COMBUSTION SENSOR TEST RESULTS

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I. EXECUTIVE SUMMARY

This report describes work performed by the U.S. Consumer Product Safety Commission (CPSC) staff in 2003 to evaluate sensor technologies to demonstrate their ability to provide detection and shutdown response to carbon monoxide (CO) concentrations in excess of 400 parts per million (ppm) within the vent system or flue passageways of a residential gas furnace. This test program was a primary task within the Vented Gas Appliance CO Sensor Project and was an extension of sensor evaluations conducted by CPSC staff in 2001.

One of CPSC's three strategic goals is to reduce the rate of death from CO poisonings associated with consumer products by 20 percent from the 1999-2000 average by the year 2013 (1999-2000 average yearly estimated CO poisoning deaths from unintentional non-fire consumer product-related incidents was 124). The goal of this test program was to support development of a performance standard that would require shutdown or some other preemptive response to elevated levels of CO within the flue passageways of vented gas heating appliances (e.g., residential furnaces, boilers, and room heaters). The intended outcome is a reduction in CO-related deaths caused by gas heating appliances.

Gas heating systems are the leading cause of CO poisoning deaths associated with consumer products. From 1999-2001, there was an average yearly estimated 126 unintentional non-fire CO poisoning deaths associated with consumer products. Heating systems of all types were associated with 69 deaths, or 65 percent of the CO poisoning deaths associated with consumer products excluding engine-powered tools. Among heating systems, from 1999- 2001, natural gas heating was associated with an average yearly estimate of 28 deaths (41% of the heating system deaths); LP gas heating was associated with an average yearly estimate of 26 deaths (38% of the heating system deaths); and unspecified gas heating was associated with an average yearly estimate of 5 deaths (7% of the heating system deaths). Overall, an average yearly estimate of 59 CO poisoning deaths from 1999-2001 were associated with the use of gas heating systems.

The objectives of this test program were to: evaluate gas sensor performance under various humidity and temperature conditions; evaluate indirect measurement and response to CO using a carbon dioxide (CO_2) sensor; evaluate sensor performance in the presence of potential interferent gases; and evaluate shutdown response from each sensor while integrated into a furnace. This sensor evaluation was comprised of characterization testing within an environmental chamber and in-situ furnace shutoff testing. The characterization testing examined each sensor's performance when exposed to target gases and non-target gases under a variety of conditions. Sensor performance observed during the characterization testing was used as a basis for selecting target parameters for in-situ furnace shutoff testing. For in-situ shutoff testing, each sensor was separately integrated into the test furnace and subjected to testing of varying durations.

Two different gas sensor technologies were evaluated. One technology used an electrochemical sensor with a target gas response range of 0 to 1000 parts per million (ppm) CO. The other technology used an infrared sensor with a target gas response range of 0 to 20.6% CO_2. The infrared carbon dioxide sensor was selected for testing on the basis that changes in flue concentrations of CO_2 might be used as an indicator of an increase in the flue concentration of CO in excess of the 400 ppm (air free) emissions standard for residential gas furnaces.

All of the objectives of this test program were accomplished. Each sensor exhibited a direct, linear response to its respective target gas and did not respond to non-target gases under various test conditions. The test results also demonstrate each sensor's capability to shutdown the furnace in response to elevated concentrations of CO within the flue. These results are limited to conditions exhibited by a high-efficiency gas furnace.

Issues such as sensor reliability, durability, expected life, and performance in higher temperature environments (e.g., 300°F to 500°F) were not addressed by this test program. Future test and evaluation of sensors should encompass a wider variety of sensor technologies, target gases, and exposure to potential contaminants. These issues are addressed in a draft test matrix developed by CPSC staff for the Canadian Standards Association (CSA)/American National Standards Institute (ANSI) Z21/83 Ad Hoc Working Group for CO/Combustion Sensors. The test matrix is part of a work plan to evaluate sensor usage in gas appliances developed by this working group for consideration by the CSA/ANSI Z21/83 Technical Committee. The CPSC staff will provide this test report to the technical committee, ad hoc working group, and the CSA/ANSI Z21.47 Central Furnace Technical Advisory Group to further support sensor evaluation and development of a performance standard.

II. INTRODUCTION

Hazard

Carbon monoxide 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.

One of CPSC's three strategic goals is to reduce the rate of death from CO poisonings associated with consumer products by 20 percent from the 1999-2000 average by the year 2013 (1999-2000 average yearly estimated CO poisoning deaths from unintentional non-fire consumer product-related incidents was 124).[1] The goal of this test program was to support development of a performance standard that would require shutdown or some other preemptive response to elevated levels of CO within the flue passageways of vented gas heating appliances (e.g., residential furnaces, boilers, and room heaters). The intended outcome is a reduction in CO-related deaths caused by gas heating appliances.

Gas heating systems are the leading cause of CO poisoning deaths associated with consumer products. From 1999-2001, there was an average yearly estimated 126 unintentional non-fire CO poisoning deaths associated with consumer products.[2] Heating systems of all types were associated with 69 deaths, or 65 percent of the CO poisoning deaths associated with consumer products excluding engine-powered tools.[3] Among heating systems, from 1999- 2001, natural gas heating was associated with an average yearly estimate of 28 deaths (41% of the heating system deaths); LP gas heating was associated with an average yearly estimate of 26 deaths (38% of the heating system deaths); and unspecified gas heating was associated with an average yearly estimate of 5 deaths (7% of the heating system deaths).[4] Overall, an average yearly estimate of 59 CO poisoning deaths from 1999-2001 were associated with the use of gas heating systems.[5]

Background

In 1996, CPSC staff proposed that the American National Standards Institute (ANSI)/Canadian Gas Association (CGA) Z21.47 Gas-Fired Central Furnace Subcommittee add requirements that furnaces shutdown when the vent pipe becomes disconnected or partially blocked to protect consumers from CO exposure hazards associated with these vent conditions.[6] 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.[7] In response to CPSC's proposal and incident data, the subcommittee, at its September 1997 meeting, voted on and adopted a draft work statement requesting that the Gas Research Institute (GRI): (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 draft work statement was submitted to GRI in December 1997. However, in the final version of the work statement, the technology assessment task was replaced with a task to conduct a root cause analysis of the CPSC IDIs.

In fiscal years 1999 and 2000, CPSC staff conducted emissions testing of five residential gas furnaces to support the continued development of performance standards to address CO exposure hazards.[8] 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 results were used to model indoor air concentrations[9] and assess health effects[10].

In 2000, the CPSC staff proposed that the furnace subcommittee adopt the following performance requirements to the furnace standard as alternatives to the disconnected and partially blocked vent proposals made in 1996:[11]

1. Require a means to prevent furnace CO emissions from exceeding the standard limits once installed in the field; or
2. Require a means, once installed in the field, to shut down the furnace if CO emissions exceed the standard limits.

Since "available technology" is often cited as a barrier to implementing performance standards, CPSC staff conducted patent and Internet searches to identify relevant technology. Two carbon monoxide sensing technologies were identified, acquired, and tested in an attempt to "prove the concept" of using sensor technology to detect elevated CO production within a gas furnace and initiate furnace shutdown in response. The objectives of that test activity were to:

1. Integrate sensor(s) into the vent system, flue passageways, or combustion chamber of a furnace;
2. Detect the presence of elevated levels of CO associated with the incomplete combustion of natural gas; and
3. Send a shutoff signal to the furnace control system when CO levels reach or exceed a pre-determined threshold.

CPSC staff successfully demonstrated this concept. In 2001, the test results[12] were shared with the ANSI Z21.47 Central Furnace Subcommittee in support of CPSC staff's proposals.[13] The furnace subcommittee voted to defer the issue to the Z21/83 Committee, citing that the issue of sensor shutdown of gas appliances was much broader than furnaces. In April 2002, the ANSI Z21/83 Committee voted to establish the CO/Combustion Sensor Ad Hoc Working Group to evaluate the use of gas sensors to shutdown gas appliances in response to excessive CO production.

The 2003 test activity reported here is an extension of the previous sensor evaluations conducted by CPSC staff and sought to address some of the issues not addressed in the previous work. In the 2003 testing, staff sought to determine whether temperature and relative humidity conditions likely encountered during appliance operation and periods of non-operation have an impact on sensor performance. Also, staff sought to use other combustion gases, such as carbon dioxide (CO_2) or oxygen (O_2), as indirect measures of elevated CO concentrations produced in an appliance during incomplete combustion. The intent is to share the findings of this study with industry groups such as the ANSI Z21/83 CO/Combustion Sensor Ad Hoc Working Group, the ANSI Z21.47 Central Furnace Technical Advisory Group, and the Gas Appliance Manufacturers Association (GAMA). The goal is to continue to stimulate the development of a CO/combustion sensor standard for vented gas heating appliances.

Objectives

The objectives of this test program were to:

1. Evaluate the performance of each sensor when exposed to the target gas in various temperature and humidity conditions;
2. Determine whether sensor performance is impacted by changes in non-target gas levels in various temperature and humidity conditions;
3. Demonstrate the ability of gas sensors to directly or indirectly measure a 400 ppm concentration of CO within the furnace vent system, combustion chamber, or flue passageways; and
4. Demonstrate the ability of gas sensors to send a shutoff signal to either the furnace control board or automatic/combination control valve in response to exposure to and direct or indirect detection of a CO concentration in excess of 400 ppm (air-free).

III. SENSOR DESCRIPTION

Electrochemical Carbon Monoxide Sensor

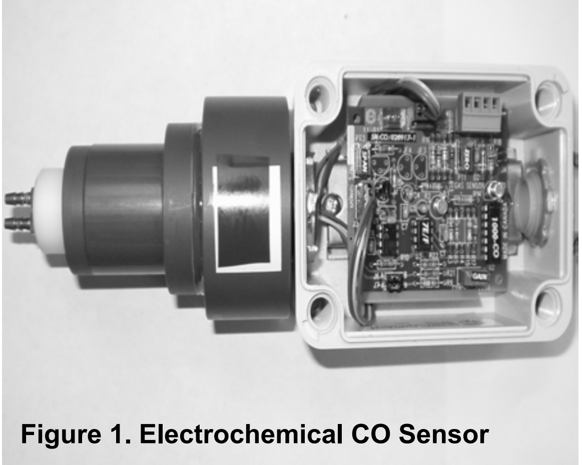


Figure 1. Electrochemical CO Sensor

One of the sensors tested by CPSC staff was a single gas, electrochemical (EC) sensor and circuit board assembly designed to detect and measure CO in concentrations between 0 and 1000 ppm. The EC sensor and circuit board assembly was provided by its manufacturer in a rugged, NEMA-4X enclosure. The unit requires a 12 to 30 direct current input voltage (VDC) to operate and provides a 4-20 mA output signal. Since the data acquisition software used by staff does not read current values, the EC sensor's current output signal was converted to a voltage output. This was accomplished by placing a 275-ohm resistor across its output terminals, which resulted in an output voltage range of approximately 1.1 to 5.5 volts. Carbon monoxide was delivered to the EC sensor cell through aspiration. This was accomplished by the use of a manufacturer supplied pump and separator assembly.

Infrared Carbon Dioxide Sensor

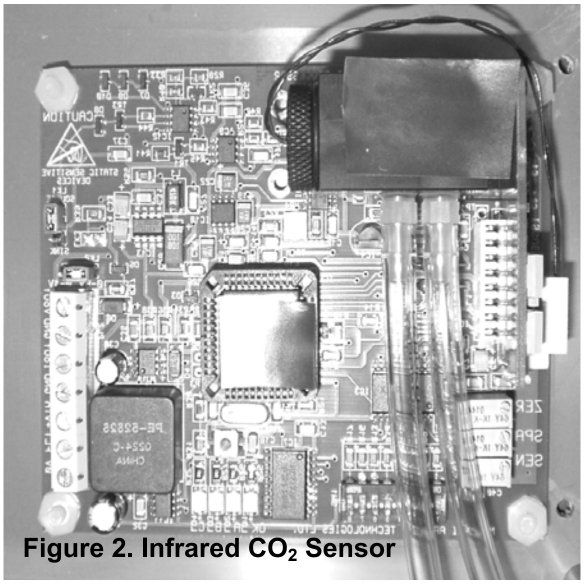


Figure 2. Infrared CO_2 Sensor

The other sensor tested by CPSC staff was a single gas, non-dispersive infrared (IR) sensor and heater board assembly designed to detect and measure carbon dioxide (CO_2) concentrations from 0 to 30%. In order to operate, the sensor and heater board assembly were connected to a 4-20mA transmitter (same manufacturer) via an 8-pin connector. The transmitter was switch configurable to operate with various IR sensors available from the manufacturer. The transmitter was equipped with an adjustable full-scale range of 8% to 100%. This allowed the sensor's full-scale output to be adjusted below its preset range of 30% CO_2. The maximum CO_2 concentration expected to be produced in the flue products of a natural gas appliance during the combustion process is approximately 12%. Staff adjusted the sensor/transmitter assembly scale setting to 20.06% to match the calibration gas used for the laboratory CO_2 analyzer. The transmitter was also equipped with switch selectable output for the standard 4-20mA current output or a 1-5 VDC output. Staff adjusted the output switch to provide a 1 to 5 VDC output to allow the signal to be read by the data acquisition software. The transmitter required 12 to 35 VDC to operate the sensor. Staff connected the sensor/transmitter assembly to a 24 VDC power supply. Carbon dioxide was delivered to the IR sensor through aspiration. This was accomplished using the pump and separator assembly used for the EC sensor.

IV. CHARACTERIZATION TEST RESULTS AND DISCUSSION

Test Chamber and Data Acquisition

Tests were conducted with the electrochemical CO sensor and the infrared CO_2 sensor to characterize their response when exposed to known concentrations of their respective target gases and possible interferent gases. The tests were conducted inside a Lunnaire model CEO932W-4 environmental chamber with a 33-ft^3 interior volume. This chamber is also used for residential CO alarm testing by CPSC staff. The chamber is equipped with Watlow Series 96 Temperature and Humidity Controllers. The Watlow 96 Temperature Controller has an adjustment range of 32°F to 210°F (0°C to 99°C). Characterization tests were conducted at nominal chamber temperature settings of 70°F and 120°F. The Watlow 96 Humidity Controller has an adjustment range of 20% to 95% relative humidity (RH). Characterization tests were conducted at nominal chamber relative humidity settings of 50% and 95%.

Since the electrochemical sensor and its circuit board were housed in a NEMA 4-4X, weatherproof, non-metallic enclosure, they were placed directly inside the chamber during testing. A small pump and separator assembly was used to draw gas samples into the sensor assembly in order to enable the chemical reaction. The infrared sensor and its circuit board were not housed in an enclosure and were therefore located outside of the chamber during testing. The pump and separator assembly used for the electrochemical sensor testing was also used to draw gas samples into the infrared sensor for measurement. The chamber is equipped with a heat exchanger and fan assembly to control temperature. The fans circulate air over the cooling coils of the heat exchanger and also mix 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. Environmental chamber and setup used for characterization testing.

Gas samples were obtained through six sample lines located within the chamber. The sample lines were joined in a common manifold from which a single mixed gas sample was sent to a multi-gas analyzer (Rosemount, Model NGA 2000). The NGA 2000 was equipped with five individual gas modules for the measurement of carbon monoxide (2 non-dispersive infrared (NDIR) gas modules, 1 carbon dioxide (NDIR) gas module, 1 oxygen (paramagnetic) gas module, and 1 hydrocarbon (NDIR) gas module). The air temperature in the chamber was measured at a single point at the approximate center of the chamber using a K-type thermocouple (Omega).

A data acquisition system was used to record the sensor performance data and gas concentrations. The data acquisition system consisted of a personal computer, data acquisition interface hardware (Data Translation), 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). For CO response and interference tests, pure CO was injected into the chamber and controlled at concentrations ranging from 100 to 500 ppm. For CO_2 response and interference tests, pure CO_2 was injected into the chamber and controlled at concentrations ranging from 1% to 12%. For O_2 response and interference tests, the chamber O_2 was depleted in increments of 1% by injecting pure nitrogen into the chamber, thus displacing chamber oxygen. The oxygen was depleted from a normal atmospheric level of approximately 20.6% down to approximately 10% in one test and 7% in another test. 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.

Response Test Discussion

One of the objectives of this test program was to evaluate sensor performance when exposed to various concentrations of a respective target gas. The response tests performed by CPSC staff included three test variables: chamber target gas concentration, chamber humidity, and chamber temperature. By controlling these variables within the environmental chamber, staff was able to assess the sensitivity of each sensor in environmental conditions that approximate likely conditions a sensor would encounter in an appliance while operating and during periods of non-operation. Each sensor's output voltage was measured in response to exposure to increasing concentrations of a target gas at varying chamber temperatures and relative humidities. The response test matrices are provided in Appendix A.

Another objective of this test program was to determine whether sensor response was impacted by temperature and relative humidity conditions likely to be encountered in a furnace during periods of operation and non-operation. Chamber conditions of 70°F and 50% RH, 70°F and 95% RH, 130°F and 50% RH, and 130°F and 95% RH were selected for that purpose. The 70°F chamber temperature was selected to represent typical ambient temperatures a sensor would be exposed to during appliance off times. The chamber temperature of 130°F was selected to expose each sensor to its maximum operating temperature as well as temperatures expected to occur in the vent pipe and flue passageways of the test furnace and other high efficiency gas furnaces. Relative humidities of 50% and 95% were selected to represent moderate and extreme conditions during appliance on times and off times. The chamber temperatures and relative humidities cited in the test matrices in Appendix A were target values and included tolerances of +/- 10°F and +/- 10% RH, respectively. The test results reported herein report sensor performance at actual temperature and relative humidity conditions.

For each test, sensor performance was evaluated using a scatter plot of sensor voltage as a function of target gas concentration. The line equation and coefficient of correlation were estimated for each scatter plot. Comparisons were made of each line equation to determine whether changes in temperature or relative humidity impacted sensor performance. The coefficient of correlation (R^2) was used to estimate how linear the sensor response was for varying concentrations of its target gas. A linear response provides a measure of whether sensor output voltage is proportional to varying concentrations of its target gas.

In addition to determining if they exhibited a linear response, each sensor's response voltage was later used to shutdown the test furnace in response to a direct or indirect measurement of a flue CO concentration of 400 ppm. Proportional and corresponding changes in other flue gases, such as carbon dioxide, oxygen, or methane were examined as possible means to indirectly measure CO. Therefore, for the electrochemical CO sensor, response voltages at this concentration were selected as the target voltages to be used later during furnace shutdown tests. It was also necessary to determine sensor response at chamber CO concentrations below 400 ppm in order to determine whether the voltages at the lower CO concentrations would be distinctive from voltages at 400 ppm. Testing the sensor at different concentrations within its response range was also needed to establish whether each sensor exhibited a linear response. For the infrared CO_2 sensor it was necessary to determine sensor output in response to a concentration of CO_2 that corresponded closely to 400 ppm CO in the flue of the furnace. The approach taken by CPSC staff to determine this concentration will be discussed in the section on infrared sensor shutoff testing.

