FURNACE COMBUSTION SENSOR TEST RESULTS

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EXECUTIVE SUMMARY

In fiscal year 2001, the U.S. Consumer Product Safety Commission (CPSC) staff conducted an evaluation of combustion sensors. The objectives of this evaluation were to determine the technical feasibility of using combustion sensing technology to detect concentrations of carbon monoxide (CO) in the flue passageways of a gas furnace that exceed the 400 ppm (air free) required by the American National Standard for Gas-Fired Central Furnaces (ANSI Z21.47), and to shut the furnace down in response. The goal of this effort is to develop a means to reduce the CO exposure risk posed to consumers by malfunctioning gas-fired central furnaces.

Samples of two different combustion sensor technologies were evaluated for their performance and application to a high-efficiency gas furnace. Characterization tests were performed to determine sensor response to various concentrations of CO. The parameters of interest were sensor output voltage and resistance, either of which could be used to send a shutoff signal to the furnace. Furnace shutoff tests were performed to determine sensor performance in an operating furnace with elevated flue concentrations of CO. A total of four sensor samples were tested; two Mixed Metal Oxide Semiconductor (MMOS) sensors and two Catalytic sensors.

During the characterization tests, each sensor type was mounted in a 100-ft^3 chamber and exposed to concentrations of CO within the response range specified by the manufacturer. Each sensor exhibited a linear response to chamber CO concentrations. The MMOS sensors were exposed to chamber CO concentrations ranging from 70 to 400 parts per million (ppm). At 400 ppm, the average voltage output of the two samples was 56 mV. This voltage was used as the setpoint during the Furnace Shutoff tests for the MMOS sensors. The Catalytic sensors were exposed to chamber concentrations ranging from 400 to 3000 ppm. At 400 ppm, the average voltage output of the Catalytic sensors was 1.16 V, which was used as the setpoint during the Furnace Shutoff tests for the Catalytic sensors.

During the Furnace Shutoff Tests, each sensor was mounted in the venting system of a high-efficiency gas furnace. The furnace manifold pressure was adjusted to its maximum spring setting of approximately 5.2 inches water column and the vent pipe blocked to approximately 90 percent of its cross-sectional area in order to produce CO concentrations in excess of the ANSI Z21.47 standard of 400 ppm (air free). Each sensor was electrically connected to the furnace thermostat terminal via a shutoff circuit. The shutoff circuit was designed to shutdown the furnace when the sensor output voltage exceeded a set value corresponding to 400 ppm of CO.

Each sensor was tested in the above arrangement within the furnace for durations of two, five, and eight minutes. These durations were chosen in order to evaluate sensor performance during a variety of time spans that were similar to shutoff time requirements found in the furnace standard (ANSI Z21.47). For each test, the durations were set by adjustment of a control knob within the shutoff circuit to the furnace. With the shutoff circuit adjusted to the setpoint voltage determined for each type of sensor, each sensor shut off the furnace within the established time. Sensors A and B shut down the furnace at times ranging from 1:49 to 2:19 minutes during the two-minute shutoff test; 4:16 to 4:51 minutes during the five-minute shutoff tests; and 7:57 to 7:59 minutes for the eight-minute shutoff tests, respectively. At the setpoint established for the Catalytic sensors, Sensors C and D shut down the furnace at times ranging from 2:01 to 2:14 minutes during the two-minute shutoff tests; 4:29 to 4:34 minutes during the five-minute shutoff tests; and 7:58 to 8:54 during the eight-minute shutoff tests. When the CO level and sensor voltage remained below the setpoint, the furnace continued to operate.

The test results demonstrated that it is technically feasible to integrate sensors into a gas furnace and provide a means to shut the furnace down when the flue concentrations of CO exceed the requirements of the ANSI standard. The sensor technologies tested are promising and should be evaluated further by the furnace industry as a means to eliminate CO exposure hazards associated with improperly adjusted or malfunctioning furnaces with compromised vent systems and flue passageways. Staff believes these technologies could also be considered for use in other residential gas appliance applications such as boilers, wall furnaces, and vented space heaters.

INTRODUCTION

Background

Carbon monoxide (CO) is a by-product of the incomplete combustion of hydrocarbon fuels such as natural gas, propane, gasoline, and oil. Incomplete combustion from gas-fired appliances, such as furnaces, boilers, and wall heaters, can occur as a result of an improper fuel-air mixture to the appliance burner, quenching of the burner flame, or over-firing of the appliance above its design energy input rate. An improper fuel-air mixture can occur as a result of a reduction or stagnation of the primary and secondary air supplied to the burner (such as might occur when an appliance vent pipe is partially blocked or when the appliance is installed in an undersized room). An improper fuel-air mixture can also occur as a result of an excessive gas manifold pressure. When the flue passageways and venting systems of appliances are intact, CO that results from incomplete combustion is safely vented to the outdoors. However, CO can enter the living space and create a hazard to consumers when a leakage path is created by a compromised flue passageway or venting system.

In 1986, the U.S. Consumer Product Safety Commission (CPSC) staff made recommendations to the American National Standards Institute (ANSI)/Canadian Gas Association (CGA) Z21.47 Gas-Fired Central Furnace Subcommittee to add requirements to the central furnace standard to protect consumers from CO exposure hazards associated with blocked and disconnected vents. The subcommittee adopted coverage for completely blocked vents and disconnected vents on draft hood-equipped furnaces in 1987. However, the requirements addressing disconnected vents were withdrawn in 1989.

In 1996, CPSC staff proposed that the furnace subcommittee add requirements that addressed partially blocked and disconnected vents to protect consumers from CO exposure hazards associated with these vent conditions. To support this proposal staff conducted a review of CPSC In-Depth Investigations (IDIs) involving disconnected furnace vents. The review results were summarized and provided to the subcommittee in 1997. The subcommittee tasked its Technical Working Group (TWG) with reviewing the CPSC summary and IDIs and developing a recommendation on a course of action for the subcommittee to pursue. Based on the IDI review, the TWG voted to develop a two-part recommendation to forward to the subcommittee. The first part of the TWG recommendation called on the subcommittee to engage the Gas Research Institute (GRI) to:

1. Develop an information and education program to warn furnace installers and consumers of the importance of proper installation and maintenance of furnaces and their vent systems; and

2. Assess technology capable of shutting off a furnace if the vent system becomes disconnected.

The second part of the TWG recommendation was that the subcommittee adopt more stringent mechanical integrity requirements for vent systems in the furnace standard. Both of these recommendations were approved by the TWG and forwarded to the furnace subcommittee.

At its September 1997 meeting, the furnace subcommittee voted on and adopted the TWG recommendations. A draft work statement developed by the TWG was submitted to GRI in December 1997. In the final version of the work statement the technology assessment task had been replaced with a task to conduct a root cause analysis of the CPSC IDIs.

In fiscal year 1999, CPSC staff conducted a furnace test program to support the continued development of performance standards to address the hazard. The goal of the test program was to determine the extent of the CO exposure hazard posed to consumers from the spillage of combustion products into a living space from a disconnected or partially blocked furnace vent. The test program consisted of testing five different furnaces under controlled conditions and measuring the amount of CO that accumulated in a room when the vent pipe was partially blocked, totally blocked, or disconnected. The test results were used to model indoor air concentrations and assess health effects.

Based on the test and analytical results, the CPSC staff proposed to the furnace subcommittee that the following performance requirements be added to the furnace standard:

(1) Require the furnace to shut off in the event the vent pipe becomes disconnected;
(2) Require the furnace to shut off in the event the vent pipe becomes totally or partially blocked; or
(3) Require a means to prevent furnace CO emissions from exceeding the standard limits once installed in the field; or
(4) Require a means, once installed in the field, to shut down the furnace if CO emissions exceed the standard limits.

Current CPSC Test Activities

Appliance performance standards often require that a physical mechanism be integrated into a product design in order to achieve the desired performance. The physical mechanism must be technically feasible and economically viable. In fiscal year 2001, CPSC staff tested and evaluated combustion sensor technologies to assess the technical means of:

(1) Preventing furnace CO emissions from exceeding the standard limits once installed in the field; or
(2) Causing a furnace to shut down when CO emissions exceed the standard limits.

CPSC staff conducted patent and Internet searches to identify relevant technology. As a result of these searches, CPSC staff identified and acquired samples of two different sensor technologies for testing.

In March 2001, CPSC staff began a test activity to determine if either of these sensor technologies, when located in the flue passageways of a furnace, could:

1. Detect the presence of elevated levels of CO or other gases related to the incomplete combustion of natural gas; and
2. Send a shutoff signal to the furnace control system.

This report provides a discussion of this activity and the test results.

SENSOR OPERATION AND SETUP

Principles of Operation

MMOS Sensor

One of the sensor technologies tested was a P-type, Mixed Metal Oxide Semiconductor (MMOS) with a Chromium Titanium Oxide sensing element. These sensors are currently used in residential carbon monoxide (CO) alarm applications and are certified to Underwriters Laboratories (UL) 2034 "Standard for Single and Multiple Station Carbon Monoxide Alarms" as well as British Standard (BS) 7860 "Specification for carbon monoxide detectors (electrical) for domestic use." The manufacturer indicates that the typical lifetime for these units exceeds 5 years. Despite its original application, the manufacturer indicates that the MMOS sensors are suitable for use in the humid, high temperature environment of a gas boiler or furnace flue. The preliminary price projections for the sensor equipped with a heater driver board for flue gas application range from approximately $13.00 to $25.00 per unit for quantities ranging from 1 million to 10 thousand units.

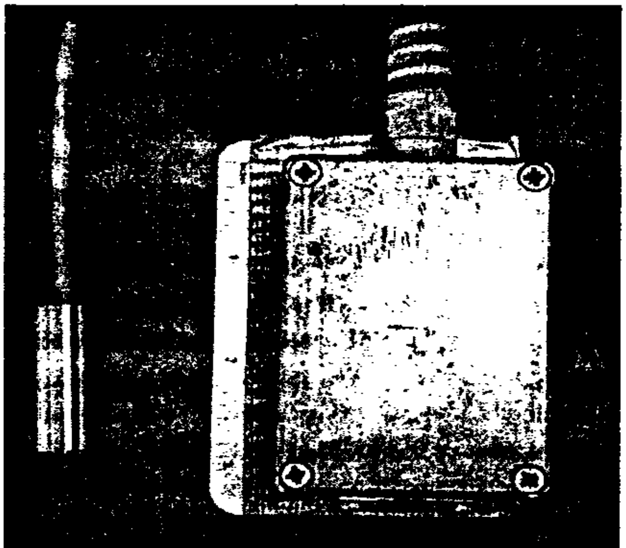


Figure 1: MMOS Sensor and Heater Driver Board

The sensor body is made of stainless steel and is cylindrical in shape, with a 0.591-inch diameter and a length of 1.389 inches. The sensing element is contained in the body and is connected to a heater driver board by 4-conductor wire. The entire assembly is shown in Figure 1. (Refer to Appendix B for sensor specifications).

The sensor is equipped with a heater driver board designed to maintain the sensing element at its operating temperature of 400°C. The sensor heater board requires a supply voltage of 7 volts DC for proper operation. The sensor is rated for a maximum output voltage of 100 millivolts (mV). In accordance with the manufacturer's instructions a 100 kilo-ohm (kΩ) resistor was placed in series with the sensor output terminals to ensure that this voltage was not exceeded.

The sensor resistance increases when exposed to an increasing concentration of carbon monoxide. The relationship between the sensor resistance and voltage and the concentration of the measured gas (CO) can be described by the equations:

$$R_g = R_o * (1+k(C)^{1/2})$$
$$V_g = V_o * (1+k(C)^{1/2})$$

Where:

R_g = resistance of sensor material in CO
R_o = resistance of sensor material at zero ppm CO
V_g = voltage of sensor material in CO
V_o = voltage of sensor material at zero ppm CO
k = constant for particular sensor when exposed to CO

C = Carbon monoxide concentration in ppm

Catalytic Sensor

The second type of sensor technology evaluated in this test program was a catalytic type that was originally designed to detect incomplete combustion in the flue passageways of domestic gas boilers and water heaters. The sensor was developed approximately eight years ago and has been on the market for two years in Japan. Although not required to be certified to a separate performance standard, the sensor must meet the standards of its end-use application. The manufacturer has indicated that at the end of 2002 gas water heaters and boilers in Japan will be required to incorporate "incomplete combustion sensors" in the flue to shutoff the appliance in the event it generates CO concentrations in excess of 300 ppm in the equipment room. The relevant product standard is Japanese Standards Association (JIS) S 2109, "Gas burning water heaters for domestic use." The test standard is Japanese Gas Appliances Testing Institute (JIA) G 024-97, "Test Standard for Incomplete Combustion Preventing Functions, Combustion equipment with Compulsory Ventilation System." The cost of the sensor equipped with a heater driver board ranges from approximately $6.00 to $13.00 per unit for quantities ranging from 500,000 to 10,000 units.

