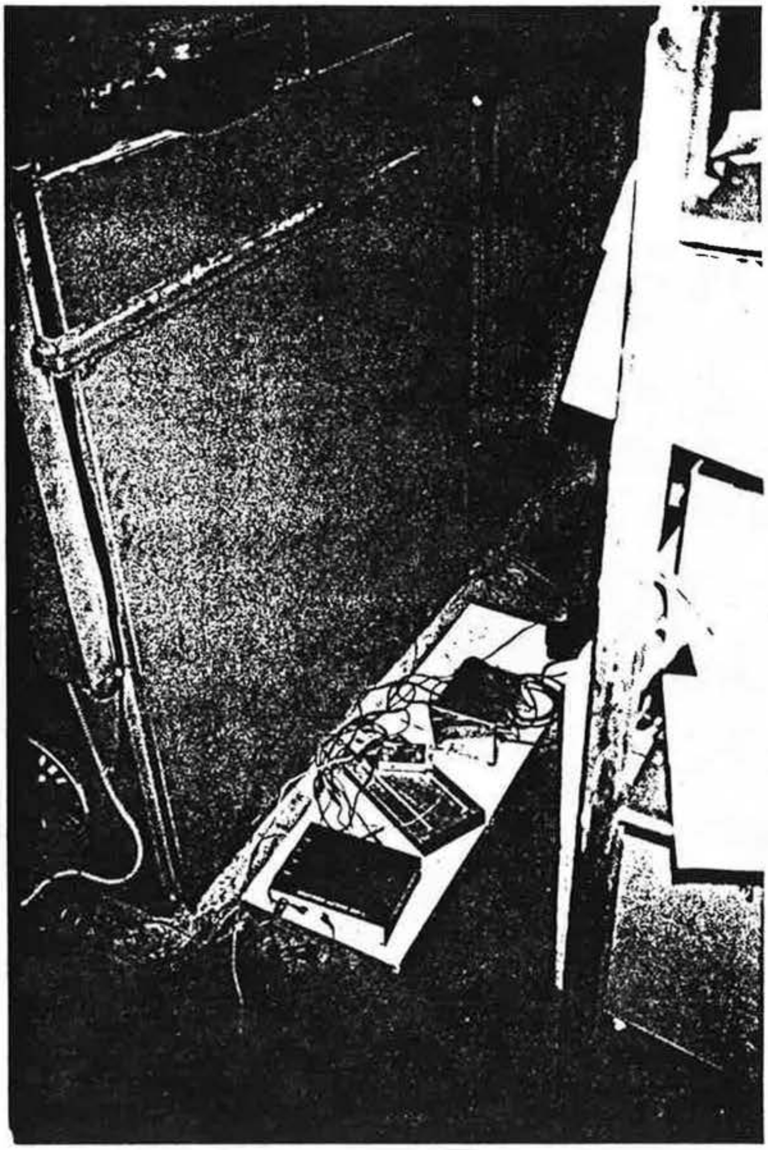


Photo E.5 - Site 3
Monitoring Equipment Installation

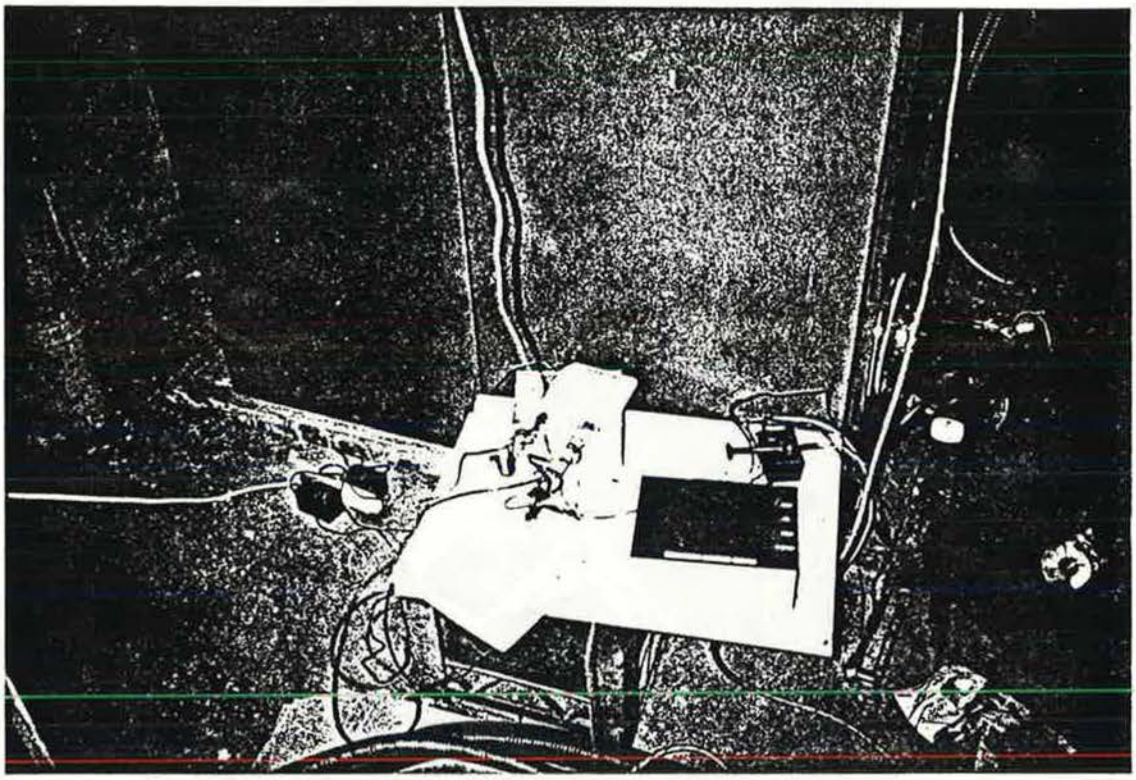


Photo E.6 - Site 4
Monitoring Equipment (Partially Decommissioned April 29, 1991)