Electrochemical CO Sensor Response Tests

The response range specified by the manufacturer of the electrochemical CO sensor is 0 to 1000 ppm of CO. Since one of the objectives was to utilize sensor response at or near 400 ppm CO, it was not necessary to test the sensor to its full range. With 24 VDC applied to the sensor, pure CO was injected into the chamber at flow rates and durations adequate to achieve nominal chamber concentrations of 100, 200, 300, 400, and 500 ppm. The response test matrices for the EC sensor are provided in Appendix A, Table A.1. Although the response range for the EC sensor is 0 to 1000 ppm CO, CPSC staff decided to determine sensor performance up to the target CO concentration of 400 ppm. The test point of 300 ppm CO was necessary to determine if the output signals were adequately distinct to prevent nuisance response at CO concentrations below the target concentration. The test point of 500 ppm CO was necessary to determine if the output signals were adequately distinct to prevent sluggish response to CO concentrations above the target concentration. The resultant sensor voltages at these concentrations were recorded using the data acquisition system described earlier. Sensor voltages were also recorded in normal air (i.e., approximately zero ppm CO). The results of the response tests are presented in Table 1 and Graphs 1 through 4.

The EC sensor exhibited a linear increase with increasing CO concentration during tests at each of the four temperature and humidity conditions. This linear relationship is illustrated in Graphs 1 through 4. For each test, the equations that describe this relationship and the coefficient of correlation (R^2) were estimated. As seen by the R^2 near unity, the EC sensor voltage increase exhibited close correlation to increases in CO concentration. At 64^oF and 50% R.H. the coefficient of correlation (R^2) was 0.9721. At 70^oF and 92% R.H. the R^2 value was 0.9963. At chamber conditions of 120^oF and 50% R.H. and 131^oF and 90% R.H. the R^2 values were 0.9875 and 0.9687, respectively.

Table 1. Electrochemical Sensor Response Test Results

EC CO Sensor Response Test (64°F, 50% RH)

	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output
	(ppm)	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**
Nominal	**100**		**200**		**300**		**400**		**500**	
Actual										
Min	101	1.24	199	1.36	320	1.51	399	1.68	488	1.82
Max	113	1.34	208	1.48	337	1.67	421	1.79	502	1.97
Avg	108	1.30	204	1.42	329	1.59	414	1.74	495	1.90

EC CO Sensor Response Test (70°F, 92% RH)

	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output
	(ppm)	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**
Nominal	**100**		**200**		**300**		**400**		**500**	
Actual										
Min	101	1.62	196	2.04	296	2.51	402	2.89	498	3.13
Max	110	1.67	213	2.16	311	2.55	414	2.91	509	3.23
Avg	105	1.65	202	2.11	303	2.55	407	2.91	503	3.21

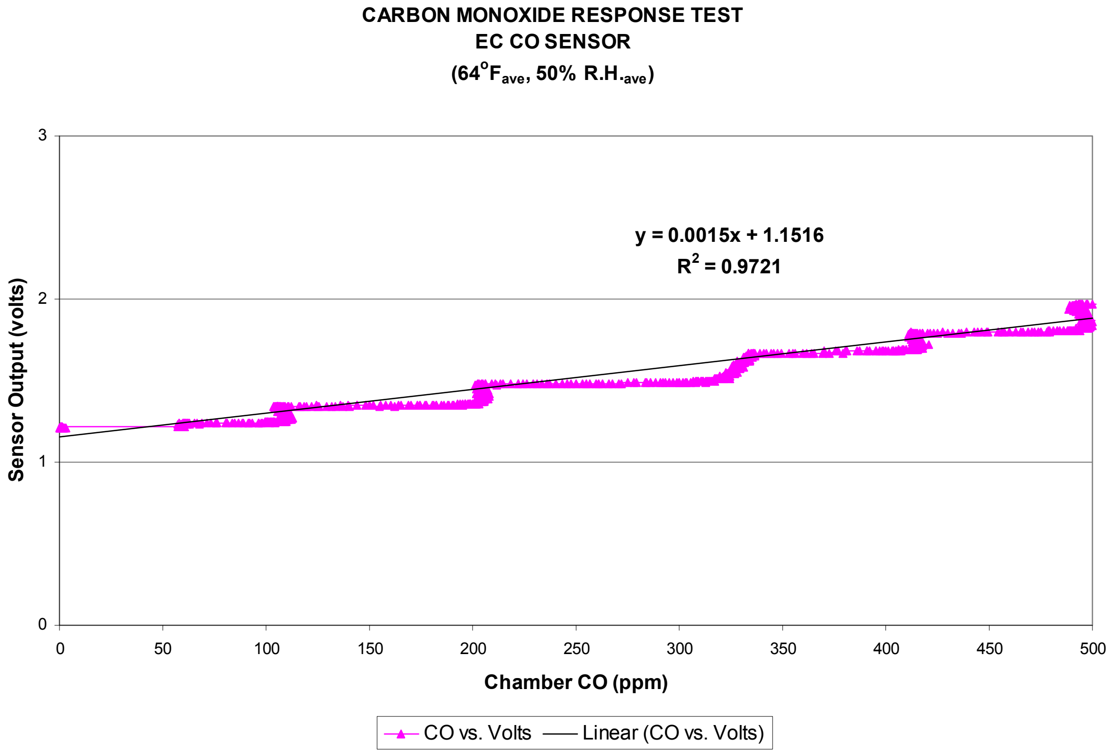
EC CO Sensor Response Test (120°F, 50% RH)

	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output
	(ppm)	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**
Nominal	**100**		**200**		**300**		**400**		**500**	
Actual										
Min	90	1.52	200	2.07	300	2.79	398	3.65	459	3.85
Max	110	1.64	216	2.19	317	3.07	413	3.69	473	3.92
Avg	97	1.58	208	2.16	310	3.02	406	3.67	469	3.90

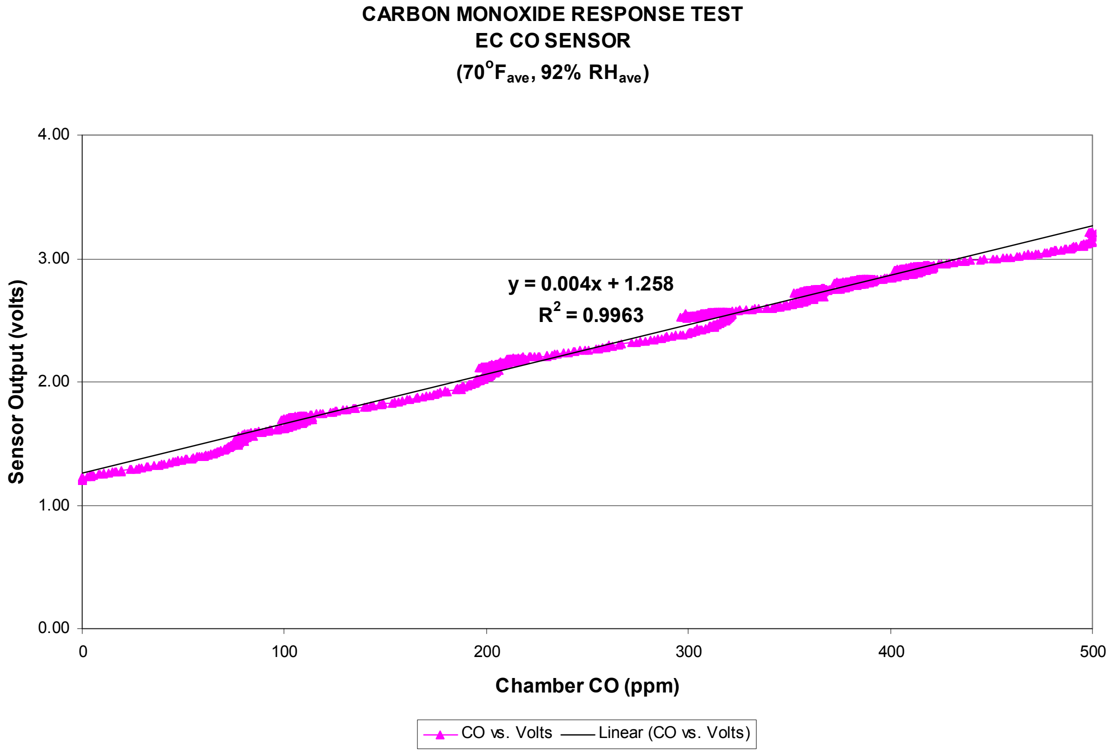
EC CO Sensor Response Test (131°F, 90% RH)

	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output	CO	Sensor Output
	(ppm)	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**	**(ppm)**	**(volts)**
Nominal	**100**		**200**		**300**		**400**		**500**	
Actual										
Min	150	1.83	280	2.61	338	3.20	401	3.62	448	3.78
Max	170	2.08	300	2.98	363	3.59	416	3.73	464	3.83
Avg	164	1.85	295	2.65	346	3.27	411	3.67	458	3.81

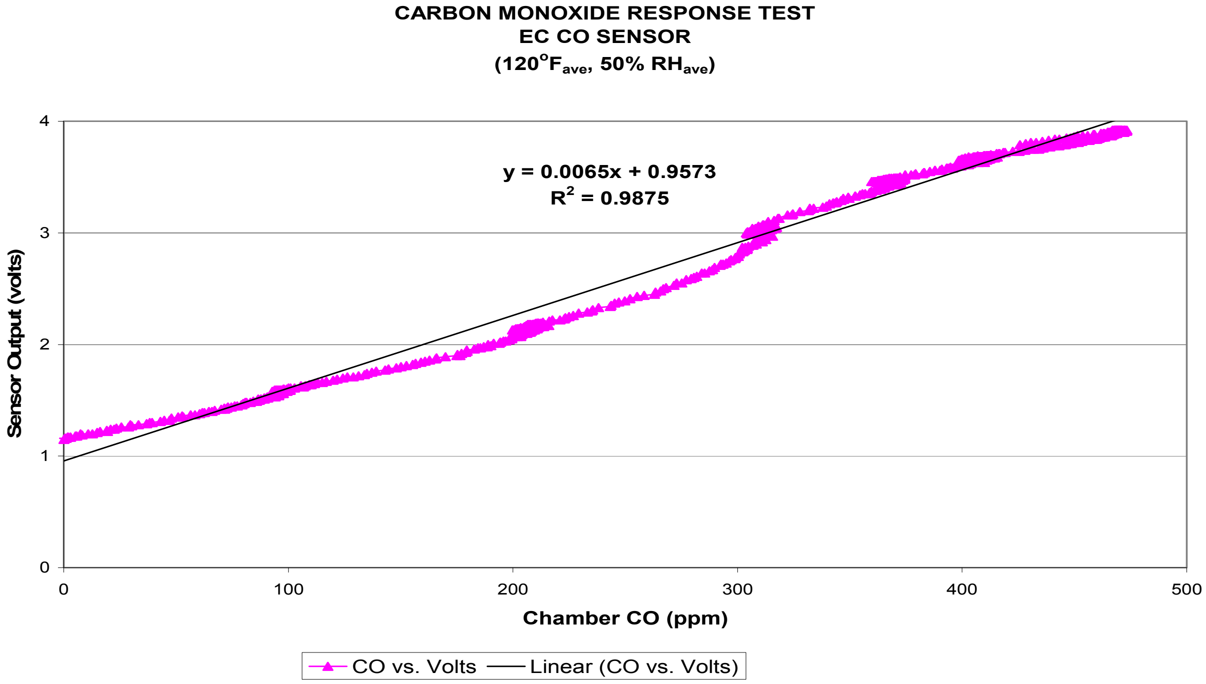
Graph 1. Electrochemical Sensor Response at 64°F and 50% Relative Humidity



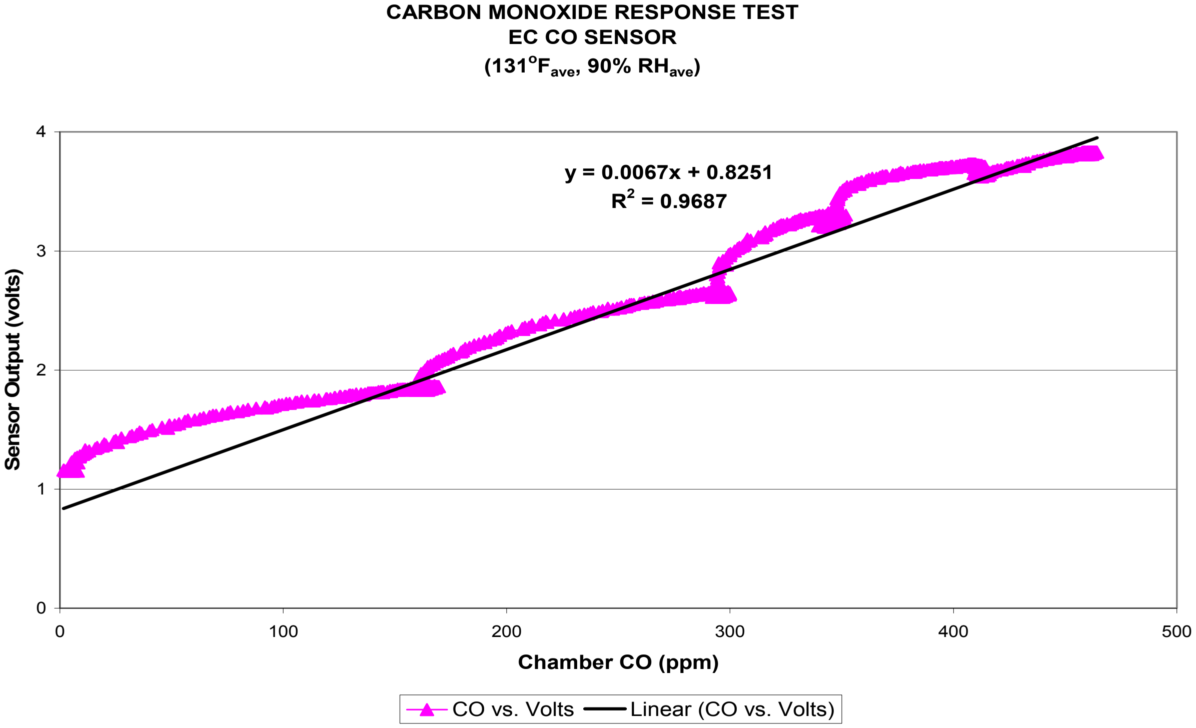
Graph 2. Electrochemical Sensor Response at 70°F and 92% Relative Humidity



Graph 3. Electrochemical Sensor Response at 120°F and 50% Relative Humidity



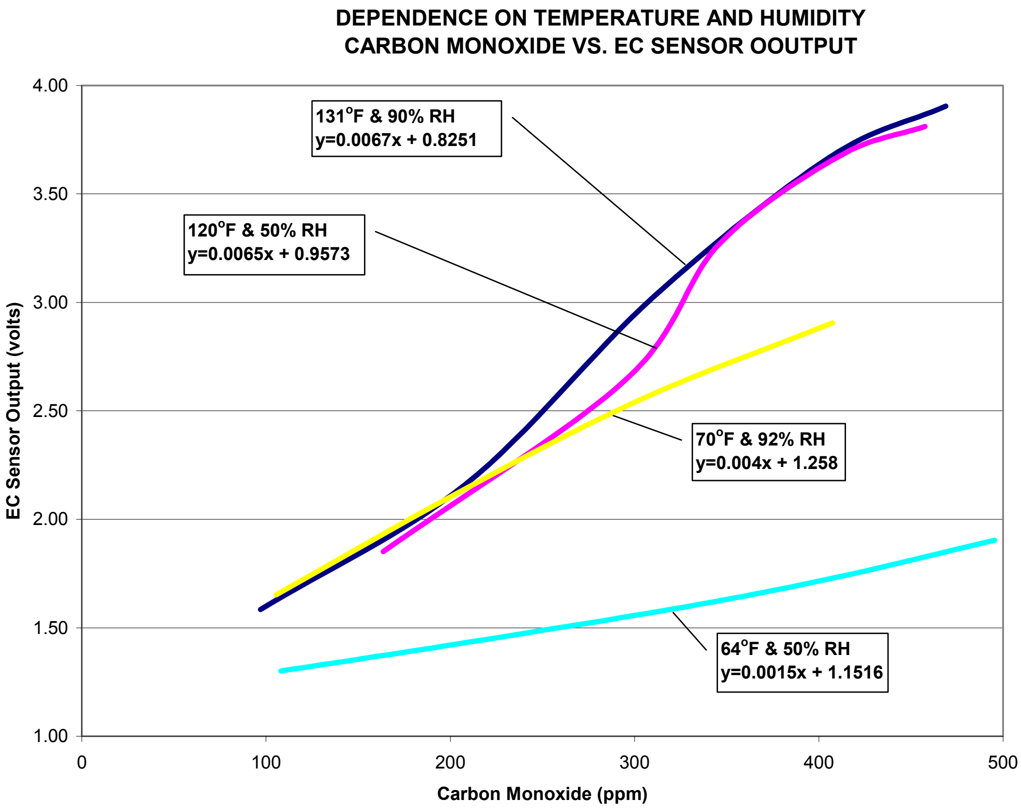
Graph 4. Electrochemical Sensor Response at 131°F and 90% Relative Humidity



Although the EC sensor exhibited a direct, linear response and close correlation to changes in CO concentration during each test, it also exhibited dependence on relative humidity and temperature. This was demonstrated by increases in response voltage as humidity and temperature was increased. Comparison of the line equations from each test revealed the slope of the line increased as temperature and humidity increased. This resulted in a larger sensor output voltage in response to the target gas. This dependency on temperature and humidity is shown in Graph 5 and in Table B.2 of Appendix B. When humidity and temperature increased, sensor voltage increased. At a nominal CO concentration of 400 ppm, the sensor exhibited an increase in response voltage as the humidity and temperatures were increased.

At average chamber conditions of 64^{o}F and 50% RH, the average sensor output was 1.74 volts at an average chamber CO of 414 ppm. At chamber conditions that averaged 70^{o}F and 92% RH, the average sensor output increased to 2.91 volts at an average chamber CO concentration of 407 ppm. This represents a 40% increase in sensor voltage over the previous chamber conditions. When the temperature was increased to an average of 120^{o}F and humidity held at 50% RH, the average sensor output increased to 3.67 volts at an average chamber CO concentration of 406 ppm. This represents a 21% increase in sensor voltage over the previous chamber conditions. When the temperature averaged 131^{o}F and the humidity held at 90% RH, the average sensor output remained at 3.67 volts at an average chamber CO of 411 ppm.

Graph 5. Electrochemical Sensor Dependence on Temperature and Relative Humidity



When test data at the nominal chamber CO concentration of 400 ppm was compared, the average sensor output increased from 1.74 volts to 3.67 volts when temperature was increased from 64°F to 120°F and humidity was held constant at 50% RH. The average sensor output increased from 2.91 volts to 3.67 volts when temperature was increased from 70°F to 131°F and humidity averaged between 90% and 92% RH. This represented changes of 53% and 21% based on the respective changes in temperature.