The sensor body is made of stainless steel and is cylindrical in shape, with a 0.582-inch diameter and a length of 0.839 inches. The sensing element is contained in the body and is connected to the heater driver board by 3-conductor, shielded wire. The entire assembly is shown in Figure 2. (Refer to Appendix B for sensor specifications).

The catalytic sensor contains two compartments. One compartment contains the sensing element and is open to the atmosphere and the gas being detected. The other compartment contains a compensator and is closed to the atmosphere and the gas being detected. The purpose of the compensator is to provide a reference point that will allow a measurable differential resistance to be created in the presence of the gas being measured.

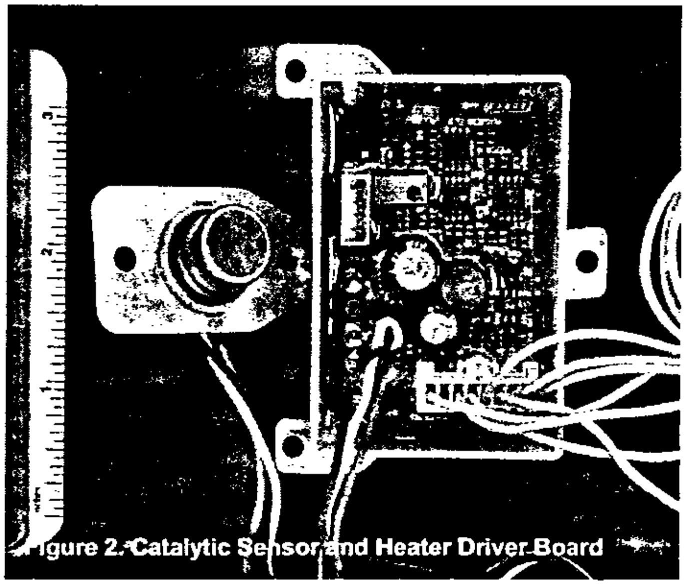


Figure 2. Catalytic Sensor and Heater Driver Board

The sensing element and the compensator are electrically connected through a coil. The sensing element is a platinum filament and is covered with a catalyst that oxidizes combustible gases. The sensing element is heated via the heater driver board to an operating temperature between 300° and 400° C. At these temperatures, oxidation of the gas being measured occurs when it contacts the sensing element, causing an increase in the sensing element temperature. The resultant temperature rise is transmitted to the sensor platinum heater coil, which results in an increase in resistance of the sensing element.

Because it is isolated from the gas being measured, oxidation does not occur on the compensator, and its electrical resistance remains unchanged. The difference in resistance between the sensing element and the compensator results in a voltage drop between the two components. The relationship between the sensor resistance and voltage and the concentration of the measured gas (CO) is described by the equation:

$$dV=(dR*V)/4R$$

Where:

dV = Output voltage
R = Resistance of sensor in clean air
V = Bridge supply voltage
dR = Resistance change of heater for the measured gas

And $dR = k*a*m*Q/C$

Where:

k = a constant
a = Thermal coefficient of heater material
m = Gas concentration
Q = Molecular heat of gas
C = Thermal capacity of sensor

The catalytic sensor is equipped with a heater driver board, which is necessary to maintain the sensing element within its operating temperature range of 300°C to 400°C. The heater driver board requires a supply voltage of 12 volts DC to operate properly, while the sensing element requires a supply voltage of 5 volts DC.

TEST RESULTS AND DISCUSSION

Sensor Characterization Tests

Test Chamber and Data Acquisition

Tests were conducted on each of the MMOS and Catalytic sensors to quantify their response when exposed to known concentrations of carbon monoxide. The tests were conducted inside a chamber with a 100-ft^3 interior volume. Each sensor and heater driver board was mounted on a metal beam suspended at the approximate center (horizontally and vertically) of the test chamber. The chamber was constructed from sheets of fire retardant boards supported by metal framework. To obtain an air exchange rate of approximately zero, the supply air inlet was sealed, while a valve located in the exhaust vent was closed, forcing all of the exhausted air to be recirculated back into the chamber. The chamber is normally used for combustion testing of gas appliances with input rates ranging from 7,000 to 15,000 Btu/hr. A fin and tube heat exchanger is used to remove heat from the chamber during combustion testing. The fans used to move air over the cooling coils of the heat exchanger also mixed the air within the chamber, thus establishing a well-mixed environment within the chamber. A full view of the Characterization Test setup is shown in Figure 3.

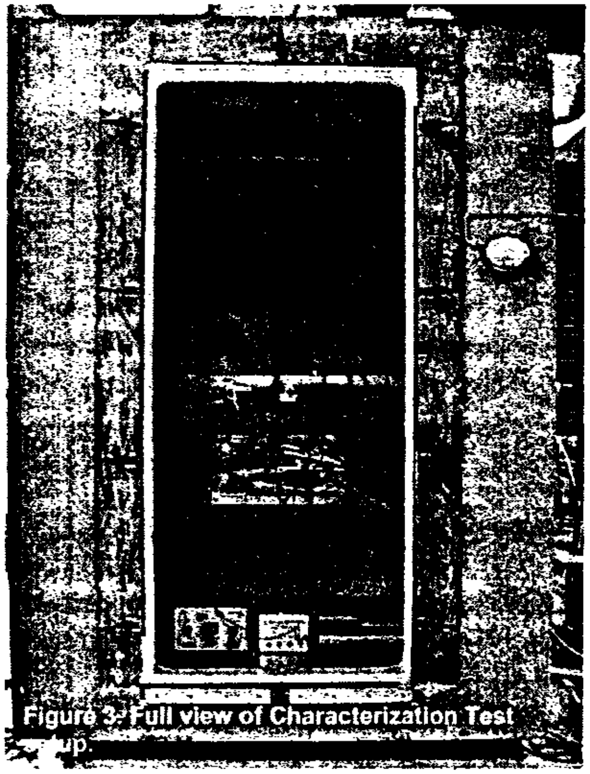


Figure 3: Full view of Characterization Test Set-up.

Gas samples were obtained from six equal length sample lines located within the chamber. These six sample lines were joined in a common manifold from which a single mixed gas sample was sent to a series of gas analyzers. The carbon monoxide (CO) concentrations were measured with non-dispersive infrared (NDIR) gas analyzers (Rosemount, Model 880). The oxygen (O_2) concentrations were measured with a paramagnetic analyzer (Rosemount, Model 755). The air temperature in the chamber was measured at the inlet of each sample tube in the chamber using K-type thermocouples (Omega).

A data acquisition system was used to record the sensor performance data and gas concentrations. The system consisted of a personal computer, data acquisition interface hardware (Keithley Instruments), and data acquisition software (LABTECH® CONTROL). Gas concentrations and temperatures were recorded every second by the data acquisition program. The program converted the voltage output from the gas analyzers into the appropriate concentration units (percent or parts per million). Pure CO was introduced into the chamber and controlled at concentrations ranging from 70 to 3000 ppm, depending on the response range of the sensor. The resultant output voltages at these concentrations were recorded for each sensor. Since the sensors operate under different principles, the test results will be discussed separately.

MMOS Sensors (Sensors A and B)

The manufacturer specified the response range for the MMOS sensors to be from 70 to 400 ppm of CO. Carbon monoxide concentrations of 400, 300, 200, 100, and 70 ppm were injected into the chamber to determine the resultant sensor voltage and to provide a well-defined response curve. Sensor voltages were also recorded in clean air (zero ppm CO) and in concentrations of

CO between 0 and 59 ppm. Because the data acquisition hardware used for testing does not directly measure resistance, the sensor output voltages, V_g, were measured and used to calculate the sensor resistance, R_g, using the equation:

$$R_g=(R_{known}*V_g)/(V_{known}-V_g)$$

Where:

R_{known} = Resistance value of resistor placed in series with the sensor = 100kOhms
V_{known} = Voltage across the known resistor, R_{known} = 100mVolts

The results of the response tests are presented in Table 1 and Graphs 1 and 2. The data shows there was an overlap of measured voltage and calculated resistance between successive test concentrations of CO. In all cases, the minimum voltages and resistances at a given CO concentration fell within the maximum and minimum values of the next lower CO concentration. For instance, the minimum voltage and resistance for Sensor A at a CO concentration of 400 ppm were 53.7 mV and 116.0 kΩ, respectively. At a concentration of 300 ppm, the measured voltage ranged from a maximum of 58.6 mV to a minimum of 48.8 mV, while the calculated resistance ranged from a maximum of 141.5 kΩ to a minimum of 95.3 kΩ. The data also revealed occasions when the maximum or minimum voltages and resistances at successive CO concentrations were the same. For instance, at CO concentrations of 300 and 200 ppm (Sensor B), the maximum voltage and resistance at each concentration was 58.6 mV and 141.5 kΩ, respectively. At CO concentrations of 70 and 100 ppm (Sensor B), the minimum voltage and resistance at each concentration was 39.1 mV and 64.2 kΩ, respectively.

TABLE 1: CHARACTERIZATION TESTS FOR MMOS SENSORS

Chamber CO Concentration (ppm)		**Sensor A**					
		Voltage (mV)			**Resistance (kΩ)**		
Nominal	**Average**	**Max.**	**Min.**	**Ave.**	**Max.**	**Min.**	**Ave.**
0	0	43.9	34.2	38.5	78.3	52.0	62.8
70	75	48.8	39.1	45.3	95.3	64.2	83.1
100	106	53.7	43.9	47.6	116.0	78.3	91.3
200	205	58.6	43.9	51.7	141.5	78.3	107.7
300	305	58.6	48.8	54.9	141.5	95.3	122.4
400	404	63.5	53.7	57.8	174.0	116.0	137.8

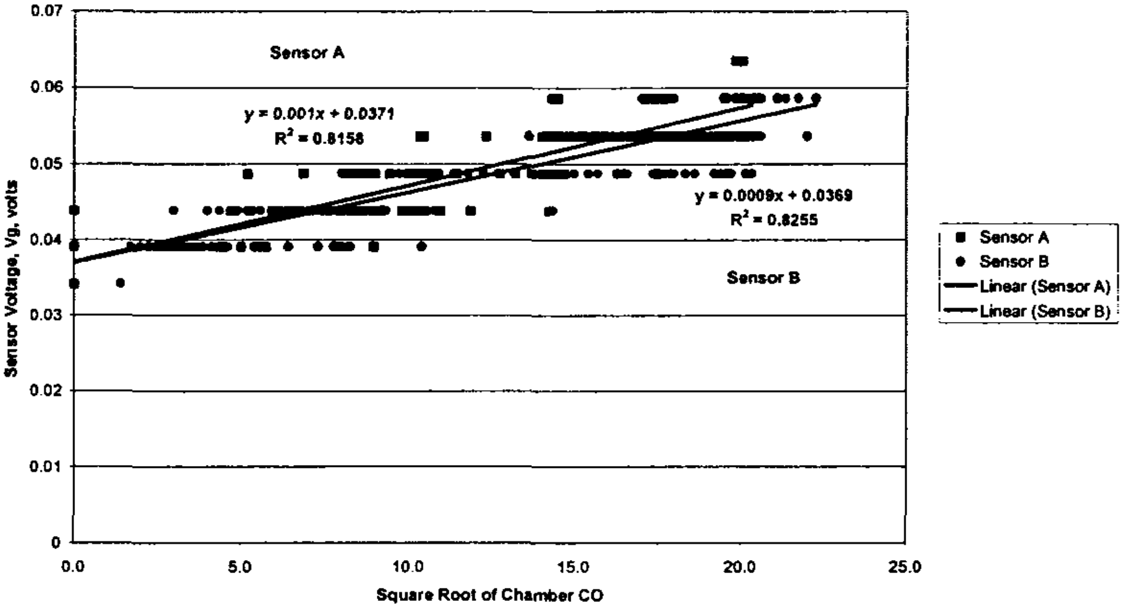
Chamber CO Concentration (ppm)		**Sensor B**					
		Voltage (mV)			**Resistance (kΩ)**		
Nominal	**Average**	**Max.**	**Min.**	**Ave.**	**Max.**	**Min.**	**Ave.**
0	0	43.9	34.2	37.6	78.3	52.0	60.5
70	66	48.8	39.1	43.7	95.3	64.2	77.9
100	105	48.8	39.1	47.1	95.3	64.2	89.4
200	206	58.6	43.9	50.8	141.5	78.3	104.1
300	309	58.6	48.8	53.8	141.5	95.3	116.9
400	405	63.5	48.8	56.0	174.0	95.3	128.1

Closer scrutiny of the data indicates that the overlapping of values was not consistent and occurred infrequently in the form of spikes or troughs and is best described as "noise." CPSC staff believes this "noise" was caused by variables such as interference from electromagnetic fields that exist in the test setup, the length of the signal wires to the data acquisition system, and the fact that the sensor output voltages were in the millivolt range and were not filtered or processed. Such variables would likely be eliminated in sensors packaged for and deployed in gas appliances.

