EVALUATION OF THE DURABILITY AND LONGEVITY OF CHEMICAL SENSORS USED IN-SITU FOR CARBON MONOXIDE SAFETY SHUTDOWN OF GAS FURNACES

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KEY DEFINITIONS

The following definitions were used in this report and for the purposes of this test program:

Sensitivity is the rate of change in sensor voltage in response to an increasing concentration of its target gas. Graphically, this was depicted as the slope of each sensor's response line (*i.e.*, $\Delta V/\Delta C$, where ΔV=the change in output voltage, and ΔC=the change in target gas concentration). This definition will be prominent in the sensitivity testing discussed in the pre-aging test phase and the post-aging test phase.

Operability is a sensor's initial ability to operate within the harsh environment of a gas furnace and still exhibit a proportional output voltage in response to changing levels of its target gas within the furnace. This definition will be prominent in the in-situ furnace testing discussed in the pre-aging test phase.

Durability is a sensor's ability to operate within the harsh environment of a gas furnace over an extended period of time and continue to exhibit a proportional output voltage in response to changing levels of its target gas within the furnace. This definition will be prominent in the in-situ furnace testing discussed in the aging test phase and the post-aging test phase.

Longevity is a sensor's durability when exposed to aging conditions over a 100-day course of corrosion testing, which is assumed to be equivalent to 20 years of operation in a gas furnace. This definition will be prominent in the in-situ furnace testing discussed in the aging test phase and the post-aging test phase.

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EXECUTIVE SUMMARY

Gas furnaces continue to be one of the leading causes of unintentional carbon monoxide (CO) poisoning deaths associated with consumer products. From 2006 through 2008, gas furnaces, including central, wall, and floor furnaces, accounted for 48 percent (an estimated 32 out of 66) of the CO deaths associated with all gas-fueled products and 17 percent (an estimated 32 out of 183) of CO deaths associated with all consumer products.[1] Despite safety improvements made in the 1980s, the governing standard for gas furnaces, ANSI Z21.47, still does not include provisions that protect consumers from CO poisoning risks caused by many common failure modes, such as disconnected and partially blocked vents, and furnaces with inadequate combustion air. In 2000, to address these hazards, CPSC staff proposed that the governing voluntary standard group, the ANSI Z21.47 Central Furnace Subcommittee, add provisions to the furnace standard that would either require a means to prevent furnaces from producing concentrations of CO in excess of 400 parts per million (ppm), or cause the shutdown of furnaces in response to those CO levels. In 2001, CPSC staff conducted "proof-of-concept" testing of sensors integrated into a gas furnace that demonstrated a technological means of implementing the proposed requirements. The results of this test program were provided to the furnace subcommittee.

In response to CPSC staff's CO shutoff proposal and "proof-of-concept" testing, the Z21/83 Technical Committee (TC) on Performance and Installation of Gas Burning Appliances and Related Accessories established the Ad Hoc Working Group (AHWG) for CO/Combustion Sensors in 2002, to develop a test criterion to evaluate the use of CO sensors in furnaces, boilers, and other vented gas heating appliances and to develop a request for proposals (RFP) to solicit bids from testing agencies to conduct the sensor evaluation. In 2004, the AHWG completed the test criterion and RFP and submitted them to the Z21/83 Technical Committee for final approval. The documents were approved; however, at its 2005 meeting, the Z21/83 Technical Committee, over CPSC staff's objections, decided not to pursue any sensor evaluation activities, citing concerns that available sensor technology was not durable enough and did not have the expected furnace lifespan of 15 to 20 years to survive in a furnace. The Technical Committee did not provide any technical documentation to substantiate their concerns.

In 2007, CPSC staff initiated a test program to evaluate the durability and longevity concerns raised by the Z21/83 Technical Committee about sensors operating in a gas furnace as a CO shutoff device. The test program was designed only to examine the electrical behavior of the sensors; mechanical behavior of the sensors was not part of the scope. A total of 10 gas sensors (6 catalytic bead CO sensors, 2 nondispersive infrared (NDIR) CO sensors and 2 NDIR carbon dioxide sensors were evaluated during all phases of testing. The nondispersive infrared (NDIR) carbon dioxide (CO_2) sensors were included in the evaluation because elevated levels of CO_2 can provide an indication of combustion conditions that could result in the production of elevated levels of CO, and therefore, they could serve as an indirect measure of CO.

The program was divided into three phases of testing (*i.e.*, pre-aging, aging, and post-aging). The pre-aging phase consisted of sensitivity testing and in-situ furnace testing of the sensors. The sensitivity testing was conducted in an environmental chamber to establish baseline sensor performance prior to exposure to the harsh environment of a furnace and the conditions used to age the sensors. The sensitivity testing established that each sensor:

- produced output voltages in response to and proportional to their respective target gases;
- exhibited strong linear relationship between their output voltage and their target gases;

- produced output voltages at CPSC's proposed CO shutoff concentration for furnaces that were distinct from non-shutoff concentrations; and
- produced distinct output voltages in response to furnace CO_2 concentrations that corresponded to CO concentrations at, or in excess of, CPSC's proposed CO shutoff concentration for furnaces.

The in-situ furnace testing was conducted with sensors installed inside the flue passageways (*i.e*., heat exchangers, vent pipes, and inducer motor housings) of the test furnaces in order to establish their baseline operability in these environments prior to exposure to the conditions used to age the sensors. The in-situ furnace testing established that:

- the catalytic bead CO sensors and the NDIR CO_2 sensors operated as expected in the test furnaces;
- the catalytic bead CO sensors and the NDIR CO_2 sensors produced voltage signals that changed in response to changes in CO and CO_2 levels within the test furnaces; and
- the NDIR CO sensors did not exhibit consistent operability in the test furnaces.

Of central importance to this test program was establishing reasonable conditions to evaluate the durability and longevity of sensors operating within a gas furnace. For purposes of this test program, "durability" was defined as a sensor's ability to operate within the harsh environment of a gas furnace over an extended period of time. "Longevity" was defined as a sensor's durability when exposed to aging conditions within a gas furnace over an extended period of time. Because sensors used in this application likely would be installed in the heat exchanger of a furnace, the sensors were subjected to the same test method and conditions, specified in Exhibit G, Corrosion Resistance Criteria and Test Method, of the ANSI Z21.47 furnace standard to qualify furnace heat exchangers for long-term resistance to corrosive attack.

The Corrosion Resistance Criteria and Test Method was part of the sensor evaluation criterion agreed upon by the AHWG and approved by the Z21/83 Technical Committee in 2004. The corrosion testing performed using this methodology was outsourced to CSA-OnSpex under CPSC contract number CPSC-S-06-0080. The following assumptions were made concerning the Corrosion Resistance Criteria and Test Method:

- The long-term corrosive attack specified by the test method was equivalent to gas furnace and boiler heat exchangers and metallic vent system life spans of up to 20 years;
- It provided an appropriate means of aging and evaluating the durability and longevity of sensors installed in furnace heat exchangers and vent pipes; and
- If the sensors were able to operate as intended under the conditions of this test method, then the sensors could be considered:
  - To be durable enough to operate in the operating environment of a furnace heat exchanger and vent pipe; and
  - To have a lifespan commensurate with the expected life of furnace heat exchangers and vent pipes of up to 20 years.

Based on the conditions imposed by the Corrosion Resistance Criteria and Test Method, staff made the following observations about sensor performance:

- The catalytic bead CO sensors and the NDIR CO_2 sensors remained operable (*i.e*., exhibited voltage signals) throughout the duration of the testing.

- The catalytic bead CO sensors and the NDIR CO_2 sensors continued to exhibit sensitivity to their respective target gases, demonstrated by voltage outputs that changed in response to the changing levels of their target gases during ON/OFF cycling of the test furnaces.
- The NDIR CO sensors did not exhibit sensitivity to CO, demonstrated by voltage outputs that did not change in response to ON/OFF cycling of the test furnaces or weekly CO injections into the test furnaces.

The post-aging phase also consisted of sensitivity testing and in-situ furnace testing. The sensor performance results obtained during this phase were compared to results obtained during the pre-aging phase to determine whether the conditions imposed during the aging phase rendered any of the sensors inoperable (*i.e*., loss of voltage signal, loss of sensitivity, weakened correlation to target gas, or inability to distinguish between proposed shutoff and non-shutoff levels of the target gas). The sensitivity testing conducted during this phase demonstrated that:

- The catalytic bead CO sensors and the NDIR CO_2 sensors continued to exhibit sensitivity and a strong, linear correlation to their target gases.
- The catalytic bead CO sensors exhibited a decrease in sensitivity when compared to the pre-aging performance results.
- The decrease in the sensitivity of the catalytic bead CO sensors was possibly caused by factors such as the sensors not being equipped with a calibration algorithm or filters.

The in-situ furnace testing conducted during this phase demonstrated that:

- The catalytic bead CO sensors and the NDIR CO_2 sensors exhibited voltage outputs that changed in response to changing concentrations of CO or CO_2 within the test furnaces.
- No further testing or analysis was conducted of the NDIR CO sensors due to their continued lack of response.
- Based on the performance of the NDIR CO sensors and discussions with their manufacturer, the problems encountered by the NDIR CO sensors throughout each phase of testing were most likely caused by interference from CO_2 or water vapor, necessitating additional development by the manufacturer for this application.

Overall, the test results demonstrated that, despite being exposed to the operating environment of a gas furnace and the aging conditions of the corrosion test, the catalytic bead CO sensors and the NDIR CO_2 sensors maintained their basic electrical operability (*e.g*., continued sensitivity to target gas, continued strong linear relationship, and a continued ability to distinguish between shutoff and non-shutoff CO or CO_2 levels). Based on this, staff concluded that the sensors were durable enough to withstand the operating environment within a gas furnace and that the results provided an indication that the sensors could reach a lifespan commensurate with that of a gas furnace. These findings address the durability and longevity concerns raised by the Z21/83 Technical Committee in 2005, and they demonstrate that chemical sensors exist that can withstand the harsh operating environment of a furnace and have the potential to survive throughout the lifespan of the furnace.

1. INTRODUCTION

1.1 HAZARD

Carbon monoxide (CO) is a byproduct 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 or secondary air supplied to the burner. A typical incomplete combustion scenario occurs 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 the gas manifold pressure being too high or inadequate combustion air being provided to the appliance. When the flue passageways and venting systems of appliances are intact, CO that results from incomplete combustion is vented safely to the outdoors. However, CO can enter a home's living space and create a hazard to consumers when a leakage path is created by a compromised flue passageway or venting system.

Historically, gas heating systems have been, and continue to be, one of the leading causes of unintentional CO poisoning deaths associated with consumer products. During the most recent period for which statistical information was available, 2006 through 2008, there was an estimated annual average of 183 carbon monoxide (CO) poisoning deaths associated with the use of consumer products.[2] Of that number, 36 percent (an estimated annual average of 66 of 183) of the CO deaths were associated with gas–fueled products. Gas furnaces (including central, floor, and wall furnaces) continue to be the leading cause of CO poisoning deaths associated with gas appliances, alone accounting for 48 percent (32 of 66) of the CO deaths associated with gas appliances or 17 percent (32 of 183) of CO deaths associated with all consumer products.[3]

1.2 GOALS AND OBJECTIVES

The goal of the Vented Gas Appliance CO Sensor Project is to help reduce the risk of CO-related deaths and injuries caused by vented gas heating appliances. CPSC staff believes that a primary means of accomplishing that goal is the development of a performance standard requiring shutdown or some other preemptive response to elevated levels of CO within the flue passageways of vented gas heating appliances, such as residential furnaces and boilers.

The purpose of this test program was twofold: (1) to determine whether commercially available or prototype chemical sensors were durable enough to operate reliably as CO monitoring and shutoff devices within the harsh operating environment of a residential gas furnace, and (2) to determine whether the lifespan of sensors operating within this type of environment would be commensurate with that of a residential gas furnace. To accomplish this, CPSC staff developed a test program that included three phases of testing: (1) pre-aging phase, (2) aging phase, and (3) post-aging phase. The objectives of each phase of testing were as follows:

Pre-aging phase test objectives:

- to establish each sensor's baseline performance prior to exposure to the harsh, potentially damaging conditions that they would encounter while operating in a furnace and under aging conditions; and
- to use the baseline results as a point of reference to compare to sensor performance measured during and after aging.

Aging phase test objective:

- to subject the sensors to environmental conditions that would age and stress them in a manner that would allow their durability and longevity to be evaluated.

Post-aging phase test objectives:

- to determine whether the sensors were still operable after aging, and
- to determine whether sensor performance had degraded as a result of aging.