The average sensor output increased from 2.91 volts to 3.67 volts when humidity was increased from an average of 50% RH to an average of 92% RH and temperature averaged between 64°F and 70°F. At 130°F, the average sensor output did not increase, but remained at 3.67 volts when humidity was increased from 50% RH to 95% RH. This represented a change of 21% and no change based on the respective changes in relative humidity. This analysis demonstrated that the EC sensor was dependent on humidity and temperature. The EC sensor seemed to be more dependent on temperature than relative humidity since the greatest percentage change in output voltage occurred when temperature was increased.

The EC sensor's dependence on temperature and humidity resulted in different output voltages at the same nominal chamber concentrations of CO. However, this fact alone would not disqualify it as a candidate sensor for gas appliance shutoff. Rather it necessitates compensation for changes in temperature and humidity and a careful selection of a target voltage at temperatures and humidities likely to be encountered in a particular gas appliance. In fact, the stronger more distinct signal at higher temperature and humidity would also prevent nuisance trips during periods in which the appliance is not operating.

Infrared CO_2 Sensor Response Tests

Prior to testing, the IR sensor's full-scale range limit was adjusted to 20.06 % CO_2 and 24 VDC was applied to it. The concentration of CO_2 within the flue products of a natural gas appliance can range from under 1% to a maximum of 12% during the combustion process. In order to assess the IR sensor's response at these concentrations, pure CO_2 was metered into the chamber at flow rates and durations that increased chamber CO_2 concentrations from 0% to 12% in increments of 1%. The response test matrices for the IR sensor are provided in Appendix A, Table A.2. The resultant sensor voltages at these concentrations were recorded using the data acquisition system described earlier. Sensor voltages were also recorded in normal air (i.e., approximately zero percent CO_2). The results of the response tests are presented in Table 2 and Graphs 6 through 9.

As was the case with the EC sensor, the IR sensor also exhibited a direct linear response to chamber CO_2 at each of the four temperature and humidity conditions. This linear relationship is illustrated in Graphs 6 through 9. For each test, the equations that describe this relationship and the coefficient of correlation (R^2) were determined. As seen by coefficients of correlation near unity (i.e., 1.0), the IR sensor also exhibited a high degree of association to CO_2 concentrations. At nominal chamber conditions of 70°F and 50% RH and 130°F and 50% RH the R^2 values were 0.9993 and 0.9995, respectively. At average chamber conditions of 125°F and 91% R.H., the R^2 values was 0.9999.

Unlike the EC sensor, the IR sensor did not exhibit any dependence on temperature or humidity. As seen by the slope of the lines for the plotted response data, the degree of change in sensor output voltage in response to increasing concentration in chamber CO_2 (i.e., the slope of the line) did not increase or decrease as temperature or humidity was increased.

Table 2. Infrared Sensor Response Test Results

IR CO$_2$ Sensor Response Test (70^{o}F, 50% RH)

	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)
Nominal	**1**		**2**		**3**		**4**		**5**		**6**	
Actual												
Min	0.90	1.18	1.90	1.37	2.91	1.56	3.90	1.75	4.91	1.95	5.91	2.13
Max	1.10	1.22	2.10	1.41	3.10	1.61	4.09	1.78	5.15	1.99	6.20	2.20
Avg	1.07	1.21	2.07	1.40	3.08	1.59	4.05	1.78	5.11	1.98	6.13	2.17

IR CO$_2$ Sensor Response Test (130^{o}F, 50% RH)

	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)
Nominal	**1**		**2**		**3**		**4**		**5**		**6**	
Actual												
Min	1.01	1.21	2.01	1.40	2.90	1.57	4.00	1.78	4.91	1.96	5.90	2.14
Max	1.43	1.29	2.40	1.48	3.19	1.62	4.39	1.86	5.20	2.02	6.20	2.20
Avg	1.35	1.27	2.35	1.46	3.06	1.60	4.27	1.83	5.03	1.98	6.09	2.18

IR CO$_2$ Sensor Response Test (125^{o}F, 91% RH)

	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)	CO$_2$ (%)	Sensor Output (volts)
Nominal	**1**		**2**		**3**		**4**		**5**		**6**	
Actual												
Min	0.91	1.16	1.92	1.35	2.91	1.52	3.90	1.71	4.91	1.89	5.91	2.07
Max	1.20	1.22	2.21	1.41	3.19	1.58	4.20	1.76	5.21	1.94	6.20	2.14
Avg	1.09	1.20	2.16	1.40	3.15	1.57	4.06	1.74	5.15	1.94	6.15	2.12

Table 2. Infrared Sensor Response Test Results (Continued)

IR CO_2 Sensor Response Test (70°F, 50% RH) - continued

	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output
	(%)	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**
Nominal	**7**		**8**		**9**		**10**		**11**		**12**	
Actual												
Min	6.90	2.31	7.90	2.50	8.90	2.65	9.90	2.85	10.91	3.03	11.40	3.13
Max	7.20	2.37	8.19	2.55	9.20	2.73	10.00	3.01	11.21	3.09	11.63	3.17
Avg	7.15	2.36	8.11	2.53	8.98	2.69	9.99	2.96	11.06	3.07	11.57	3.16

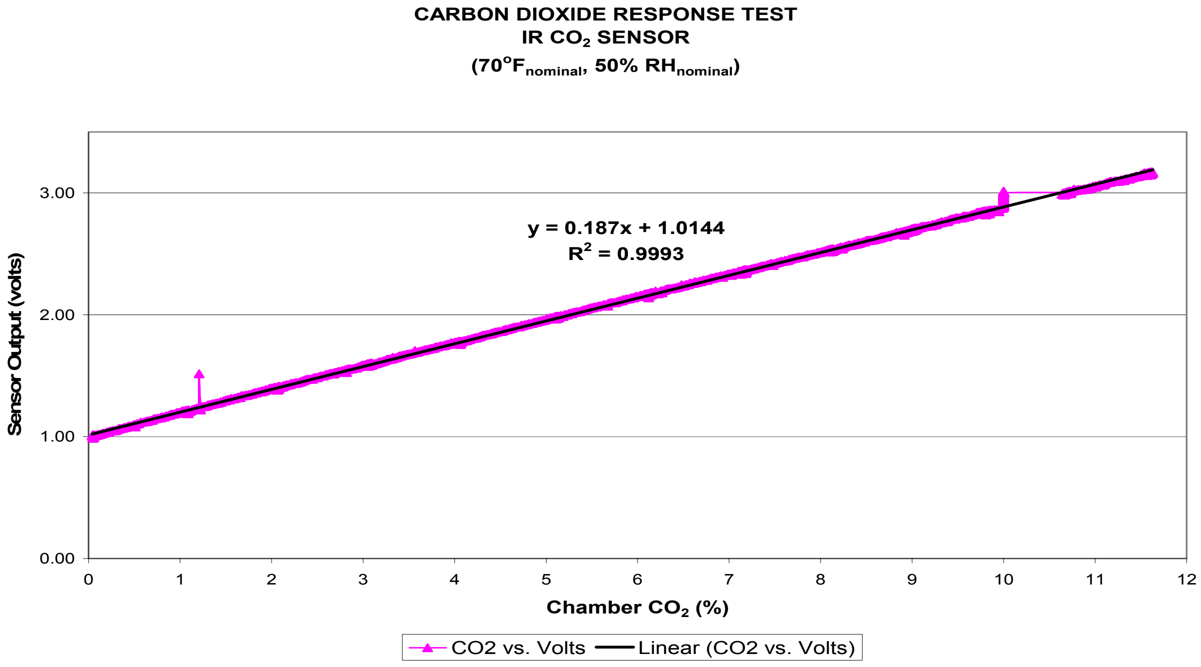
IR CO_2 Sensor Response Test (130°F, 50% RH) - continued

	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output
	(%)	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**
Nominal	**7**		**8**		**9**		**10**		**11**		**12**	
Actual												
Min	6.90	2.33	7.91	2.51	8.90	2.64	9.91	2.89	10.90	3.08	11.90	3.27
Max	7.20	2.37	8.20	2.56	9.19	2.75	10.87	3.07	11.20	3.13	12.09	3.31
Avg	7.11	2.36	8.14	2.55	9.15	2.74	10.00	2.93	11.06	3.11	12.05	3.30

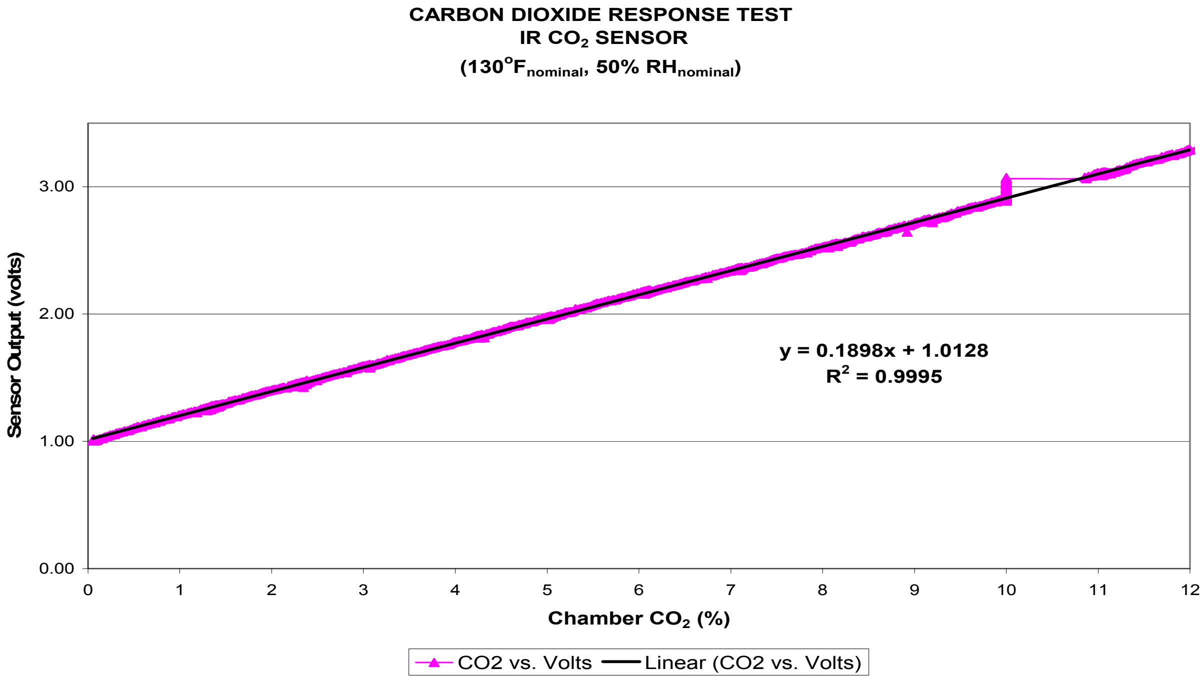
IR CO_2 Sensor Response Test (125°F, 91% RH) - continued

	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output	CO_2	Sensor Output
	(%)	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**	**(%)**	**(volts)**
Nominal	**7**		**8**		**9**		**10**		**11**		**12**	
Actual												
Min	6.91	2.25	7.91	2.42	8.90	2.60	9.91	2.78	10.90	2.97	11.90	3.14
Max	7.11	2.29	8.11	2.46	9.20	2.66	10.20	2.85	11.20	3.02	12.22	3.21
Avg	7.04	2.28	7.99	2.45	8.99	2.62	10.06	2.83	11.06	3.00	12.10	3.19

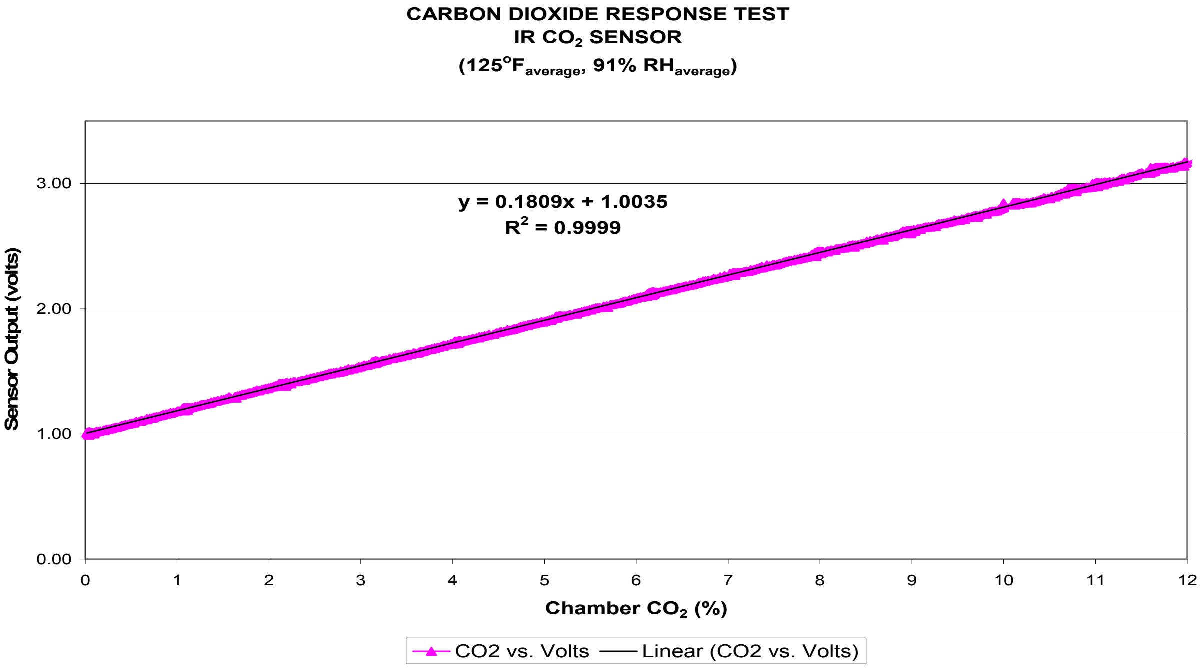
Graph 6. Infrared Sensor Response at 70°F and 50% Relative Humidity



Graph 7. Infrared Sensor Response at 130°F and 50% Relative Humidity



Graph 8. Infrared Sensor Response at 125^{o}F and 91% Relative Humidity



Interference Tests

National standards for residential CO alarms such as CSA 6.19 and UL 2034 require that CO alarms be subjected to a selectivity test which involves exposure to a variety of gases that represent possible household contaminants. The purpose of the selectivity test is to determine if any of the contaminant gases will trigger a CO alarm actuation. The objective of the interference tests conducted by CPSC staff was similar in that it allowed staff to determine if varying quantities of "non-target" gases encountered in the operating environment of a sensor impacted sensor performance. This evaluation, however, was not as exhaustive as those required by UL and CSA. Test gases were limited to those for which CPSC had analytical equipment with which to measure the gases. For a more exhaustive evaluation of sensor selectivity, gas sensors considered for deployment in appliances should be subjected to selectivity test requirements similar to those found in CSA 6.19 and UL 2034.

As with the response tests discussed earlier, the Interference Tests are also essentially three tests in one, since they combine various humidity and temperature conditions with selectivity testing. The electrochemical sensor and infrared sensor are each designed to respond to a single gas species. However, during the combustion of natural or liquefied petroleum gas (LP-gas) a variety of chemical species and other by-products of combustion are produced. Therefore, any single gas species sensor that might be deployed in a gas appliance would also be exposed to other gas species produced during the combustion process. If a sensor were to be deployed in a gas appliance, these other gas species might impact or interfere with sensor performance and cause a nuisance shutdown, or worse, prevent the sensor from sending a shutoff signal during a hazard condition. CPSC staff conducted a series of tests to determine whether other combustion products had an interfering effect on sensor performance. Although there are also a variety of potential contaminants found in the household environment that might interfere with sensor performance, testing was limited to only those gas species that CPSC had analytical equipment to measure: carbon monoxide, carbon dioxide, and oxygen.

Interference tests involved exposing each sensor to various concentrations of non-target gases. Therefore, the interferent gases used to test the electrochemical CO sensor were carbon dioxide and oxygen. The test matrices used to evaluate the EC sensor response to interferent gases are provided in Appendix A, Tables A.2. and A.3. The interferent gases used to test the infrared CO_2 sensor were carbon monoxide and oxygen. The test matrices used to evaluate the IR sensor response to interferent gases are provided in Appendix A, Tables A.1. and A.3. As part of the interference testing, the chamber temperature and relative humidity were adjusted to replicate operating conditions within the vent system or flue passageways of the test furnace, as well as ambient conditions within the household during periods of appliance inactivity. Thus, tests were conducted at combinations of chamber temperatures of 70^{o}F and 120^{o}F to 130^{o}F and relative humidities of 50% and 95%, respectively. The test gases were introduced into the test chamber as described earlier. After being exposed to the test gases, if a given sensor did not generate a voltage response above its output in normal air, then the test gas was not considered to have an interferent effect on the sensor.

The manner in which the test gas was introduced into the chamber was varied among tests. In some of the tests, the test gases were ramped up in incremental amounts and held at these concentrations for periods ranging from approximately two to five minutes. This approach is denoted by the stepped gas concentration curves. In the other tests, the test gases were introduced into the chamber via constant injection. This approach is denoted by the continuous curves showing a rapid increase in the concentration of the test gases.

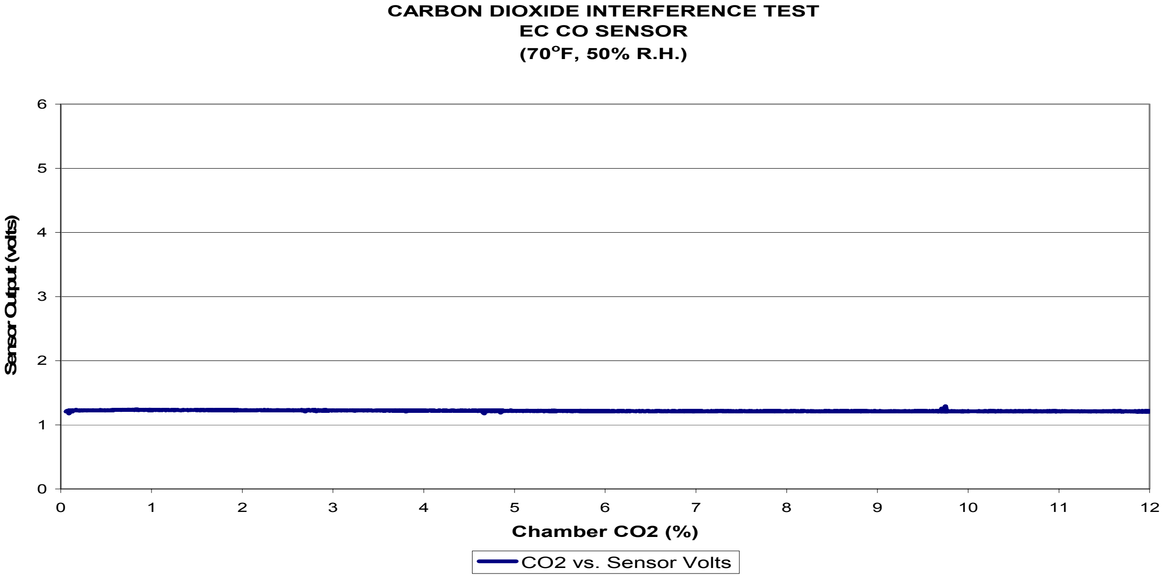
Electrochemical CO Sensor Interference Test Results

The voltage output for the electrochemical CO sensor in normal air was approximately 1.2 volts. As seen by the plots of the test results of the electrochemical sensor voltage (Graphs 9-12), the voltage did not change when exposed to CO_2 or O_2. During one of the interference tests involving CO_2 (see Graph 12) a momentary, negligible change in voltage was observed from the electrochemical CO sensor. This change in voltage was attributed to the fact that the test gas (CO_2) used during this test was not pure and had trace amounts of CO in it. Under the specified test conditions the electrochemical CO sensor did not exhibit interference when exposed to increased concentrations of CO_2 or depleted concentrations of O_2. The CO_2 interference test was designed to expose the EC sensor to the full range (0 to 12%) of CO_2 concentrations in flue products it would likely encounter during furnace operation and periods of non-operation.