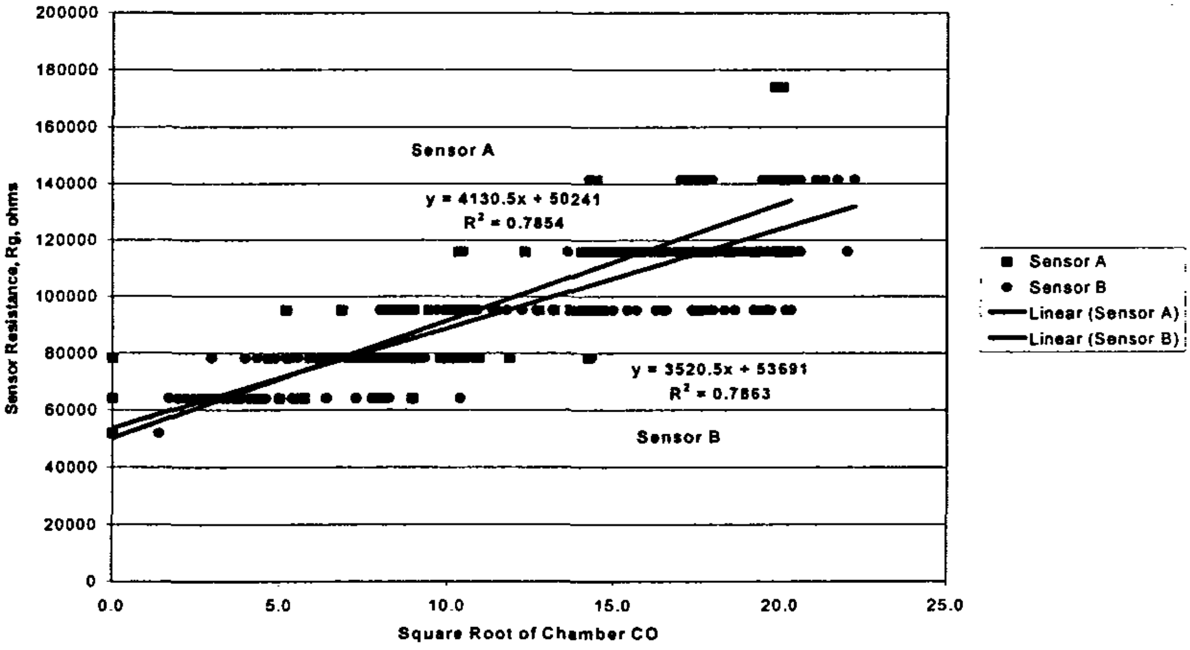
Despite the occurrence of noise in the data, the sensors provided a linear response to carbon monoxide when tested as described above. This linear relationship is demonstrated when sensor resistance and voltage are plotted against the square root of the CO concentration as shown in Graphs 1 and 2. For Sensor A, the coefficient of correlation, R^2, of sensor resistance, R_g, to the square root of the CO concentration was 0.7854, while that for sensor voltage, V_g, was 0.8158. For Sensor B, the coefficient of correlation, R^2, of sensor resistance, R_g, to the square root of the CO concentration was 0.7863 while that for sensor voltage, V_g, was 0.8255. CPSC staff believes that an even closer correlation would have been achieved in a full production application of this particular sensor since it would not likely be subjected to interference.

To evaluate the performance of the sensors with the effect of noise reduced, averages of the sensor resistances and voltages were calculated and plotted against the corresponding square roots of the average CO at the test concentrations. The results are presented in Graphs 3 and 4. As seen in the graphs, the effect of reducing noise from the data significantly improves the correlation of sensor voltage and resistance to the square root of the chamber CO. The coefficient of correlation, R^2, of the average resistance for Sensor A to the square root of the average chamber CO concentrations was 0.9648, while that for average sensor voltage, V_g, was 0.9931. For Sensor B, the correlation for average resistance and voltage values was 0.9777 and 0.9935, respectively.

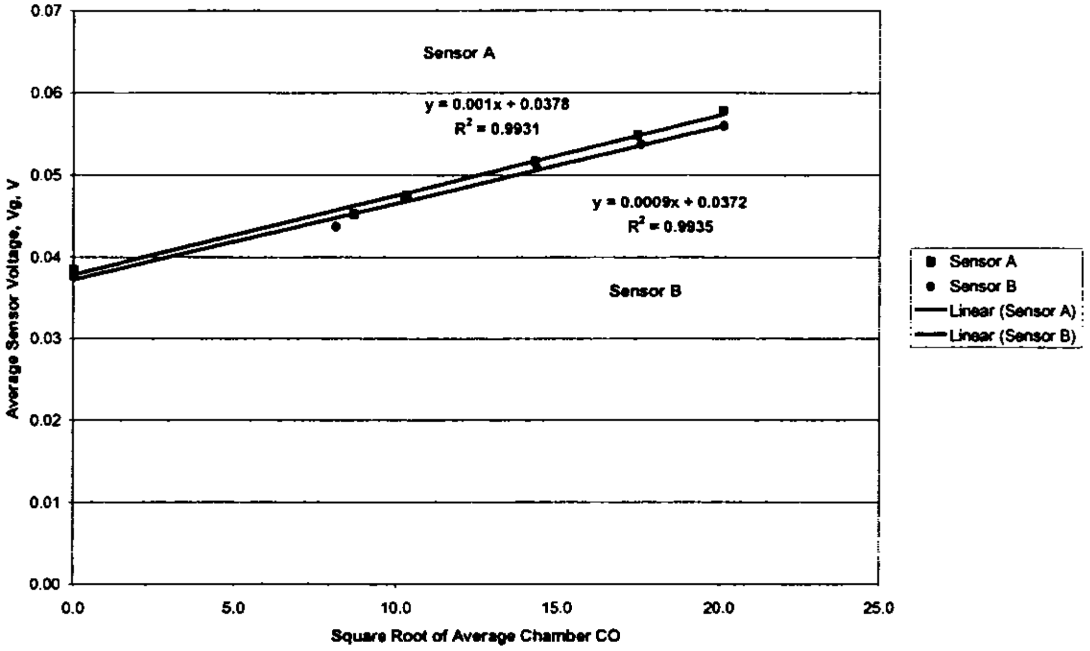
GRAPH 1. RESPONSE CURVE FOR MMOS SENSORS
SQRT CO vs. Vg



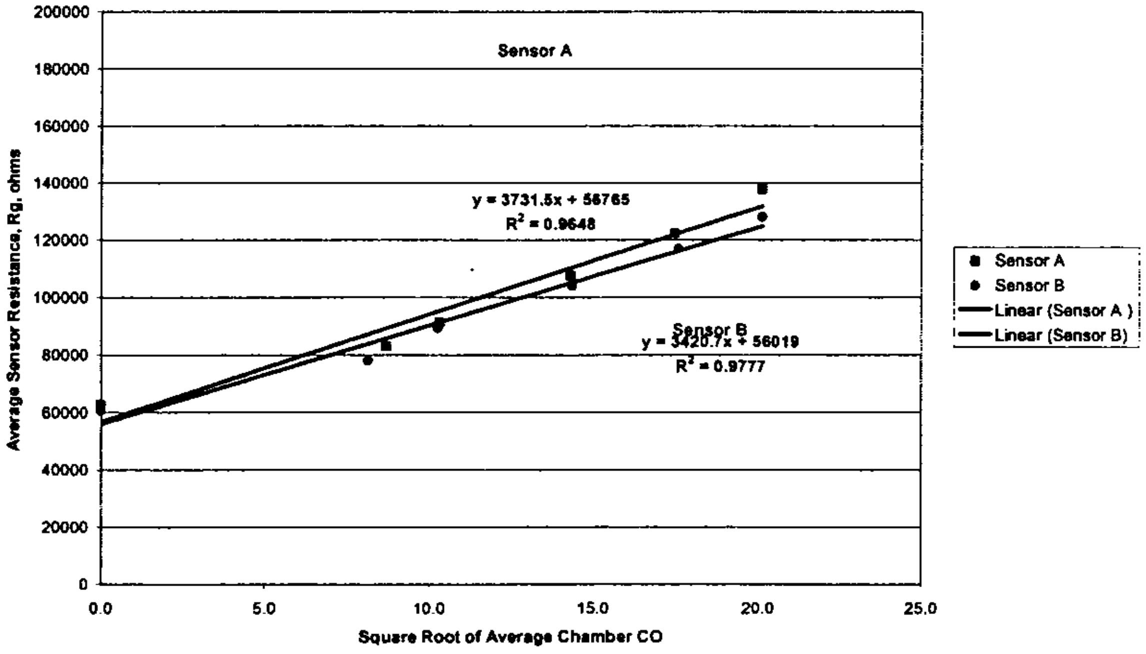
GRAPH 2. RESPONSE CURVE FOR MMOS SENSORS
SQRT CO vs. Rg



GRAPH 3. RESPONSE CURVE FOR MMOS SENSORS
SQRT Ave. CO vs. Vg Ave.



GRAPH 4. RESPONSE CURVE FOR MMOS SENSORS
SQRT Ave. CO vs. Ave. Rg



Catalytic Sensors (Sensors C and D)

The manufacturer specified the response range for the Catalytic sensors to be from 500 to 3000 ppm of CO. Therefore, nominal CO concentrations of 400, 800, 1200, 1500, 2000, 2500, and 3000 ppm were introduced into the test chamber and maintained. Because the data acquisition hardware used for testing does not directly measure resistance, the sensor output voltage, V_g, was measured. The results are presented in Table 2 and in Graphs 5 and 6.

TABLE 2: CHARACETERIZATION TESTS FOR CATALYTIC SENSORS

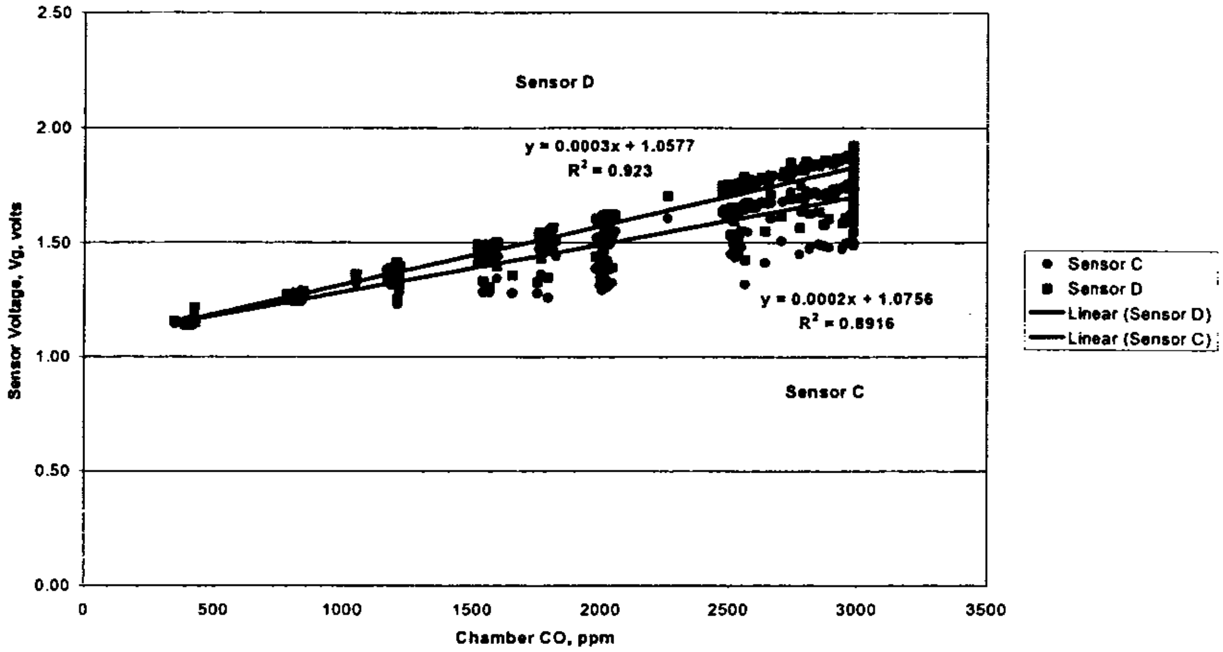
Chamber CO Concentration (ppm)		**Sensor C**			**Sensor D**		
		Voltage (V)			**Voltage (V)**		
Nominal	**Average**	**Max.**	**Min.**	**Ave.**	**Max.**	**Min.**	**Ave.**
400	415	1.20	1.14	1.15	1.22	1.14	1.16
800	825	1.26	1.25	1.25	1.29	1.27	1.28
1200	1184	1.36	1.23	1.34	1.42	1.25	1.38
1500	1648	1.49	1.26	1.42	1.57	1.31	1.48
2000	2016	1.55	1.29	1.48	1.63	1.37	1.56
2500	2547	1.68	1.32	1.62	1.80	1.43	1.73
3000	2927	1.78	1.45	1.68	1.92	1.57	1.81

The data showed there was an overlap of measured voltage and calculated resistance between successive test concentrations of CO. For instance, the minimum voltage for Sensor C at a CO concentration of 1500 ppm was 1.26 V. At a concentration of 1200 ppm, the measured voltage ranged from a maximum of 1.36 V to a minimum of 1.23 V. Closer review of the data indicated that the overlapping of values was not consistent and occurred infrequently in the form of spikes or troughs and is best described as "noise."