1.3 BACKGROUND

In 1996, CPSC staff proposed that the American National Standards Institute (ANSI)/Canadian Standards Association (CSA) Z21.47 Gas-Fired Central Furnace Subcommittee adopt provisions to the furnace standard, ANSI Z21.47, Standard for Gas-Fired Central Furnaces, that would require furnaces to shut down when the vent pipe became disconnected or partially blocked in order to protect consumers from CO exposure hazards associated with these vent conditions.[4] To support this proposal, staff conducted a review of CPSC In-Depth Investigation (IDI) reports involving disconnected furnace vents. The IDI review results were summarized and provided to the subcommittee in 1997.[5] In response to CPSC staff's proposal and incident data, the subcommittee, at its meeting in September 1997, 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 became 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 (Item 2) was replaced with a task to conduct a root-cause analysis of the CPSC IDIs.[6] CPSC staff objected to this change because it did not include assessment of a technological means to address the problem and because the IDIs had been reviewed already.[7]

In fiscal years 1999 and 2000, CPSC staff conducted emissions testing of five residential gas furnaces to explore some of the failure modes that lead to CO production and leakage and 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 due to spillage of combustion products into a living space from a disconnected or partially blocked furnace vent. CPSC staff solicited and received input from the gas furnace industry on the test plan and setup. The test results were used to model indoor air concentrations[9] and to assess the health effects[10] that would be associated with these concentrations. The results of this analysis were shared with the furnace subcommittee and GAMA in 2000.

In 2000, CPSC staff proposed that the furnace subcommittee adopt the following performance requirements in 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[i] once installed in the field, or

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[i] "A furnace shall not produce a concentration of carbon monoxide in excess of 0.04 percent in an air-free sample of the flue gases when tested in an atmosphere having normal oxygen supply," Section 2.8,

2. require a means, once installed in the field, to shut down the furnace if CO emissions exceeded the standard limits.

In 2001, out of concern that the availability of technology could pose a potential barrier to implementing these proposed performance standards, CPSC staff conducted patent and Internet searches to identify relevant technologies. Two carbon monoxide sensing technologies (*i.e.*, catalytic bead and mixed metal oxide semiconductor) were identified and evaluated in a "proof-of-concept" test program to use gas sensing technology to detect elevated CO production within a gas furnace and initiate furnace shutdown in response. The objectives of this test program were to demonstrate the concept of using CO sensing technology to shut down a furnace by:

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

CPSC staff accomplished these objectives and, in doing so, successfully demonstrated the concept of using sensor technology for shutdown response to hazardous CO levels within a furnace. In 2001, CPSC staff shared the test results[12] 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, asserting that the issue of sensor shutdown of gas appliances was much broader than furnaces.[14,15] In April 2002, the Z21/83 Committee voted to establish the Ad Hoc Working Group (AHWG) for CO/Combustion Sensors to evaluate the use of gas sensors to shut down gas appliances in response to excessive CO production.[16] CPSC staff volunteered to serve on the AHWG and participated until it was disbanded in 2005.

In 2003, CPSC staff began a test program to extend the work conducted in 2001, by addressing some of the issues that were not addressed in that work. In particular, staff conducted testing to determine the effects on sensor performance of temperature and relative humidity variations during appliance ON/OFF cycles. Staff also used carbon dioxide (CO_2) as a proxy, or indirect measure, of normal and elevated CO concentrations produced in an appliance during incomplete combustion. Staff acquired two sensing technologies that were not evaluated in the previous work; namely, electrochemical sensors to detect CO and nondispersive infrared (NDIR) sensors to detect CO_2. As in the sensor test activity in 2001, these sensor technologies were integrated into the vent system of a furnace and tested. The objectives of the 2003 test activity were to provide empirical data to demonstrate further and support the concept of using CO sensing technology to shut down a furnace by:

1. Evaluating the performance of each sensor when exposed to the target gas in various temperature and humidity conditions;
2. Determining whether sensor performance is impacted by changes in non-target gas levels in various temperature and humidity conditions;

Combustion, ANSI Z21.47/CSA 2.3, American National Standard/CSA Standard for Gas-Fired Central Furnaces.

3. Demonstrating the ability of gas sensors to measure directly or indirectly a 400 parts per million (ppm)[ii] concentration of CO within the furnace vent system, combustion chamber, or flue passageways; and
4. Demonstrating 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).

All of the objectives of this test program were accomplished and the findings[17] were shared with the Z21/83 Committee, the Z21/83 AHWG for CO/Combustion Sensors, the ANSI Z21.47 Central Furnace Technical Advisory Group, and the Gas Appliance Manufacturers Association (GAMA) in 2005.[18]

Although the 2003 test program objectives were accomplished, more work was required. Sensor performance had to be evaluated at the higher temperatures (*i.e.*, 200^{o}F to 500^{o}F) that exist in different regions of heat exchangers used in high and mid-efficiency gas furnaces. Sensor reliability, durability, and life expectancy also required evaluation. It was also noted in the 2003 sensor test report that future test 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, as well as periods in which the appliance was not in operation. These test and evaluation considerations were included in a draft test matrix developed by the AHWG for CO/Combustion Sensors and completed in 2004. The test matrix was part of a work plan to evaluate sensor usage in gas appliances developed by the working group for consideration by the Z21/83 Technical Committee. The working group effort spanned the period from 2002 to 2004, and it culminated in a Request for Proposals (RFP) that included the test matrix and work plan.

The RFP was presented to the Z21/83 Technical Committee at its meeting in September 2004, for final approval of its technical/test content. The Technical Committee approved the content of the RFP, but it deferred approval to send the RFP out for solicitation to the Z21/83 Advisory Council. Upon approval by the Advisory Council, the process of funding the work plan and sending the RFP out to solicit qualified test agencies to conduct the work would have begun. Prior to granting this approval, the Z21/83 Advisory Council requested that the Gas Research Institute (GRI) develop an estimate of the cost to conduct the work outlined in the test matrix and work plan. GRI estimated that it would cost $875,000 to conduct the work. In November 2004, the Z21/83 Advisory Council opted to solicit financial assistance from gas industry stakeholders to help fund the work. In February 2005, the CPSC was included in the group of stakeholders.[19] However, at their meeting in September 2005, the Z21/83 Technical Committee voted not to fund the RFP, and decided to disband the AHWG for CO/Combustion Sensors.[20]

The rationale cited by the Z21/83 Committee for not funding the RFP was that, based on some of the Committee members' experience, available CO sensing technologies: (1) were not durable enough to withstand the harsh environments of furnace flue passageways, and (2) did not have the life expectancy of furnaces, which is generally considered to be an average of 15 years. However, the Technical Committee did not provide any technical documentation to substantiate their concerns or support their position. The AHWG for CO/Combustion Sensors was disbanded because the Technical Committee viewed it as having fulfilled its mission. Prior to the Technical Committee's September 2005 meeting, CPSC staff received a letter from GAMA, indicating that GAMA members did not support funding the RFP because they also

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[ii] A CO concentration of 400 ppm was selected as a detection level because this is the emission limit specified by ANSI Z21.47, Standard for Gas-Fired Central Furnaces.

believed that available CO sensing technologies: (1) were not durable enough to withstand the harsh environments of furnace flue passageways, and (2) did not have the life expectancy of furnaces, which is generally considered to be an average of 15 years.[21] To address the issue of CO exposure and poisoning, GAMA indicated that they would pursue efforts requiring the installation of residential CO alarms in homes in the United States.

CPSC staff objected to the Technical Committee and GAMA's positions and the actions taken by the Technical Committee because: (1) none of these concerns were raised as obstacles to moving forward during the preceding 3 years that the AHWG was active; (2) no technical documentation was presented to substantiate the position; and (3) the purpose of the test criterion developed by the AHWG was to explore these and other issues.[22] Staff also objected to the rationale for the approach taken by GAMA because it contradicted one of their stated rationales for not wanting to pursue sensor use in furnaces. In 2005, the typical lifespan of residential CO alarms was widely believed to range from 2 to 5 years, well short of the expected 15-year-long life span for gas furnaces. Thus, in effect, GAMA was proposing the use of a device (*i.e.*, residential CO alarms) that did not have the life span of gas furnaces. CPSC staff argued that this was significant because the protective device could stop working well before the end of life of the furnace, and thus, it would not be able to provide a warning to consumers in the event of CO exposure. CPSC staff also argued that this approach removed the responsibility for consumer safety from the appliance manufacturer and would be able to warn consumers only if it is installed and functioning properly but not cause shutdown or another preemptive response of the furnace.

Because the primary concerns raised by the Z21/83 Committee and GAMA at the September 2005 meeting were about sensor durability and longevity, staff sought to develop an approach to address these concerns. At the September 2005 meeting, appliance manufacturing members of both the Z21/83 Committee and GAMA stated that they had conducted limited testing of CO sensors in gas furnaces and that the sensors did not perform well when installed in those appliances. In order to examine these claims, CPSC staff sent letters to the presidents of approximately 40 appliance manufacturing firms (furnaces, boilers, and vented space heaters), requesting confidential meetings with their technical staff members who were involved in relevant sensor research. In response to this inquiry, three major furnace manufacturers invited CPSC staff to visit their facilities to discuss their experiences with CO sensor testing in gas appliances.

In 2006, CPSC staff visited the facilities of these manufacturers to discuss their experiences and to use them for input in developing an approach to address sensor durability and longevity concerns. The technical information shared by these manufacturers was very limited, ranging from generalities about testing, to sharing limited test outcomes. In the instances in which test outcomes were discussed, the manufacturer indicated that the sensors experienced failures that ranged from erratic, non-distinct voltage output signals, to sensors becoming completely inoperable and unable to generate a voltage signal, all within a matter of a few days to a week. CPSC staff used information gleaned from these meetings, the existing requirements within the furnace standard, and the Z21/83 Committee-approved tests, and the RFP developed by the AHWG for CO/Combustion Sensors to develop an approach to evaluate sensor durability and longevity. Based on these sources, CPSC staff concluded that the best approach to address sensor durability and longevity was to subject sensors, while integrated into furnace heat exchangers and flue passageways, to the same test conditions used to evaluate the durability and longevity of heat exchangers and venting systems in furnaces and boilers. The rationale for this approach was that sensors used in this application, if adopted by the Z21/83 Committee into appliance standards, likely would be integrated into furnace and boiler heat exchangers. Thus, the aging conditions used to evaluate heat exchangers would provide the same conditions that sensors would be exposed to over their life cycle within the heat exchanger of a furnace or boiler, and therefore, provide a suitable means to evaluate sensors in this application. The test conditions are found in Exhibit G, Corrosion Resistance Test Methodology, ANSI Z21.47, Standard for Gas-Fired Central Furnaces.

In 2006, CPSC staff developed a test program to implement this strategy. The test program consisted of setting up two test furnaces, one, a propane unit, and the other one, a natural gas unit. Each unit was equipped with an array of gas sensors located at various points within the flue passageways (*i.e*., primary heat exchanger, secondary heat exchanger, and vent system) and subjected to the test conditions of Exhibit G. The test program was divided into three major parts: pre-aging, aging, and post-aging. All of the pre-, and a portion of the post-aging tests, were conducted at the combustion test facilities at the CPSC laboratory in Gaithersburg, MD. All of the aging and a portion of the post-aging tests were outsourced to CSA-OnSpex under CPSC contract number CPSC-S-06-0080 and conducted at CSA's test facility in Cleveland, OH. The test program was completed in 2008, and the results are reported here.

1.4 SENSOR DESCRIPTION

Two different gas-sensing technologies (*i.e*., catalytic bead and nondispersive infrared (NDIR))—with CO as the target gas—were used for this test program. In addition to CO, NDIR sensors with CO_2 as the target gas were also used. A total of 18 gas sensors were acquired for this test program. The sensor distribution included two different models of catalytic bead CO sensors (five of each model, or a total of 10), 4 NDIR CO sensors, and 4 NDIR CO_2 sensors. All 18 of the sensors were subjected to sensitivity testing within an environmental chamber. However, due to space limitations within the two test furnaces, not all sensors were subjected to in-situ furnace testing. A total of 10 sensors were subjected to in-situ furnace testing. The distribution of sensors in each of the two test furnaces was as follows: 3 catalytic bead CO sensors, 1 NDIR CO sensor, and 1 NDIR CO_2 sensor. A brief description of each technology follows.

Catalytic Bead Sensors

Catalytic bead sensors measure a change in resistance that occurs when the target gas is oxidized on the surface of the sensing element. A catalytic bead sensor has two compartments, one open to the atmosphere and the gas being measured, the other is closed to the atmosphere and the gas being measured. The open compartment contains the sensing element. The sensing element is a platinum filament that is covered with a catalyst, which when heated, oxidizes combustible gases—including CO— that come into contact with it. This is accomplished by increasing the sensing element operating temperature to between 300^o and 400^o C using a heater driver board. At these temperatures, oxidation of the gas being measured occurs when it contacts the sensing element, causing an increase in the sensing element temperature and a corresponding increase in resistance. The other compartment contains a compensator that is connected electrically by a coil to the sensing element. Because it is isolated from the gas being measured, oxidation does not occur on the compensator. As a result, the compensator temperature and resistance remain unchanged, providing a reference point that allows a measurable differential resistance between it and the sensing element in the presence of the gas being measured. The differential resistance between the sensing element and the compensator results in an output voltage drop that is proportional to the concentration of gas being measured.