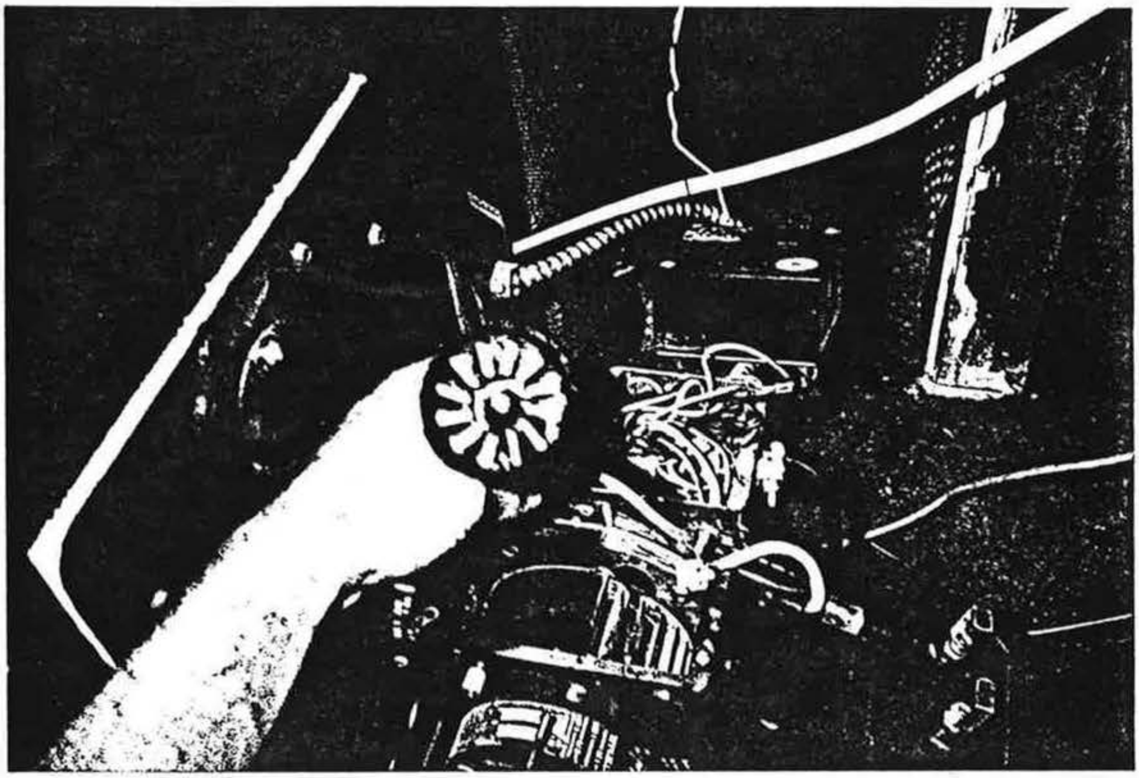


Photo E.7 - Site 5
Burner Assembly (April 29, 1991)

APPENDIX F

Test System Calibration and Site Data

House Data Sheet

Identification

House Number:	1	2 Furnaces Identical
Homeowner Name:	Redmond H. (Reg)	
Address:	1077 Island View Drive, Manotick	
Phone (Res):	(613) 692-4785	
Phone (Furnace):	(613) 692-4595	

House Detail

Age of House (yrs):	17
Stories:	2
Location of Furnace:	S.E.
Occupancy & Patterns:	2 (usually 1 at any time)
Estimated Annual Oil Consumption	$1600 - (two furnace)

Furnace Detail

Furnace Make/Model:	Beach 801-A Customline
Furnace Age:	17 years
Comment on Heat Exchanger:	Good Condition
Comment on Chamber (fouling, leaks):	No leaks - stainless steel type
Chimney Height:	
Barometric Damper Make/Model:	Canaline
Barometric Damper Condition:	Excellent
Furnace Nameplate Data:	95,000 Btu/hr @ .85 gph
Service History:	Always under service contract

Existing Burner Detail

Burner Make/Model:	Beach C66
Burner Age:	17 years
Firing Rate:	.85 @ 80 now at .65 (Carlin)
Firetube Length:	≈8"
Burner Nameplate Data:	

Comments

Furnace A - Most use - Kitchen, L.R., Family R., port 1 C200
Furnace B - Less - Bedrooms, Rec. Room, port 8 C200

A - thermocouple in flue @ flue junction to furnace
B - thermocouple in flue close to damper (cooler flue temperature)

Note: positioning CAD cell at 2" from nozzle caused CAD cell damage, then positioned both at 4" from nozzle, and it worked okay. This was the case for both furnaces.

House Data Sheet

Identification

House Number:	3
Homeowner Name:	Mark and Jane Lawton
Address:	1559 Balena Ave., Ottawa, Ontario
Phone (Res):	(613) 739-1229
Phone (Furnace):	same (require co-ordination)

House Detail

Age of House (yrs):	21
Stories:	1
Location of Furnace:	south west corner
Occupancy & Patterns:	2 adults and baby
Estimated Annual Oil Consumption	$ 525.00

Furnace Detail

Furnace Make/Model:	Beach Proline 602
Furnace Age:	Same as house
Comment on Heat Exchanger:	Fine
Comment on Chamber (fouling, leaks):	Fine, no leaks
Chimney Height:	≈ 16' from grade
Barometric Damper Make/Model:	Exact Med. 8" (Canada)
Barometric Damper Condition:	Excellent
Furnace Nameplate Data:	93,000 Btu/hr @ .85 gph 80°
Service History:	Don't know

Existing Burner Detail

Burner Make/Model:	Beach C66 -20RZ3 - C
Burner Age:	Same as house
Firing Rate:	.75 gph
Firetube Length:	9"
Burner Nameplate Data:	None

Comments

House Data Sheet

Identification

House Number:	4
Homeowner Name:	Eleanor Millson
Address:	477 Dawson Ave, Ottawa, Ontario
Phone (Res):	(613) 724-1178
Phone (Furnace):	(613) 729-0098

House Detail

Age of House (yrs):	30
Stories:	1 1/2
Location of Furnace:	South Wall, Basement, open
Occupancy & Patterns:	1 working adult
Estimated Annual Oil Consumption	$1600 - 1848 l @ $.319/l CAD

Furnace Detail

Furnace Make/Model:	Findlay W095
Furnace Age:	30 years
Comment on Heat Exchanger:	No leaks, but inside hjas crusty appearance
Comment on Chamber (fouling, leaks):	Old one burnt out, replaced with a sarafelt pot
Chimney Height:	16'
Barometric Damper Make/Model:	No name
Barometric Damper Condition:	Very old, appears to work fine.
Furnace Nameplate Data:	90,000 Btu/hr max fuel: .85 gph 80°
Service History:	Under contract for past 2 years at least.

Existing Burner Detail

Burner Make/Model:	Findlay J6210
Burner Age:	30
Firing Rate:	0.75 gph (original) 0.5 gph (Carlin)
Firetube Length:	9"
Burner Nameplate Data:	

Comments

Installation of new sarafelt combustion chamber just prior (days) to Carlin burner installation.

House Data Sheet

Identification

House Number:	5
Homeowner Name:	James Cleary
Address:	109 Hamilton Avenue, Ottawa, Ontario
Phone (Res):	(613) 722-3375
Phone (Furnace):	(613) 722-9924

House Detail

Age of House (yrs):	40 years
Stories:	2
Location of Furnace:	Basement; soon to be enclosed in room 3X furnace volume
Occupancy & Patterns:	2 working
Estimated Annual Oil Consumption	$600 CAD $.32/l

Furnace Detail

Furnace Make/Model:	Brock L01M
Furnace Age:	1982
Comment on Heat Exchanger:	Excellent
Comment on Chamber (fouling, leaks):	O.K.
Chimney Height:	23'
Barometric Damper Make/Model:	Tradeline
Barometric Damper Condition:	Very bad*
Furnace Nameplate Data:	74 000 - .65; 86 000 - .75; 47 000 - .35; 112 000 - 1.0
Service History:	"not bad"

Existing Burner Detail

Burner Make/Model:	Brock QH1AR
Burner Age:	1982
Firing Rate:	.85 gph before .85 gph hollow (Carlin)
Firetube Length:	9"
Burner Nameplate Data:	

Comments

* We wired damper in fixed position for draft of .02" H_2O; will get new one installed and draft set to same.