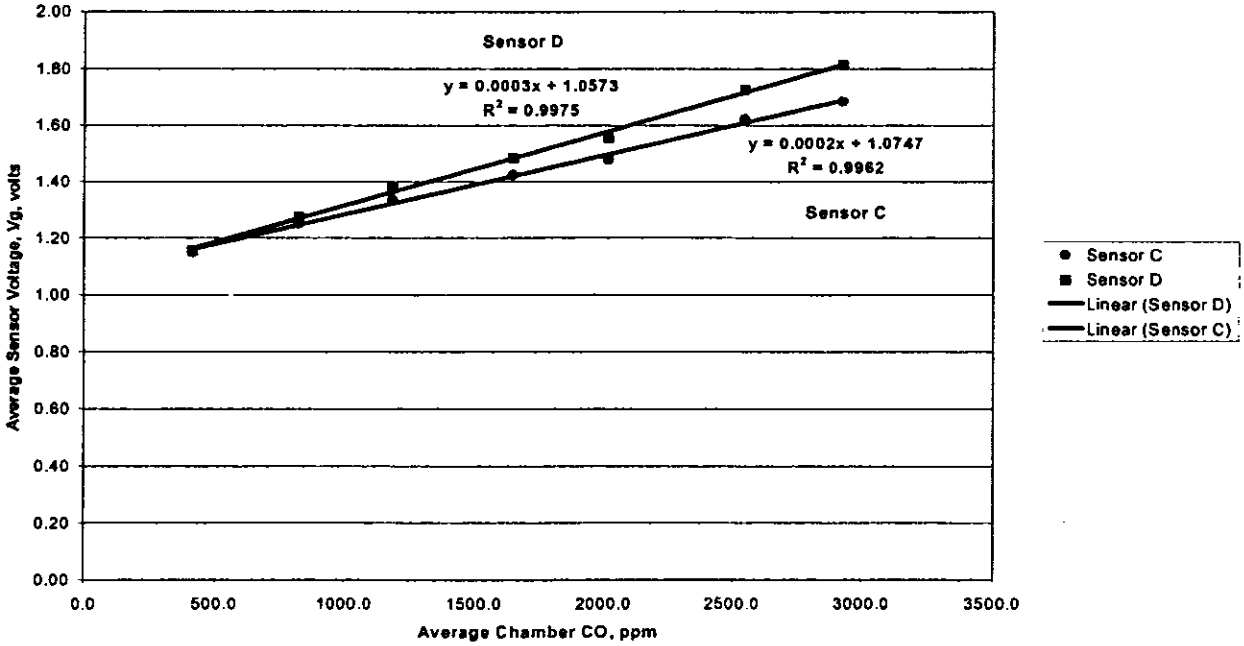
As with the MMOS sensors, CPSC staff believes this "noise" was caused by variables such as interference from electromagnetic fields that exist in the test setup, the length of the signal wires to the data acquisition system, and the fact that the sensor output voltages were not filtered or processed.

Despite the apparent noise, the Catalytic sensors exhibited good linear response to CO. As shown in Graph 5, Sensor C and D outputs exhibited a close correlation to the chamber CO with coefficients of correlation of 0.8916 and 0.9230, respectively. In order to assess the catalytic sensor performance with the effects of noise reduced, staff calculated the average sensor voltages at the various concentrations, as shown in Table 2. The effect of the noise reduction was a better correlation between sensor voltage and CO concentration. As seen in Graph 6, the coefficient of correlation for Sensor C improved to 0.9962, while that for Sensor D improved to 0.9975.

GRAPH 5. RESPONSE CURVE FOR CATALYTIC SENSORS
CO vs. Vg



GRAPH 6. RESPONSE CURVE FOR CATALYTIC SENSORS
Ave. CO vs. Vg Ave.



Furnace Sensor Shutoff Tests

Test Chamber and Data Acquisition

The purpose of this phase of testing was to evaluate the ability of the sensors to operate in a furnace environment, accurately detect CO concentrations in excess of 400 ppm in the furnace flue products, and send a shutoff signal to the furnace controls. Each sensor was mounted in the threaded, 90-degree section of a 3-inch diameter Schedule 40 PVC Vent Tee. A hole slightly larger than the outside diameter of the casing of each type of sensor was drilled through the center of two 3-inch diameter Schedule 40 PVC, threaded Vent Tee plugs (one for each sensor type). Each sensor was inserted through the drilled out hole to a depth that allowed the top of the sensing area to line up flush with the interior walls of the PVC pipe. The supply voltage and output voltage wires extended from the exterior portion of the plug/sensor interface to the control and data acquisition circuit. Since the furnace standard requires that furnace CO concentrations not exceed 400 ppm in an air free flue sample, this concentration was selected as the setpoint for adjusting each sensor. The voltage alarm relay of the shutoff circuit (discussed in the next section) was adjusted to the output voltage of each sensor that corresponded to approximately 400 ppm of CO in the Characterization Tests.

The tests were conducted inside a chamber with internal dimensions of 10 feet wide, by 12 feet long, by 7 feet high. The internal volume of the chamber was 837 cubic feet. The furnace was located within a closet inside the chamber. The closet was constructed using ½ inch drywall and metal studs for framing. The exterior dimensions of the closet were 4.33 feet wide, by 6.25 feet long, by 7.08 feet high. The internal volume of the closet was 196 cubic feet. A full view of the Furnace Sensor Shutoff Test Setup is shown in Figure 4.

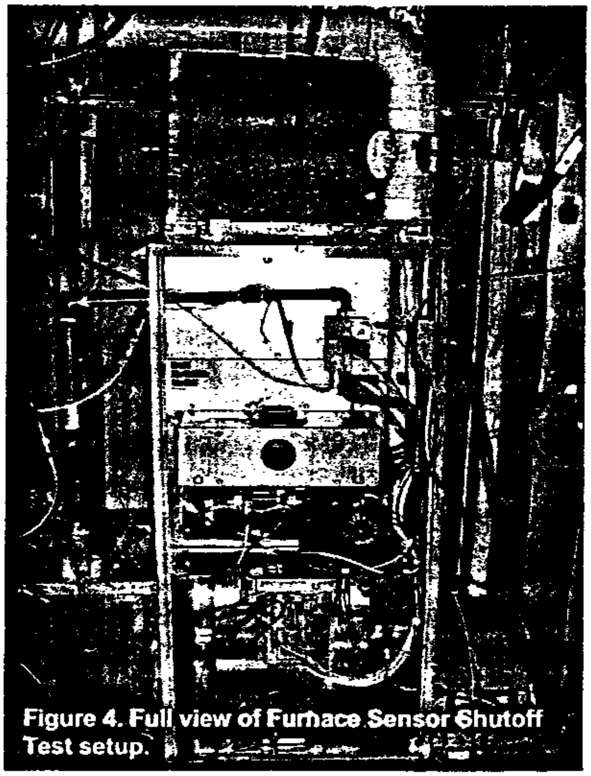


Figure 4. Full view of Furnace Sensor Shutoff Test setup.

Two sampling systems were used to measure the concentrations of different chemical species at various locations. The first system was used to obtain CO, CO_2, and O_2 samples from the flue gas and furnace closet. A three-way valve was used to switch between the closet and flue gas sampling lines. Flue gas samples were taken from a single location downstream of the flue collar, adjacent to the vent-mounted CO sensor. Closet air samples were taken from five locations inside the closet. The sampling lines from the five closet locations fed into a common mixing manifold that was then connected to the three-way valve using a single sampling line. A basic heat exchange system using recirculated chilled water was used to condense the water out of the gas sample to prevent condensation inside the gas analyzers during the sampling of the flue gas.

The second system was used to obtain CO, CO_2, and O_2 samples from five locations inside the chamber. The sampling lines from these five locations fed into a common mixing manifold. The mixing manifold was then connected to the gas analyzers using a single sampling line. Both systems used non-dispersive infrared (NDIR) gas analyzers to measure CO and CO_2 concentrations and paramagnetic analyzers to measure O_2 concentrations.

Shutoff Circuit to Furnace

Output voltages for both sensor types were obtained while the sensors were exposed to CO concentrations within the ranges specified by the manufacturers. The output voltage corresponding to approximately 400 ppm of CO for each sensor was used as the setpoint signal value to shutoff the furnace. In order to provide a means of sending the shutoff signal to the furnace after each sensor detected 400 ppm of CO in the flue products, a shutoff circuit was built between the sensor and the furnace. In addition to providing shutoff capabilities, a time delay feature was incorporated into the shutoff circuit to prevent spurious voltage signals from shutting off the furnace. The shutoff circuit to the furnace was comprised of the following commercially available components and was mounted on the floor of the furnace blower compartment as shown in Figure 5:

- DC Input Limit Alarm (DILA), Model DRG-AR-DC
- Delay-on-Make Timer (DMT), Model TD-69, Omega Engineering, Inc.
- 120 Volt Relay

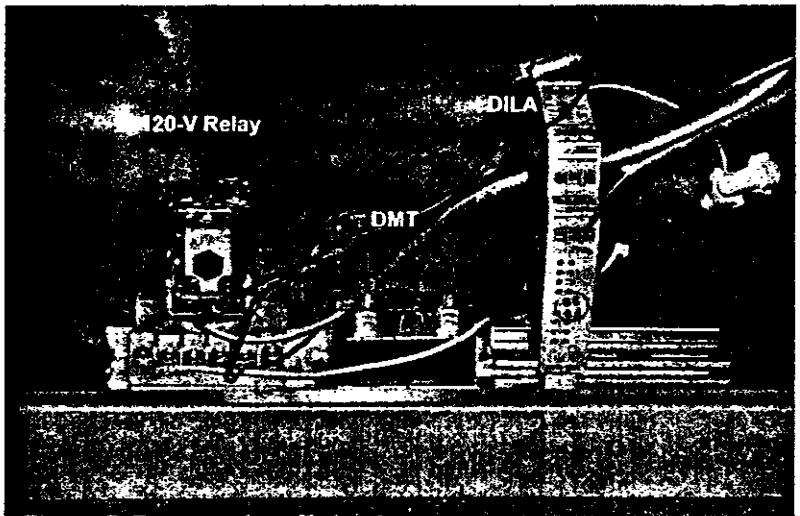
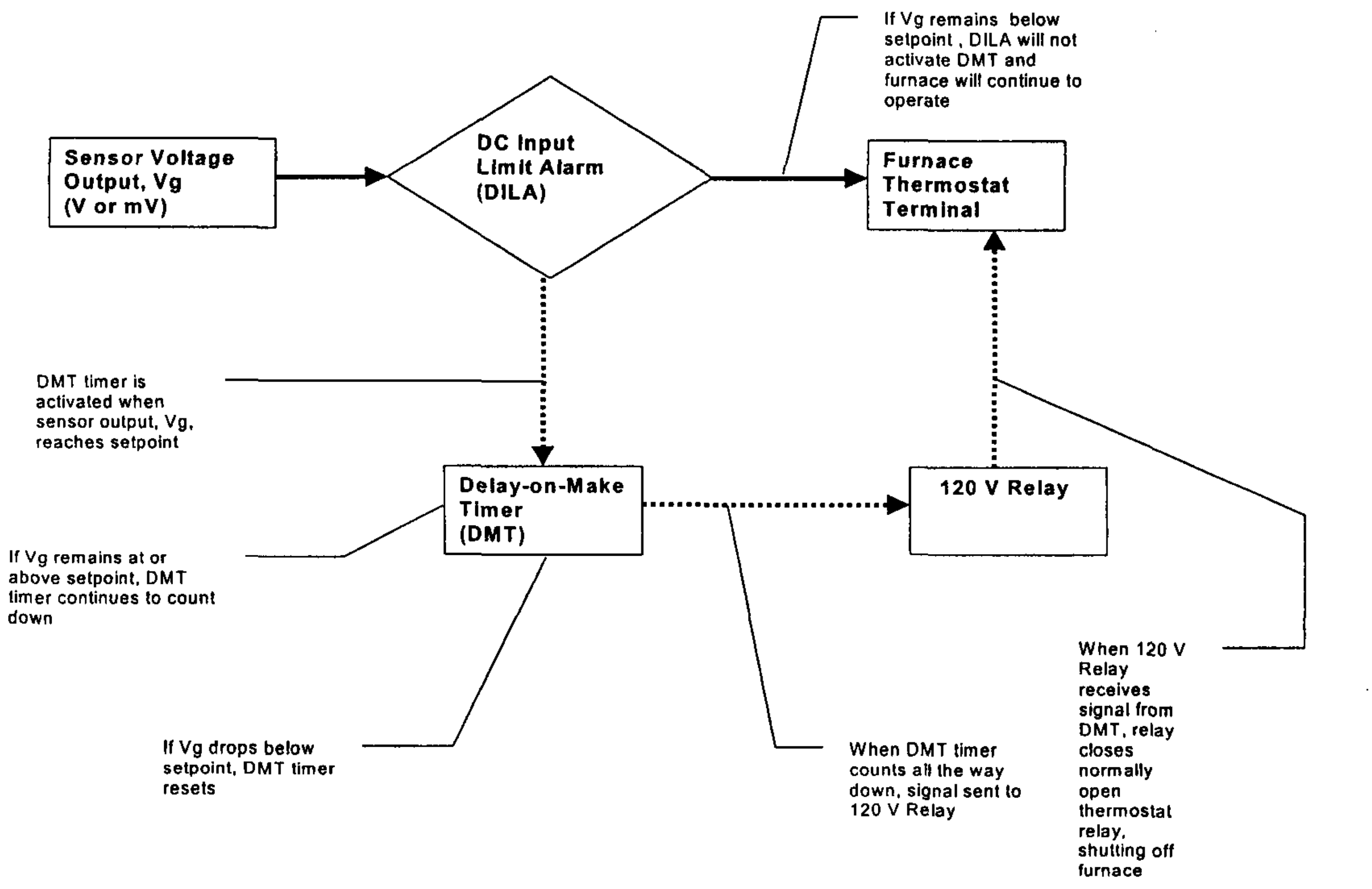


Figure 5. Furnace shutoff circuit components.