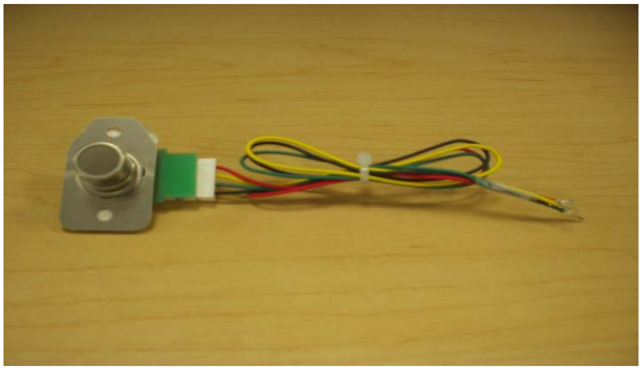

Figure 1. Catalytic bead CO sensor (CB79)

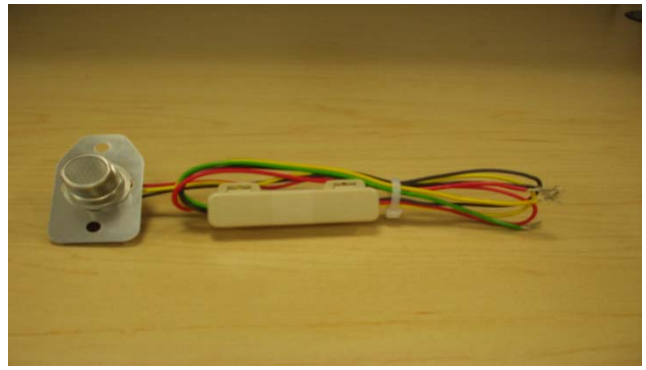

Figure 2. Catalytic bead CO sensor (CB78)

The catalytic bead sensors used in this test program are the same model sensors previously tested by CPSC staff to demonstrate the concept of using sensors for safe shutoff of gas furnaces in response to dangerous levels of CO.[23] According to the manufacturer's literature, these sensors have been commercially available and sold for CO shutoff of gas boilers and water heaters in Japan since 2001. A total of 10 sensors were acquired; five identified, for the purposes of this test program, as CB78 CO sensors and five identified as CB79 CO sensors. The CB78 and CB79 sensors were essentially the same model. The primary difference was that the control circuitry for the CB79 sensors (Figure 1) was miniaturized and integrated into the main sensor body, eliminating the need for the wire harness and circuit board used for the CB78 version (Figure 2). Neither of the sensors was shipped packaged with a calibration algorithm for re-zeroing or calibration. Instead, the manufacturer provided an example of a methodology to accomplish that but left that to the end user (*e.g.*, gas appliance manufacturer, test agency) to implement.

Nondispersive Infrared Sensors

Infrared sensors measure the electromagnetic signature of gas molecules that have been exposed to an infrared light source. The major components of an infrared sensor are the gas cell, infrared light source, optical filter, and detector. The infrared sensors used in this test program were the nondispersive infrared type (NDIR), meaning they used a discrete optical band-pass filter to eliminate optical wavelengths other than those of the respective target gases being measured. For each sensor, a gas sample was drawn into the inlet port of the gas cell by aspiration and exited through an outlet port. The infrared light source was located at one end of the gas cell and the optical filter and detector at the other end. As the gas sample traveled through the gas cell, light was beamed from the infrared light source through the gas sample and optical filter to the detector.

Some of the radiation emitted by the infrared light source is absorbed by the gas molecules, while the remainder of the radiation passes through the gas molecules. When gas molecules absorb radiation, they vibrate more rapidly, resulting in an increase in their temperature that is proportional to the concentration of the gas being measured. The optical filter screens out the specific wavelength for the gas species being measured from radiation emitted from the infrared light source. The detector converts the temperature change to a voltage signal that is proportional to the gas concentration being measured.

The nondispersive infrared (NDIR) CO sensors (Figure 3) and CO_2 sensors (Figure 4) used for this test program were each commercially available for other applications, but were prototype units for the in-situ furnace test application.

Figure 3. Nondispersive infrared CO sensor (NDIRCO)

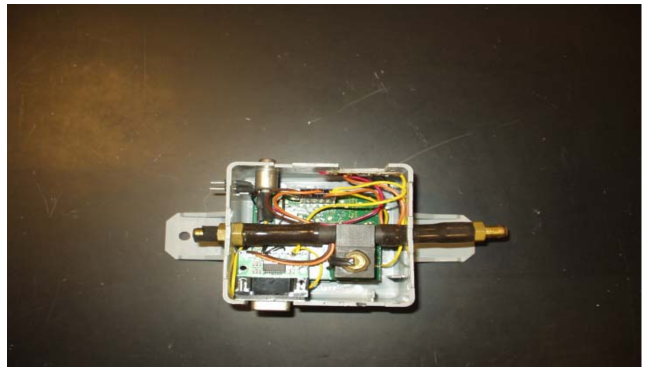

Figure 4. Nondispersive infrared CO_2 sensor (NDIRCO2)

Each sensor type had to undergo some design modifications by the manufacturer in order to be used in the in-situ furnace application. A total of four each were acquired for this test program.

2. PRE-AGING TEST PHASE

The purpose of the tests conducted during the pre-aging phase were (1) to establish each sensor's baseline performance prior to exposure to the harsh, potentially damaging conditions they would encounter during aging in a furnace, and (2) to use the baseline results as a point of reference to compare to sensor performance data measured during and after aging. The pre-aging test phase was comprised of sensitivity testing and in-situ furnace testing. All pre-aging phase testing was conducted in the combustion test facilities located at CPSC's Directorate for Laboratory Sciences. A summary of all pre-aging phase test objectives and whether the objective for each sensor was met is provided in Appendix F.

2.1 SENSITIVITY TESTING

2.1.1 Sensitivity Test Methodology and Setup

Method

Sensor sensitivity indicates how much a sensor's output voltage changes in response to changes in its target gas and is defined as the ratio between the two properties. Based on the manufacturers' literature, each of the sensors reported on here are designed to produce an output voltage that is linear and proportional to its respective target gas. To perform the necessary measurements, each sensor was placed in the environmental chamber described below, energized at its rated voltage, and exposed to its respective target gas, as described below under "Gas Injection and Sampling System."

Setup

Chamber

Sensitivity testing of all sensors was conducted inside of an environmental chamber (Figure 5) to characterize each sensor's response to varying concentrations of its respective target gases. The interior volume of the chamber is 32 ft^3 and has walls constructed of stainless steel. The environmental chamber provided a controlled environment in which target gas, temperature, and humidity could be monitored and regulated through the use of a heat exchanger and fan assembly to control temperature and air mixing. The fan assembly circulated air over the cooling coils of the heat exchanger, creating a well-mixed environment within the chamber. The air temperature in the chamber was measured at a single point at the approximate center of the chamber using a K-type thermocouple. The chamber was equipped with control units to control temperature and relative humidity within the chamber. The temperature controller had an adjustment range of 32^{o}F to 210^{o}F (0^{o}C to 99^{o}C). The humidity controller had an adjustment range of 20 percent to 95 percent relative humidity (RH). Characterization tests were conducted at nominal chamber conditions of 70^{o}F and 50 percent RH.

Gas Injection and Sampling System

The target gas of each sensor was introduced into the chamber through a gas injection system that consisted of bottled target gas (*i.e.,* either pure CO or CO_2), a digital mass flow controller, and solenoid valves. Chamber gas concentrations were controlled to within +/- 10 ppm for CO and +/- 0.1 percent for CO_2. For CO sensor performance, pure CO was introduced into the chamber through the gas injection system at flow rates that allowed chamber CO concentrations to be in attained and controlled in increments of 100 ppm through a range up to 1000 ppm. For CO_2 sensor performance, pure CO_2 was injected into the chamber at flow rates that allowed chamber CO_2 to be attained and controlled in increments of 1 percent through a range up to 12 percent.

Gas samples were drawn from the chamber through a gas sampling system that consisted of six separate sample ports and lines, a sample pump, solenoid valves, and a multi-gas analyzer (Rosemount, Model NGA 2000). The sample lines were connected to a manifold which combined all six of the samples into a single, mixed gas sample prior to entry into the multi-gas analyzer. The multi-gas analyzer was equipped with five individual gas measurement modules, including two nondispersive infrared (NDIR) gas modules for CO, 1 NDIR gas module for carbon dioxide, 1 paramagnetic gas module for oxygen, and 1 NDIR gas module for hydrocarbons. The CO modules in the multi-gas analyzer were calibrated daily in accordance with the manufacturer's instructions. In general, the CO modules were zeroed with nitrogen gas and then spanned using a primary standard gas mixture. In addition, the gas analyzer was checked at several other gas concentrations to verify proper operation over the test range of 0-1,000 ppm of CO.

Data Acquisition System & Sensor Signals
A data acquisition system was used to record sensor performance data. Chamber gas concentrations were recorded manually. The data acquisition system consisted of a personal computer, data acquisition (DAQ) interface hardware, and data acquisition software. Analog output signals were transmitted from each sensor to the DAQ hardware through approximately 20 feet of wire. Once gas concentration equilibrium was achieved, the data acquisition system recorded data at a rate of one sample per second.

2.1.2 SENSITIVITY TEST RESULTS

Sensitivity testing was conducted to establish each sensor's baseline performance in the controlled chamber environment described under the "Sensitivity Testing/Setup" subsection. For the purposes of this test, sensor sensitivity was defined as the rate of change in sensor voltage in response to an increasing concentration of its target gas. Sensor sensitivity is illustrated by the slope of the line created when sensor voltage is plotted against the concentration of the target gas in the chamber and is represented by m in the resultant equation of the line, $y=mx+b$. This was depicted in Graphs A.1 through A.18 in Appendix A as the slope of each sensor's response line (*i.e.,* $\Delta V/\Delta C$, where ΔV=the change in sensor output voltage and ΔC=the change in target gas concentration). Each sensor was exposed to normal air (*i.e.,* zero or negligible concentrations of each sensor's target gas) and to increasing concentrations of their respective target gas.

The objectives of the sensitivity testing of the CO sensors were to: (1) determine the strength and direction of the linear relationship between the target gas and the sensor response or output voltage, (2) establish sensor sensitivity, (3) determine each sensor's output voltage in response to the proposed CO shutoff level (*i.e.,* nominally 400 ppm) for gas furnaces, and to (4) determine whether sensor response to the proposed CO shutoff level was distinct from background CO levels (*i.e.,* 100 ppm or less) and non-shutoff/nuisance CO levels (*i.e.,* 101 to 299 ppm). The strength of the linear relationship between a given sensor and its target gas was determined by calculating the Correlation Coefficient, r. Correlation Coefficients greater than 0.7 were considered to be strong; correlations between 0.3 and 0.7 were considered to be moderate; and correlations less than 0.3 were considered to be weak.[24] The objectives of the sensitivity testing of the CO_2 sensors were similar, but each sensor's ability to distinguish between CO_2 levels that corresponded to the proposed CO shutoff levels (*i.e.,* approximately 9 to 11 percent CO_2) and CO_2 levels that corresponded to background/non-shutoff levels (*i.e.,* CO_2 concentrations of 8.5 percent or less) were considered. These data were used as a baseline for comparison to sensor performance measured during the post-aging test phase to determine whether the effects of aging and the harsh conditions inside the furnace had any detrimental effect on sensor operation.

Catalytic Bead CO Sensors

Sensitivity testing was conducted on a total of 10 catalytic bead CO sensors; five identified as CB78#1, CB78#2, CB78#3, CB78#4, and CB78#5 and five identified as CB79#4 , CB79#5, CB79#6, CB79#7, and CB79#8. Testing was conducted at a nominal chamber temperature of 70^{o}F and relative humidity of 50 percent. The CB78 sensors had a zero offset voltage that ranged from approximately 20 to 35 mV, while the CB79 sensors had a zero offset voltage that ranged from approximately 90 to 130 mV. Each of the catalytic bead CO sensors had a voltage drop (ΔV) of between 0 and 3 millivolts (mV) when exposed to CO across a measurement range of 0 to 1000 ppm.[iii] This degree of change in output voltage (*i.e.,* 3 mV) was smaller than the zero offset voltage ranges of 20 to 35 mV for the CB78 sensors and 90 to 130 mV for the CB79 sensors. Thus, in order to differentiate more clearly the change in sensor voltage from the base (*i.e.,* zero) voltage, the sensor test results were reported with the zero offset voltages subtracted. It is also important to note that, although recommended by the manufacturer, CPSC staff did not incorporate filters, amplifiers, or calibration algorithm/electronics[iv] into the catalytic bead sensors. This was done in order to allow for an assessment of raw, unaltered sensor performance.