Note: furnace going off on limit because return air is insufficient and filters need changing - corrected 02/26/90.

2513 - Installation Data Sheet

House No.: 1A
Date: 3/1/90

1 - Initial fire-up, adjust to trace smoke   initial CO_2: 9.8 58Ω

2 - Calibrate CAD cell

			Target CO2	Actual CO2	Smoke No.	CAD Ohms
low ex., hi CO2		1	smoke ~6	11.4	6	44
RCL .5		2	10.6	10.8	3	45
RCL .4		3	10.2	10.4	1	50
RCL .3	(initial)	4	9.8	9.8	0.5	58
RCL .2		5	9.4	9.2	0	62
RCL .1		6	8.9	9	0	64
RCL .0		7	8.6	8.7	0	70

3 - Reset burn, connect CAD cell to FQI (Note: adjust trim pot until Vcad= 1/2 of V1-22)

Vsetpoint: 2.5

4 - Dial up air until Hi light

Smoke(hi): 0 CO2(hi): 8.4 Vhi: 2.91

5 - Dial down air until Low light

Smoke(low): 1 CO2(low): 10.3 Vlow: 2.33

6 - Reset burn to Vsetpoint

7 - Data acquisition

2513 - Installation Data Sheet

House No.: 1 B
Date: 1/28/90

1 - Initial fire-up, adjust to trace smoke   initial CO_2: 9.8

2 - Calibrate CAD cell

		Target CO2	Actual CO2	Smoke No.	CAD Ohms
low ex., hi CO2	1	smoke ~6	11.2	3	37
RCL .5	2	10.6	10.4	2	39
RCL .4	3	10.2	10.2	1	46
RCL .3 (initial)	4	9.8	9.8	0.5	56
RCL .2	5	9.4	9.5	0	60
RCL .1	6	9	8.9	0	64
RCL .0	7	8.6	8.6	0	71

3 - Reset burn, connect CAD cell to FQI (Note: adjust trim pot until Vcad= 1/2 of V1-22)

Vsetpoint: 2.5

4 - Dial up air until Hi light

Smoke(hi): 0   CO2(hi): 8.5   Vhi: 2.9

5 - Dial down air until Low light

Smoke(low): 1   CO2(low): 11   Vlow: 2.33

6 - Reset burn to Vsetpoint

7 - Data acquisition

2513 - Installation Data Sheet

House No.: 3
Date: 2/22/90

1 - Initial fire-up, adjust to trace smoke initial CO2: 9.7 62Ω

2 - Calibrate CAD cell

			Target CO2	Actual CO2	Smoke No.	CAD Ohms
low ex., hi CO2		1	smoke ~6	13.8	9 +	44
RCL .5		2	10.5	11.1		56
RCL .4		3	10.1	10.9	1	61
RCL .3	(initial)	4	9.7	10.3	0	68
RCL .2		5	9.3	9.5	0	76
RCL .1		6	8.9	8.7		85
RCL .0		7	8.5	8.3		95

3 - Reset burn, connect CAD cell to FQI (Note: adjust trim pot until Vcad= 1/2 of V1-22)

Vsetpoint: 2.50V

4 - Dial up air until Hi light

Smoke(hi): 0 CO2(hi): 8.5 Vhi: 2.88V

5 - Dial down air until Low light

Smoke(low): 2 CO2(low): 12.3 Vlow: 2.3V

6 - Reset burn to Vsetpoint 10.5 CO2 2.4V

7 - Data acquisition

2513 - Installation Data Sheet

House No.: 4
Date: 2/27/90

1 - Initial fire-up, adjust to trace smoke   initial CO_2: 8 85Ω

2 - Calibrate CAD cell

			Target CO2	Actual CO2	Smoke No.	CAD Ohms
low ex., hi CO2		1	smoke ~6	9.3	4	66
RCL .5		2	8.67	8.7	2	73
RCL .4		3	8.3	8.3	1	83
RCL .3	(initial)	4	8	8	≈ .5	85
RCL .2		5	7.6	7.5	0	104
RCL .1		6	7.3	7.2	0	123
RCL .0		7	7	6.8	0	155

3 - Reset burn, connect CAD cell to FQI (Note: adjust trim pot until Vcad= 1/2 of V1-22)

Vsetpoint: 2.5

4 - Dial up air until Hi light

Smoke(hi): 0 CO_2(hi): 6.2 Vhi: 2.9

5 - Dial down air until Low light

Smoke(low): ≈ 2 CO_2(low): 8.8 Vlow: 2.32

6 - Reset burn to Vsetpoint

7 - Data acquisition

2513 - Installation Data Sheet

House No.: 5
Date: 2/23/90

1 - Initial fire-up, adjust to trace smoke initial CO2: 10 45Ω

2 - Calibrate CAD cell

			Target CO2	Actual CO2	Smoke No.	CAD Ohms
				12	7	35
low ex., hi CO2		1	smoke ~6	11.5	5	36
RCL .5		2	11	11.2	4	37
RCL .4		3		10.3	~.5	43
RCL .3	(initial)	4	10	10	0	45
RCL .2		5	9.6	9.7	0	47
RCL .1		6	9.2	9.3	0	50
RCL .0		7	8.7	8.9	0	57

3 - Reset burn, connect CAD cell to FQI (Note: adjust trim pot until Vcad= 1/2 of V1-22)