The DC Input Limit Alarm (DILA) is a voltage-controlled relay that used the CO sensor as input and was powered with a 12-volt power supply. When the CO sensor supplied the DILA with a voltage above a user determined upper limit, the DILA closed a set of contacts which supplied power to the Delay-on-Make Timer (DMT). The DMT was used to provide a time delay before energizing the 120- volt relay.

When the DMT timed out, it energized the coil of the 120-volt relay. The relay was connected in series with the thermostat loop to control the ON/OFF cycling of the furnace. When the flue CO concentration was below the setpoint of 400 ppm, each sensor output remained below its respective setpoint voltage and the furnace continued to operate. When the flue CO concentration exceeded the setpoint, sensor output would exceed the setpoint voltage and cause the furnace to shut down. When the flue CO concentration dropped below the setpoint, the sensor output would drop below the voltage setpoint. This caused the DILA to de-energize, and thus reset the DMT, which allowed the furnace to cycle back on. A lockout mechanism was not built into the shutoff circuit. Therefore, during furnace shutdown, once the elevated CO concentration was exhausted from the vent pipe, the furnace would cycle back on. This typically took between 30 and 60 seconds and allowed multiple tests to be completed in succession during a single test run. A functional diagram of the shutoff circuit is shown in Figure 6. For expediency, external power supplies were used to operate the sensors. However, given the supply voltages required for each sensor type (7 V for the MMOS sensors and 12 V for the Catalytic sensors), staff would expect that a sensor deployed in a furnace out in the field would receive its power from the furnace control board.

Figure 6. Flowchart for Shutoff Circuit to Furnace



MMOS Sensors (Sensors A and B)

During the characterization testing it was determined that at CO concentrations of 400 ppm, the corresponding output voltage from the MMOS sensors ranged from 48.8 to 63.5 mV. The average for both sensors was approximately 56.4 mV, and this was used as the setpoint for furnace shutoff. Each sensor was tested at target shutoff times of two, five, and eight minutes while mounted in the furnace vent pipe. The shutoff time was set by adjusting the Delay-on-Make Timer (DMT) to a desired time. The eight-minute shutoff time was selected because the maximum adjustment range for the DMT is eight minutes. The two and five minute times were selected to assess sensor shutoff performance over shorter spans of time.

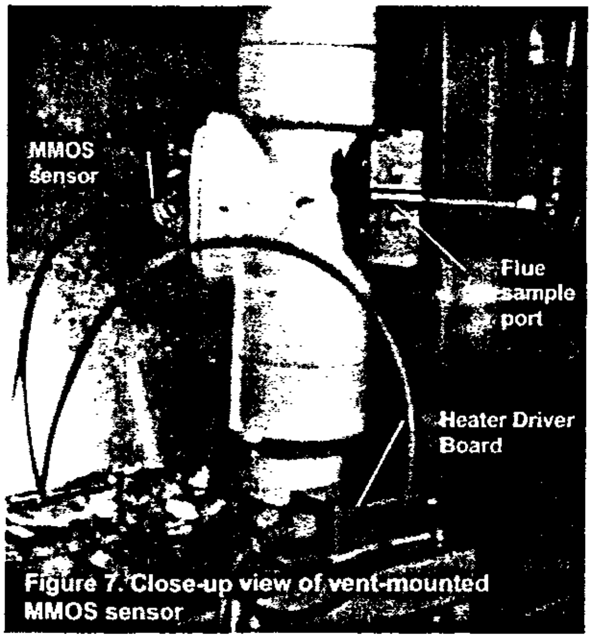


Figure 7. Close-up view of vent-mounted MMOS sensor

A data collection rate of 1 cycle per second was selected for the data acquisition system to capture any sensor voltages that might have dropped below the setpoint. This was necessary to provide a means to determine if a failure to shutdown was attributable to the shutoff circuit Time Delay Relay being reset as a result of an extraneous sensor voltage below the setpoint. A close-up view of the MMOS sensor mounted in the vent tee plug is shown in Figure 7.

When tested at each of the target shutoff times, Sensors A and B performed well, shutting the furnace down each time. Although the sensors shut the furnace down, there were slight differences between the actual shutoff times and the target times. These differences were caused by variations in the adjustment of the DMT knob to exact time settings.

The test results for Sensors A and B are shown in Tables 3 and 4, respectively, and also in Graphs 7-12. Since a lock out mechanism was not built into the shutoff circuit, the furnace cycled back on after elevated CO was exhausted from the vent pipe. This allowed multiple tests to be conducted in succession during the Two, Five, and Eight-Minute Shutoff Tests. This is indicated in Tables 3 and 4 by the number of times a test was repeated (i.e. repetition number). Multiple repetitions of a test are also indicated in Graphs 7-12 by the gas flow curve. During furnace operation, gas flow to the furnace ranged from 2.20 to 2.25 cubic feet per minute (cfm) and is represented by each plateau within this range. Shutdown of the furnace is represented by the drop in the gas flow to near zero cfm. Thus, each successive plateau on the gas flow curve between 2.20 and 2.25-cfm represents a single test. In order to reach an equilibrium temperature, the furnace was allowed to warm up for 16 minutes prior to blocking the vent. This is indicated in the graphs by the initial gas flow plateau. When a series of test conditions were run in succession, staff did not run the furnace through an additional warm-up period, since it already achieved an equilibrium temperature from the previous set of tests.

The sensor output is indicated in each of the graphs by the sensor voltage curve. Because it was not processed or filtered, the sensor voltage signal varied over this range as a result of interference from the test setup. Staff believes a filtered, processed signal would have exhibited a much smoother profile.

When the furnace vent pipe was blocked to approximately 90 percent of its cross-sectional area, the flue CO concentration rose rapidly. As the flue CO concentration increased, sensor output increased. Whenever the sensor output exceeded and remained above the setpoint, the DMT activated and began to count down for the targeted shutoff time period set by adjustment of the DMT knob. At the end of the time period, the normally closed 120-volt relay would open the thermostat contact, causing the furnace to shut down. Furnace shutdowns are indicated in each of the graphs by the sudden drop in the gas flow to zero cfm. When the furnace shut down, the flue CO concentration would gradually drop below the 400 ppm setpoint, thus causing the sensor output to drop below the voltage setpoint of 56.4 mV. Because a lockout circuit was not incorporated into the shutoff circuit design, the DMT would reset, allowing the furnace to cycle back on. Due to the length of the CO sampling line from the vent pipe to the gas analyzer, there was a time lag of approximately 20 to 30 seconds between the sensor response and that of the gas analyzer measuring flue CO concentrations. As a result, the data exhibited flue concentrations above the target CO value of 400 ppm, although the sensor output dropped below the voltage setpoint.

TABLE 3: SHUTOFF TESTS FOR MMOS SENSOR A

Test	Rep. No.*	Time Delay Relay Set Time, min	At furnace shutoff:		
			Vent CO, ppm	Sensor Voltage, mV	Time to shutoff, min:sec
Two-Minute Shutoff	1	2	691	87.9	2:19
	2	2	2933	102.5	2:18
	3	2	2851	97.7	2:17
	4	2	2999	97.7	2:16
Five-Minute Shutoff	1	5	2999	97.7	4:35
	2	5	2999	127.0	4:29
	3	5	2999	102.5	4:16
Eight-Minute Shutoff	1	8	2999	102.5	7:57
	2	8	2999	102.5	7:57

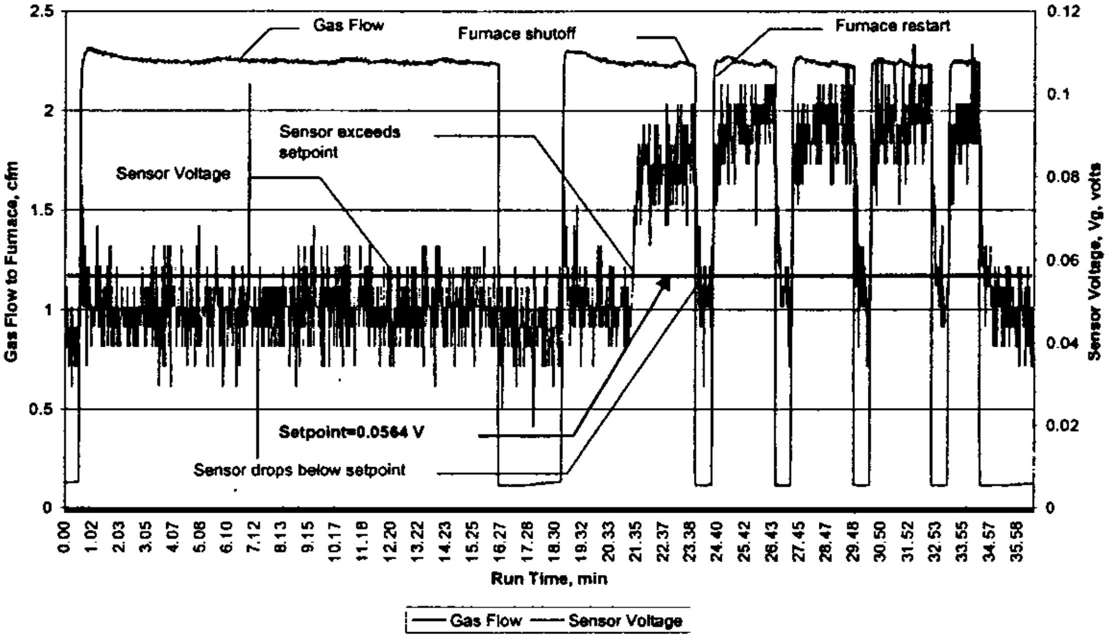
*Rep. No. = the number of times a test condition was repeated.

TABLE 4: SHUTOFF TESTS FOR MMOS SENSOR B

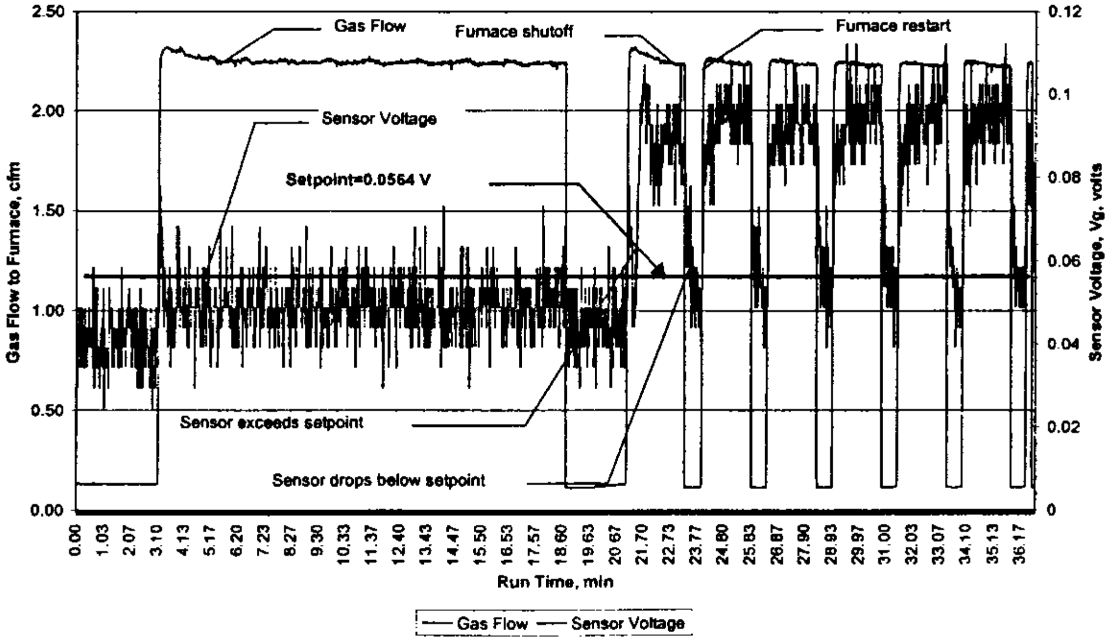
Test	Rep. No.*	Time Delay Relay Set Time, min	At furnace shutoff:		
			Vent CO, ppm	Sensor Voltage, mV	Time to shutoff, min:sec
Two-Minute Shutoff	1	2	1113	92.8	1:49
	2	2	2979	87.9	1:52
	3	2	2999	92.8	1:50
	4	2	2999	97.7	1:50
	5	2	2999	97.7	1:50
	6	2	2999	92.8	1:50
Five-Minute Shutoff	1	5	677	83.0	4:51
	2	5	2711	102.5	4:50
	3	5	2999	92.8	4:50
	4	5	2999	97.7	4:34
Eight-Minute Shutoff	1	8	1718	92.8	7:59

*Rep. No. = the number of times a test condition was repeated.