Three sensitivity tests were conducted for the CB79 catalytic bead CO sensors and two for the CB78 catalytic bead CO sensors. The test results are presented in Graphs A.1 through A.10 and Tables A.1 through A.10 of Appendix A. In order to compare sensor performance, each set of test results for individual sensors are presented in a separate graph and table. The sensors exhibited some variation in output voltages at target chamber CO concentrations throughout each set of tests. For example, at nominal chamber CO concentrations of 400 ppm during test numbers 1, 2, and 3 (actual chamber CO concentrations were 413, 396, and 398 ppm, respectively), the corresponding average voltages for CB79#6 were 0.9, 0.9, and 1.4 mV (see Graph A.3 and Table A.3). Similarly, during testing of CB78#3, average voltages were 1.0 and 1.4 mV at nominal chamber CO concentrations 400 ppm (actual chamber concentrations of 396 ppm and 398 ppm). Staff believes that this variability occurred because the sensors were not equipped with a calibration algorithm/electronics and underscores the importance of having this capability in production units if they were used for CO shutoff control of furnaces and boilers.

Despite not being equipped with a means of calibration and the resulting variability in output signal, each sensor exhibited an increasing linear voltage output in response and proportional to the increasing concentrations of CO injected into the chamber. As shown in Graphs A.1 through A.10, the sensors exhibited high degrees of correlation to CO, demonstrated by correlation coefficient (r) values ranging from 0.72 to 0.96. The sensitivity to CO for this group of sensors ranged from 0.21 to 0.26 mV for every 100 ppm of CO injected into the chamber. Thus, although CB79#6 and CB78#3 exhibited variability, each sensor still exhibited sensitivity, or response, to CO. For CB79#6, this was demonstrated by relatively consistent sensitivities of 0.23, 0.24, and 0.23 mV per 100 ppm of CO (see Graph A.2) for the

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[iii] According to the manufacturer's literature, the catalytic bead sensors are designed to detect CO and hydrogen (H_2) produced during incomplete combustion of hydrocarbon fuels in a gas appliance and exhibit a voltage drop in response to the energy released during the combustion process. The sensitivity tests were conducted with only CO, not a CO and H_2 mixture, because the CPSC test apparatus (*i.e.* the gas injection and sampling systems and multi-gas analyzers) were not equipped to inject and sample H_2 into and from the environmental chamber or measure H_2 directly. As a result, the output voltage measurements for the catalytic bead sensors were generally lower during the sensitivity testing than they would have been had a CO/H_2 mixture been used throughout the testing. The specifications for these sensors indicates they have a voltage drop of between 5 and 7 mV in a 2 to 1 CO/H_2 mixture of 1000 ppm CO and 500 ppm H_2.

[iv] The sensor manufacturer included a recommendation in their User's Manual that the sensors be re-zeroed every two to three hours due to how small the sensor output signals were and to assure greater accuracy. The manufacturer also included a sample re-zeroing algorithm in the User's Manual.

three tests to which it was subjected. CB78#3 also exhibited relatively consistent sensitivities to CO of 0.25 and 0.26 mV per 100 ppm CO (see GraphA.8).

Exceptions to this were seen when CB78#4 and CB79#8 did not respond to CO during Test #2 and again when CB79#8 did not respond to CO during Test #3. In each case, this resulted in low r values of 0.0091 and 0.0017 respectively, for CB78#4 and CB79#8 during Test #2 and an r value of 0.0026 for CB79#8 during Test #3. Staff believes that because CB79#8 and CB78#4 each exhibited behavior more in line with the other catalytic bead sensors during other sensitivity tests, this behavior could have been caused by a loose wire, a faulty data channel in the data acquisition, or a problem with the data acquisition program. During Test #1, CB79#8 exhibited an increasing linear voltage output in response and in proportion to increasing chamber CO concentrations. CB79#8 exhibited a sensitivity of 0.21 mV per 100 ppm of CO and a correlation coefficient, r, of 0.72. In Test #3, CB78#4 exhibited linear response, with a sensitivity of 0.22 mV per 100 ppm CO and an r value of 0.88.

With the exception of the behavior of CB78#4 during Test #1 and CB79#8's behavior during Tests #2 and #3, all of the catalytic bead CO sensors exhibited average output voltages, at or near nominal chamber CO levels of 400 ppm, which were distinct from average sensor voltages at or near nominal chamber CO levels of 300, 200, 100, and 0. While sensor voltages showed some overlap at successive CO concentrations, CPSC staff believes this could be attributed to the fact that the voltage drop across the measurement range was relatively small (*i.e.,* less than 3 mV) and that the sensors were not equipped with filters to remove or reduce signal noise potentially introduced from the test environment or the data acquisition system. Thus, given the magnitude of the sensor voltage, noise would have a more noticeable effect.

Despite the observations about noise and overlap, the average sensor voltages were distinct at each successive CO concentration, and thus, the sensors were able to distinguish between the proposed CO shutoff concentrations and non-shutoff concentrations for furnaces. As seen by the "Diff Avg" columns in Tables A.1 through A.5, the average sensor voltages for CB79#4 , CB79#5, CB79#6, CB79#7, and CB79#8 at nominal chamber CO concentrations of 400 ppm differed from the average voltages at nominal chamber concentrations of 300 ppm by 0.2 to 0.3 mV. The average voltages for CB78#1, CB78#2, CB78#3, CB78#4, and CB78#5 at nominal chamber CO concentrations of 400 ppm were also distinct and differed from the average voltages at concentrations of 300 ppm by 0.2 to 0.3 mV (see Tables A.6 through A.10). A full set of results for the catalytic bead CO sensors is provided in Appendix A, under the heading, Pre-Aging Sensitivity Test Data.

NDIR CO Sensors

Sensitivity testing was conducted on a total of four non-dispersive infrared (NDIR) CO sensors designated as NDIRCO#1, NDIRCO#2, NDIRCO#3, and NDIRCO#5. Testing was conducted at a nominal chamber temperature of 70^{o}F and relative humidity of 50 percent. The test results are presented in Graphs A.11 through A.14 and Tables A.11 through A.14 of Appendix A. In order to compare sensor performance, each set of test results for individual sensors is presented in the same graph and table. The test results for this group of sensors were mixed. Although each sensor exhibited an increasing linear voltage output in response and in proportion to the increasing concentrations of CO injected into the chamber, none of the sensors exhibited repeatable results between tests. Some of the sensors also exhibited a considerable lag in response to chamber CO. As seen from the slope of each sensor's response line in Graphs A.11 through A.14, the NDIR CO sensors' sensitivity ranged from 0.29 volts for every 100 ppm change in chamber CO concentration to 0.52 V per 100 ppm CO and showed a high degree of correlation to CO, demonstrated by correlation coefficient, r, values that ranged from 0.82 to 0.99. Each sensor also exhibited voltage outputs in response to the CPSC's proposed furnace CO shutoff concentration (*i.e.,* 400 ppm CO) that was distinct from non-shutoff chamber concentrations (*i.e.* between 101 and 299 ppm CO) and from chamber CO concentrations that fell within a normal furnace operating range (*i.e.,* 100 ppm CO and lower).

During Test #1, NDIRCO#1 exhibited an immediate, proportional response to CO (see Graph A.11), whereas NDIRCO#2 (Graph A.12) and NDIRCO#5 (Graph A.14) each exhibited a delayed response. This also occurred during Test #2, where NDIRCO#3 (Graph A.13) and NDIRCO#5 (Graph A.14) each exhibited immediate response to CO, while NDIRCO#2 again exhibited a delayed response. Variability in sensor performance was also witnessed between tests for NDIRCO#2 and NDIRCO#3. During Test #1, due to the lag it exhibited, NDIRCO#2's average output at a nominal chamber CO concentration of 400 ppm was one volt compared to 0.2 volts during Test #2 (see Tables A.12). The average voltages exhibited by NDIRCO#5 during Tests #1 and #2 were 0.3 and 3.4, respectively. Due to space limitations within the test setup, NDIRCO#1 and #3 were not both tested during Tests #1 and #2; NDIRCO#1 was only tested during Test #1, and NDIRCO#3 was only tested during Test #2.

NDIRCO#1 and NDIRCO#3 exhibited the most comparable performance. During Test #1, average voltages of 1.4, 2.1, 2.5, 3.1, and 3.6 volts were recorded for NDIRCO#1 at actual chamber CO concentrations of 3, 103, 199, 290, and 404 ppm, respectively. During Test #2, average voltages of 1.2, 1.7, 2.4, and 2.7 volts were recorded for NDIRCO#3 at actual chamber CO concentrations of 0, 104, 203, 304, and 404 ppm, respectively. Space constraints within the test furnaces would allow for mounting of only one NDIRCO sensor per furnace. Based on this and their comparable performance during sensitivity testing, staff selected NDIRCO#1 and NDIRCO#3 for all subsequent in-situ furnace testing during the pre-aging, aging, and post-aging phases of this test program.

Given the late arrival of the NDIR CO sensors and the need to move ahead to the in-situ furnace testing and aging-phase testing, there was not adequate time to conduct additional testing to determine definitively the cause of the lag and to obtain repeatable results. However, staff believes that the lag in response may have been caused by the sampling line setup for sensitivity testing; the sensor sample lines were connected in series with a single sample pump; thus, the chamber CO sample was not delivered to the sensors at the same time. In retrospect, a parallel sample line setup would have been more appropriate, as it would have allowed sample delivery to each sensor at the same time. For a full set of results for the NDIR CO Sensors, see Appendix A, Pre-Aging Sensitivity Test Data.

NDIR CO_2 Sensors
Sensitivity testing was conducted on four NDIR CO_2 sensors designated NDIRCO2#1, NDIRCO2#2, NDIRCO2#3, and NDIRCO2#4. Sensitivity tests were conducted at a nominal chamber temperature of 70^{o}F and relative humidity of 50 percent. NDIR CO2#2 and NDIR CO2#3 each had a measurement range of 0 to 9 percent CO_2; NDIRCO2#1 had a measurement range of 0 to 11 percent CO_2; and NDIRCO2#4 had a measurement range of 0 to 12 percent CO_2. Each of the sensors had a voltage drop, ΔV, of 4 volts across their respective ranges. CPSC staff used the CO_2 sensors as a means to detect furnace combustion conditions at which CO concentrations would become elevated above the proposed shutoff limit of 400 ppm. Through emissions testing of the two test furnaces, staff established that 9 percent CO_2 corresponded to conditions within the furnaces at which concentrations of CO in excess of 400 ppm could be produced. This level would vary in different gas furnaces.

The test results are presented in Graphs A.15 through A.18 and Tables A.15 through A.18 of Appendix A. In order to compare sensor performance, each set of test results for individual sensors is presented in the same graph and table. As seen in Graphs A.15 through A.18, each NDIR CO_2 sensor exhibited an increasing linear voltage output in response and proportional to the increasing concentrations of CO_2 injected into the chamber. Sensor sensitivities ranged from averages of 0.34 to 0.36 volts for every 1 percent change in the chamber CO_2 concentration and exhibited a high degree of correlation to CO_2, demonstrated by correlation coefficient, r, values that ranged from 0.95 to 0.99.

Each sensor exhibited distinct voltage output at each incremental CO_2 level, within their measurement range, which was injected into the chamber. NDIR CO2#2 and NDIR CO2#3 each exhibited full-scale voltage (4 volts) at 9 percent CO_2; NDIR CO2#1 exhibited full-scale voltage at 11 percent CO_2, and NDIR CO2#4 exhibited full-scale voltage at 12 percent CO_2. As seen during Test #1 at a nominal chamber CO_2 concentration of 8 percent (7.96 percent actual), the average voltages for sensors NDIRCO2#1, NDIRCO2#2, NDIRCO2#3, and NDIRCO2#4 were 2.8, 3.4, 3.3, and 2.7 volts, respectively. At a nominal chamber CO_2 concentration of 9 percent (8.97 percent actual), the average voltages for these sensors were 3.2, 4.0, 3.9, and 3.1 volts, respectively. NDIRCO2#2 and NDIRCO2#3 were at or near their full-scale voltages. At a nominal chamber CO_2 concentration of 10 percent, the average voltages for sensors NDIRCO2#1 and NDIRCO2#4 were 3.5 and 3.4 volts, respectively. At 11 percent chamber CO_2 (11.01 percent actual), the average voltage for NDIRCO2#1 reached full scale and NDIRCO2#4 was 3.8 volts. At 12 percent CO_2, NDIRCO2#4 exhibited its full-scale output of 4 volts.

The test results were repeatable between the first and second tests and the sensors exhibited linear voltages that corresponded to changing concentrations of CO_2 injected into the chamber. Sensor voltages were distinct at each concentration of CO_2. During Test #2 at a nominal chamber CO_2 concentration of 8 percent (7.96 percent actual), the average voltages for sensors NDIRCO2#1, NDIRCO2#2, NDIRCO2#3, and NDIRCO2#4 were 2.8, 3.6, 3.4, and 2.7 volts, respectively. At a nominal chamber CO_2 concentration of 9 percent (8.97 percent actual), the average voltages for these sensors were 3.2, 4.0, 3.9, and 3.1 volts. For a full set of results for the NDIR CO_2 sensors, see Appendix A, Pre-Aging Sensitivity Test Data.