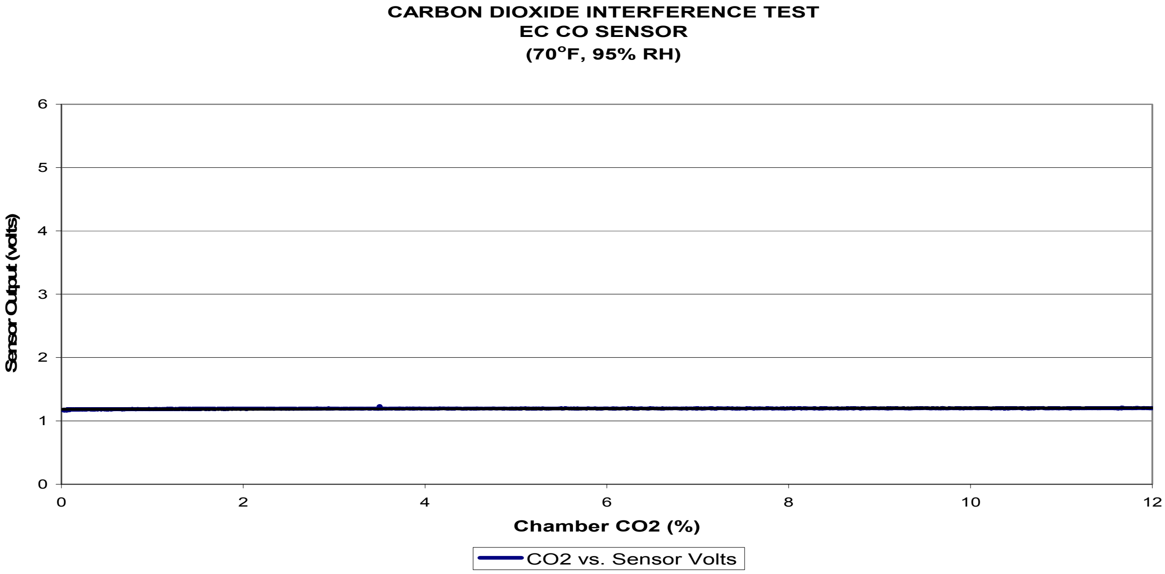
The purpose of the O_2 interference tests was to determine whether the EC sensor performance was affected when exposed to concentrations of O_2 during periods of non-operation and periods of furnace operation. An O_2 concentration of 20.94% was selected to represent a level a sensor (deployed in a furnace) would be exposed to during appliance non-operation. During furnace operation, O_2 concentrations can vary from 10% to as low as 1%, depending on the firing rate and other factors that lead to CO production, such as a partially blocked vent.

The EC sensor performance was not interfered with at O_2 concentrations between 21% and 6.81%. This was demonstrated by the constant trace of sensor voltage in Graph 13. Sensor voltage remained at its zero CO level of approximately 1.2 V. Unfortunately, staff encountered difficulty depleting chamber O_2 concentrations below 6.81%. As shown later in the flue gas profile tests in Table B.1 in Appendix B, average flue concentrations of O_2 ranged from 6.46% to 9.34% depending on the manifold pressure before the vent became blocked. Average CO concentrations in the flue ranged from 8 to 13 ppm. When the vent was blocked, O_2 was depleted and CO concentrations rose rapidly. Average O_2 concentrations within the flue ranged from 3.78% to as low as 1.1%. Average CO concentrations ranged from 62 to 432 ppm. Such a significant change suggests that O_2 depletion would be an excellent proxy to indicate excessive levels of CO.

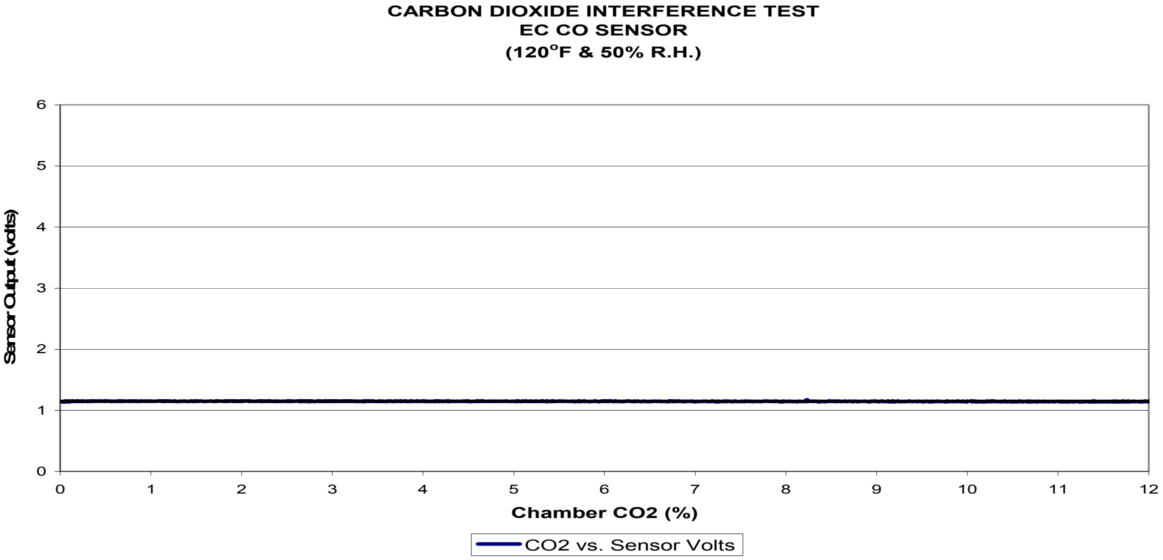
Graph 9. EC Sensor Interference from CO_2 at 70°F and 50% Relative Humidity



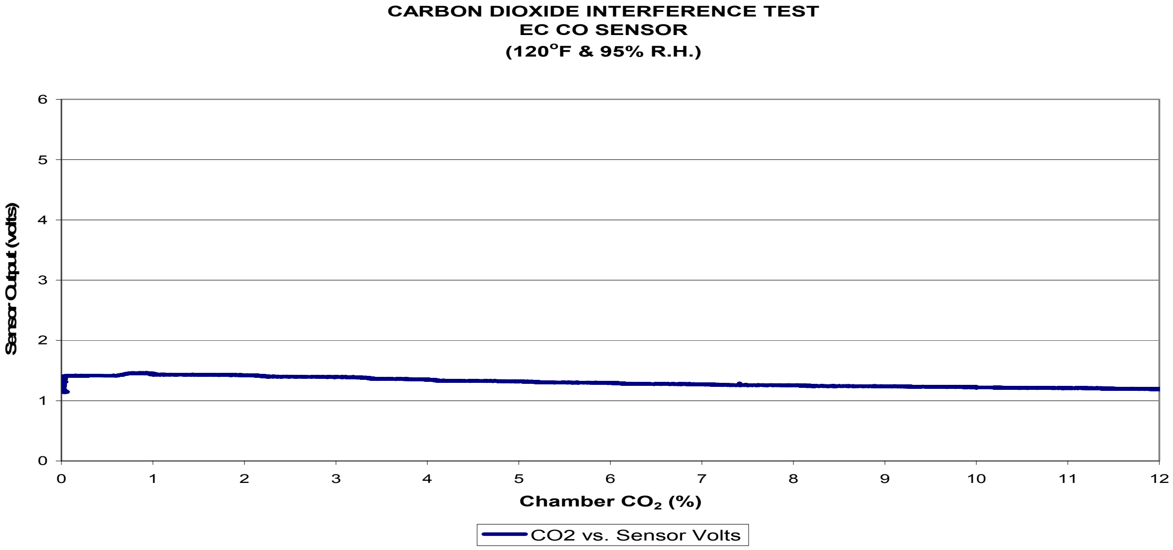
Graph 10. EC Sensor Interference from CO_2 at 70°F and 95% Relative Humidity



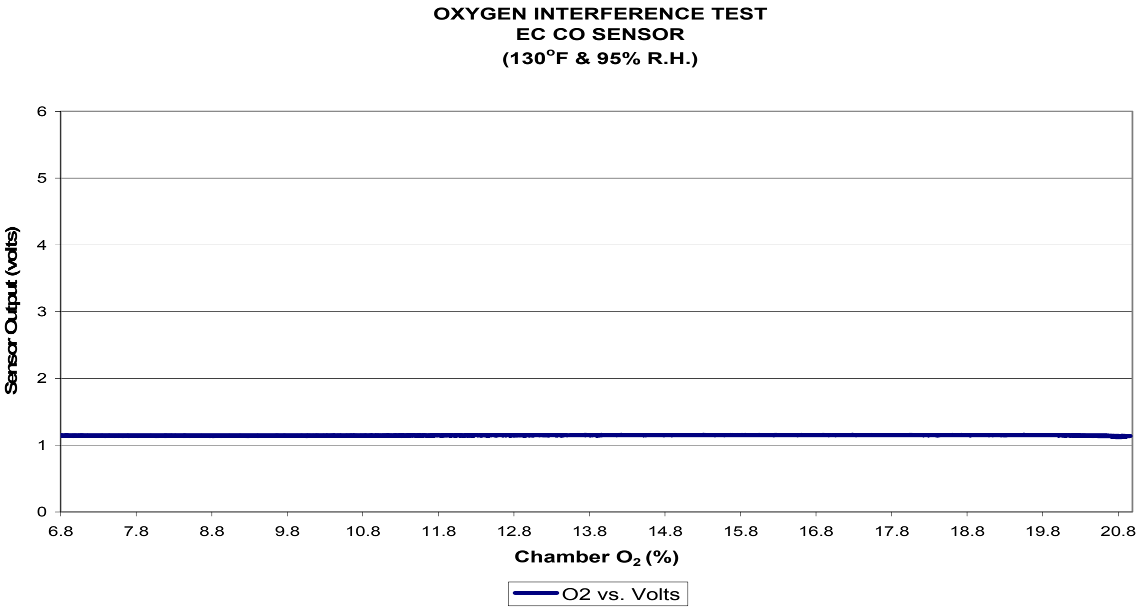
Graph 11. EC Sensor Interference from CO_2 at 120°F and 50% Relative Humidity



Graph 12. EC Sensor Interference from CO_2 at 120°F and 95% Relative Humidity



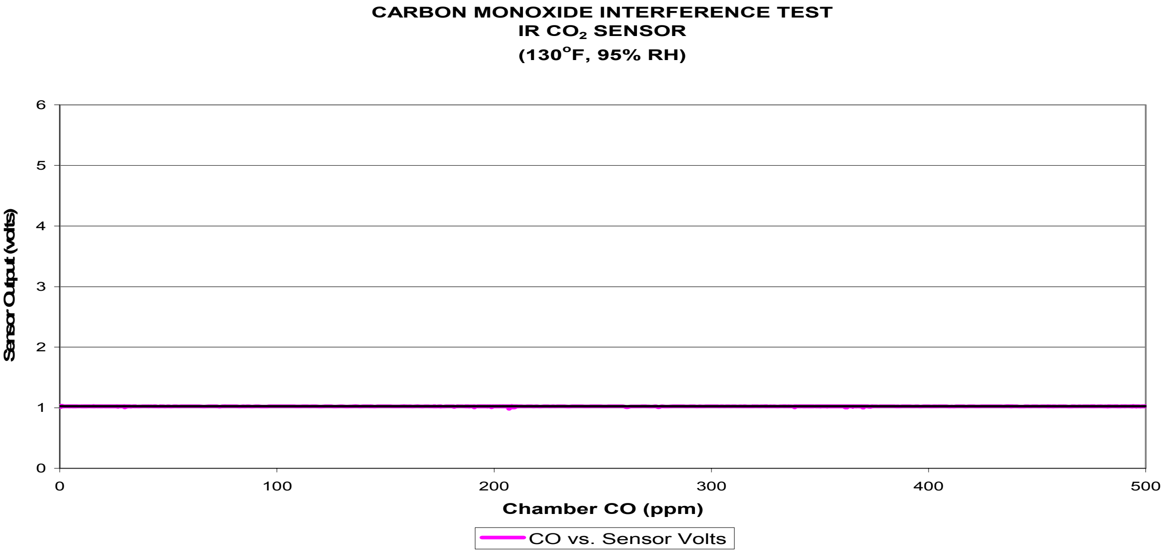
Graph 13. EC Sensor Interference from O_2 at 130°F and 95% Relative Humidity



<u>Infrared CO_2 Sensor Interference Test Results</u>

The voltage output for the infrared CO_2 sensor in normal air was approximately 1.0 volts. As seen in Graph 14, sensor voltage did not change when the sensor was exposed to different concentrations of CO at a chamber condition of 130°F and 95% RH. Time did not permit testing of the IR sensor under the various other chamber conditions. However, the conditions it was tested under are the most representative of what the sensor would encounter during furnace operation. Also, due to the problems encountered depleting the chamber O_2 levels to those encountered during incomplete combustion (See Table B.1, Appendix B), staff did not conduct an interference test with the IR sensor exposed to declining concentrations of O_2.

Graph 14. IR Sensor Interference from CO at 130°F and 95% Relative Humidity



V. FURNACE SENSOR SHUTOFF TESTS AND DISCUSSION

Test Chamber and Flue Gas Sampling

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, as well as corresponding CO_2 concentrations in the furnace flue products, and send a shutoff signal to the furnace controls. As received, the sensing elements for the electrochemical CO sensor or the infrared CO_2 sensor were not designed for exposure to condensate. Therefore, gas samples were drawn from the furnace vent pipe using the pump and separator assembly used during characterization testing. Flue gas samples were drawn from a threaded, 90-degree section of a 3-inch diameter Schedule 40 PVC Vent Tee. A 1/8 inch brass fitting was tapped into the center of a 3-inch diameter Schedule 40 PVC, threaded Vent Tee plug. Plastic tubing with brass couplings was connected between the sensor and the Vent Tee plug.

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 standard for residential gas furnaces, ANSI Z21.47, American National Standard for Gas-Fired Central Furnaces, requires that furnace CO concentrations not exceed 400 ppm in an air free flue sample, this concentration was selected as the set point 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, directly or indirectly, to approximately 400 ppm of CO in the characterization tests. Attempts were made to adjust the degree of vent blockage and manifold pressure to ensure that the furnace would generate 400 to 450 ppm of CO. However, it was found that more precise control of these parameters would be needed in order to assure that the furnace CO generation would consistently be in that range.

Figure 4. Furnace shutoff test setup.

The tests were conducted inside a chamber with internal dimensions of 10 feet wide, by 12 feet long, by 7 feet high and an internal volume of 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 closet dimensions were 4.33 feet wide, by 6.25 feet long, by 7.08 feet high and an internal volume of 191.6 cubic feet. A full view of the Furnace Sensor Shutoff Test Setup is shown in Figure 4.

A gas sampling system was used to measure the concentrations of different chemical species within the flue gas products of the furnace. The system was used to obtain CO, CO_2, O_2, and methane (CH_4) samples from the flue gas. Flue gas samples were taken from a single location downstream of the flue collar, adjacent to the vent-mounted CO sensor. The system was equipped with three non-dispersive infrared (NDIR) gas analyzers to measure CO, CO_2, and CH_4 concentrations and one paramagnetic analyzer to measure O_2 concentrations.

Shutoff Circuit to Furnace

Staff used the same furnace and shutoff circuit used in previous CO sensor testing (ref. *Furnace Combustion Sensor Test Results*, 2001). During characterization testing, output voltages for the electrochemical sensor were obtained while exposed to CO concentrations within the ranges specified by its manufacturer. The output voltage corresponding to approximately 400 ppm of CO for the electrochemical sensor was used as the set point signal value to shutoff the furnace. In order to provide a means of sending the shutoff signal to the furnace after the sensor detected 400 ppm of CO in the flue products, a shutoff circuit was built between the sensor and the furnace.

Also during characterization testing, output voltages for the infrared CO_2 sensor were obtained while exposed to CO_2 concentrations within the ranges specified by its manufacturer. As mentioned earlier, it was necessary to determine the infrared CO_2 sensor output in response to a concentration of CO_2 that corresponded to 400 ppm of CO in the flue of the furnace. The approach taken by CPSC staff to determine this concentration will be discussed in the section on infrared sensor shutoff testing.