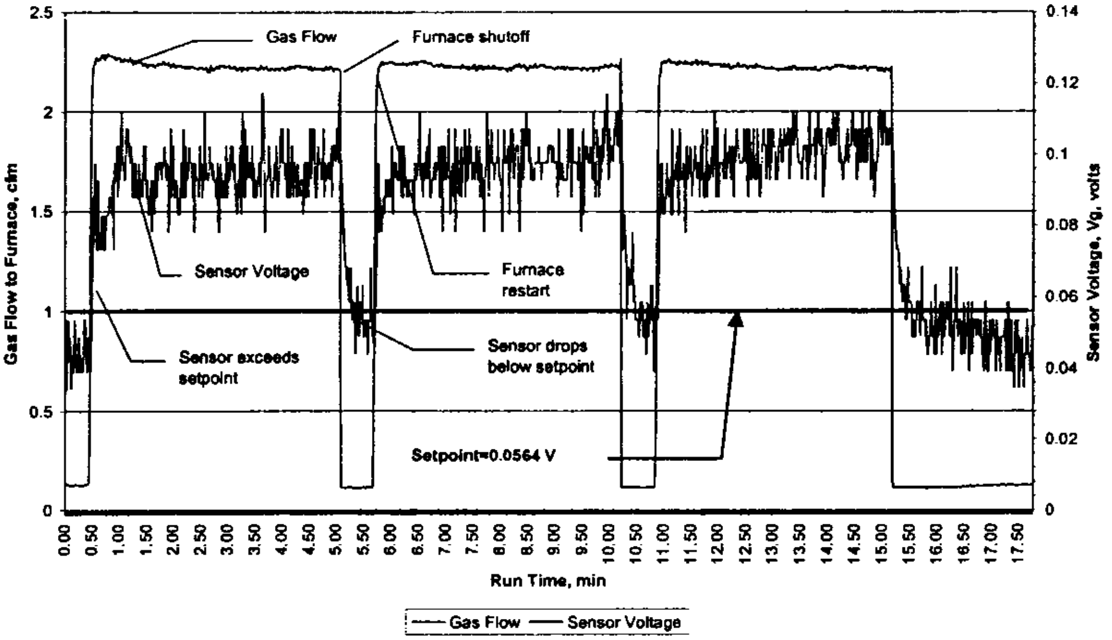
GRAPH 7. TWO MINUTE SHUTOFF TEST
MMOS SENSOR A
(w/16-minute warm-up)



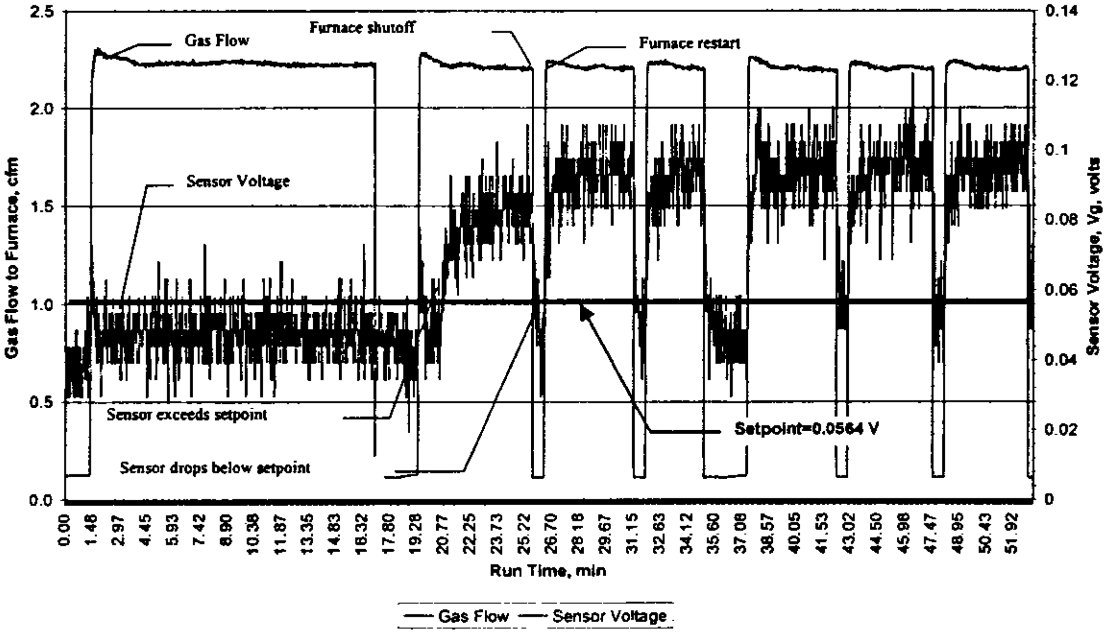
GRAPH 8. TWO MINUTE SHUTOFF TEST
MMOS SENSOR B
(w/16-minute warm-up)



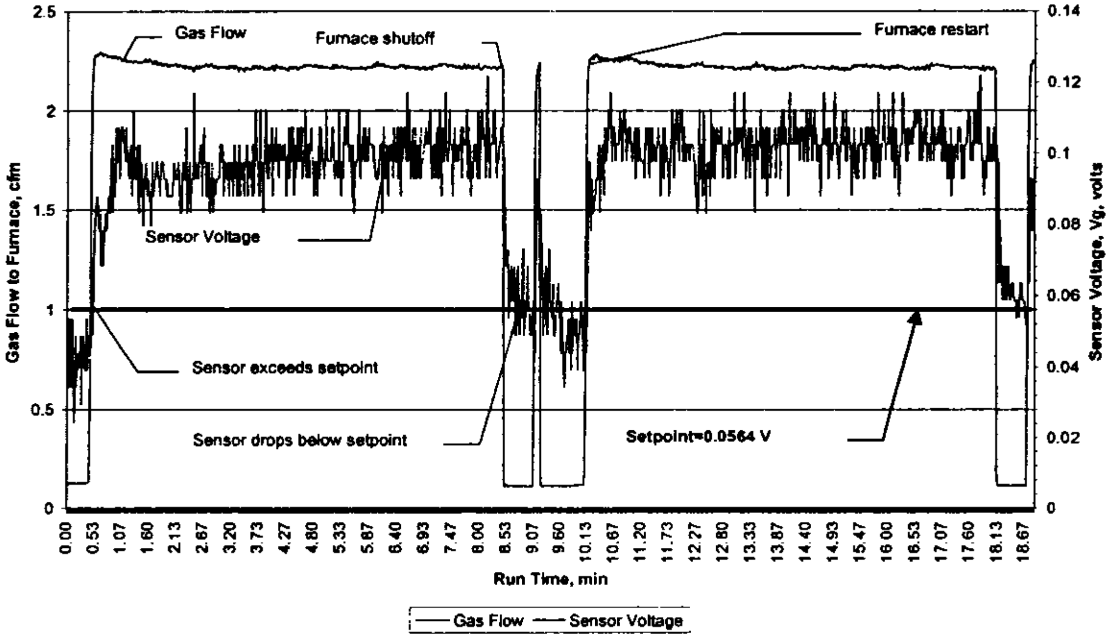
GRAPH 9. FIVE MINUTE SHUTOFF TEST
MMOS SENSOR A
(no warm-up period)



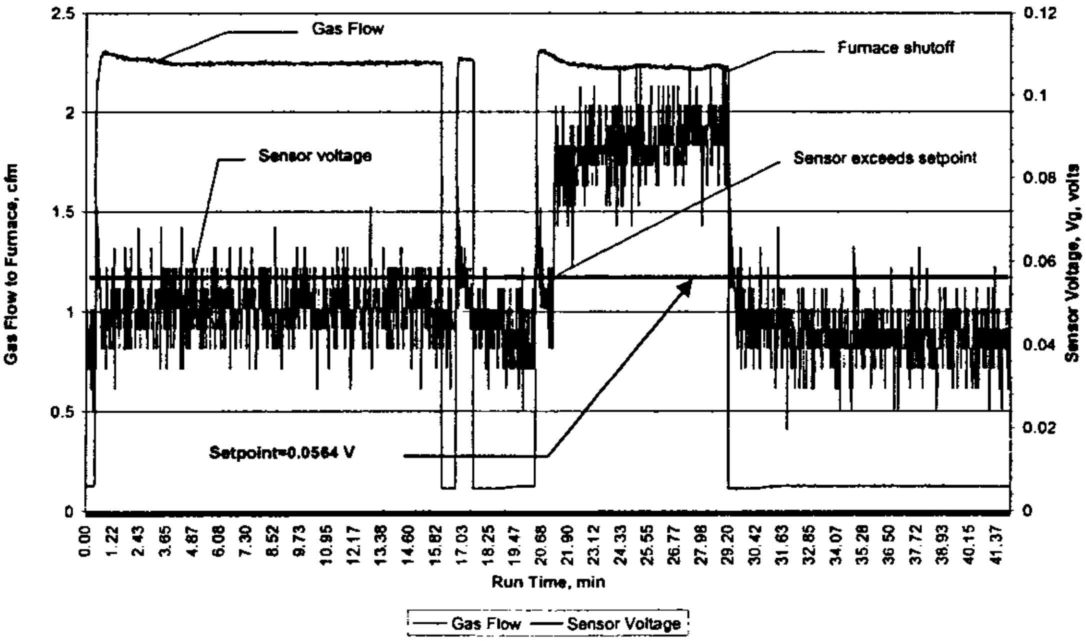
GRAPH 10. FIVE MINUTE SHUTOFF TEST
MMOS SENSOR B
(w/16-minute warm-up)



GRAPH 11. EIGHT MINUTE SHUTOFF TEST
MMOS SENSOR A
(no warm-up period)



GRAPH 12. EIGHT MINUTE SHUTOFF TEST
MMOS SENSOR B
(w/16-minute warm-up)



Catalytic Sensors (Sensors C and D)

During the characterization testing it was determined that at CO concentrations of 400 ppm, the corresponding output voltage from the catalytic sensors ranged from 1.14 to 1.22 V. The average for both sensors was approximately 1.16 V, and this was used as the setpoint for furnace shutoff. Each sensor was tested at target shutoff times of two, five, and eight minutes while mounted in the furnace vent pipe. A close-up view of the Catalytic sensor mounted in the vent tee plug is shown in Figure 8.

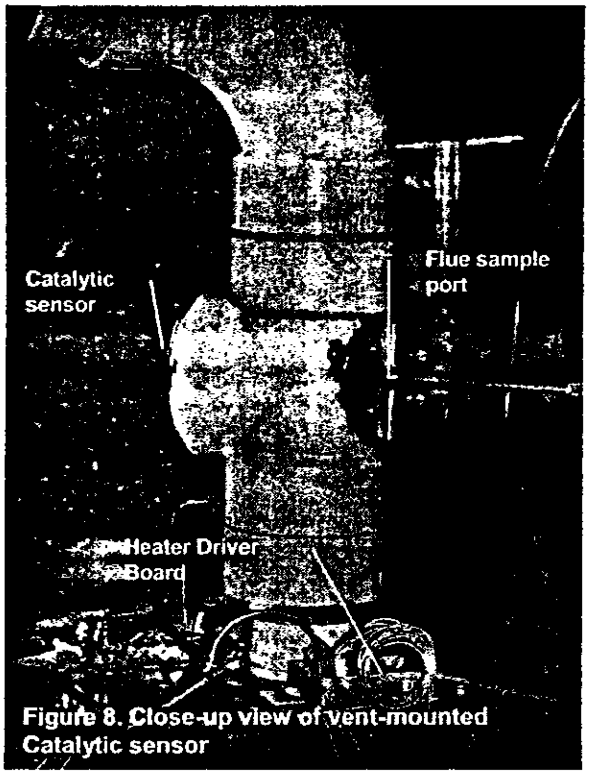


Figure 8. Close-up view of vent-mounted Catalytic sensor

Shutoff of the furnace required that the output of each sensor exceed 1.16 V for a specified period of time. The shutoff time was set by adjusting the Delay-on-Make Timer (DMT) to a desired time. A data collection rate of 1 cycle per second was selected for the data acquisition system to capture any sensor voltages that might have dropped below the setpoint. This was necessary to provide a means to determine if a failure to shutdown was attributable to the shutoff circuit Time Delay Relay being reset as a result of an extraneous sensor voltage below the setpoint.