2.2 IN-SITU FURNACE TESTING OF SENSORS

2.2.1 In-Situ Furnace Test Method and Setup

Method

The in-situ testing was conducted to establish the initial operability of each sensor in a furnace environment. Tests were conducted under normal and abnormal furnace operating conditions known to occur in the field and that produce harmful levels of CO (*i.e.*, furnace operating in an over-fire[v] condition with reduced air flow through the furnace flue passageways). For the purposes of this test program, operability was defined as a sensor's ability to operate within the harsh environment of a gas furnace and still exhibit a proportional output voltage in response to changing levels of its respective target gas within the furnace.

For the CO sensors, the objectives of the in-situ furnace testing were to: (1) establish the operability of sensors in the furnace environment; (2) determine whether sensor output voltage changed in response to changing concentrations of the target gas during ON/OFF cycling or continuous operation of the furnace;

[v] Over-fire is an abnormal operating condition in which the appliance energy input rate (*e.g.*, BTU/hr) is adjusted to a higher rate than the manufacturer's design specification. A common mechanism for appliance over-firing occurs when the appliance manifold pressure is improperly adjusted upwards, causing a greater flow rate of fuel to the burner.

(3) determine whether the CO sensors were capable of detecting the proposed CO shutoff level (*i.e.*, nominally 400 ppm) in the furnace; and (4) were capable of distinguishing between shutoff CO levels and background CO levels (*i.e.*, 100 or less) and non-shutoff/nuisance CO levels (*i.e.,* 101 to 300 ppm).

For CO_2 sensors, the objectives were to: (1) determine whether the sensors could detect CO_2 levels that corresponded to the proposed CO shutoff level (*i.e.*, nominally 9 percent); and (2) distinguish between that level and background/non-shutoff levels (*i.e.*, 8 percent CO_2 or lower). These data served as a baseline to compare sensor performance measured during and after the aging test phase to determine whether the aging effects of the corrosion test and harsh conditions within a furnace had a detrimental effect on sensor performance. Prior to conducting the in-situ testing the sensors and test furnaces were prepared, as described below, under "Setup."

Setup

Test Furnace Description

Two high-efficiency upflow gas furnaces were used as test beds for the sensors. Each furnace had an energy input rating of 105,000 BTU/hr and Annualized Fuel Utilization Efficiency (AFUE) of 92 percent. The furnaces are divided into three primary sections: the burner vestibule (Figure 5), the primary and secondary heat exchanger assembly (Figure 6), and the circulation air compartment (not pictured).

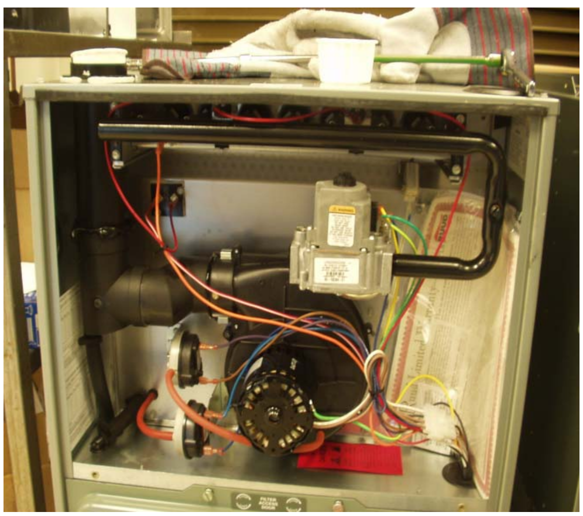


Figure 5. Burner vestibule

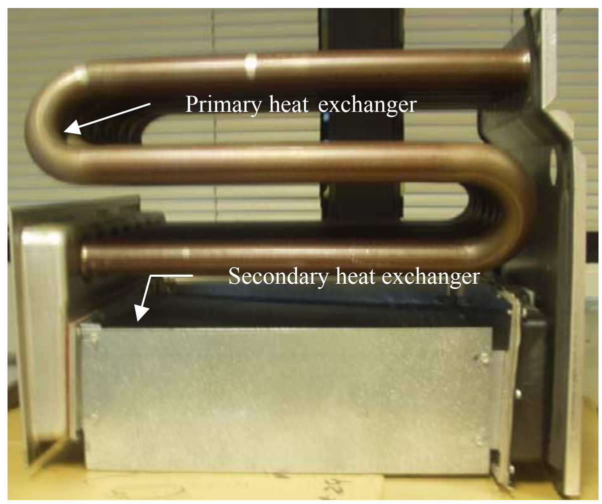


Figure 6. Heat exchanger assembly

Most of the furnace controls are located in the burner vestibule, including the gas valve and manifold, in-shot burners, ignition control, pressure switches, a variety of temperature limits, and the draft inducer motor assembly. Gas, at a maximum pressure of ½ pound per square inch (psi), is supplied to the furnace through the household gas piping system. The gas piping system is connected directly to the furnace gas valve, allowing gas to enter the furnace for combustion. The gas valve reduces the gas pressure from ½ psi to 3.5 inches of water column (in. w.c.) in natural gas installations and 7.0 in. w.c. in propane gas installations. At these pressures, gas travels through the gas manifold and enters the combustion chamber through a seven nozzle, mono-port in-shot burner assembly, which is aligned with seven heat exchanger cell openings of the combustion chamber. The in-shot burners have venturi openings that allow primary air to enter and mix with the gas prior to ignition. As it passes through the orifice and in-shot burner nozzles, the velocity of the gas increases, pulling in the primary air through the venturi openings.

The gas-air mixture is ignited at the outlet of each burner nozzle, and the resulting high velocity burners' flames are shot into (hence the term "in-shot"), the corresponding heat exchanger cell openings. The hot combustion products are pulled through the primary and secondary heat exchangers by the inducer motor, pass through the inducer motor housing assembly, exit the outlet of the inducer motor housing assembly to a short, integral vent pipe that terminates at the interior wall of the furnace cabinet. A coupling that passes through the interior wall to the exterior wall of the furnace cabinet is connected to the integral vent pipe. When the furnace is installed in a house, the installer must connect a vent system to this coupling to vent the combustion products safely outside of the house. The primary and secondary heat exchangers are enclosed within the furnace cabinet, and when installed in a house, the furnace cabinet is connected to the household duct system, which has to be installed by the installer. As the hot combustion gases pass first through the primary heat exchanger, and then the secondary heat exchanger, heat is transferred through the heat exchanger walls to the air surrounding the heat exchangers. The circulation air blower blows this heated air up through the household duct system, providing comfort heat throughout the house through air registers in each room.

Test Furnace Preparation

One unit was set up as configured at the factory to operate with natural gas. The other unit was converted to operate with propane gas, using a field conversion kit. Staff selected each furnace's flue collector pan, condensate pan, vent pipe, and inducer motor housing assembly for sensor placement. To ensure placement in areas of the furnace that were within each sensor's maximum operating temperature limits, screening tests were conducted to determine the operating temperatures of each furnace location. The physical dimensions, operating temperature range, and gas sampling requirements of the sensors dictated into which locations of each test furnace the sensors were installed. The basic operating conditions, temperature range, and humidity level of each furnace location are listed in Table 1. Relative humidity was not measured, so the locations were characterized as either condensing or non-condensing to describe the operating conditions.

Table 1	**Furnace Environment Conditions**				
	Vent Pipe	**Condensate Pan**	**Flu Collector**	**Inlet port from Vent Pipe ***	**Outlet port to Condensate Pan***
Natural Gas Furnace					
T_{Min} (^oF)	70	74	384	85	85
T_{Max} (^oF)	93	108	465	89	89
T_{Avg} (^oF)	75	103	422	87	87
Condensing/non-condensing?	condensing	Condensing	non-condensing	condensing	condensing
Propane Furnace					
T_{Min} (^oF)	86	90	400	70	70
T_{Max} (^oF)	92	97	489	86	86
T_{Avg} (^oF)	90	94	465	79	79
Condensing/non-condensing?	condensing	Condensing	non-condensing	condensing	condensing

*Temperatures gas samples measured using flow-through temperature probe of combustion gases pulled from the vent pipe and re-circulated back into the condensate pan.

Each test furnace had to be partially dismantled in order to cut access holes into the primary and secondary heat exchangers, inducer motor, and integral vent pipe to allow for installation of the various sensors, as well as measurement/sampling apparatus to record furnace operating parameters (*i.e.,* temperature and CO, CO_2, and O_2 concentrations). The catalytic bead sensors were 1.42 inches x 1.81 inches x 1.11 inches, had a maximum operating temperature limit of 446^{o}F, and required immersion of their sensing element in the target gas for detection. The infrared CO_2 sensors were 3.06 inches x 3.02

inches x 1.51 inches, had an operating temperature limit of 122°F, and required aspiration of the target gas to the sensing chamber for detection.

Sensor Preparation

Sensor preparation for in-situ testing was minimal. Based on the furnace operating conditions listed in Table 1, the physical dimensions and operating limits of each sensor, each sensor was installed in the locations of the furnaces listed in Table 2. Individual power supplies for each sensor technology were mounted to the interior walls of the circulation blower compartment of each test furnace. Power supply wiring was routed from the power supplies inside of the circulation blower compartment to each of the sensors. The environmental chamber used to house the test furnaces for in-situ testing of the sensors was much larger than the chamber used for sensitivity testing, resulting in greater distances for signal transmission and gas sampling. Thus, each sensor was outfitted with longer runs of signal wire, which was routed from each sensor, through the furnace cabinet and chamber interior, out to the instrument rack housing the data acquisition system. Due to space limitations within the test furnaces, only 10 of the 18 gas sensors acquired by CPSC staff were installed (*i.e.*, 5 sensors per furnace) and subjected to in-situ furnace testing. The sensor allocation for each furnace included three catalytic bead CO sensors, one NDIR CO sensor, and one NDIR CO_2 sensor. The chart below provides the areas of the furnace in which the sensors were installed.

Table 2	**In-Situ Furnace Location and Target Gas Exposure Mechanism for Sensors**								
	Immersion					**Aspiration**			
	Vent Pipe	**Condensate Pan**		**Flu Collector**		**Inlet port from Inducer Housing**	**Outlet port to Condensate Pan**	**Inlet port from Vent Pipe**	**Outlet port to Condensate Pan**
Natural Gas Furnace	CB79#6	CB78#3	VM#2	CB79#8	VM#4	NDIR CO #2		NDIR CO_2 #2	
Propane Furnace	CB79#5	CB78#1	VM#1	CB79#7/ CB78#2	VM#3	NDIR CO #1		NDIR CO_2 #3	

Flue Collector Pan

The flue collector pan (Figure 7) is a transition point between the outlet of the primary heat exchanger and inlet of the secondary heat exchanger of the furnace. A total of six openings were measured and cut into the flue collector pan to accommodate one catalytic bead CO sensor, one voltammetric CO sensor, one gas sample line, one insertion-type temperature probe, one flow-through temperature probe, and one spare port opening (Figure 8).

Figure 7. Flue collector pan

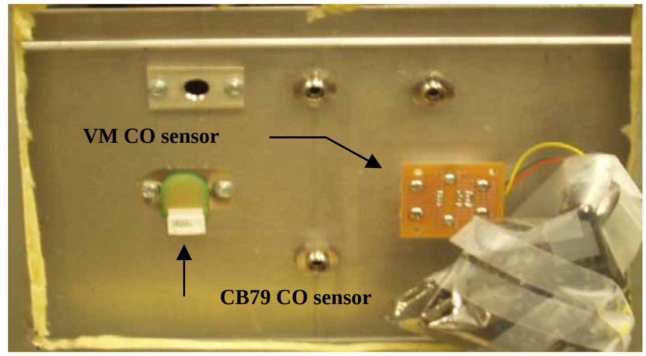


Figure 8. Installation of sensors and measurement ports in the flue collector pan

The insertion-type temperature probes, catalytic bead sensors, and voltammetric sensors were designed for either insertion or flush mounting and required different access opening dimensions. The NDIR CO and CO_2 sensors, gas sample line, and flow-through temperature probes each required aspiration for gas flow and sampling; thus, access into the flue collector pan was accomplished with the same ¼-inch stainless steel compression fittings. Based on their maximum operating temperatures, only the catalytic bead and voltammetric CO sensors were found to be suitable for placement into this area of the furnace. The access fittings for these sensors were merely capped off using a SwageLok ¼-inch pipe plug.

Condensate Pan

The condensate pan (Figure 9) is located after the secondary heat exchanger of the furnace and is located behind a heat shield that separates it from the burner vestibule. The secondary heat exchanger is designed to extract additional heat out of the combustion gases of a high efficiency furnace (*i.e.*, AFUE ≥ 90 percent). This process reduces the temperature of the combustion gases below their dew point, resulting in condensation of water vapor from the combustion gases. The condensate pan is made of plastic and is designed to collect the condensate formed in the coils of the secondary heat exchanger and funnel it into a drain and out of the furnace. CPSC staff fabricated two mounting plates to reduce the risk of cracking the condensate pan and to accommodate the sensors, gas sampling ports, and temperature probes designated for the condensate pan.