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

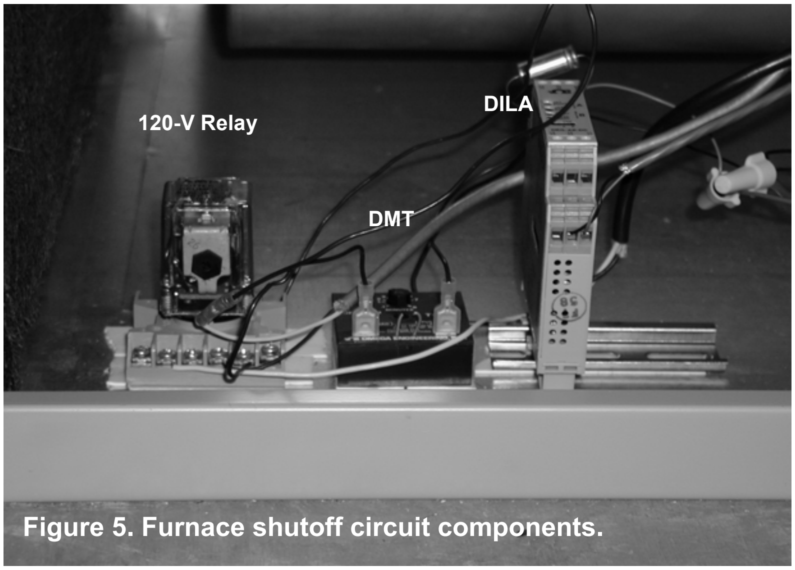
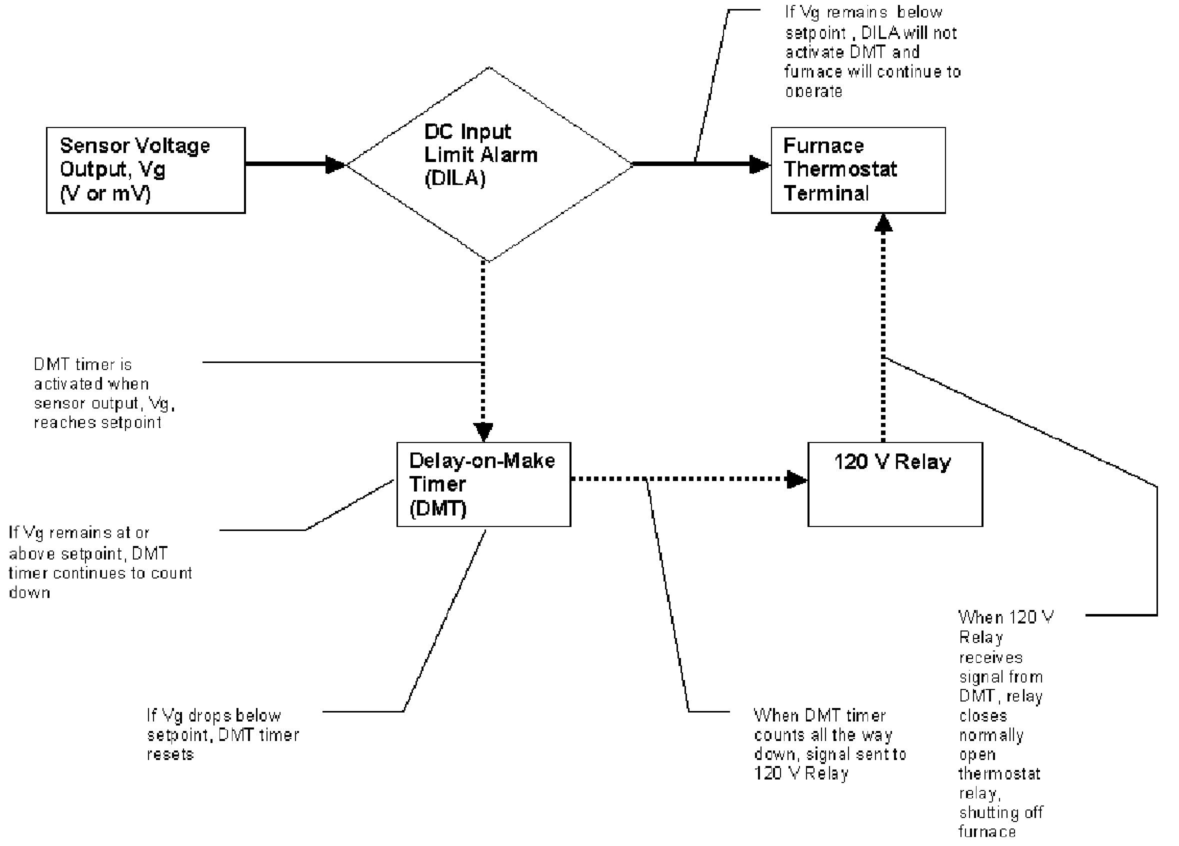


Figure 5. Furnace shutoff circuit components.

The DC Input Limit Alarm (DILA) is a voltage-controlled relay that used the CO sensor as input and was powered with a 24-volt power supply. When the electrochemical CO sensor and infrared CO_2 sensor were individually integrated into the furnace, they 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. The DMT time delay settings are knob-adjustable and range from 30 seconds to 8 minutes. Staff was not able to make precise time delay adjustments at the intermediate settings of 2 and 5 minutes due to parallax encountered when lining the adjustment knob with the time settings. 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 set point of 400 ppm, each sensor output remained below its respective set point voltage and the furnace continued to operate. When the flue CO or CO_2 concentration exceeded the set point, sensor output would exceed the set point voltage and cause the furnace to shut down. When the flue CO or CO_2 concentration dropped below the set point, the sensor output would drop below the voltage set point. 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 or CO_2 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 (24 VDC), staff would expect that a sensor deployed in a furnace would receive its power from the furnace control board.

Figure 6. Flowchart for Shutoff Circuit to Furnace



If Vg remains below setpoint , DILA will not activate DMT and furnace will continue to operate

DMT timer is activated when sensor output, Vg, reaches setpoint

If Vg remains at or above setpoint, DMT timer continues to count down

If Vg drops below setpoint, DMT timer resets

When DMT timer counts all the way down, signal sent to 120 V Relay

When 120 V Relay receives signal from DMT, relay closes normally open thermostat relay, shutting off furnace

Electrochemical Carbon Monoxide Sensor Shutoff Test Results

The EC sensor was subjected to the tests outlined in the test matrix provided in Appendix A, Table A.4. Depending on the chamber temperature and relative humidity during characterization testing, the average measured voltage of the EC sensor ranged from 1.74 V to 3.67 V at average chamber CO concentrations that ranged from 406 to 414 ppm. This difference in voltages was due to the EC sensor's dependence on temperature and relative humidity. Using the line equations from the plot of sensor response at the various chamber conditions, calculated voltage of the EC sensor ranged from 1.75 V to 3.56 V for a CO concentration of 400 ppm. The calculated voltages for the EC sensor at different levels of CO are found in Appendix B, Table B.2. As temperature and relative humidity were increased, voltage also increased. The chamber conditions of 130^{o}F/50% RH and 130^{o}F/95% RH most closely reflected the conditions likely to be encountered in the vent pipe of the furnace. The equations that described sensor performance at chamber conditions of 130^{o}F/50% RH and 130^{o}F/95% RH were $y = 0.0065x + 0.9573$ and $y = 0.0067x + 0.8251$, respectively. Each equation was used to calculate the EC sensor response under the respective chamber conditions and at 400 ppm CO, resulting in voltages of 3.56 V and 3.51 V. For simplicity, 3.5 V was selected as the set point for the shutoff circuit.

The EC sensor was tested at target shutoff times of two, five, and eight minutes. The EC sensor successfully shutdown the furnace at each of the target shutoff times. Each test was repeated with the same results. The results of the shutoff testing are presented in Table 3 and Graphs 15-20.

Graphs 15-20 are plots of the flue CO, EC sensor voltage, and gas flow to the furnace as a function of time. The gas flow was used as the indicator of when the furnace was operating and when it shutoff. Its trace remained constant until the furnace shutdown. The brief spike in flue CO at the start of each CO trace occurred as the result of a cold start up of the furnace. In each test, the furnace was allowed to warm-up for at least 5 minutes prior to vent blockage. After the vent was blocked, the CO concentration in the flue rose rapidly and quickly exceeded 400 ppm. As mentioned earlier, attempts were made to limit CO production between 400 and 450 ppm. However, the lack of more precise control of the degree of vent blockage and the amount of excess air brought to the combustion chamber resulted in variation in the amount of CO produced from one test to another. Thus, the actual flue CO concentrations were higher than 1000 ppm, as evidenced by the constant CO trace on each graph that corresponds to 1000 ppm. The CO analyzer used for flue measurements was set to a range that had an upper limit of 1000 ppm.

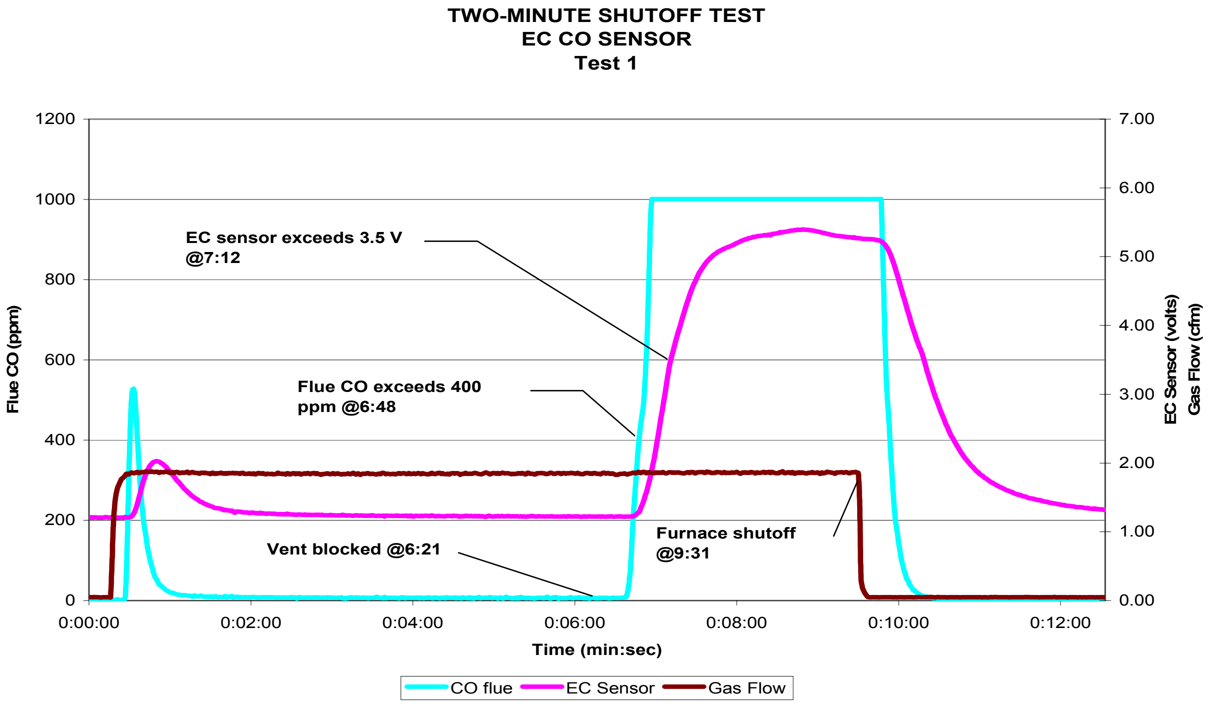
Table 3: Shutoff Test Results using EC CO Sensor

Shutoff Test	Test No.	TARGET CO & SENSOR RESPONSE EXCEEDED					AT FURNACE SHUTDOWN			Actual Shutoff Time
		Sensor	Run Time	CO	Run Time	Lag Time	CO	Sensor	Run Time	
		volts	mm:ss	ppm	mm:ss	mm:ss	ppm	volts	mm:ss	mm:ss
Two-Minute	1	3.56	7:12	414	6:48	0:24	1000	5.26	9:31	2:17
	2	3.52	7:36	405	6:52	0:44	1000	4.66	9:57	2:17
Five-Minute	1	3.52	7:31	401	6:56	0:35	1000	4.28	12:13	4:35
	2	3.56	7:16	409	6:52	0:24	1000	5.76	11:52	4:34
Eight-Minute	1	3.50	7:13	422	6:0	0:23	1000	4.80	15:15	7:58
	2	3.54	7:20	399	6:58	0:22	1000	5.94	15:21	7:59

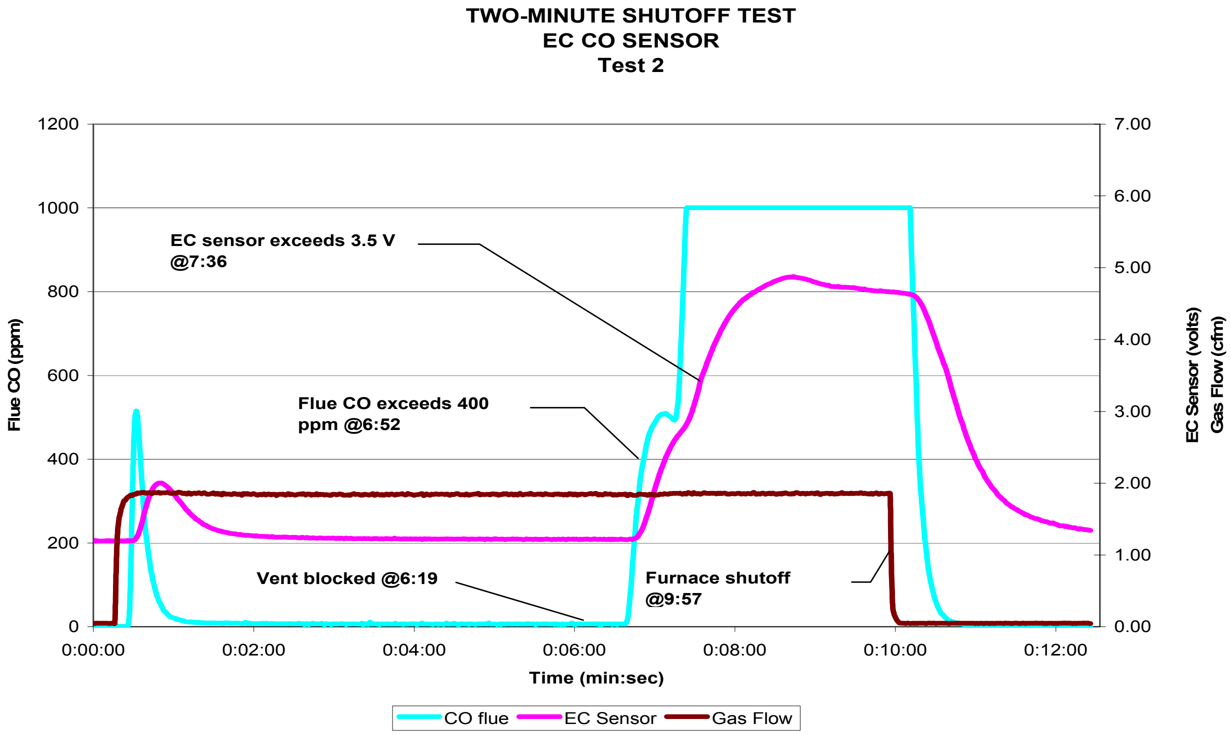
Note. All times are in minutes and seconds (or mm:ss). The target shutoff times are specified in the test name.

After the vent was blocked, the EC sensor responded with a rapid rise in voltage that quickly exceeded the shutoff circuit set point of 3.5 V. As shown in Table 3, the EC sensor response lagged the CO rise from times ranging from 22 to 48 seconds. The CO column represents the flue concentrations of CO recorded during the test. There were slight differences between Target Shutoff time and the Actual Shutoff time. These differences were caused by the difficulty of aligning the time delay adjustment knob hash mark on the DMT with the time delay setting.

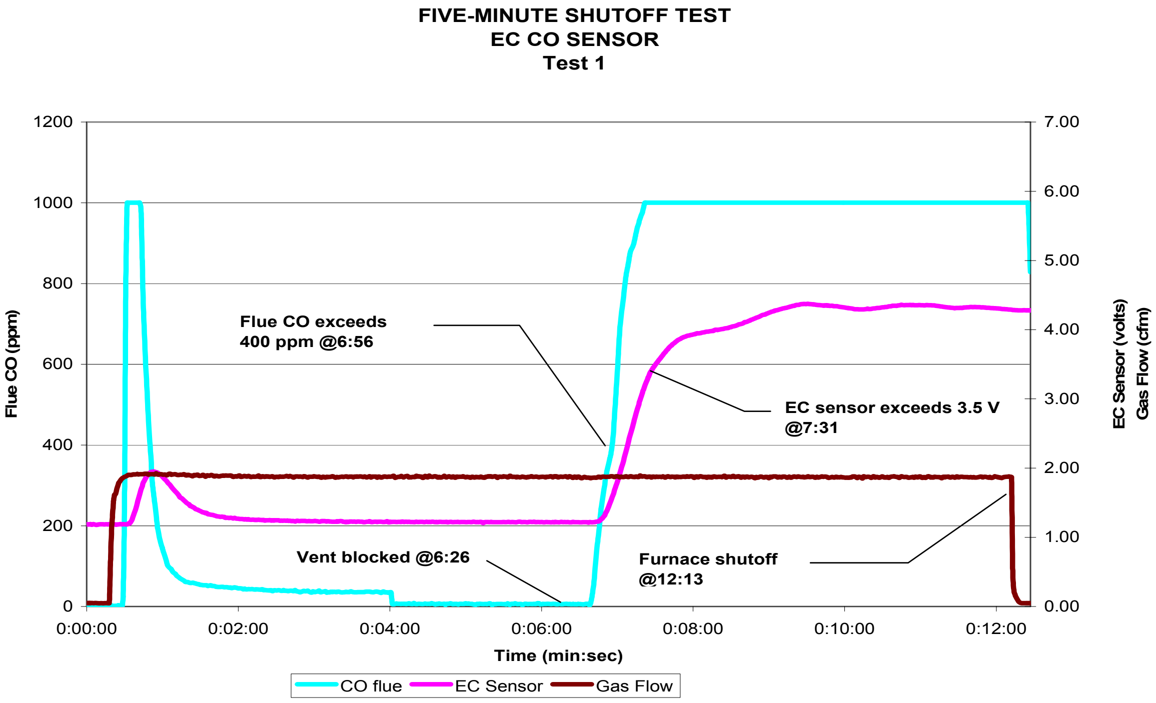
Graph 15. In-Situ Furnace Shutoff at 2-Minutes with EC Sensor



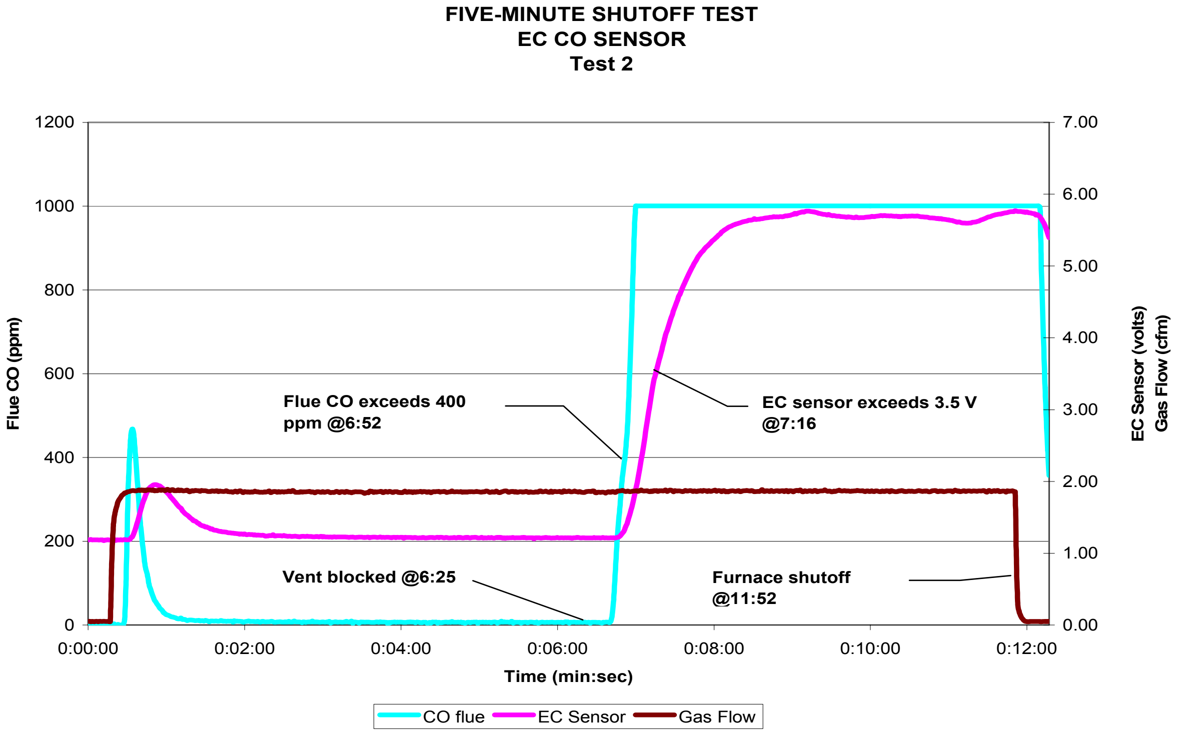
Graph 16. In-Situ Furnace Shutoff at 2-Minutes with EC Sensor