Vsetpoint: 2.2

4 - Dial up air until Hi light

Smoke(hi): Ø CO2(hi): 9.3 Vhi: 2.35

5 - Dial down air until Low light

Smoke(low): 4 CO2(low): 11.2 Vlow: 2.05

6 - Reset burn to Vsetpoint 2.2V

7 - Data acquisition

APPENDIX G

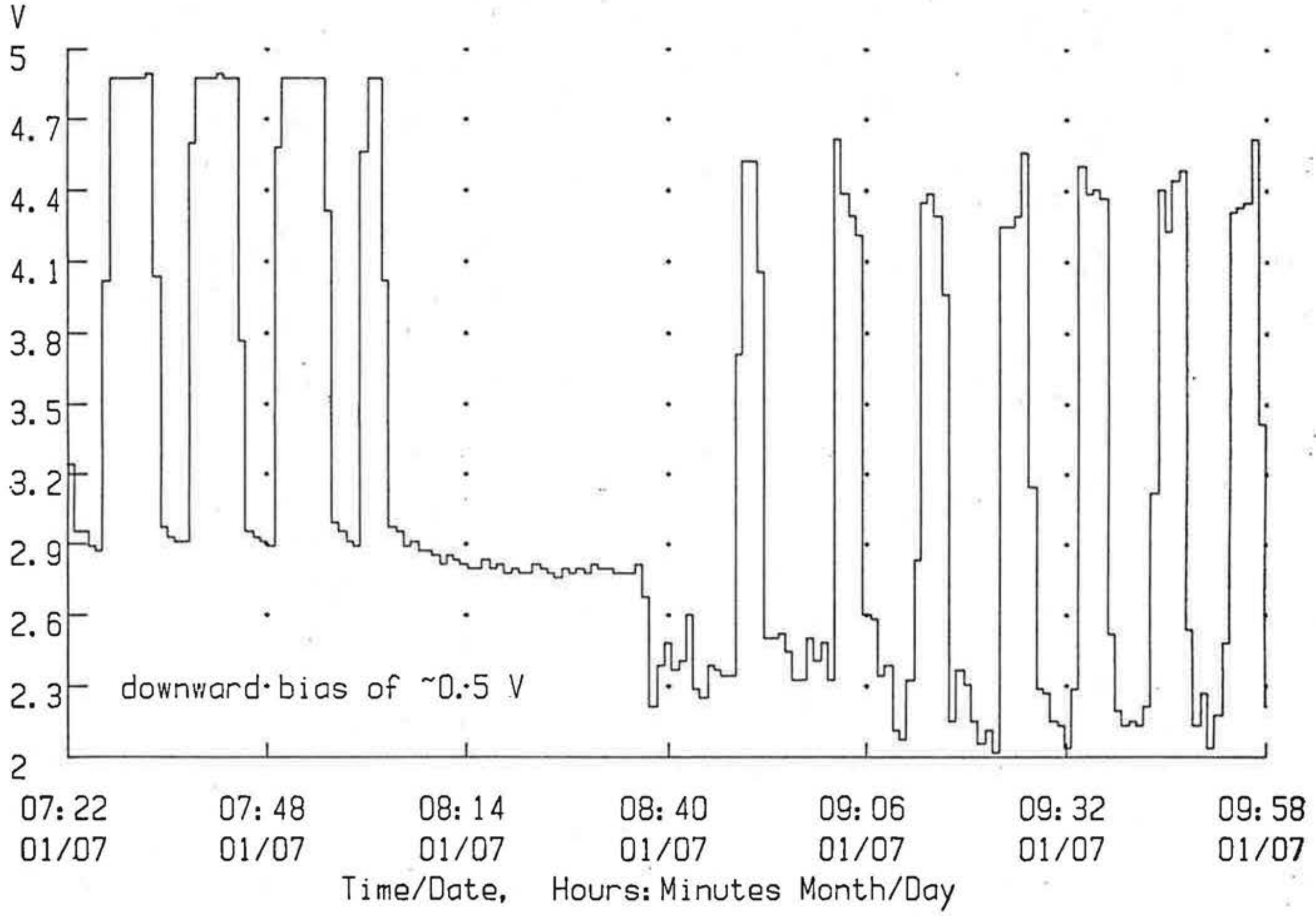
Oil Delivery Data

Table G.1 - Oil Deliveries

Location	Date	Quantity
Site 1		
	03-01-90	558L
	03-21-90	313L
	08-27-90	462L
	11-19-90	499L
	12-19-90	521L
	01-10-91	489L
	01-31-91	527L
	02-25-91	421L
	03-26-91	561L
Site 3		
	03-23-90	510L
	11-22-90	403L
	01-11-90	900L
	03-8-91	463L
Site 4		
	03-06-90	479L
	01-29-90	446L
	09-10-91	350L
	12-03--91	350L
	01-15-91	504L
Site 5		
	03-19-90	335L
	10-23-90	266L
	12-21-90	460L
	01-29-91	505L
	03-13-91	415L
	04-04-91	137L