Figure 9. Condensate pan

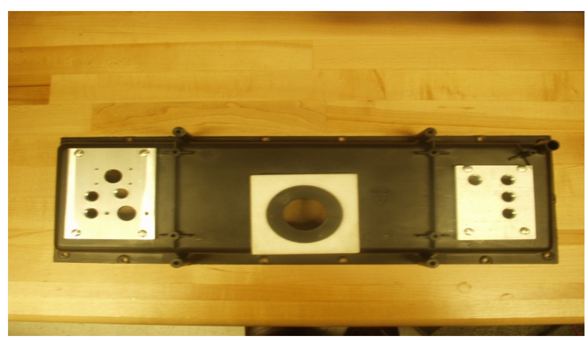


Figure 10. Condensate pan with mounting plates

A total of nine port openings were measured and cut into the mounting plates for the condensate pan (Figure 10). The port openings were used to accommodate one catalytic bead CO sensor, one voltammetric CO sensor, one NDIR CO sensor, one NDIR CO_2 sensor, one gas sample line, one insertion-type temperature probe, and one flow-through temperature probe, and for added flexibility, two spare port openings for ¼-inch SwageLok fittings (Figures 11 and 12).

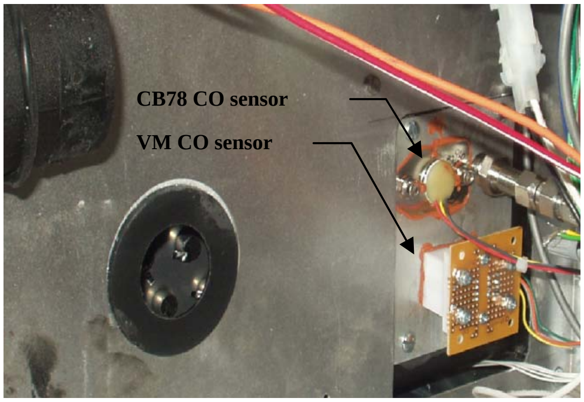


Figure 11. Sensors mounted to condensate pan through the heat shield

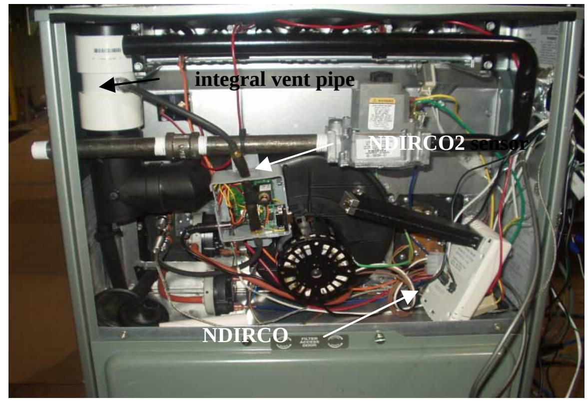


Figure 12. Sensors connected to vent pipe, inducer housing, and condensate pan

Two access openings were cut into the condensate pan, and each mounting plate was fastened and sealed to the exterior wall of the condensate pan using screws and a putty-like sealing compound as a gasket.

Inducer Motor Housing Assembly

The inducer motor is used to pull (*i.e.*, induce the flow of) combustion gases that originate in the furnace burner and combustion compartment, through the primary and secondary heat exchangers, and into the furnace vent system where they are exhausted to the outdoors. The inducer motor housing is attached to the condensate pan and pulls combustion gases through an opening in the condensate pan. One port opening was measured and cut into the inducer motor housing assembly and was used to install a ¼-inch SwageLok fitting, which served as the inlet port for the NDIR CO sensor. Because the NDIR CO sensor had a flow-through design for its sensing cell, the outlet of the sensor was connected to one of the spare port openings in the condensate pan to allow recirculation of the gas sample back into the furnace.

Integral Vent Pipe

The vent system is used to exhaust the combustion gases from the furnace to the outdoors. Two short lengths of plastic vent pipe were factory-installed by the manufacturer to convey combustion products outside of the furnace cabinet, where they are connected to a house venting system at the time of installation to exhaust the combustion gases to the outdoors. One section of vent pipe was horizontal and connected to the outlet of the inducer housing; the other section of vent pipe was vertical and was connected to the horizontal section by a 90^{o} elbow and extended to the top of the furnace cabinet, where it was connected to a field-installed vent system that exits the structure, either through the roof or side wall, to accomplish venting of combustion gases. In order to accommodate the port opening needed for the integral vent pipe and reduce the risk of cracking it, a 6-inch section of vent pipe was cut out and replaced with white PVC. An access hole was cut into the new section of vent pipe and a ¼-inch SwageLok fitting installed to allow it to serve as the inlet port for the NDIRCO2 sensor (Figure 13).

Figure 13. Sensor mounted in vent tee

Because the NDIRCO2 sensors had a flow-through design for their sensing cell, one of the spare openings in the condensate pan was used as the outlet port to allow recirculation of the gas sample back into the furnace. In addition, a 3-inch vent tee with a threaded plug was added to the vertical section of vent pipe to accommodate installation of one of the CB79 CO sensors. A hole was drilled through the vent tee plug and a CB79 CO sensor was inserted into the opening and screwed and cemented into place, providing a flush mount of the sensor perpendicular to the flow of exhaust gases travelling through the vertical section of vent pipe (Figure 14).

Gas Sampling System and Data Acquisition System

Flue gases (CO, CO_2, and O_2) were sampled as close as possible to each sensor location to attain the most accurate sensor voltage responses. Three separate gas sampling systems were used to obtain flue samples of CO, CO_2, and oxygen (O_2) from each test furnace's primary heat exchanger, secondary heat exchanger, and vent system. Carbon monoxide and carbon dioxide were measured using the multi-gas analyzer's NDIR modules, and oxygen (O_2) was measured using the multi-gas analyzer's paramagnetic module. A single flue gas sample was drawn from each port cut into the primary and secondary heat exchangers and vent pipe. To prevent water from condensing inside the multi-gas analyzer during the sampling of the flue gas, the water was condensed out of the sample prior to entering the analyzers. A simple heat exchange system using re-circulated, chilled water was used to condense the water out of each flue gas sample line. A data acquisition system was used to record the furnace flue gas data and sensor performance data. The data acquisition system consisted of a personal computer, data acquisition (DAQ) interface hardware (Data Translation), and data acquisition software (TEST POINT). Analog output signals were transmitted from output terminals of the multi-gas analyzer and each sensor to the DAQ hardware through approximately 20 feet of signal wire. The data acquisition system recorded data at a rate of one sample per second.

Furnace Adjustment for Testing at Normal and Abnormal Conditions

Testing was conducted to establish normal operation and abnormal operation of the furnaces. "Normal operation" was defined as each furnace being set at its design input rate with normal vent conditions. The natural gas furnace design input rate was achieved by adjusting its gas valve manifold pressure to approximately 3.5 inches of water column (in. w.c.) in accordance with the furnace manufacturer's installation instructions. The propane gas furnace rated input was achieved by adjusting its gas valve manifold pressure to approximately 10.0 inches w.c. in accordance with the furnace manufacturer's installation instructions. The ON cycles were marked by these manifold pressures, as well as a positive gas flow rate of approximately 1.6 cubic feet per minute (CFM) for the natural gas furnace and approximately 0.8 CFM for the propane gas furnace. The start of each ON cycle was marked by a spike in the CO level lasting approximately 60 seconds.

Abnormal operation was achieved through a combination of operating each furnace above its design energy input rating (*i.e.,* over-firing), reducing air flow through the furnace vent system, and/or reducing circulation air flow across the furnace primary heat exchanger. Operation of each furnace above its design energy input rating was accomplished by adjusting its gas valve manifold pressure to the maximum pressure setting. The maximum gas valve manifold pressure settings were approximately 4.2 inches w.c. and 14 inches w.c. for the natural gas furnace and propane furnace, respectively. The ON cycles were marked by these manifold pressures, as well as a positive gas flow of approximately 1.6 CFM for the natural gas furnace and approximately 0.8 CFM for the propane gas furnace. As with the natural gas unit, the start of each ON cycle for the propane unit was marked by a spike in the CO level, lasting approximately 60 seconds. The propane gas furnace was operated abnormally by reducing the air flow through its vent system. Reduced air flow through the vent system was accomplished by reducing the line voltage to the inducer motor to approximately 67 percent of rated voltage using a voltage variac connected to the furnace power supply wiring.

The natural gas furnace was tested first, but would cycle off whenever all three adjustments were made. Staff made several attempts to overcome this issue and achieve the desired test conditions (*i.e*., elevated CO and CO_2 levels); however, the furnace continued to cycle off. In order to maintain the test schedule, staff opted to move on to testing of the propane furnace, although the desired conditions of elevated CO and CO_2 levels in the natural gas furnace had not been achieved. As a result, the sensors in the natural gas furnace were not exposed to elevated CO and CO_2 levels. After proceeding to the propane furnace, and after further investigation, staff learned that it was the upper limit that caused the furnace to cycle off. The upper limit switch is designed to shut the furnace off when the temperature of the circulation air across the primary heat exchanger reaches or exceeds 200°F.

2.2.2 In-Situ Sensor Test Results in the Natural Gas Furnace

Catalytic Bead CO Sensors

Three catalytic bead CO sensors (CB79#6, CB78#3, and CB79#8) were subjected to in-situ testing in the natural gas test furnace. As shown in Table 2, "In-Situ Location of Sensors within Test Furnaces," CB79#6 was installed in the furnace vent pipe, CB78#3 in the condensate pan, and CB79#8 was installed in the flue collector. Two tests were conducted with the furnace operating under normal conditions. [vi] During these tests, each sensor exhibited voltage outputs that corresponded to the changing concentrations of CO during the furnace ON/OFF cycles. Using the gas sampling system, CO samples were drawn from the areas of the furnace in which the sensors were located.

For Test #1, April 2, 2007, the performance of CB79#6, CB78#3, and CB79#8 is shown in Graphs B.1, B.2, and B.3, respectively. The average temperatures recorded in the vent pipe, condensate pan, and flue collector during Test #1 were 95, 99, and 451°F, respectively, with peak temperatures reaching 107, 116, and 474°F in these areas. The gas manifold pressure was adjusted to approximately 4.0 inches water column (in. w.c.). Sensor response is shown by the sharp increase in voltage output that corresponded to the spike in CO levels within the furnace at the start of the ON cycle, followed by a drop in voltage as furnace CO levels decreased to normal, steady state levels and when the furnace cycled OFF. At the start of the furnace ON cycle, the CO concentrations in the vent pipe, condensate pan, and flue collector rose rapidly from approximately 2 to 3 ppm, to peak levels of 60, 159, and 178 ppm, respectively. Each sensor tracked this spike in CO closely. Corresponding voltage outputs for CB79#6, CB78#3, and CB79#8 peaked at 5.0, 6.0, and 4.6 mV, respectively. After the initial spike, furnace CO levels dropped to normal, steady state averages of 25, 27, and 50 ppm. Sensor response tracked this decline in CO levels, dropping to averages of 1.5, 1.6, and 0.3 mV. When the furnace cycled off, average CO levels dropped to 7 ppm in the vent pipe and flue collector and 3 ppm in the condensate pan. Average sensor voltages at these levels were 0.7, 2.0, and 0.1 mV for CB79#6, CB78#3, and CB79#8. CB78#3 exhibited noisy behavior, demonstrated by wide variations in output voltage. Despite this, all sensor output at elevated CO levels was very distinct from output at low, steady state CO levels. The test data are summarized in Table B.1.

[vi] CPSC staff was unable to over-fire the natural gas furnace and reduce airflow without the unit shutting off; thus, CO levels in the natural gas unit never reached or exceeded 400 ppm. Consequently, the sensors installed on the natural gas unit furnace were not exposed to target CO (400 ppm) or CO_2 (11 percent) levels. After some investigation, staff learned that the over-fire conditions and reduced air flow caused a rise in temperature across the unit's primary heat exchanger in excess of the upper limit set point of 180°F, causing the upper limit switch to actuate and shut the furnace off. To address this issue, staff bypassed the upper limit switch on the propane furnace by shorting its terminals together. Time did not permit for this to be done on the natural gas furnace.

For Test #2, April 3, 2007, the data for CB79#6, CB78#3, and CB79#8 is plotted in Graphs B.5, B.6, and B.7. The average temperatures recorded in the vent pipe, condensate pan, and flue collector during Test #2 were 106, 99, and 449°F, respectively, with maximum temperatures reaching 109, 115, and 465°F in these areas. The gas manifold pressure was adjusted to approximately 4 inches w.c. Behavior of the sensors in Test #2 was similar to that in Test #1. The sensors continued to exhibit voltage output that corresponded to increasing furnace CO levels. When the furnace was cycled ON, CO levels within the vent pipe, condensate pan, and flue collector peaked at 80, 226, and 194 ppm and CB79#6, CB78#3, and CB79#8 exhibited corresponding peak voltages of 4.8, 4.9, and 4.9 mV. At steady state averages of 26, 54, and 29 ppm CO, average voltages for CB79#6, CB78#3, and CB79#8 dropped to 1.5, 1.6, and 0.2 mV.