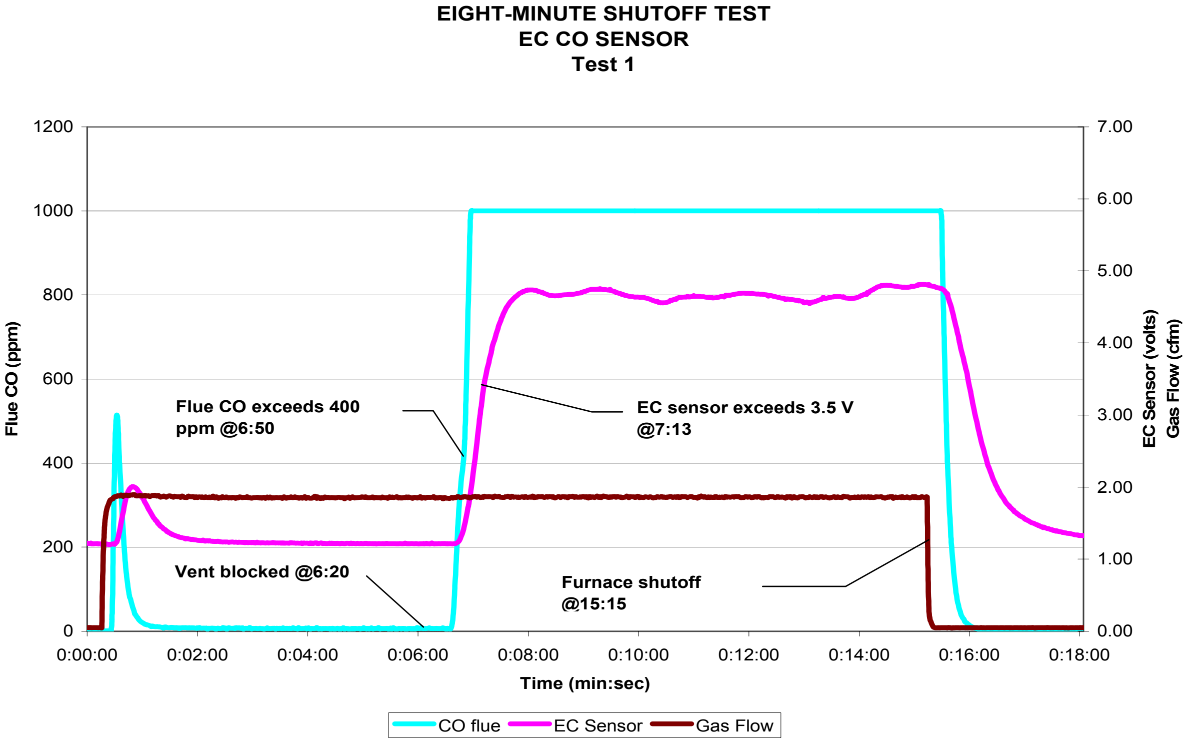
Graph 17. In-Situ Furnace Shutoff at 5-Minutes with EC Sensor



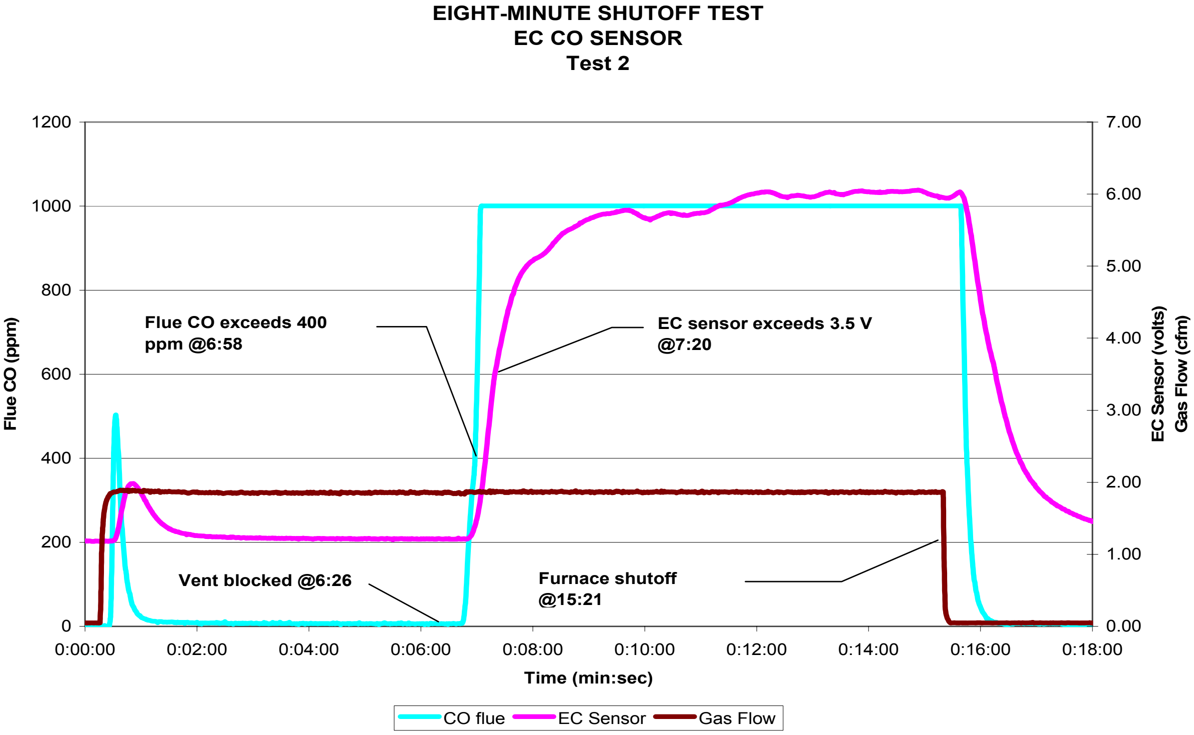
Graph 18. In-Situ Furnace Shutoff at 5-Minutes with EC Sensor



Graph 19. In-Situ Furnace Shutoff at 8-Minutes with EC Sensor



Graph 20. In-Situ Furnace Shutoff at 8-Minutes with EC Sensor

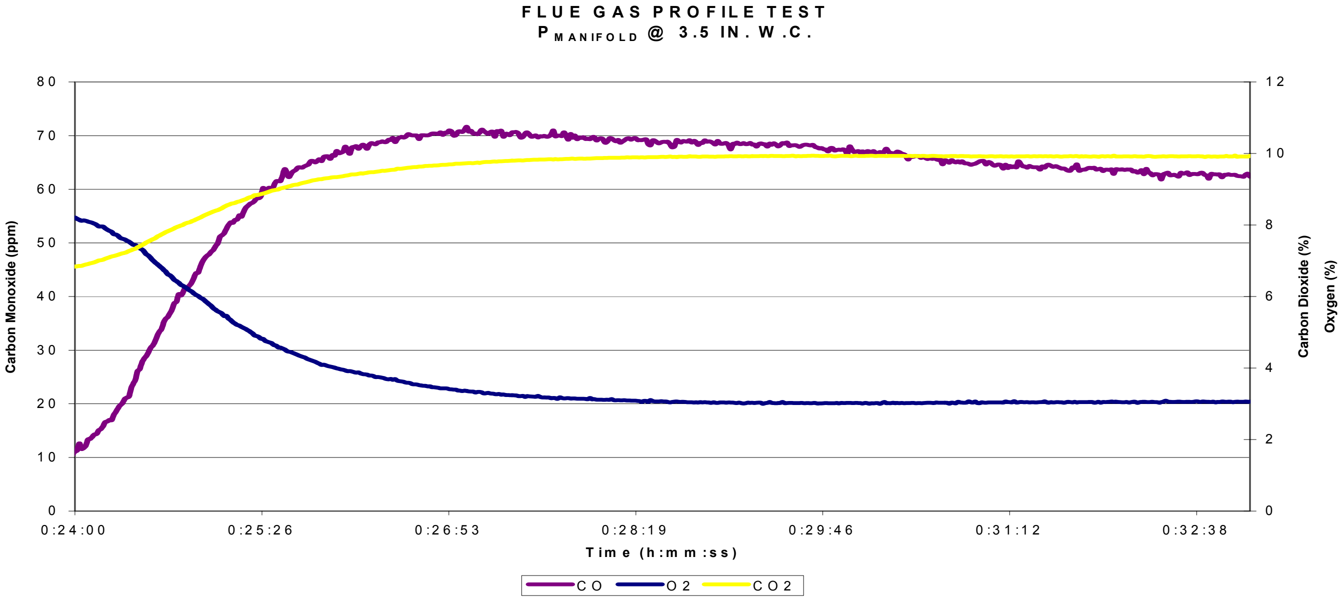


Flue Gas Profile Tests

The IR sensor was subjected to the tests outlined in the test matrix provided in Appendix A, Table A.4. The infrared carbon dioxide sensor was selected for testing on the basis that changes in flue concentrations of CO_2 might be used as an indicator of an increase in the flue concentration of CO in excess of the 400 ppm (air free) emissions standard for residential gas furnaces. Generally speaking, as the flue concentration of CO_2 increases, the flue concentration of CO also increases, while the flue concentration of O_2 is depleted. In order to use CO_2 as an indicator of the flue concentration of CO, it was necessary to experimentally establish the flue concentration of CO_2 that closely corresponded to flue CO concentrations of 400 ppm. To accomplish this, CPSC staff conducted combustion tests using the test furnace to develop a profile of the combustion products at three different furnace firing rates (based on adjustment of the furnace gas manifold pressure) and two vent pipe conditions.

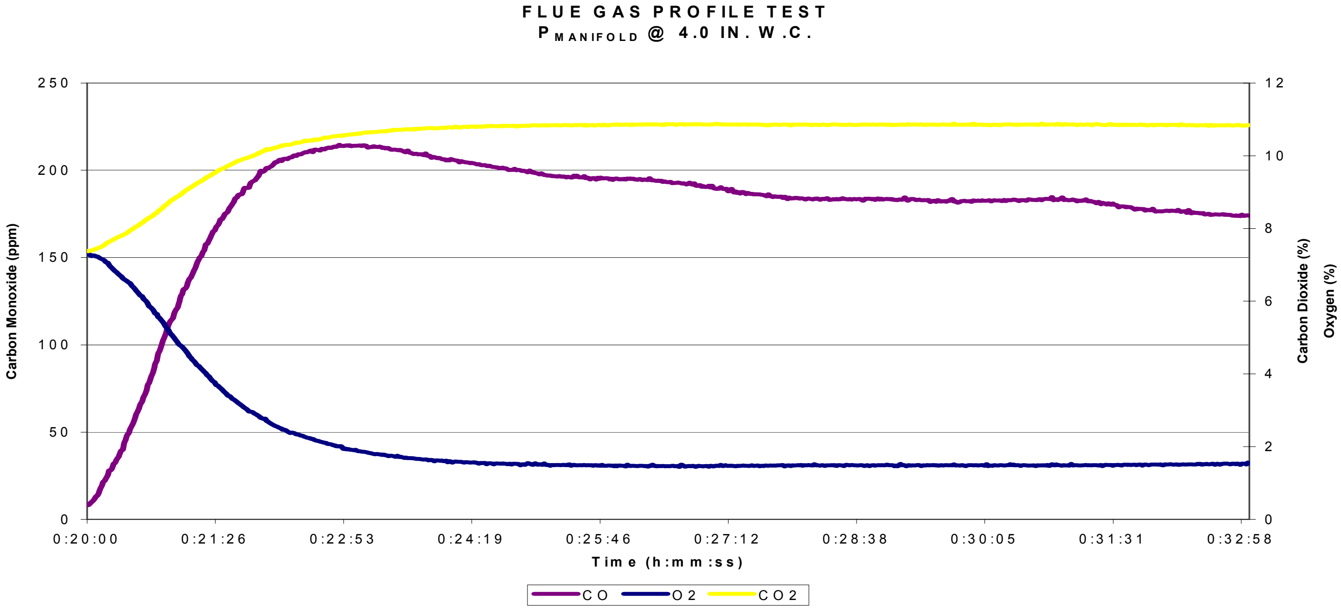
The furnace was tested during normal operation (3.5 in. w.c. manifold pressure), moderate over-firing (4.0 in. w.c. manifold pressure), and worst case over-firing (4.3 in. w.c. manifold pressure). Flue measurements were recorded during each of these operating conditions with a normal, unblocked vent pipe and with a partially blocked vent pipe. During partial blockage testing, the vent was blocked to the maximum extent possible without causing the furnace pressure switch to actuate and shutdown the furnace in response to the increase in static pressure caused by the vent blockage. The most extreme of these conditions (i.e., 4.3 in. w.c. manifold pressure and partially blocked vent pipe) caused furnace emissions to approach or exceed the 400 ppm standard and helped establish CO_2 concentrations that corresponded to this CO concentration. The least extreme and moderate conditions were necessary to determine whether the CO_2 levels at 400 ppm of CO were distinct enough to be used as target levels for shutdown of the furnace. In addition to CO and CO_2, the changes in the flue concentrations of oxygen were also observed. The flue concentrations during these operating conditions, with the furnace vent pipe partially blocked, are charted below. Table B.1 in Appendix B presents a tabulation of data before and after the vent pipe was blocked.

Graph 21. Flue Gas Profile at 3.5 in. w.c.

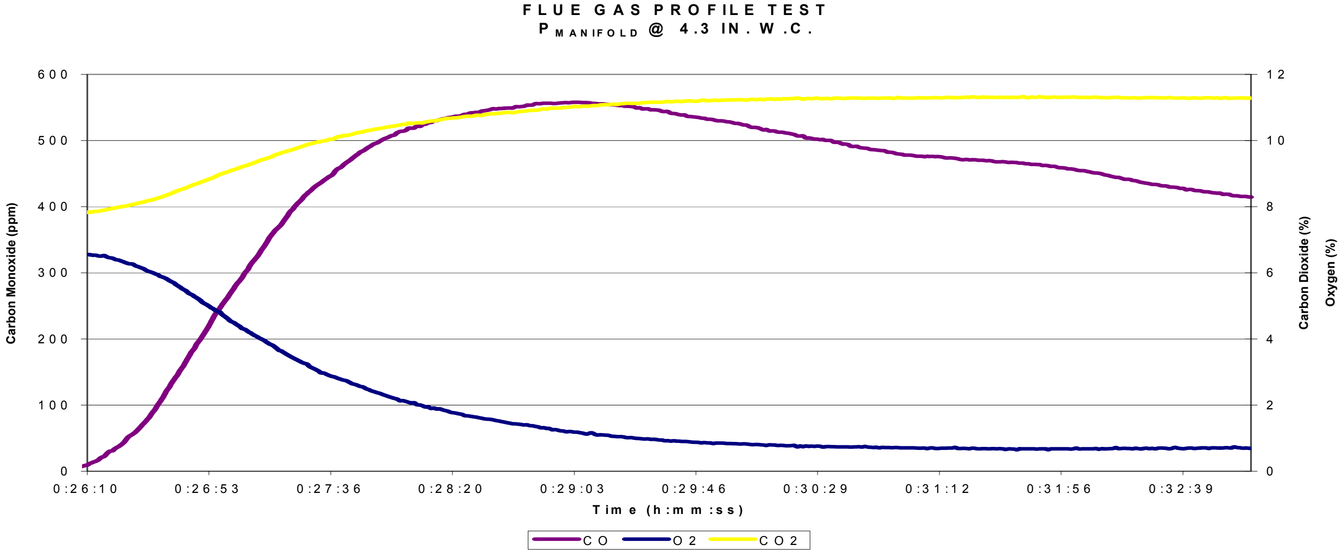


As seen in each of the flue gas profiles, when the furnace vent pipe was blocked, the flue concentrations of CO_2 and CO increased, while the O_2 in the flue was depleted. At a manifold pressure of 3.5-in. w.c., the average concentrations of flue CO, CO_2, and O_2 after the vent was blocked were 62 ppm, 9.48%, and 3.78%, respectively. When the manifold pressure was increased, the flue concentrations of CO and CO_2 increased, while the O_2 continued to become depleted. At a manifold pressure of 4.0-in. w.c., the average concentrations of flue CO, CO_2, and O_2 after the vent was blocked, were 179 ppm, 10.55%, and 2.01%, respectively. At a manifold pressure of 4.3-in. w.c., the average concentrations of flue CO, CO_2, and O_2 after the vent was blocked were 433 ppm, 11.07%, and 1.10%, respectively. Based on these results, 11% CO_2 was selected as the proxy indicator as to when flue CO would exceed 400 ppm.

Graph 22. Flue Gas Profile at 4.0 in. w.c.



Graph 23. Flue Gas Profile at 4.3 in. w.c.



Infrared Carbon Dioxide Sensor Shutoff Tests

As discussed in the Gas Profile Tests section, staff selected 11% CO_2 as the proxy indicator of when the flue CO concentration would exceed 400 ppm, and thus the target flue CO_2 concentration. Unlike the EC sensor, the IR sensor did not exhibit any dependence on temperature or humidity during characterization testing. The IR sensor's average voltage did not increase or decrease during characterization tests at the various chamber conditions combinations of 70°F, 130°F, 50% RH, and 95% RH. Using the line equations from the plot of sensor response at the various chamber conditions, the calculated voltage of the IR sensor ranged from 2.99 V to 3.10 V for a CO_2 concentration of 11%. The calculated IR sensor response values at different levels of CO_2 are found in Appendix B, Table B.3. The equations that described sensor performance at chamber conditions of 130°F/50% RH and 125°F/91% RH were $y = 0.1898x + 1.0128$ and $y = 0.1809x + 1.0035$, respectively. Each equation was used to calculate the IR sensor response under the respective chamber conditions and at 11% CO_2, resulting in voltages of 3.10 V and 2.99 V. The average of the two calculated voltages, 3.05 V, was selected as the set point for the shutoff circuit.

The IR sensor was tested at target shutoff times of two, five, and eight minutes. The IR sensor successfully shutdown the furnace at each of the target shutoff times. Each test was repeated with the same results. The results of the shutoff testing are presented in Table 4 and Graphs 24-29. These tests followed essentially the same course as those conducted using the EC sensor. Thus the layout and interpretation of the graphs and table follow those for the EC sensor testing.