When tested at each of the target shutoff times, Sensors C and D performed well, shutting the furnace down each time. Although the sensors shut the furnace down, there were slight differences between the actual shutoff times and the target times. These differences were caused by variations in the adjustment of the DMT knob to exact time settings.

The test results for Sensors C and D are shown in Tables 5 and 6, respectively, and also in Graphs 13-18. Since a lock out mechanism was not built into the shutoff circuit, the furnace cycled back on after elevated CO was exhausted from the vent pipe. This allowed multiple tests to be conducted in succession during the Two, Five, and Eight- Minute Shutoff Tests. This is indicated in Tables 5 and 6 by the number of times a test was repeated (i.e. repetition number). Multiple repetitions of a test are also indicated in Graphs 13-18 by the gas flow curve. During furnace operation, gas flow to the furnace ranged from 2.20 to 2.25 cfm and is represented by each plateau within this range. Shutdown of the furnace is represented by the drop in the gas flow to near zero cfm. Thus, each successive plateau on the gas flow curve between 2.20 and 2.25 cfm represents a single test. In order to reach an equilibrium temperature, the furnace was allowed to warm up for 16 minutes prior to blocking the vent. This is indicated in the graphs by the initial gas flow plateau. When a series of test conditions were run in succession, staff did not run the furnace through an additional warm-up period, since it already achieved an equilibrium temperature from the previous set of tests.

The sensor output is indicated in each of the graphs by the lower line. Although it was not filtered, the sensor voltage signal remained relatively steady during the testing. The data revealed a few instances in which voltage values declined momentarily. Staff believes these troughs are the result of interference from the test setup and would have been reduced if the signal had been filtered.

When the furnace vent pipe was blocked to approximately 90 percent of its cross-sectional area, flue CO concentration rose rapidly. As the flue CO concentration increased, sensor output increased. Whenever the sensor output exceeded and remained above the setpoint, the DMT activated and began to count down for the targeted shutoff time period set by adjustment of the DMT knob. At the end of the time period, the normally closed 120-volt relay would open the thermostat contact, causing the furnace to shut down. Furnace shutdowns are indicated in each of the graphs by the sudden drop in the gas flow to zero cfm. When the furnace shut down, the flue CO concentration would gradually drop below the 400 ppm setpoint, thus causing the sensor output to drop below the voltage setpoint of 1.16 V. Because a lockout circuit was not incorporated into the shutoff circuit design, the DMT would reset, allowing the furnace to cycle back on. Due to the length of the CO sampling line from the vent pipe to the gas analyzer, there was a time lag of approximately 20 to 30 seconds between the sensor response and that of the gas analyzer measuring flue CO concentrations. As a result, the data exhibited flue concentrations above the target CO value of 400 ppm, although the sensor output dropped below the voltage setpoint.

TABLE 5: SHUTOFF TESTS FOR CATALYTIC SENSOR C

Test	Rep. No.*	Time Delay Relay Set Time, min	At furnace shutoff:		
			Vent CO, ppm	Sensor Voltage, V	Time to shutoff, min:sec
Two-Minute Shutoff	1	2	759	1.51	2:13
	2	2	2024	3.39	2:10
	3	2	2124	3.30	2:17
	4	2	2410	3.51	2:04
Five-Minute Shutoff	1	5	2999	2.88	4:33
	2	5	2999	2.67	4:33
	3	5	2999	2.70	4:33
Eight-Minute Shutoff	1	8	2999	2.84	7:56
	2	8	2999	2.61	7:57

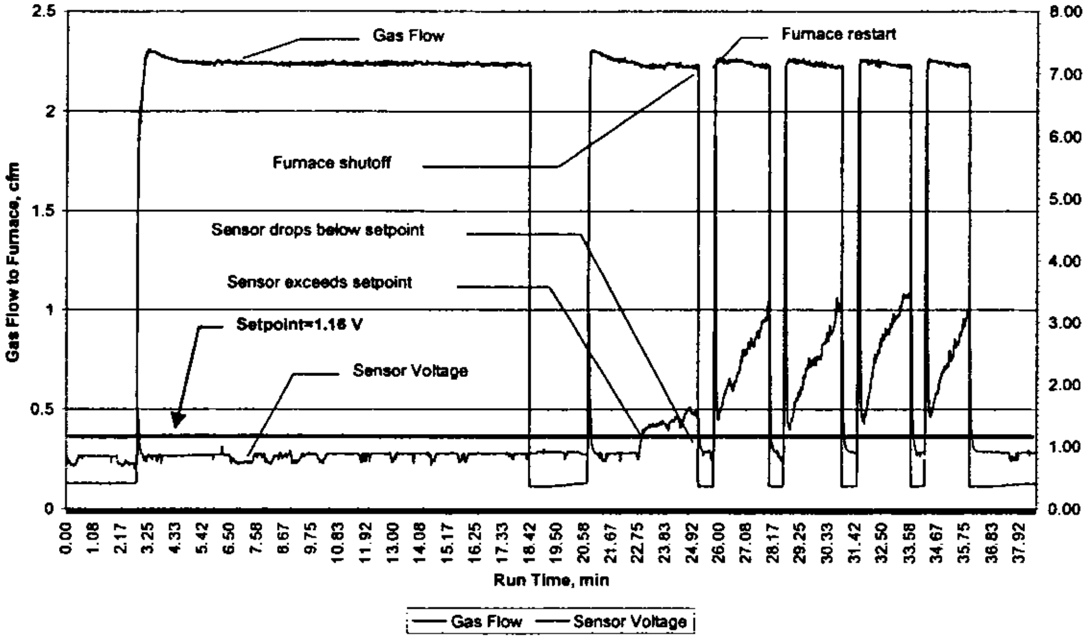
*Rep. No. = the number of times a test condition was repeated.

TABLE 6: SHUTOFF TESTS FOR CATALYTIC SENSOR D

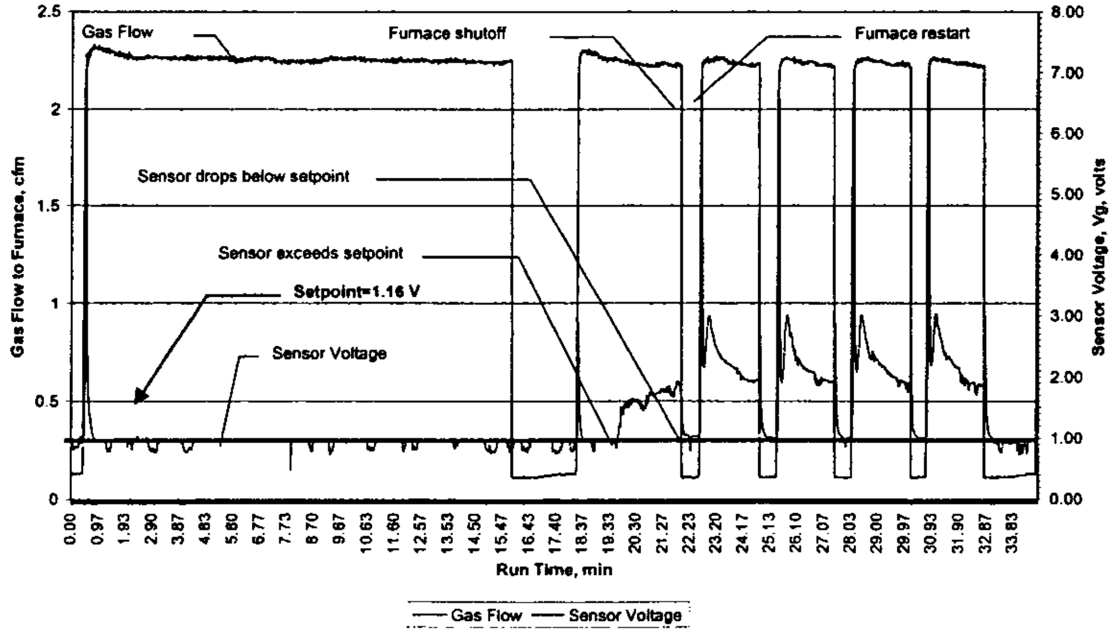
Test	Rep. No.*	Time Delay Relay Set Time, min	At furnace shutoff:		
			Vent CO, ppm	Sensor Voltage, V	Time to shutoff, min:sec
Two-Minute Shutoff	1	2	1107	1.70	2:14
	2	2	2998	1.93	2:09
	3	2	2999	1.88	2:04
	4	2	2999	2.67	2:06
	5	2	2999	1.85	2:01
Five-Minute Shutoff	1	5	2560	2.93	4:29
	2	5	2999	2.43	4:34
	3	5	2999	1.54	4:33
	4	5	2999	1.58	4:34
Eight-Minute Shutoff	1	8	2999	1.80	8:54
	2	8	2232	2.50	7:58

*Rep. No. = the number of times a test condition was repeated.

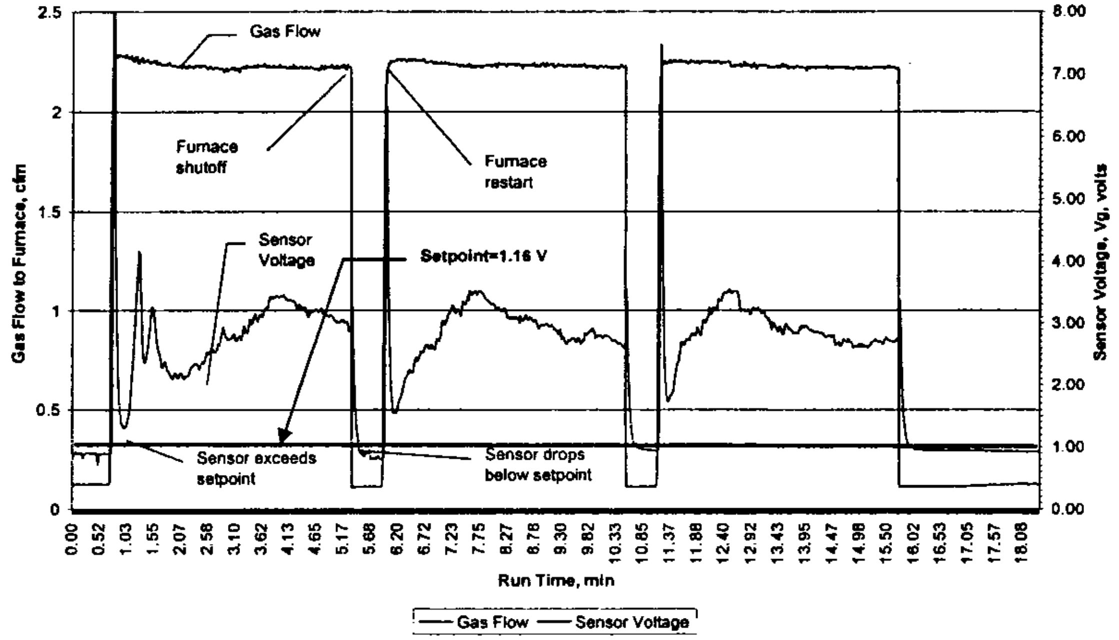
GRAPH 13. TWO MINUTE SHUTOFF TEST
CATALYTIC SENSOR C
(w/16-minute warm-up)



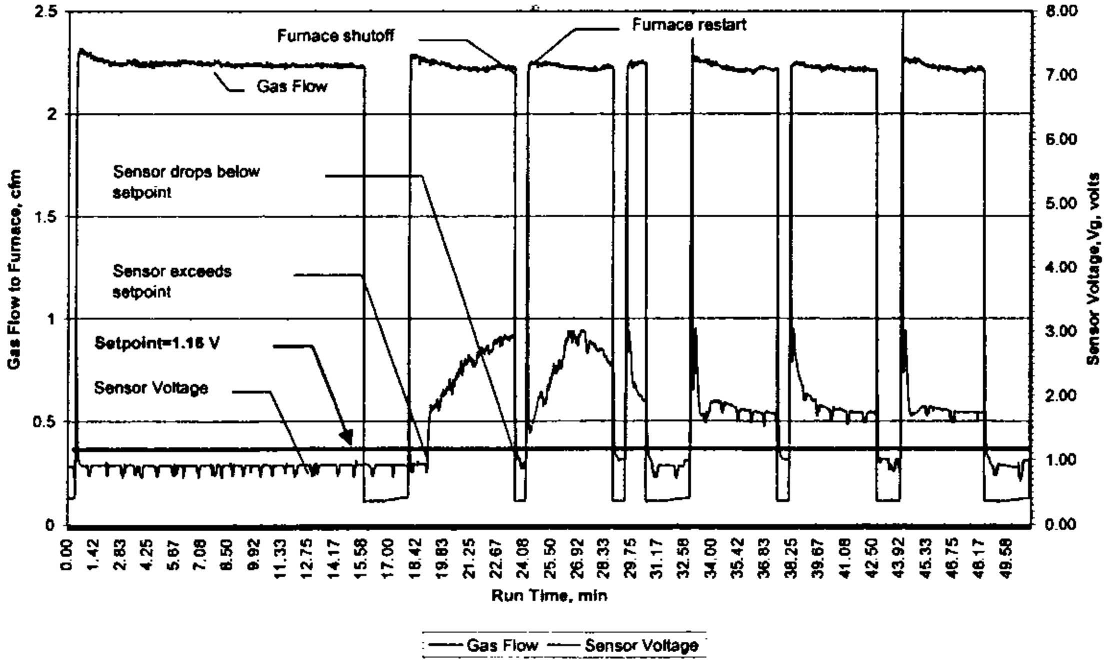
GRAPH 14. TWO MINUTE SHUTOFF TEST
CATALYTIC SENSOR D
(w/16-minute warm-up)