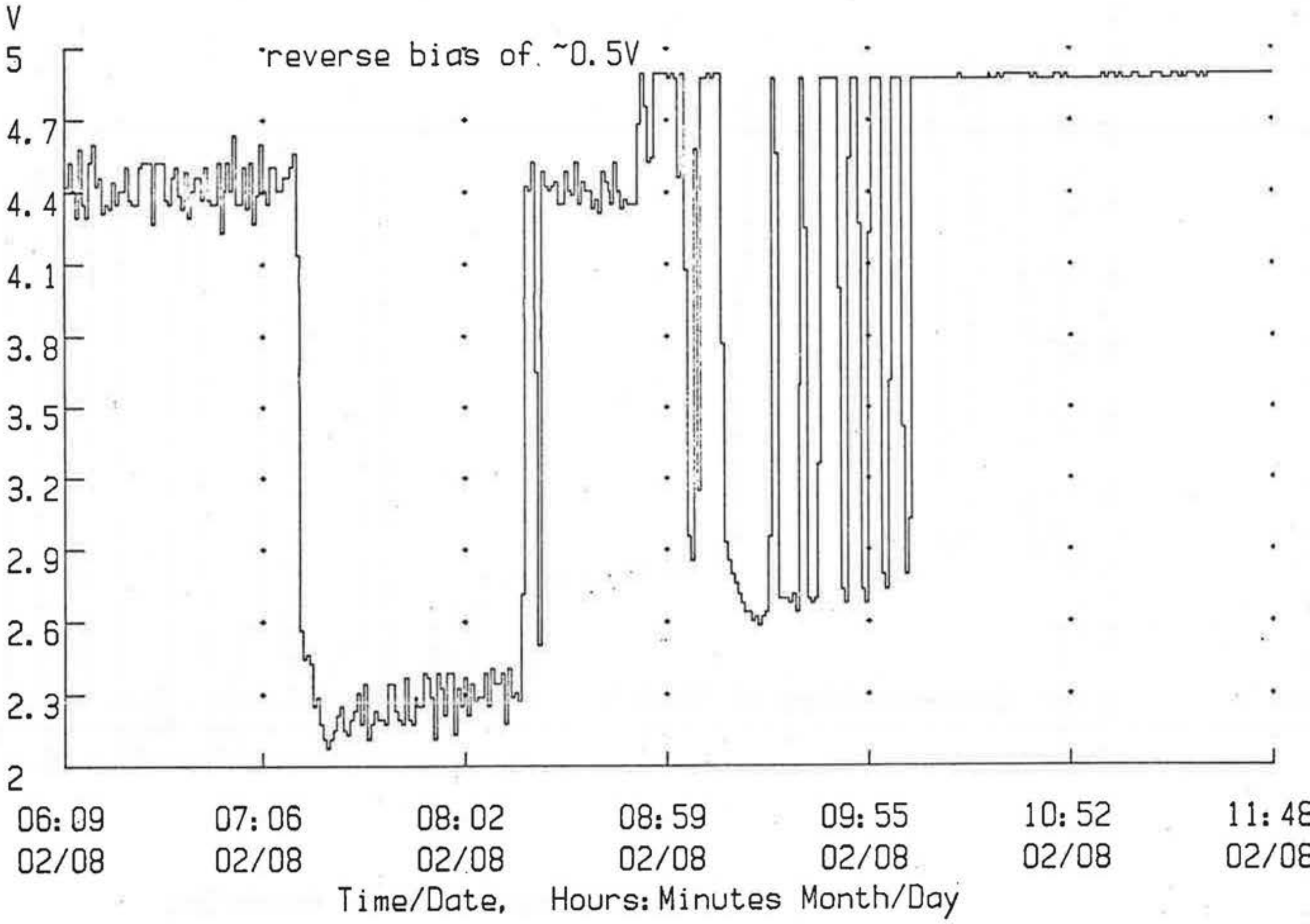
APPENDIX H

Site 1A Off-Cycle Voltage Anomalies

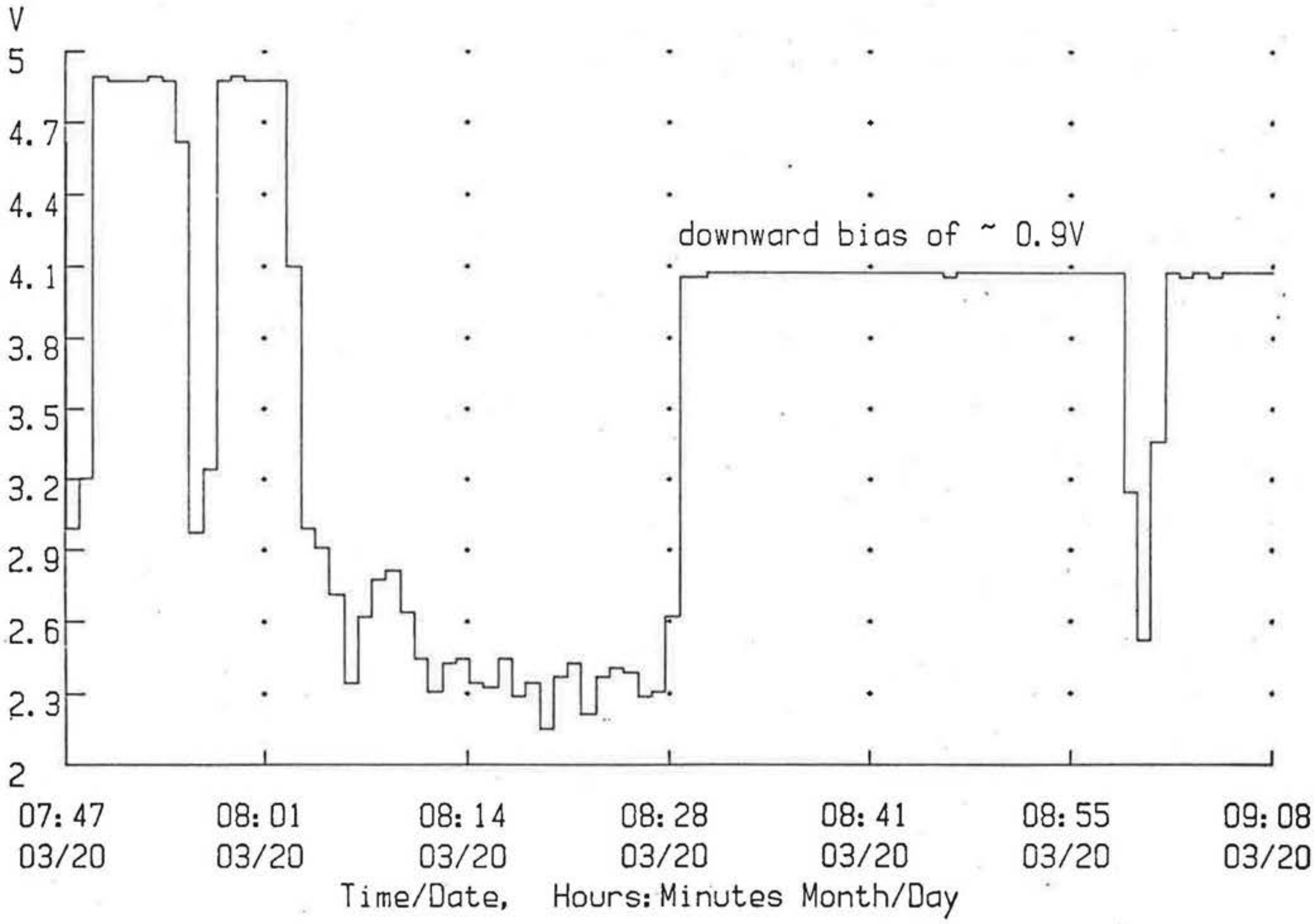


Site 1A First Off Cycle Voltage Anomaly

Figure H.1



Site 1A Second Off Cycle Voltage Anomaly
Figure H.2



Site 1A Third Off Cycle Voltage Anomaly

Figure H.3

APPENDIX I

FQI Field Setup Instructions

BROOKHAVEN NATIONAL LABORATORY
FLAME QUALITY INDICATOR
EXPERIMENTAL PROTOTYPE FIELD SETUP INSTRUCTIONS

The purpose of these instructions is to provide guidance for the installation and adjustment of the BNL Flame Quality Indicator in the field. These units are being made available on a very limited basis strictly for evaluation purposes. If a "red light" condition or unusual situation occurs please inform us as soon as possible. If possible we would like to be notified before any burner readjustment is done.

Step 1. Installation of the Sensor Cad Cell

The sensor cad cell to be used in these tests should be mounted on the burner fuel line and secured with plastic tie straps or the line clamp which come with the unit. The exact location is not very important but the sensor must be securely held. In our tests we installed the sensor about 3" back from the nozzle. We have observed some overheating of the sensor if installed too far forward in furnaces but not boilers. The sensor lead wires should be routed out of the burner through the junction box. Secure the leads as needed to ensure that they cannont interfere with the fan or electrodes.

Step 2. Installation of the FQI Indicator Box

The FQI indicator box can be installed anywhere it is convenient. Two power inputs are required to the box. These are both supplied with the wall transformers which come with the unit. One of these should be plugged into an outlet which is continuously powered. The plug from this transformer is then connected into the left jack on the FQI box as shown in the attatched figure. The other wall transformer must be powered only when the burner is on. To do this a female 110 V cord receptical and short cord are included with the FQI package. This should be wired with the burner motor. This wall transformer is then connected to the remaining power jack on the FQI box. The leads from the sensor cad cell are plugged into the banana jacks on the FQI box. Since the sensor cell is just a photoresistor, there is no polarity for the sensor. On the attatched drawing the two banana jacks are marked + and -. This polarity is imposed by the circuit and is not effected by the sensor cell leads.

Step 3. Adjustment of the Burner.