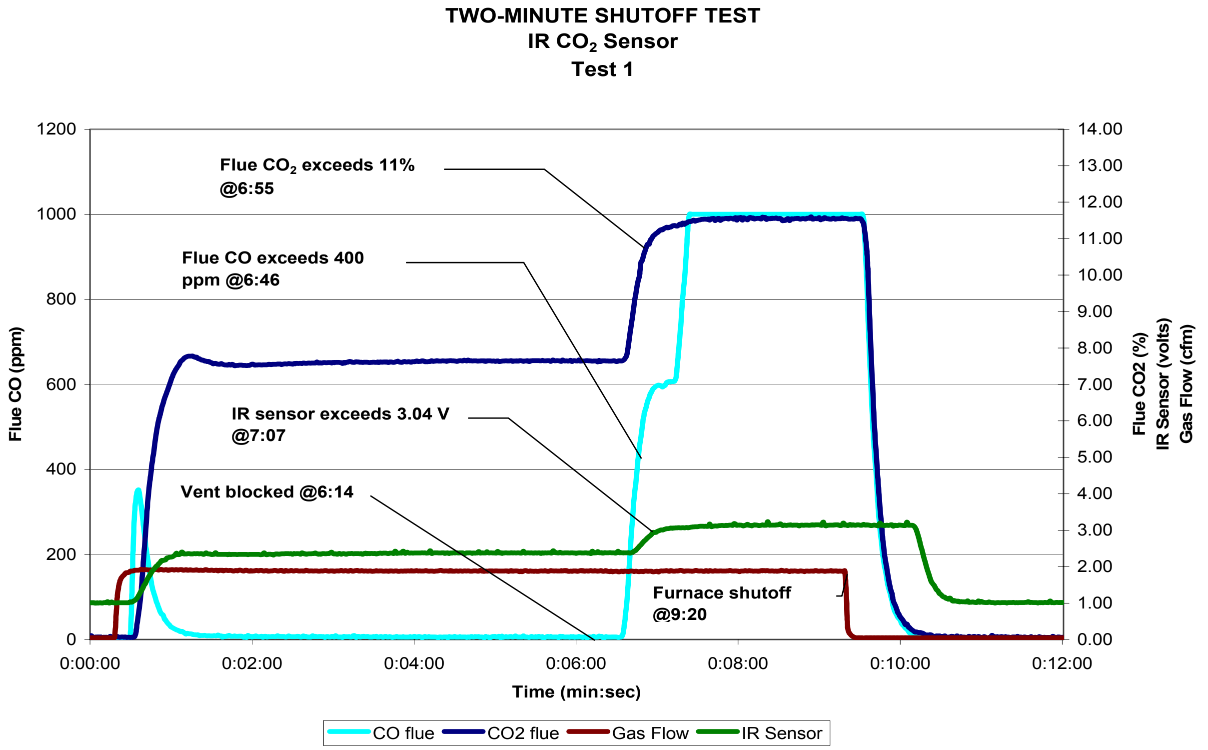
Table 4. Shutoff Test Results using IR Sensor

		TARGET CO_2, CO, & SENSOR RESPONSE EXCEEDED							AT FURNACE SHUTOFF				Actual Shutoff Time
Test Name	Test No.	Sensor	Run Time	CO_2	Run Time	CO	Run Time	Sensor Lag	CO_2	CO	Sensor	Run Time	
		volts	mm:ss	%	mm:ss	ppm	mm:ss	mm:ss	%	ppm	volts	mm:ss	mm:ss
Two-Minute Shutoff	1	3.03	7:07	10.95	6:55	428	6:46	0:12	11.54	1000	3.14	9:20	2:13
	2	3.04	7:03	11.01	6:53	417	7:12	0:10	11.43	619	3.10	9:13	2:10
Five-Minute Shutoff	1	3.05	7:22	11.00	7:05	420	7:17	0:17	11.46	775	3.10	11:43	4:27
	2	3.11	7:21	11.00	7:16	402	7:27	0:05	11.48	779	3.11	11:48	4:21
Eight-Minute Shutoff	1	3.05	10:58	11.04	10:50	400	10:59	0:08	11.37	555	3.09	18:52	7:54
	2	3.12	11:13	11.02	11:10	432	11:29	0:03	11.32	417	3.10	19:11	7:58

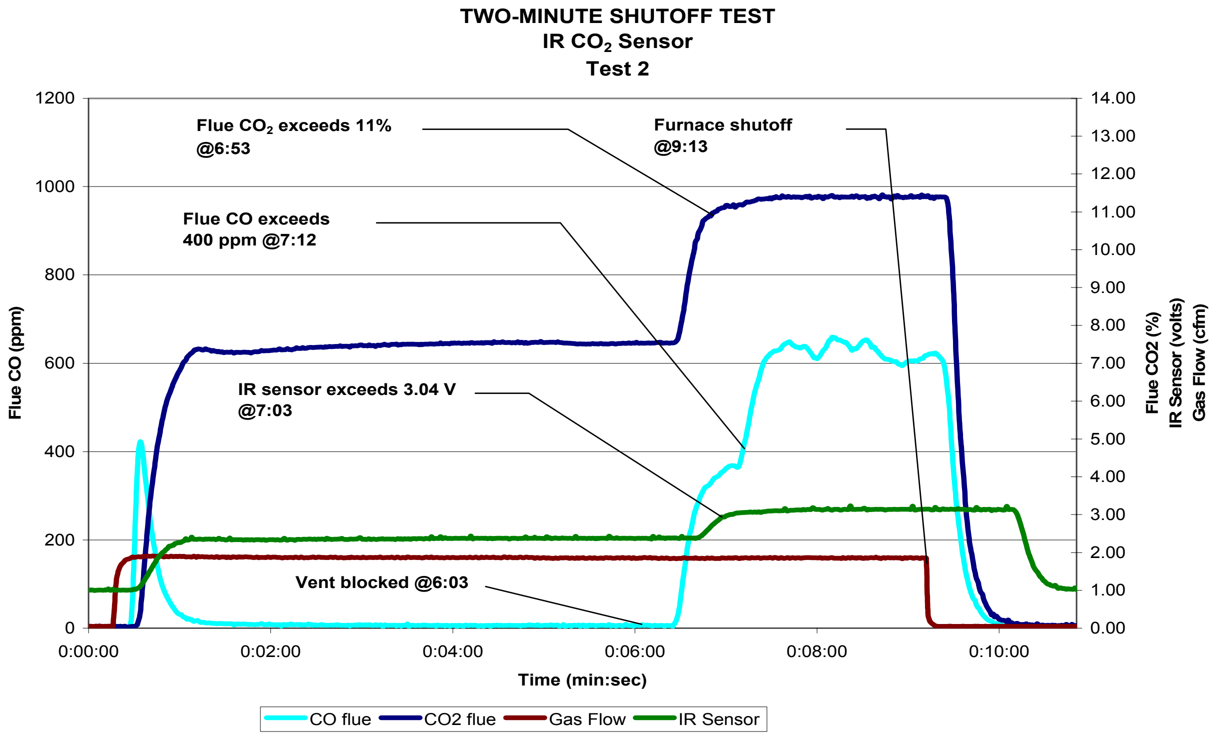
Note. All times are in minutes and seconds (or mm:ss). The target shutoff times are specified in the test name.

Graphs 24-29 are plots of the flue CO_2, IR sensor voltage, and gas flow. The flue CO was also included to confirm whether the target CO_2 corresponded to flue CO concentrations of 400 ppm. When the vent was blocked, flue concentrations of CO_2 and CO rose rapidly, quickly exceeding the target CO_2 concentration of 11% and the reference CO target of 400 ppm. The IR sensor exhibited a rapid response to the rise in CO_2 and only minor time lags ranging from 3 to 17 seconds. As shown in Table 4, the 11% CO_2 concentration consistently corresponded to points in the combustion process during which the CO concentration reached or exceeded 400 ppm.

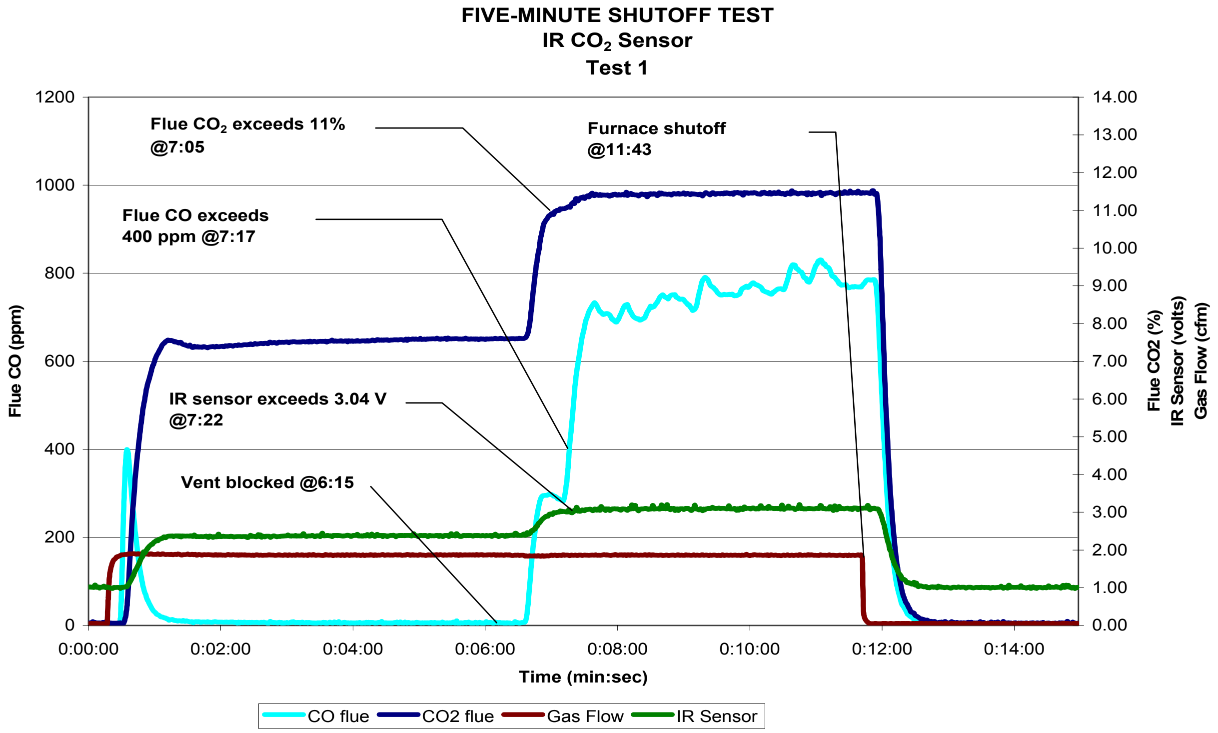
Graph 24. In-Situ Furnace Shutoff at 2-Minutes using IR Sensor



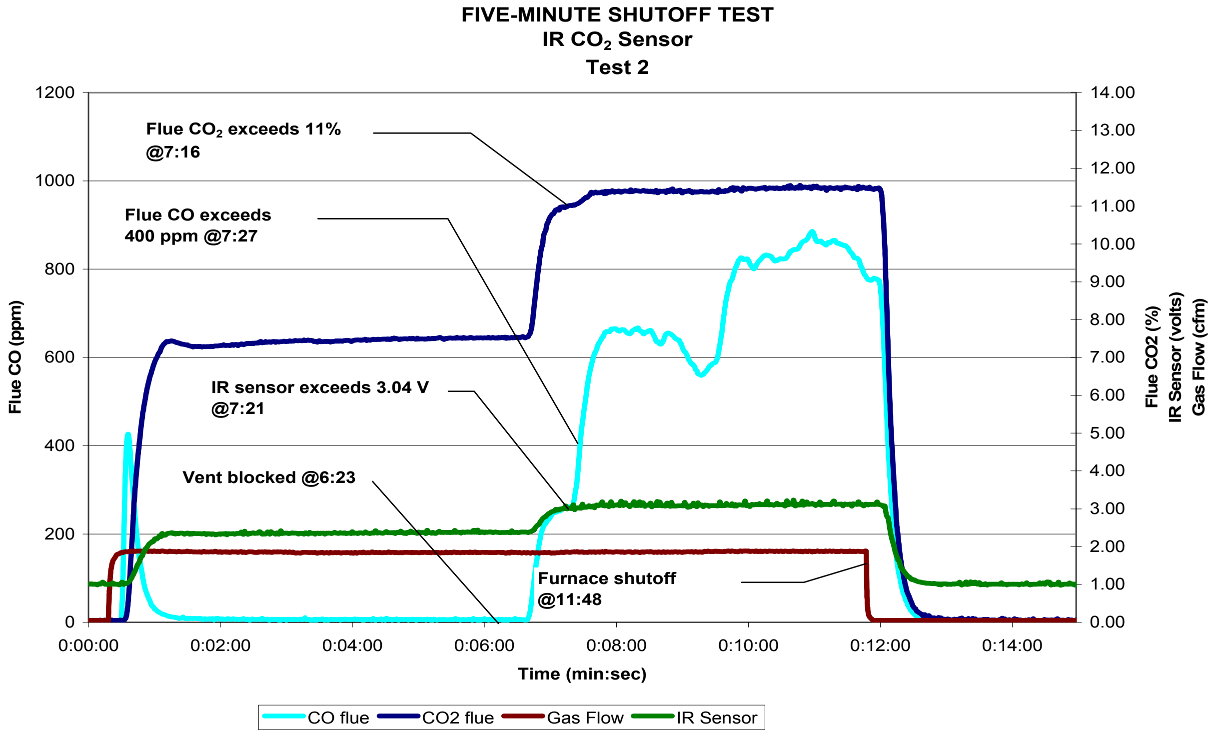
Graph 25. In-Situ Furnace Shutoff at 2-Minutes using IR Sensor



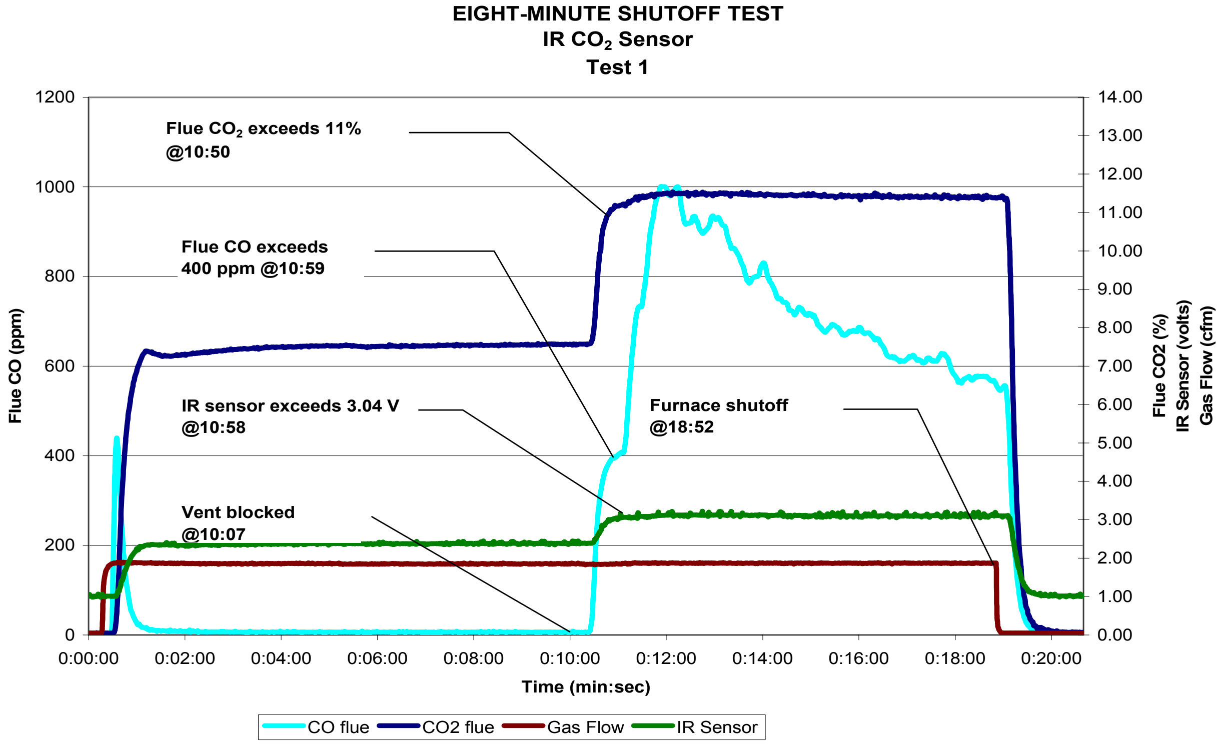
Graph 26. In-Situ Furnace Shutoff at 5-Minutes using IR Sensor



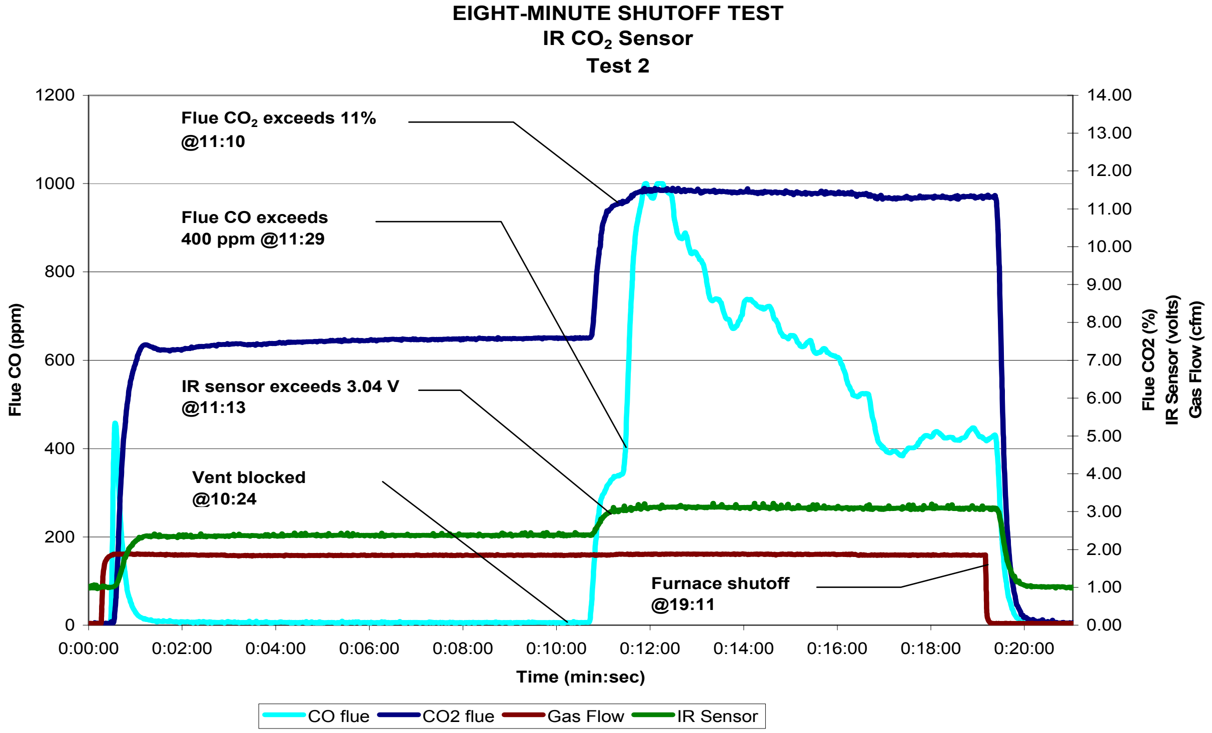
Graph 27. In-Situ Furnace Shutoff at 5-Minutes using IR Sensor



Graph 28. In-Situ Furnace Shutoff at 8-Minutes using IR Sensor



Graph 29. In-Situ Furnace Shutoff at 8-Minutes using IR Sensor



VI. SUMMARY

One electrochemical gas sensor and one infrared gas sensor were subjected to characterization testing and in-situ furnace shutoff testing outlined in the matrices in Appendix A. The electrochemical sensor was designed to measure CO and has a response range of 0 to 1000 ppm CO. The EC sensor requires12 to 30 VDC to operate and provides an output signal of 1.0 to 5.5 V. The infrared sensor was designed to measure CO_2 and has a response range of 0 to 20.06 % CO_2. The IR sensor requires 12 to 35 VDC to operate and provided an output signal of 1.0 to 5.0 V.