The results from this set of tests helped establish the operability of catalytic bead CO sensors in a natural gas furnace environment during normal operating conditions. The following general observations were made of sensor performance. First, each sensor exhibited increasing voltage outputs that corresponded to rising levels of CO within the furnace. The sensors did not track furnace CO levels at or below steady state very well. However, it is important to note that each sensor's output voltages at increasing CO levels was very distinct from those voltages exhibited at normal, steady state CO levels and during OFF cycles. This is significant because a sensor used for CO shutoff must detect elevated or target CO levels accurately and distinguish those levels from CO levels at or below normal, steady state operating conditions.

Finally, the sensors exhibited a lot of noise in their output. The presence of noise was recognized during sensitivity testing and discussed in the Sensitivity Test section of this report. As discussed earlier, CPSC staff believes this noise could be attributed to the fact that the sensors had a small voltage drop across their gas measurement range and were not equipped with filters to remove or reduce signal noise potentially introduced from the test environment or the data acquisition system. A full set of results for the catalytic bead CO sensors is located in Appendix B, Pre-Aging Phase In-Situ Test Data.

NDIR CO Sensors

One NDIR CO sensor (NDIRCO#2) was subjected to in-situ testing in the natural gas furnace under normal operating conditions.[vi] Because the sensor is a flow-through type sensor (*i.e.,* target gas flows through an inlet and is exhausted through an outlet), it was installed to receive its inlet gas sample from the port fittings installed in the inducer housing and exhausted that sample through the port fitting installed in the condensate pan.

During testing under normal operating conditions, the sensor exhibited a voltage response that initially corresponded to changing concentrations of CO associated with the furnace ON/OFF cycles. However, in subsequent test runs, sensor output changed to a steady full-scale reading. Staff theorized that condensate was accumulating in the sensing cell and may have obfuscated a true sensor reading. Another possibility is that the sensor signal may have experienced interference from the CO_2 present in the furnace. This behavior recurred throughout the remainder of the in-situ furnace testing during the pre-aging, aging, and post-aging phases and indicated that additional development was needed before the NDIR CO sensors could be used as a CO shutoff device.

NDIR CO_2 Sensors
NDIRCO2#2 and NDIRCO2#1 were each subjected separately to in-situ testing in the natural gas furnace under normal operating conditions.[vii] These sensors were also flow-through types and thus, gas samples were received through the sensor inlet from the port fittings installed in the furnace vent pipe and exhausted through the sensor outlet into the port fittings installed in the furnace condensate pan. Each sensor was tested concurrently with catalytic bead CO sensors CB79#6, CB78#3, and CB79#8. Each sensor exhibited a voltage response that corresponded to changing concentrations of CO_2 associated with the furnace ON/OFF cycles.

During Test #1, April 2, 2007, when the furnace cycled ON, the condensate pan CO_2 increased from 0 to a peak level of 6.8 percent before settling to a steady state average of 6.6 percent. The voltage output for NDIRCO2#2 closely tracked the condensate pan CO_2 levels, peaking at 2.2 volts, which was also its steady state average (reference Graph B.4 and Table B.1). The average temperature recorded in the condensate pan during Test #1 was 99^{o}F and the maximum temperature reached 116^{o}F. During Test #2, condensate pan CO_2 levels peaked at 7.7 percent before reaching a steady state average of 7.6 percent. The voltage output for NDIRCO2#1 peaked at 3.4 volts and averaged 3.3 volts under steady state conditions. The average temperature recorded in the condensate pan during Test #2 was 99^{o}F, and the maximum temperature reached was 115^{o}F (see Graph B.8 and Table B.2).

These results helped establish the operability of the NDIR CO_2 sensors in the furnace environment. This was evidenced by the fact that the sensors: (1) operated in the harsh and humid environments of the furnace secondary heat exchanger and vent system; and (2) exhibited output voltages that corresponded to the concentration of CO_2 to which they were exposed. A full set of results for the NDIR CO_2 sensors is located in Appendix B, Pre-Aging Phase In-Situ Test Data.

2.2.3 In-Situ Sensor Test Results in the Propane Furnace

Catalytic Bead CO Sensors
Three catalytic bead CO sensors (CB79#5, CB78#1, and CB79#7) were subjected to in-situ testing within the propane gas furnace. The sensors were subjected to normal and abnormal furnace operating conditions, the latter resulting in CO concentrations at, near, or in excess of the proposed shutoff level (*i.e.*, 400 ppm). The following adjustments were made to achieve abnormal operation of the furnace and to cause it to generate CO levels in excess of 400 ppm:

- Reduced air flow through flue passageways and exhaust blower[viii] and
- By-passed Upper Limit Switch.

[vii] "Ibid"

[viii] Reduced air flow was attempted in preliminary testing of the natural gas furnace, however, the furnace would cycle off before the testing could be completed. Time did not allow staff to determine what was causing the natural gas furnace to cycle off and as a result, that unit was only subjected to normal operating conditions. Additional review of test data later revealed that temperatures in the supply air duct exceeded the actuation set point of the unit's upper limit switch, causing the furnace to shutdown. The upper limit switch was by-passed by removing its signal wire from the switch terminals and jumpering the two wires together. When this was done, staff was able to operate the furnace continuously, under the abnormal conditions without the furnace cycling off.

Prior to testing, the line voltage was connected to the furnace with a voltage variac between the furnace and the 120 volt line. The voltage variac was used to control the percentage of voltage supplied to the furnace and had an adjustment range from 100 percent down to 0 percent in 1 percent increments. These adjustments were made to the propane furnace during the course of testing and are denoted in the graphs and tables as “Adjustment” 1 or 2, depending on the number of adjustments that were made during testing. The time that each adjustment was made is noted in the “Start of Cycle” column of Tables B.3 and B.4.

Each of the catalytic bead CO sensors exhibited changes in voltage output that corresponded to the changes in furnace CO levels during ON/OFF cycles; when furnace CO levels rose, sensor output voltage rose. CO samples were drawn from the regions of the furnace in which sensors were located. For Test #1, April 19, 2007, the furnace was cycled ON and OFF twice. The performance of CB79#5, CB78#1, and CB79#7 is presented in Graphs B.9, B.10, and B.11. The average temperatures recorded in the vent pipe, condensate pan, and flue collector were 82, 111, and 341^{o}F, respectively, during the first furnace ON cycle with peak temperatures reaching 91, 144, and 468^{o}F in these areas. The gas manifold pressure was adjusted to approximately 9.9 in. w.c. During the second ON cycle, the average temperatures recorded in the vent pipe, condensate pan, and flue collector were 85, 168, and 439^{o}F, respectively, with maximum temperatures reaching 94, 193, and 517^{o}F in these areas. During the first furnace ON-cycle, the CO concentration in the vent pipe, condensate pan, and flue collector rose rapidly from 1 to 2 ppm to peak levels of 97, 204, and 315 ppm, respectively. At this point, the output voltages of CB79#5, CB78#1, and CB79#7 rose to corresponding peak levels of 7.0, 9.7, and 10.8mV, respectively. Furnace performance under abnormal conditions can be erratic, thus a steady state CO concentrations were not attained. During the second ON cycle, peak CO levels in the vent pipe, condensate pan, and flue collector rose to 100, 245, and 297 ppm, respectively. The corresponding output voltages for CB79#5, CB78#1, and CB79#7 rose to peak levels of 8.6, 7.8, and 10.7 mV, respectively.

As shown in Table B.3 and Graphs B.9, B.10, and B.11, the first adjustment was made at a cycle time of 12-minutes and 18 seconds (12:18). At this time, the variac was adjusted to 85 percent, reducing the line voltage to the furnace to approximately 93.5 volts, which in turn, reduced air flow through the flue passageways and exhaust blower of the furnace. This had little effect on CO production; at this adjustment level, CO levels within the vent pipe, condensate pan, and flue collector peaked at 34, 56, and 83 ppm, respectively. However, during the second adjustment, the variac was set to 65 percent, reducing line voltage to the furnace to approximately 71.5 volts. When this happened, peak CO levels in the vent pipe, condensate pan, and flue collector reached 60, 279, and 615 ppm, before dropping to average levels of 47, 207, and 411 ppm. At these CO levels, the voltage outputs from CB79#5, CB78#1, and CB79#7 peaked at 1.2, 4.9, and 24 volts, before dropping to average levels of 0.8, 3.5, and 11.8 volts.

For Test #2, April 23, 2007, the performance CB79#5, CB78#1, and CB79#7 is presented in Graphs B.13, B.14, and B.15. The gas manifold pressure was adjusted to approximately 10.1 in. w.c. The average temperatures recorded in the vent pipe, condensate pan, and flue collector during testing were 99, 188, and 479103, 209, and 520^{o}F, respectively, during the furnace ON cycle with peak temperatures reaching 106, 226, and 532^{o}F in these areas. Peak CO levels in the vent pipe, condensate pan, and flue collector were 75, 163, and 285 ppm before dropping to average levels 36, 60, and 97 ppm. The peak voltages for CB79#5, CB78#1, and CB79#7 were 2.7, 3.5, and 10 mV, respectively. The average voltages for these sensors were 0.6, 2.0, and 7.3 mV. When the adjustment was made to the furnace operation peak temperatures rose to 118, 242, and 643^{o}F, before settling to average values of 111, 236, and 618^{o}F. Peak CO levels rose to 41, 188, and 374 ppm before settling to averages of 33, 128, and 233 ppm. Under these conditions, peak sensor voltages rose to 0.7, 3.9, and 9.6 mV, before settling to averages of 0.3, 2.7, and 8.8 mV.

These results help establish the operability of the catalytic bead CO sensors in the furnace environment. This was evidenced by changes in sensor output voltage that corresponded to and was proportional to changes in the CO concentrations during furnace ON/OFF cycles. These results also demonstrated that when CO concentrations reached or exceeded the proposed shutoff level of 400 ppm (see Graphs B.9 and B.13), sensor output voltages were distinct from voltage levels at non-shutoff CO levels. A full set of results for Test #2 of the catalytic bead CO sensors installed in the propane test furnace are located in Appendix B, Pre-Aging Phase In-Situ Test Data, Graphs B.13, B.14, and B.15 and Table B.4.

NDIR CO Sensors
Two infrared CO sensors, NDIRCO#1 and NDIRCO#3, were subjected to separate in-situ tests in the propane furnace under normal and abnormal operating conditions. Each sensor received its gas sample from the port fittings installed in the furnace inducer housing and re-circulated the sample back into furnace through the port fittings installed in the furnace condensate pan.

There were a number of operational problems associated with the NDIR CO sensors that made it difficult to fully evaluate their performance in this test program. In preliminary checkout, each sensor initially exhibited voltage response that corresponded to changing concentrations of CO associated with the furnace ON/OFF cycles. However, in subsequent test runs, sensor output changed to a steady full scale reading. A possible cause of this might have been from the formation of condensate in the sensing cell, obfuscating a true sensor reading. Another possibility is that the sensor signal may have experienced interference from the CO_2 present in the furnace. This behavior recurred throughout the remainder of the in-situ furnace testing during Pre-aging, Aging, and Post-aging testing. In addition, there was a considerable time lag before each sensor exhibited a voltage response to CO. During Test #3, NDIRCO#1 had an approximately 9-minute time lag before it exhibited response to furnace CO levels that peaked at 573 ppm (see Graph B.17 and Table B.5). NDIR CO#3 exhibited a 4-minute time lag in response to furnace CO levels that exceeded 1000 ppm during Test #4 (see Graph B.18 and Table B.6). These results indicate that additional development work needs to be done with the NDIR CO sensors to overcome interference or other factors that might have caused or contributed to the unresponsive behavior in these tests.

NDIR CO_2 sensors
NDIRCO2#3 was subjected to in-situ testing concurrently with catalytic bead CO sensors CB79#5, CB78#1, and CB79#7 in the propane gas furnace under normal and abnormal operating conditions. This sensor received its gas sample from the port fittings installed in the furnace vent pipe and exhausted through the sensor outlet into the port fittings installed in the furnace condensate pan. Each sensor exhibited voltage response that corresponded to changing concentrations of CO_2 associated with the furnace ON/OFF cycles.

During the first furnace ON cycle of Test #1, April 19, 2007 (see Graph B.12 and Table B.3), the condensate pan CO_2 levels increased from 0 to a peak levels of 7.3 percent before settling to a steady state average level of 4.1 percent. As shown in Graph B.12, the voltage output for NDIRCO2#3 closely tracked the condensate pan CO_2 levels, peaking at 2.7 volts at the peak CO_2 level before reaching a steady state average output of 2.2 volts. The average temperature in the condensate pan during the first ON-cycle of Test #1 was 111^{o}F and the maximum temperature was 144^{o}F. During the second furnace ON-cycle, the condensate pan CO_2 levels peaked at 7.8 percent. The corresponding peak CO concentration in the condensate pan at this point was 204 ppm and the peak voltage output of NDIRCO2#3 was 2.8 volts. As discussed earlier, in order to increase CO and CO_2 production, staff reduced the air flow through the flue passageways and exhaust fan of the furnace by reducing the line voltage to the furnace at a cycle time of 12-minutes and 18-seconds (12:18 minutes/seconds). This is shown in Graph B.12 as a slight increase in CO_2 concentration and sensor voltage at a cycle time of approximately 13 minutes. The peak CO_2 concentration in the condensate pan rose to 8.7 percent after this adjustment, before settling to an average of 8.4 percent. The voltage for NDIRCO2#3 peaked at 3.1 volts and averaged 3.0 volts. Staff reduced air flow through the furnace again at a cycle time of approximately 19:01 minutes/seconds. After this adjustment furnace CO_2 levels and sensor voltage output peaked at 11.7 percent and 4.0 volts and averaged of 11.2 percent and 3.9 volts, respectively. The average temperature recorded in the condensate pan was 236^{o}F and the maximum temperature reached 239^{o}F.