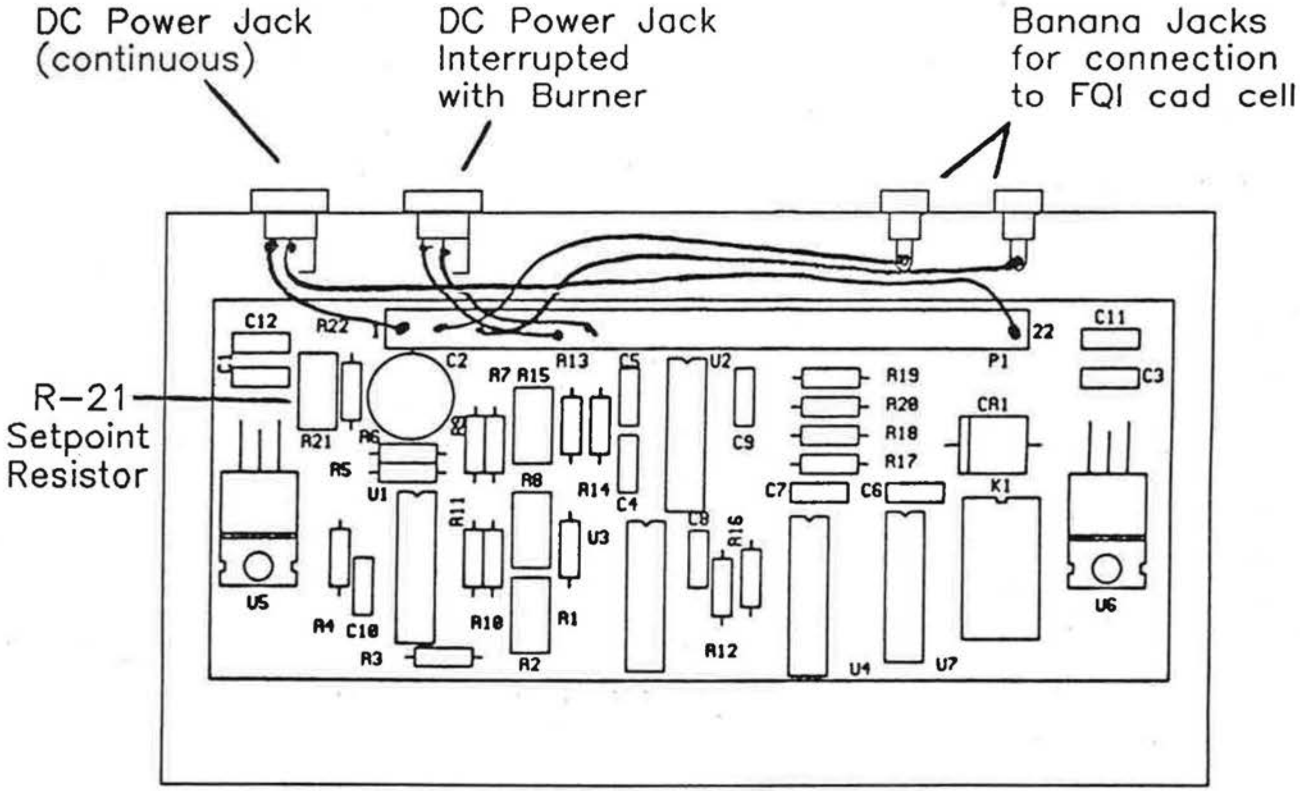
The burner excess air should be set as normal, using a smoke gun and CO_2 or oxygen meter. The FQI is intended as a tool for monitoring changes in performance over time after a routine service call. If the burner is operating to the satisfaction of the installer after the FQI has been installed it is not necessary to readjust it. The operation of the FQI is not dependent on the excess air setting chosen by the serviceman. For the purposes of this test project it is important, however, that accurate smoke and CO_2 or oxygen measurements be made after the burner air setting has been finalized and the set screw on the air shutter has been tightened.

Step 4. Adjustment of the FQI Setpoint.

After the burner has been adjusted (if necessary) the setpoint on the FQI must be adjusted. Open the FQI box and find the trim resistor "R-21". (See the attached sketch.) Using a digital voltmeter measure the voltage between the two sensor cell leads with their plugs inserted in the banana jacks and the burner running at or close to steady. A convenient place to make this voltage measurement is at the back of the banana jacks. Adjust the trim resistor R-21 until this voltage reads 2.50 V. When making this adjustment ensure that the system is fully warmed-up. The burner should run for at least two minutes before setting R-21.

Step 5. Monitoring

The FQI system installation is now complete and the burner can be used as normal. In normal operation, when the burner first starts a red light condition should be evident and the amber light should be off. After a brief warmup period the green light will come on and the red light will go off. At burner shutdown, the green light should remain on and the amber light should come on indicating a "hold" mode. The lights should remain in this condition until the beginning of the next firing cycle. If a red light condition persists through the firing cycle and into the off cycle, a problem has occured. The burner smoke number and CO_2 or oxygen should be checked as soon as possible in this case. Also please notify us at BNl (T. Butcher 516-282-7916 or Y. Celebi 516-282-4013).



DC Power Jack
(continuous)
DC Power Jack
Interrupted
with Burner
Banana Jacks
for connection
to FQI cad cell
R-21
Setpoint
Resistor

APPENDIX J

Oxygen Sensor Information

ZrO_2 oxygen sensor

C. FRANX

Conventional oxygen sensors are often bulky and expensive. The sensor described here is small, requires no reference gas and gives an output signal proportional to the oxygen partial pressure of the gas mixture to be measured. The sensor has an operating pressure range from a few mbar up to several bar. It can be used in gases up to 500 °C* flowing at up to 10 m/s. A feature of the sensor is that it can be operated in such a way that the temperature-dependence of the output signal is virtually zero, eliminating the need for temperature control circuitry in all but the most exacting applications. The circuitry needed to operate the sensor is simple. Calibration is straightforward and once this has been done, the oxygen content of a gas mixture can be measured to an accuracy better than 2 mbar. Table 1 (page 220) gives additional data on the sensor.

The sensor's wide operating temperature range and ruggedness make it ideal for:

- analysing the exhaust gases of industrial burners and car engines
- controlling furnace atmospheres
- high-efficiency self-controlling domestic oil-fired and gas-fired boilers.

In flue gas analysis, an advantage of an oxygen sensor is that it can be used both to measure and to control the efficiency of combustion.

* versions for use in gases up to 700 °C are available.

OPERATING PRINCIPLE OF EXISTING SENSORS

Most oxygen sensors make use of one of two properties of stabilised zirconium oxide, ZrO_2, namely:

- at high temperatures, ZrO_2 is a solid electrolyte for oxygen

and

- when the partial pressures on each side of a ZrO_2 disc are unequal, a voltage (Nernst voltage) is generated across it.

Oxygen sensors using Faraday's Law

At about 700 °C, stabilized zirconium oxide is a solid electrolyte for oxygen. A ZrO_2 disc with porous electrodes connected to a d.c. current source can therefore transport oxygen ions from the ambient through the disc, liberating at the anode an amount of oxygen proportional to the charge transported, which according to Faraday's First Law of Electrolysis is:

$$N = \frac{it}{zF}$$

where N is the number of moles of oxygen transported in t seconds by a constant current i, z is the ionic valence of oxygen (4) and F is the Faraday constant 96 487 C/mol.

In sensors using Faraday's Law, a ZrO_2 disc is attached to a porous disc of known leakage. The current needed to maintain a constant oxygen transport through the ZrO_2 disc is a measure of the surrounding oxygen pressure.

A disadvantage of this type of oxygen sensor is the requirement for very accurate oxygen dosing or a 'calibrated leak'. Furthermore, both dose rate and leakage are very dependent on temperature, the gases in the system and on the system cleanliness.