The characterization tests are outlined in Tables A.1, A.2, and A.3 of Appendix A and consisted of evaluating each sensor's response to its respective target gas and also whether each sensor responded to non-target gases. Various concentrations of CO, CO_2, and N_2 (for O_2 depletion) were introduced into the environmental chamber. Sensor response to varying degrees of O_2 depletion were not fully assessed due to difficulties encountered depleting chamber O_2 to concentrations expected to be seen in the flue.

The findings of the characterization testing of the EC sensor were as follows:

- The EC sensor exhibited a direct linear response to CO under all chamber conditions.
- The EC sensor exhibited dependence on temperature and relative humidity, as demonstrated by its increase in voltage at higher temperature and relative humidity.
- The EC sensor was not subject to interference from CO_2 or O_2.

The findings of the characterization testing of the IR sensor were as follows:

- The IR sensor exhibited a direct linear response to CO_2 under all chamber conditions.
- The IR sensor did not exhibit any dependence on temperature and relative humidity.
- The IR sensor was not subject to interference from CO or O_2.
- Furnace testing indicated that a flue CO_2 concentration of 11% provided a good indicator of when flue CO would exceed 400 ppm.

In-situ furnace testing of the sensors consisted of separately integrating each sensor into the furnace to demonstrate shutoff in direct or indirect response to 400 ppm of CO in the vent. Integration of each sensor consisted of mechanically tapping the vent system to deliver a flue sample to the sensor, and electrically connecting each sensor to the furnace via a shutoff mechanism, using target voltages as setpoints for testing. Each sensor was subjected to the shutoff tests outlined in Table A.4 of Appendix A.

The findings of the shutoff tests using the EC and IR sensors were as follows:

- The EC sensor successfully shutdown the furnace at each of the target shutoff times.
- The EC sensor response lagged the actual CO rise by between 22 and 48 seconds.
- The IR sensor successfully shutdown the furnace at each of the target shutoff times.
- The IR sensor response lagged the actual CO_2 rise by between 3 and 17 seconds.
- The target flue CO_2 concentration (11%) consistently corresponded to the target flue CO concentrations in excess of 400 ppm.

VII. CONCLUSION

CPSC staff accomplished all of the objectives of this test program. The test results demonstrate that each sensor exhibited linear response to its respective target gas and did not respond to non-target gases under various conditions. The test results also demonstrate each sensor's capability to shutdown the furnace in direct and indirect response to elevated concentrations of CO within the flue. These results are limited to conditions exhibited by a high-efficiency gas furnace.

This test program did not evaluate sensor performance in higher temperature environments (i.e., 200°F to 500°F) that exist in the flue passageways of mid-efficiency or low-efficiency gas appliances. Nor did this test program seek to evaluate sensor reliability, durability, and expected life. Future testing and evaluation of sensors should consider a wider variety of technologies and target gases, and include sensor exposure to a wider variety of conditions and contaminants likely to occur during appliance operation and non-operation. These issues are addressed in a draft test matrix developed by the CSA/ANSI Z21/83 Ad Hoc Working Group for CO/Combustion Sensors. The test matrix is part of a work plan to evaluate sensor usage in gas appliances developed by the working group for consideration by the CSA/ANSI Z21/83 Technical Committee.

The CPSC staff will provide this test report to the Z21/83 Technical Committee and the Ad Hoc Working Group to further support sensor evaluation and development of a performance standard to require shutdown or some other preemptive response to elevated CO in gas appliances. Gas heating appliances have historically been and continue to be the major cause of non-fire related and non-automotive CO deaths in the U.S. Sensor intervention could serve to reduce the occurrence of these deaths.

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

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General Support on Electrical Wiring:
Richard Schenck, U.S. CPSC, Directorate for Laboratory Sciences
Randy Butturini, U.S. CPSC, Directorate for Engineering Sciences

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APPENDIX A. TEST MATRICES

Table A.1. Carbon Monoxide Response Test Matrices

Response to Carbon Monoxide at 70°F and 50% Relative Humidity

Chamber			Sensor Response to:	
Carbon Monoxide (ppm +/- 10 ppm)	Relative humidity (% +/- 10%)	Temperature (°F +/- 10°F)	Target Gas (V or mV)	Non-Target Gas (V or mV)
0	50	70		
100	50	70		
200	50	70		
300	50	70		
400	50	70		
450	50	70		
500	50	70		

Response to Carbon Monoxide at 70°F and 95% Relative Humidity

Chamber			Sensor Response to:	
Carbon Monoxide (ppm +/- 10 ppm)	Relative Humidity (% +/- 10%)	Temperature (°F +/- 10°F)	Target Gas (V or mV)	Non-Target Gas (V or mV)
0	95	70		
100	95	70		
200	95	70		
300	95	70		
400	95	70		
450	95	70		
500	95	70		

Response to Carbon Monoxide at 130°F and 50% Relative Humidity

Chamber			Sensor Response to:	
Carbon Monoxide (ppm +/- 10 ppm)	Relative Humidity (% +/- 10%)	Temperature (°F +/- 10°F)	Target Gas (V or mV)	Non-Target Gas (V or mV)
0	50	130		
100	50	130		
200	50	130		
300	50	130		
400	50	130		
450	50	130		
500	50	130		

Response to Carbon Monoxide at 130°F and 95% Relative Humidity

Chamber			Sensor Response to:	
Carbon Monoxide (ppm +/- 10 ppm)	Relative Humidity (% +/- 10%)	Temperature (°F +/- 10°F)	Target Gas (V or mV)	Non-Target Gas (V or mV)
0	95	130		
100	95	130		
200	95	130		
300	95	130		
400	95	130		
450	95	130		
500	95	130		

Table A.2. Carbon Dioxide Response Test Matrices

Response to Carbon Dioxide at 70^oF and 50% Relative Humidity

Chamber			Sensor Response to:	
Carbon Dioxide (% +/- 0.5 %)	**Relative humidity (% +/- 10%)**	**Temperature (^oF +/- 10^oF)**	**Target Gas (V or mV)**	**Non-Target Gas (V or mV)**
0	50	70		
1	50	70		
2	50	70		
3	50	70		
4	50	70		
4	50	70		
5	50	70		
6	50	70		
7	50	70		
8	50	70		
9	50	70		
10	50	70		
11	50	70		
12	50	70		

Response to Carbon Dioxide at 70^oF and 95% Relative Humidity

Chamber			Sensor Response to:	
Carbon Dioxide (% +/- 0.5 %)	**Relative Humidity (% +/- 10%)**	**Temperature (^oF +/- 10^oF)**	**Target Gas (V or mV)**	**Non-Target Gas (V or mV)**
0	95	70		
1	95	70		
2	95	70		
3	95	70		
4	95	70		
4	95	70		
5	95	70		
6	95	70		
7	95	70		
8	95	70		
9	95	70		
10	95	70		
11	95	70		
12	95	70		

Table A.2. Carbon Dioxide Response Test Matrices

Response to Carbon Dioxide at 130°F and 50% Relative Humidity

Chamber			Sensor Response to:	
Carbon Dioxide (% +/- 0.5 %)	Relative Humidity (% +/- 10%)	Temperature (°F +/- 10°F)	Target Gas (V or mV)	Non-Target Gas (V or mV)
0	50	130		
1	50	130		
2	50	130		
3	50	130		
4	50	130		
4	50	130		
5	50	130		
6	50	130		
7	50	130		
8	50	130		
9	50	130		
10	50	130		
11	50	130		
12	50	130		

Response to Carbon Dioxide at 130°F and 95% Relative Humidity

Chamber			Sensor Response to:	
Carbon Dioxide (% +/- 0.5 %)	Relative Humidity (% +/- 10%)	Temperature (°F +/- 10°F)	Target Gas (V or mV)	Non-Target Gas (V or mV)
0	95	130		
1	95	130		
2	95	130		
3	95	130		
4	95	130		
4	95	130		
5	95	130		
6	95	130		
7	95	130		
8	95	130		
9	95	130		
10	95	130		
11	95	130		
12	95	130		

Table A.3. Oxygen Response Test Matrices

Response to Oxygen at 70^{o}F and 50% Relative Humidity

Chamber			Sensor Response to:	
Oxygen (% +/- 0.5 %)	**Relative Humidity (% +/- 10%)**	**Temperature (^{o}F +/- 10^{o}F)**	**Target Gas (V or mV)**	**Non-Target Gas (V or mV)**
20.94	50	70		
20	50	70		
19	50	70		
18	50	70		
17	50	70		
16	50	70		
15	50	70		
14	50	70		
13	50	70		
12	50	70		
11	50	70		
10	50	70		
9	50	70		
8	50	70		
7	50	70		
6	50	70		
5	50	70		
4	50	70		
3	50	70		
2	50	70		
1	50	70		
0	50	70		

Table A.3. Oxygen Response Test Matrices

Response to Oxygen at 70^{o}F and 95% Relative Humidity

Chamber			**Sensor Response to:**	
Oxygen (% +/- 0.5 %)	**Relative Humidity (% +/- 10%)**	**Temperature (^{o}F +/- 10^{o}F)**	**Target Gas (V or mV)**	**Non-Target Gas (V or mV)**
20.94	95	70		
20	95	70		
19	95	70		
18	95	70		
17	95	70		
16	95	70		
15	95	70		
14	95	70		
13	95	70		
12	95	70		
11	95	70		
10	95	70		
9	95	70		
8	95	70		
7	95	70		
6	95	70		
5	95	70		
4	95	70		
3	95	70		
2	95	70		
1	95	70		
0	95	70		

Table A.3. Oxygen Response Test Matrices

Response to Oxygen at 130^{o}F and 50% Relative Humidity

Chamber			Sensor Response to:	
Oxygen (% +/- 0.5 %)	**Relative Humidity (% +/- 10%)**	**Temperature (^{o}F +/- 10^{o}F)**	**Target Gas (V or mV)**	**Non-Target Gas (V or mV)**
20.94	50	130		
20	50	130		
19	50	130		
18	50	130		
17	50	130		
16	50	130		
15	50	130		
14	50	130		
13	50	130		
12	50	130		
11	50	130		
10	50	130		
9	50	130		
8	50	130		
7	50	130		
6	50	130		
5	50	130		
4	50	130		
3	50	130		
2	50	130		
1	50	130		
0	50	130		

Table A.3. Oxygen Response Test Matrices

Response to Oxygen at 130^{o}F and 95% Relative Humidity

Chamber			Sensor Response to:	
Oxygen (% +/- 0.5 %)	**Relative Humidity (% +/- 10%)**	**Temperature (^{o}F +/- 10^{o}F)**	**Target Gas (V or mV)**	**Non-Target Gas (V or mV)**
20.94	95	130		
20	95	130		
19	95	130		
18	95	130		
17	95	130		
16	95	130		
15	95	130		
14	95	130		
13	95	130		
12	95	130		
11	95	130		
10	95	130		
9	95	130		
8	95	130		
7	95	130		
6	95	130		
5	95	130		
4	95	130		
3	95	130		
2	95	130		
1	95	130		
0	95	130		

Table A.4. In-Situ Furnace Shutoff Test Matrices

			Flue						
Target Shutoff Time (minutes)	**Partial Vent Blockage (% cross-sectional area)**	**Manifold Pressure (in. w.c.)**	**CO (ppm)**	**CO_2 (%)**	**O_2 (%)**	**Temp. (^oF)**	**RH (%)**	**Sensor Voltage (V or mV)**	**Actual Shutoff Time (minutes)**
2	90	4.3							
5	90	4.3							
8	90	4.3							
2	90	4.3							
5	90	4.3							
8	90	4.3							

APPENDIX B. ADDITIONAL DATA

Table B.1. Comparison of Line Equations of EC Sensor Response

Nominal Test Conditions (^{o}F, % RH)	**Average Test Conditions (^{o}F, % RH)**	**Line Equation**	**Slope, m**	**Nominal CO Concentration (ppm)**				
				100	**200**	**300**	**400**	**500**
				Response Voltage (volts)				
70, 50	64, 50	y = 0.0015x + 1.1516	0.0015	1.30	1.45	1.60	1.75	1.90
70, 95	70, 92.3	y = 0.004x + 1.258	0.0040	1.66	2.06	2.46	2.86	3.26
130, 50	120, 50	y = 0.0065x + 0.9573	0.0065	1.61	2.26	2.91	3.56	4.21
130, 95	131, 90	y = 0.0067x + 0.8251	0.0067	1.50	2.17	2.84	3.51	4.18
		Average	1.52	1.98	2.45	2.92	3.39	
		Std. Dev.	0.1581	0.364	0.599	0.840	1.083	

Table B.2. Comparison of Line Equations of IR Sensor Response

Nominal Test Conditions (^{o}F, % RH)	**Average Test Conditions (^{o}F, % RH)**	**Line Equation**	**Slope, m**	**Nominal CO_2 Concentration (%)**											
				1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
				Response Voltage (volts)											
70, 50		y = 0.187x + 1.0144	0.1870	1.20	1.39	1.58	1.76	1.95	2.14	2.32	2.51	2.70	2.88	3.07	3.26
130, 50		y = 0.1898x + 1.0128	0.1898	1.20	1.39	1.58	1.77	1.96	2.15	2.34	2.53	2.72	2.91	3.10	3.29
130, 95	125, 91	y = 0.1809x + 1.0035	0.1809	1.18	1.37	1.55	1.73	1.91	2.09	2.27	2.45	2.63	2.81	2.99	3.17
		Average	1.20	1.38	1.57	1.75	1.94	2.13	2.31	2.50	2.68	2.87	3.06	3.24	1.20
		Std. Dev.	0.0102	0.015	0.019	0.024	0.028	0.033	0.037	0.042	0.046	0.051	0.055	0.060	0.010

APPENDIX B. ADDITIONAL DATA

Table B.3. Flue Gas Profile Test Data

	CO	CO_2	O_2
@ 3.5 in. w.c.			
Before Vent Blocked			
Min	1	0.73	8.16
Max	59	6.84	18.83
Ave	13	6.13	9.34
After Vent Blocked			
Min	11	6.84	2.99
Max	72	9.94	8.21
Ave	62	9.48	3.78
@ 4.0 in. w.c.			
	CO	**CO_2**	**O_2**
Before Vent Blocked			
Min	6	7.35	5.77
Max	33	8.24	7.32
Ave	9	7.42	7.20
After Vent Blocked			
Min	12	7.42	1.44
Max	215	10.88	7.26
Ave	179	10.55	2.01
@4.3 in. w.c.			
	CO	**CO_2**	**O_2**
Before Vent Blocked			
Min	5	7.81	5.65
Max	36	8.35	6.59
Ave	8	7.87	6.46
After Vent Blocked			
Min	12	7.84	0.54
Max	558	11.40	6.55
Ave	433	11.07	1.10

Table B.4. Additional Data from Furnace Shutoff Tests using EC Sensor

Test No.	Target Shutoff Time (min:sec)	TARGET CO EXCEEDED, RESULTANT EC SENSOR OUTPUT				
		Sensor (volts)	RunTime (min:sec)	CO (ppm)	RunTime (min:sec)	Sensor Lag (min:sec)
1	2:00	3.56	7:12	414	6:48	0:24
2	2:00	3.52	7:36	405	6:52	0:44
1	5:00	3.52	7:31	401	6:56	0:35
2	5:00	3.56	7:16	409	6:52	0:24
1	8:00	3.50	7:13	422	6:50	0:23
2	8:00	3.54	7:20	399	6:58	0:22

Table B.5. Additional Data from Furnace Shutoff Tests using IR Sensor

Test No.	Target Shutoff Time (mm:ss)	Target Flue CO2 and CO Exceeded, Resultant IR Sensor Output						
		Flue CO_2 %	Run Time (mm:ss)	Flue CO ppm	Run Time (mm:ss)	Sensor Output volts	Run Time (mm:ss)	Sensor Lag (mm:ss)
1	2:00	10.95	6:55	428	6:46	3.03	7:07	0:12
2	2:00	11.01	6:53	417	7:12	3.04	7:03	0:10
1	5:00	11.00	7:05	420	7:17	3.05	7:22	0:17
2	5:00	11.00	7:16	402	7:27	3.11	7:21	0:05
1	8:00	11.04	10:50	400	10:59	3.05	10:58	0:08
2	8:00	11.02	11:10	432	11:29	3.12	11:13	0:03

ENDNOTES

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[1] "Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products-1999 and 2000 Annual Estimates," Vagts. U.S. Consumer Product Safety Commission (CPSC) (2003).

[2] "Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products-2001 Annual Estimates," Carlson. U.S. Consumer Product Safety Commission (CPSC) (2004).

[3] " "

[4] From 1994-1998, there were an average yearly estimated 106 CO poisoning deaths associated with natural gas, LP-gas, and unspecified gas heating systems. A new methodology was used to produce the annual CO poisoning estimates starting with the 1999 data. The notable reduction in estimates from 1994-1998 and 199-2001 could be a result of the change in methodology. For more discussion on this topic, see "Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products-1999 and 2000 Annual Estimates," Vagts. U.S. Consumer Product Safety Commission (CPSC) (2003).

[5] "Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products-2001 Annual Estimates," Carlson. U.S. Consumer Product Safety Commission (CPSC) (2004).

[6] Letter, dated May 1997, from R. Jordan, CPSC to R. Stack, International Approval Services, Inc.

[7] "Review of Selected Furnace Investigations Involving Disconnected Vent Pipes (1989-1996)," U.S. CPSC (1997).

[8] "Furnace CO Emissions Under Normal and Compromised Vent Conditions," Emissions reports for furnaces #1-5, C. Brown, R. Jordan, D. Tucholski, U.S. CPSC, (2000).

[9] "Indoor Air Modeling for Furnaces with Blocked or Disconnected Vents" IAQ modeling reports for furnaces #1-5, W. Porter, U.S. CPSC, (2000).

[10] "Carbon Monoxide (CO) emissions from Furnaces: Health concerns related to projected consumer exposure," Health assessment reports for furnaces #1-5, S. Inkster, U.S. CPSC (2000).

[11] Letter, dated November 2000, from R. Jordan, CPSC to R. Stack, Canadian Standards Association International.

[12] "Furnace Combustion Sensor Test Results," R. Jordan, U.S. CPSC (2001).

[13] Letter, dated November 2001, from R. Jordan, CPSC to R. Stack, Canadian Standards Association International.