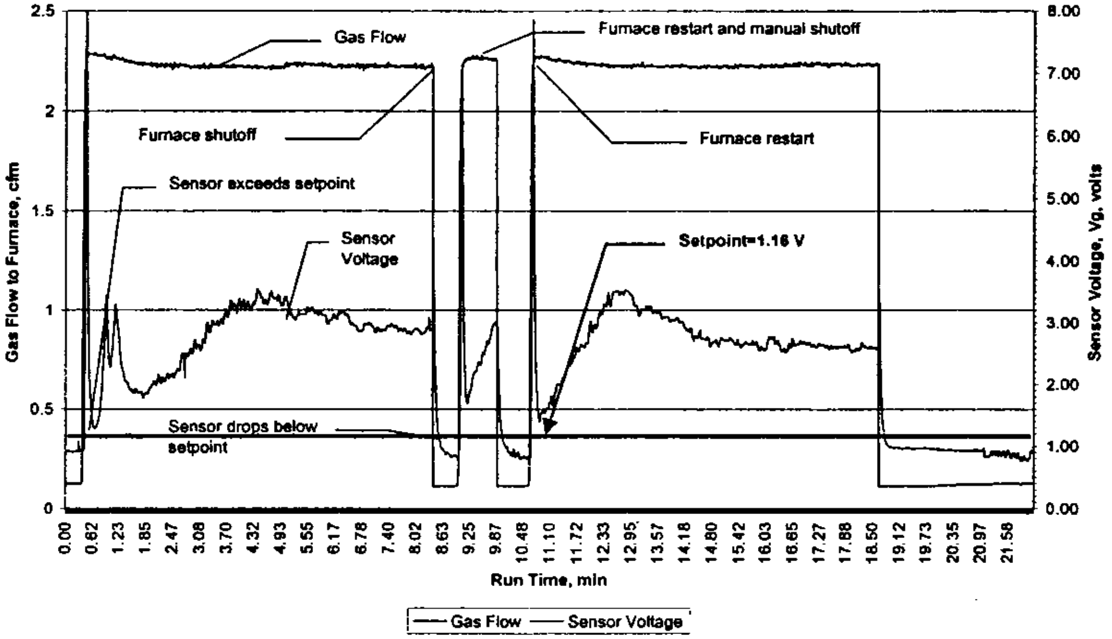
GRAPH 15. FIVE MINUTE SHUTOFF TEST
CATALYTIC SENSOR C
(no warm-up period)



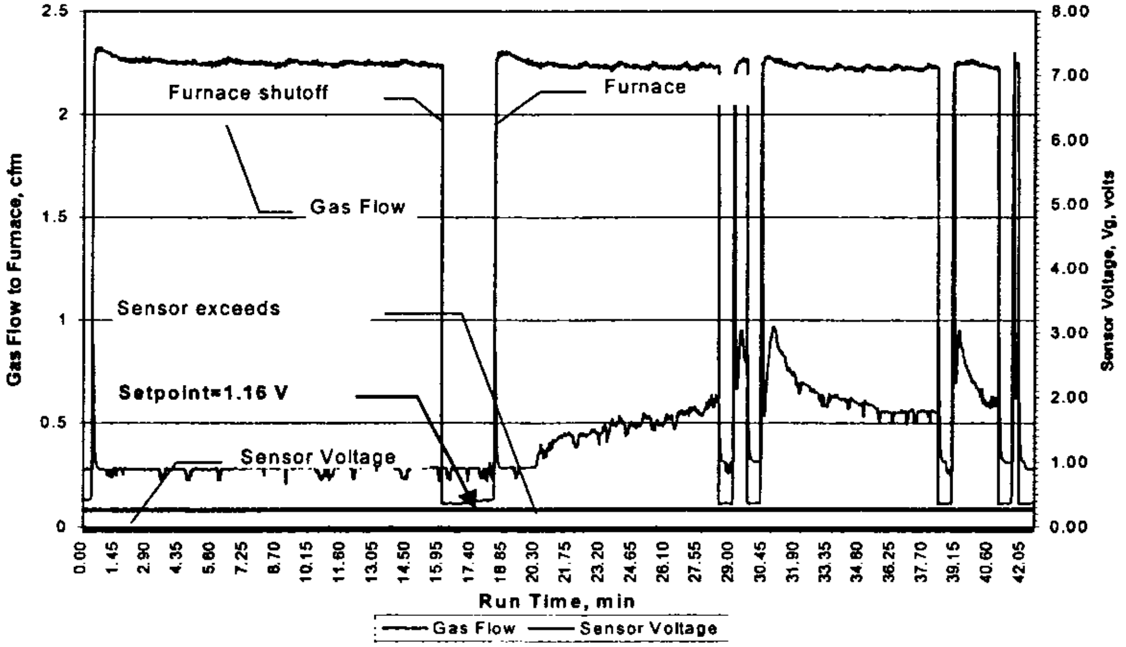
GRAPH 16. FIVE MINUTE SHUTOFF TEST
CATALYTIC SENSOR D
(w/16-minute warm-up)



GRAPH 17. EIGHT MINUTE SHUTOFF TEST
CATALYTIC SENSOR C
(no warm-up period)



GRAPH 18. EIGHT MINUTE SHUTOFF TEST
CATALYTIC SENSOR D
(w/16-minute warm-up)



SUMMARY

Two samples each of the MMOS sensors and Catalytic sensors were subjected to the characterization and furnace shutoff tests outlined in the matrices in Appendix A. Although the output signals were not filtered or processed, the sensors exhibited good performance. Sensor performance can be summarized as follows:

- There was linear response to CO concentrations within manufacturer specified ranges.

- The linear response for all sensors improved significantly when the effects of noise and interference were reduced.

- MMOS sensor voltage output averaged 56.5 mV at approximately 400 ppm CO.

- Catalytic sensor voltage output averaged 1.16 V at approximately 400 ppm CO.

- All sensors shut the furnace down at set times of two, five, and eight minutes.

CONCLUSION

The test results demonstrate that it is technically feasible to integrate sensors into a gas furnace and provide a means to shut the furnace down when flue CO concentrations exceed the requirements of the ANSI standard. The sensor technologies tested are promising and should be evaluated further by the furnace industry as a means to eliminate CO exposure hazards associated with malfunctioning furnaces with compromised vent systems and flue passageways. Staff believes these technologies could also be considered for use in other residential gas appliance applications such as boilers, wall furnaces, and vented space heaters.

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Dave Tucholski, U.S. CPSC, Directorate for Laboratory Sciences

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Dean LaRue, U.S. CPSC, Directorate for Engineering Sciences

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Dave Tucholski, U.S. CPSC, Directorate for Laboratory Sciences
Chris Brown, U.S. CPSC, Directorate for Laboratory Sciences
Tewabe Asebe, U.S. CPSC, Directorate for Health Sciences

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Richard Schenck, U.S. CPSC, Directorate for Laboratory Sciences
Ron Reichel, U.S. CPSC, Directorate for Laboratory Sciences
Ed Krawiec, U.S. CPSC, Directorate for Laboratory Sciences

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APPENDIX A. TEST MATRICES AND PROCEDURE

Test Matrices

CHARACTERIZATION TESTS FOR MMOS SENSORS			
TEST NUMBER	TEST DESCRIPTION	NUMBER OF SAMPLES	TOTAL NUMBER OF TESTS
1	0 ppm CO clean air	2	2
2	70 ppm CO injection	2	2
3	100 ppm CO injection	2	2
4	200 ppm CO injection	2	2
5	300 ppm CO injection	2	2
6	400 ppm CO injection	2	2

CHARACTERIZATION TESTS FOR CATALYTIC SENSORS			
TEST NUMBER	TEST DESCRIPTION	NUMBER OF SAMPLES	TOTAL NUMBER OF TESTS
1	0 ppm CO clean air	2	2
2	400 ppm CO injection	2	2
3	800 ppm CO injection	2	2
4	1200 ppm CO injection	2	2
5	1500 ppm CO injection	2	2
6	2000 ppm CO injection	2	2
7	2500 ppm CO injection	2	2
8	3000 ppm CO injection	2	2

SHUTOFF TESTS FOR MMOS SENSORS			
TEST NUMBER	TEST DESCRIPTION	NUMBER OF SAMPLES	TOTAL NUMBER OF TESTS
1	2-Minute Shutoff	2	4
2	5-Minute Shutoff	2	4
3	8-Minute Shutoff	2	4

SHUTOFF TESTS FOR CATALYTIC SENSORS			
TEST NUMBER	TEST DESCRIPTION	NUMBER OF SAMPLES	TOTAL NUMBER OF TESTS
1	2-Minute Shutoff	2	4
2	5-Minute Shutoff	2	4
3	8-Minute Shutoff	2	4

Furnace Sensor Shutoff Test Procedures

At the start of each day, the gas analyzers were calibrated according to the instructions specified by the manufacturer of the analyzer. In general, the meters were zeroed with nitrogen gas and spanned using a gas of known concentration (EPA protocol). The analyzers were also checked at mid- and low-range concentrations to verify the performance of the analyzers. In order to generate flue concentrations of CO at or above the 400 ppm air free standard, the furnace manifold pressure was increased to between 4.2 and 5.2 inches of water, and the vent pipe was blocked to about 90 percent of its cross-sectional area. This resulted in furnace vent pipe concentrations in excess of 400 ppm of CO. For more information on furnace installation and operating parameters, refer to the CPSC report titled, "Furnace CO Emissions Under Normal and Compromised Vent Conditions: Furnace #5 - High-Efficiency Induced Draft," (Brown, Jordan, Tucholski) September 2000.

To begin each test, the data acquisition program was started. The manifold pressure was adjusted prior to the start of each test to attain the desired input rate. A cycle timer was used to simulate a call for heat by a thermostat and start the furnace. The cycle timer was set to cycle the furnace on for sixteen minutes and off for two minutes. In order to reach an equilibrium temperature, the furnace was allowed to warm up for 16 minutes prior to blocking the vent. After the warm-up period and initial two-minute off cycle, staff would enter the chamber and block the vent to obtain a flue CO concentration in excess of 400 ppm. The closet and chamber doors were closed at the conclusion of the vent adjustments.

Each test was complete once the sensor and shutoff circuit shut the furnace down. The shutoff circuit was not designed to lock out after the furnace shut down. Therefore, the furnace would restart once the decrease in the flue concentration of CO caused by a shutdown allowed the sensor voltage to decrease below its setpoint. This allowed a given test to be repeated between 1 and 5 times within a sixteen minute on cycle, depending on the target shutoff time selected. When a series of test conditions were run in succession, staff did not run the furnace through an additional warm-up period, since it already achieved an equilibrium temperature from the previous set of tests.

APPENDIX B: SENSOR SPECIFICATIONS

SPECIFICATIONS FOR MMOS SENSORS*	
Type	Mixed Metal Oxide Semiconductor (MMOS)
Dimensions	0.591 in. (diameter) x 1.389 in. (length)
Material	Chromium Tin Oxide (catalyst) Stainless steel (Sensor cover)
Weight	Not provided
Power Consumption	350 mW
Input Voltage	7 V DC (heater driver board); 100 mV DC (sensing element)
Output Voltage to Gas concentrations	Not provided
Maximum Operating Temperature	Not provided
Relative Humidity	95%
Expected life	> 5 years
Response Range	0-400 ppm CO
Tolerance	30 ppm +/- 3 ppm CO 70 ppm +/- 5 ppm CO 150 ppm +/- 5 ppm CO 400 ppm +/- 10 ppm CO

SPECIFICATIONS FOR CATALYTIC SENSORS*	
Type	Catalytic
Dimensions	0.582 in. (diameter) x 0.839 in. (length)
Materials	Tin oxide + precious metal (catalyst) Platinum (heater coil) Stainless steel (Sensor cover)
Weight	10g (Sensor); 63 g (Control unit and harness)
Power Consumption	Less than 1 W
Input Voltage	12 V DC (heater driver board); 5 V DC (sensing element)
Output Voltage to Gas concentrations	0.2 - 4.8 V DC
Maximum Operating Temperature	260 °C
Relative Humidity	≤ 95%
Expected life	≥ 10 years
Response Range	0-3000 ppm CO
Tolerance	0 ppm +/- 200 ppm CO 500 ppm +/- 200 ppm CO 1000 ppm +/- 250 ppm CO 2000 ppm +/- 300 ppm CO 3000 ppm +/- 450 ppm CO

***Listed specifications were provided by the respective sensor manufacturer.**