Oxygen sensors using Nernst's Law

Sensors that make use of Nernst's Law also employ a ZrO_2 disc. When the oxygen partial pressures on each side of the disc are unequal, the voltage generated across the disc, V_s, is proportional to the logarithm of the ratio of the two partial pressures:

$$V_s = \frac{RT}{zF} \ln (p_1/p_2)$$

where:

V_s is the voltage generated across the disc (the Nernst voltage)

R is the universal gas-constant (8,314 J/mol K)

T is the absolute temperature of the gas (K)

p_1 is the higher of the two oxygen partial pressures p_1 and p_2 on each side of the disc.

Sensors of this type require a reference pressure. Often atmospheric pressure is used as the reference, but variations in this and the relative humidity of the atmosphere limit the accuracy of this type of sensor.

A NEW OXYGEN SENSOR

The new sensor uses Faraday's First Law and Nernst's Law simultaneously, overcoming the drawbacks of conventional oxygen sensors. For example, the new sensor doesn't require a reference gas, accurate dosing or a calibrated leak.

CONSTRUCTION

As Figs 1 and 2 show, the sensor consists of two identical ZrO_2 discs with porous platinum electrodes and a platinum ring which enclose a small chamber. One disc is used as a reversible pump for oxygen ions by connecting it to a reversible constant-current source (the reason why the pump is reversible will become apparent presently). The other is used as an oxygen partial pressure sensor, generating a Nernst voltage proportional to the logarithm of the ratio of the oxygen partial pressure in the chamber to that outside.

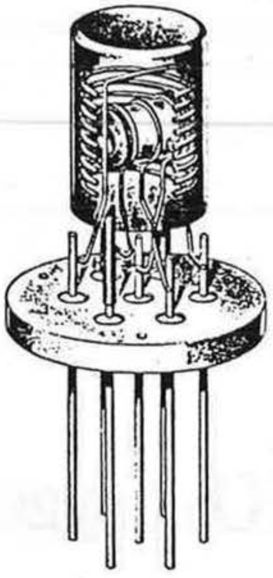


Fig.1 Cutaway view of the oxygen sensor. Two zirconium oxide discs with porous platinum electrodes attached to a platinum ring enclose a small chamber, see Fig.2. Surrounding the disc and ring assembly is a heating coil. Unlike other oxygen sensors, this sensor requires no reference gas or 'calibrated leak"

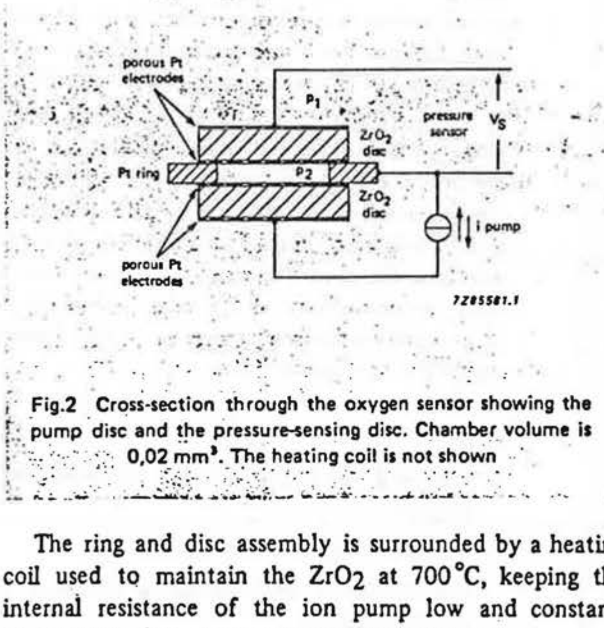


Fig.2 Cross-section through the oxygen sensor showing the pump disc and the pressure-sensing disc. Chamber volume is 0,02 mm³. The heating coil is not shown

The ring and disc assembly is surrounded by a heating coil used to maintain the ZrO_2 at 700 °C, keeping the internal resistance of the ion pump low and constant, irrespective of the surrounding gas temperature.

The platinum electrodes catalyse the ionization and recombination of oxygen in both the gas mixture whose pressure is to be measured and the chamber.

A feature of the sensor is its small size, just 17,5 mm long (excluding leads) and its maximum width, less than 10 mm. The mass of the sensor is 1,2 g.

OPERATION

Assume that the sensor is at operating temperature and that the oxygen partial pressure in the chamber is $p_{2\,high}$ and that of the gas to be measured is p_1. The ratio of these pressures as a function of the Nernst voltage V_1 generated across the sensing disc is from Nernst's Law:

$$p_{2\,high}/p_1 = \exp(-4FV_1/RT) = c_1 \text{ say.} \qquad (1)$$

The constant-current ion pump is now turned on so as to pump oxygen out of the chamber. The amount of oxygen transported (N moles) is proportional to the charge supplied by the pump (Faraday's First Law):

$$N = \frac{it}{4F} \qquad (2)$$

The fall in pressure in the chamber (volume v) due to pumping out N moles of oxygen at temperature T is:

$$(p_{2\,high} - p_{2\,low}) = RTN/v \text{ (from the Gas Laws)}$$
$$= RTit/4Fv \text{ from Eqn. (2).} \qquad (3)$$

And the ratio of the pressure in the chamber, $p_{2\,low}$, to the unknown pressure p_1 is indicated by the Nernst voltage V_2 ($V_2 > V_1$) where:

$$p_{2\,low}/p_1 = \exp(-4FV_2/RT) = c_2 \text{ say.} \qquad (4)$$

From equations (1), (3) and (4):

$$p_1 = \frac{RT}{4Fv\,(c_1 - c_2)}\ it. \qquad (5)$$

Equation (5) shows that the unknown oxygen partial pressure p_1 is proportional to the charge (it) transported by the pump in time t. For a constant pump current and a constant temperature, p_1 is simply proportional to the time to pump between any two pressures $p_{2\,high}$ and $p_{2\,low}$, a parameter that can be measured easily. The temperature dependence of c_1 and c_2 can be compensated by appropriate choice of operating conditions.

One could continue to evacuate the chamber, however the minimum allowable chamber pressure will eventually be reached. A suitable method of operation which provides a continuous output is to operate the sensor between two reference voltages, reversing the pump each time the output of the sensor reaches one of the references. In theory, any two voltages can be used, as defined above, because from these and a knowledge of the charge transported, the partial pressure can be calculated, see Eqn. (5). The choice of references is described in the next section.

Suppose the constant-current ion pump is reversed when the output voltage of the sensor is V_2, see Fig.3. The pump transports oxygen into the chamber, increasing the pressure there and causing V_s to decrease. When V_s falls to V_1 say, the pump is reversed again and the cycle repeated, generating a voltage waveform whose period, t_p is proportional to the unknown oxygen partial pressure p_1 to be measured.

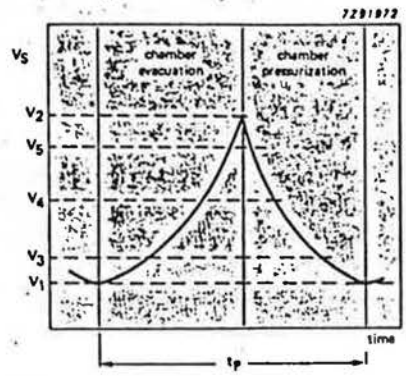


Fig.3 Nernst voltage as a function of time for a constant pump current and constant ambient temperature. The period of the Nernst voltage generated (t_p, set by levels V_1 and V_2) is proportional to the pressure surrounding the sensor. In practice, use is made of three additional preset voltages V_3, V_4 and V_5 in the measurement of the period. This is to overcome the effect of an electric double layer formed at the platinum-electrolyte interface

In this description, oxygen was pumped out of the chamber. Clearly, the same relationship between p_1 and the pumping time can be derived if oxygen is pumped into the chamber.

PRACTICAL CONSIDERATIONS

Let's now assign values to V_1 and V_2 at which the ion pump is reversed. In theory, any two values can be used, in practice, V_1 and V_2 are chosen:

- to eliminate the effect of an electric double layer in the ZrO_2 discs formed by space charges
- for the best response time for the application
- to eliminate the temperature-dependence of Nernst's Law and the Gas Laws.

Compensating for the electric double layer

Not all the charge supplied by the current source contributes to a pressure change in the chamber; some is absorbed by an electric double layer formed at the platinum-electrolyte interface as the current source is reversed. The effect of the double layer is particularly noticeable:

- at extremes of pressure
- near the pump reversal points.

At extremes of pressure, substantially more charge is needed to change the pressure in the chamber, reducing the accuracy of the sensor. To compensate for this effect, the working chamber pressure range should be about 1% to 10% of the ambient pressure.

To overcome the influence of the double layer near the pump reversal points, pumping times should be measured, not between the reversal points, but for Nernst voltages well away from them. For practical reasons, two measurements are made each compression cycle and each evacuation cycle, between voltages V_3 and V_4, and V_4 and V_5, see Fig.3. As a guideline, V_1 should be about 90% of V_3; V_2 about 110% of V_5. It can be shown (Ref.1) that the effect of the electric double layer can be compensated when V_4 is approximately the mean of V_3 and V_5.

Response time

When operated as described, the response time of the sensor is about one period of V_s, see Table 1. Therefore, V_1 and V_2 should be close to each other for a fast response when measuring high pressures. This will not affect the accuracy of the sensor significantly, because the effect of offset variations at high pressures is small.

TABLE 1
Brief data on the oxygen sensor

ambient gas	virtually all exhaust gases of combustion, and many gas mixtures[1]
ambient gas temperature range	0 to +500 °C
ambient gas flow rate	up to 10 m/s
measuring range of oxygen partial pressures	1 mbar to several bar
accuracy	±2 mbar[2]
calibration	in air; no reference gas needed
sensor output voltage V_s	$0{,}0495T \log (p_1/p_2)$ mV[3]
operating output voltage V_s	25 to 110 mV range (typ.)
response time	one period of V_s
period of V_s	
at 200 mbar	1 s (typ.)
at 20 mbar	100 ms (typ.)
warming-up time	45 s (typ.)
supplies	
oxygen pump	35 µA (typ.) constant-current source
heater, in still gas	1,8 A; 10 W (typ.)

[1]) Halides, lead and particulate matter can degrade performance over long periods of operation. Reducing atmospheres may in time impair the catalytic effect of the platinum electrodes.

[2]) with OMA21 measuring assembly.

[3]) T is the sensor temperature in K; p_1 is the higher of the pressures p_1 and p_2 on each side of the pressure-sensing disc.

Compensating for temperature-dependence

That the period t_p of the Nernst voltage is temperature-dependent can be seen in Eqn.(5). However, the temperature-dependence is such that under certain operating conditions, the combined temperature-dependence of Nernst's Law and the Gas Laws is virtually zero, see Fig.4. A similar effect can be observed for different voltage pairs V_1 and V_2. In Ref.1, values of V_1 and V_2 that correspond to a zero temperature coefficient are given.

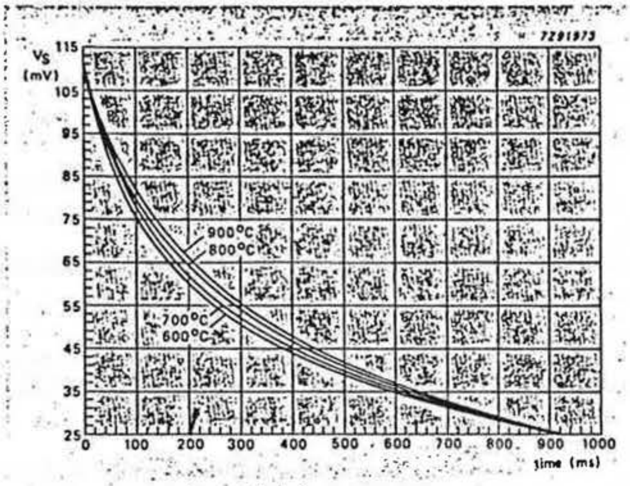


Fig.4 Reversing the sensor's current pump at Nernst voltages of about 25 mV and 115 mV largely eliminates the temperature-dependence of the period of the Nernst voltage generated. Refinement of this approach gives zero temperature coefficient. i = 40 µA; p_1 = 208 mbar

Table 2 lists values of V_3, V_4 and V_5 that will give a zero temperature coefficient (to a 1st-order approximation) and a linear response. The values are for a sensor operating at 750 °C, a pumping current of 40 µA, an equilibrium pressure of 0,316 mbar and $V_4 = (V_3 + V_5)/2$. The cycle time, t_p, is for an oxygen pressure of 50 mbar. The remaining relative error in pressure readings due to temperature is plotted in Fig.5 for 700 °C, 750 °C and 800 °C.

TABLE 2
Output voltages V_3, V_4 and V_5 for a linear output and zero temperature coefficient

V_3 (mV)	V_4 (mV)	V_5 (mV)	t_p (ms)	Relative error in % at 650 °C	750 °C	850 °C
60,38	66,38	72,38	125	−1,23	0	−1,53
57,72	66,72	75,72	163	−1,23	0	−1,53
54,38	67,38	80,38	214	−1,22	0	−1,51
51,28	68,28	85,28	266	−1,20	0	−1,49
48,40	69,40	90,40	317	−1,19	0	−1,47
45,11	71,11	97,11	382	−1,16	0	−1,43
42,15	73,15	104,15	447	−1,14	0	−1,39
39,50	75,50	111,50	511	−1,12	0	−1,34
36,71	78,71	120,71	586	−1,10	0	−1,27

REFERENCES

1. FRANX, C. 1985. A dynamic oxygen sensor with zero temperature coefficient. Sensors and Actuators 7, 263-270.
2. ZrO_2 oxygen sensor. Elcoma Technical Publication, ordering code 9398 021 60011.
3. OSU21: Dynamic oxygen sensor unit.
   Ordering code 9398 328 90011.
   This leaflet introduces the sensor, its power supply and measuring circuitry.