During Test #2, April 23, 2007 (see Graph B.16 and Table B.4), after the furnace cycled ON, the condensate pan CO_2 peaked at 8 percent before settling to a steady state average of 7.1 percent. The output of NDIRCO2#3 tracked CO_2 levels very well, peaking at 2.9 volts before reaching a steady state average of 2.7 volts. At a cycle time of 15:54 staff adjusted the line voltage to the furnace in order to reduce the circulation air flow through the furnace and increase CO and CO_2 levels. After making this adjustment, furnace CO_2 levels peaked at 11.4 percent before settling to a stead state average of 10.8 percent. NDIRCO2#3 continued to track CO_2 levels well, peaking at 4.0 volts before reaching a steady state average of 3.6 volts. The average temperature recorded in the condensate pan was 236^{o}F and the maximum temperature reached 242^{o}F.

As with the results from in-situ testing in the natural gas furnace, these results helped establish the operability of the NDIR CO_2 sensors in the furnace environment. This was evidenced by the fact that the sensors (1) operated in the harsh, hot, and depending on location, humid environments of the furnace heat exchangers and vent system; (2) exhibited output voltages that were proportional to the concentration of CO_2 to which they were exposed; and (3) their output voltages at or near CO_2 levels that corresponded to the proposed CO shutoff level were distinct from voltage levels at CO_2 levels that corresponded to non-shutoff CO levels. For a full set of results for the NDIR CO_2 sensors installed in the propane test furnace, see Appendix B, Pre-Aging Phase In-Situ Test Data, Graphs B.12 and B.16 and Tables B.3 through B.4.

3. AGING TEST PHASE

The purpose of the aging test phase was to subject the sensors to environmental conditions that that would stress them in a manner that would allow their durability and longevity to be evaluated. As applied to sensors used in this application, durability of a sensor would need to include its ability to continue to operate, as intended, in a furnace environment. Longevity would need to include a sensor's expected lifespan when operating in a furnace environment and would require gathering life data in a relatively short period of time. In order to gather life data in a short timeframe, the sensors were subjected to a mechanism that would accelerate aging. Since there were no performance standards designed to evaluate the durability and longevity or to accelerate aging of sensors used in this application, staff devised an approach to do so using the current corrosion test methodology specified in Exhibit G[ix] of ANSI Z21.47, Standard for Gas-Fired Central Furnaces.

The corrosion test methodology is the means by which CSA-America (*i.e.*, the standards developer and certification agency for ANSI Z21 gas appliance standards, including ANSI Z21.47) qualifies heat exchangers and metallic vent systems used in gas furnaces and boilers to long-term resistance to corrosive attack. This long-term resistance has, unofficially, been equated to a 20-year operating life for furnace and boiler heat exchangers. A CO shutoff sensor designed for direct detection of CO would likely be located in a furnace heat exchanger or vent. Therefore, staff also considered it reasonable to assume that, if the ANSI corrosion test is used to qualify furnace/boiler heat exchangers for long life, then this test is also appropriate to evaluate the longevity of sensors in those environments. In addition to the chemical attack accomplished through the mixing and combustion of the spiking gases and the fuel gas, the corrosion test requires furnace burner to be cycled on and off at a rate of 4 minutes ON and 8 minutes OFF for a total of 12,000 burner ON/OFF cycles throughout the duration of the 100-day period in which the corrosion test is conducted. Throughout the duration of the corrosion testing, the average temperatures in the furnace flue collector were 334^{o}F during the ON cycles and 234^{o}F during the OFF cycles. In the furnace condensate pan, the average temperatures during the ON cycles were 97^{o}F and 87^{o}F during the OFF cycles. Temperatures were not recorded in the vent pipe; however, would be on the order of those in the condensate pan or lower. Thus, the heat exchanger and vent systems, as well as the sensors installed in them were subjected to some degree of thermal cycling in the vent pipe, condensate pan, and flue collector. The condensate pan and vent pipe and the sensors installed at these locations were also subjected to some degree of humidity cycling (although the degree of humidity exposure could not be quantified since humidity levels were not measured or recorded). To summarize, CPSC staff made the following assumptions:

Assumption #1: The Corrosion Resistance Test Methodology, Exhibit G, ANSI Z21.47 is used to qualify heat exchangers and metallic vent systems in gas furnaces and boilers for life spans equivalent to approximately 20 years.

[ix] As mentioned earlier, the ANSI Z21/83 Committee's September 2005 position on the durability and longevity of sensors, and their subsequent decision not to fund the work necessary to develop a CO shutoff standard, was based on the experiences that some appliance manufacturers had conducting in-situ testing of sensors in appliances. Some of the observations that came out of manufacturer testing included sensor failures in which the sensor no longer produced voltage output or whose voltage output became erratic. These experiences, as well as the test criteria developed by the Ad Hoc Working Group for CO and Combustion Sensors (2002 to 2005), helped form the basis for the approach taken by CPSC staff to evaluate the durability and longevity of sensors used in a gas furnace.

Assumption #2: The Corrosion Resistance Test Methodology, Exhibit G, ANSI Z21.47 is an appropriate methodology to evaluate the durability and longevity of sensors installed in furnace heat exchangers and vent pipes.[x]

Assumption #3: If the sensors are able to perform, as specified by this test program, after being subjected to the Corrosion Resistance Test Methodology, then the sensors can be deemed to:

1. be durable enough to operate in the prescribed furnace and boiler heat exchanger and vent pipe environments, and
2. have longevity commensurate with that of furnace and boiler heat exchangers and vent pipes and equivalent to 20 years.

Testing was conducted as described below under "Corrosion Test Methodology and Setup." Definitions and evaluation criteria were established below for durability and longevity in order to assess sensor performance during this phase of testing.

Durability
Durability was defined as a sensor's ability to operate within the harsh environment of a gas furnace over an extended period of time and continue to exhibit a proportional output voltage in response to changing levels of its respective target gas within the furnace. The evaluation criteria for sensor durability for this test were as follows:

- Did each sensor continue to exhibit a proportional output voltage in response to changing levels of its target gas within the furnace?
- Did each sensor continue to exhibit an output voltage at the proposed CO shutoff level of 400 ppm CO that was distinct from the voltage output at non-shutoff levels of CO (*i.e.*, 300 ppm and lower)?

These criteria provided a direct measure of whether the harsh conditions within a furnace or those imposed by the corrosion test conditions rendered a sensor inoperable or less sensitive to its target gas.

Longevity
Longevity was defined as a sensor's durability when exposed to aging conditions over the 100-day course of the corrosion test, which was assumed to be equivalent to 20 years of operation in a gas furnace. The evaluation criterion for sensor longevity for this test was as follows:

- Did each sensor continue to meet the above durability criteria (1) and (2) throughout the duration of the 100-day corrosion test?

This criterion provided a measure of whether sensor lifespan was equivalent to that of a heat exchanger or metallic vent pipe exposed to the same environmental and aging conditions. Continued sensitivity of each sensor was assessed throughout the duration of the corrosion testing by conducting weekly injections of CO into the flue passageways of each of the two test furnaces. Continued sensitivity of each CO sensor was based on whether the sensor continued to exhibit a proportional response to the CO injected into the

[x] It should be noted that this testing was designed to evaluate the operability of sensors in a furnace environment only. This test and evaluation program was not intended to evaluate the mechanical condition of sensing elements or other components of a sensor that might undergo physical degradation due to exposure to the harsh test and furnace environments.

furnace. Injection of CO_2 was not conducted for the CO_2 sensors since the background levels of CO_2 were not near zero. The voltammetric sensors were subjected to all of the testing conducted during the aging phase. However, because their performance had to be evaluated using proprietary software developed by the sensor manufacturer, the test results for the voltammetric sensors were not included in this report. A summary of all aging phase test results is provided in Appendix C, Graphs C.1 through C.4 and Tables C.1 through C.4. A summary of all aging phase test objectives and whether or not each sensor met the objectives is located in the table in Appendix F.

3.1 IN-SITU FURNACE CORROSION TESTING OF SENSORS

3.1.1 Corrosion Method and Test Setup

An array of gas sensors were installed and operated within the flue passageways in each of the two gas furnaces (as described earlier in the section on Setup, In-Situ Furnace Testing, Pre-Aging Testing) throughout the duration of the approximately 100 days of corrosion testing. Aging of the sensors was accomplished by subjecting them to the harsh operating conditions within a gas furnace and the corrosive acids (*i.e*., hydrogen chloride and hydrogen fluoride) produced by the mixture and combustion of the spiking gas and the hydrocarbon fuel (*i.e.,* natural gas or propane gas). Setup and testing of each furnace and array of sensors was conducted in accordance with the corrosion test procedure outlined in Exhibit G of ANSI Z21.47, *Standard for Gas-Fired Central Furnaces*. A separate spiking gas system was set up and connected to each test furnace in accordance with Section G.2, Spiking Gas System, of Exhibit G. Bottled refrigerant-11 (R-11) was used as the spiking gas and was mixed with each fuel gas by connection to each respective fuel gas supply line. The test furnaces were operated at a cycle rate of 4 minutes ON and 8 minutes OFF until a minimum of 12,000 burner cycles had been completed in accordance with Section G.3, Corrosion Test Procedure, of Exhibit G. The output of each test sensor and the operating parameters of each test furnace were recorded continuously throughout the duration of the corrosion testing at a rate of two samples per minute, using a data acquisition computer software and hardware system. The duration of the corrosion testing was approximately 100 days or 14 weeks. The corrosion testing was conducted at CSA-America's test facility in Cleveland, Ohio.

One furnace was set up to operate with natural gas and the other with propane gas. This test procedure required that the furnaces be operated at their designed input rate and under normal venting conditions. Because acidic condensate produced during the corrosion test would likely have damaged the laboratory grade combustion analyzers, combustion samples were not drawn from the furnace. Thus, actual CO and CO_2 levels within each furnace could not be confirmed. However, under these conditions, the furnaces were expected to produce negligible CO levels (*i.e*., < 9 ppm) and CO_2 levels between 6 percent and 8 percent. Thus, throughout the course of the corrosion testing, all of the CO sensors' output voltages were essentially at zero conditions. In order to (1) determine whether the sensors were still sensitive to CO, and (2) if not, determine at what point sensitivity began to degrade, staff included provisions for the contractor to inject CO into the furnace while operating. This was done on a weekly basis, after the spiking gas had been shut off.

Sensor output signals were expected to be commensurate with those recorded under similar conditions during the pre-aging phase in-situ furnace testing. However, the effect, if any, of the harsh acids produced by the combustion of fuel gas and R-11 on sensor performance were not known, but would be determined by analysis and comparison of sensor performance before aging (*i.e*., pre-aging testing), during aging (*i.e*., corrosion testing), and after aging (*i.e*., post-aging testing).

Continued Operation
No additional setup was required to assess whether the sensors continued to operate. Continued operation of the sensor was based on:

1. Whether there was a loss of signal, and
2. Whether sensor voltage remained responsive to and changed in sequence with the furnace ON/OFF cycles and associated increases and decreases in CO concentrations during the start of an ON cycle.

3.1.2 In-Situ Corrosion Test Performance of Sensors in the Natural Gas Furnace

Catalytic Bead CO sensors
Continued Operation
The ON cycle data for the catalytic bead CO sensors installed in the natural gas test furnace are presented in Graph C.1 and Table C.1 in Appendix C. As discussed earlier (see Section 1.4, Sensor Description, and Section 2.1.2, Sensitivity Test Results), these sensors were not equipped with an algorithm or other means for re-zeroing or calibration. As a result, sensor voltage at or near zero ppm CO (described previously as the zero offset) did not remain constant during corrosion testing. Given that the zero offset did not remain constant, staff did not subtract the zero offset from the total voltage and thus, the data presented in Graph C1. and Table C.1 include the zero offset voltage. Changes in the zero offset voltage were not that noticeable during the Pre-Aging Phase sensitivity and in-situ testing, as the test durations were much shorter. This again underscores the importance of equipping these sensors with a means for zeroing and calibration in future testing or production.

Catalytic bead sensors CB79#6 and CB79#8 continued to operate throughout the duration of the corrosion test; they did not exhibit any loss of output voltage signal during testing, and remained responsive to changes in furnace operating conditions that signified changes in CO concentrations (i.e., increased gas manifold pressure, momentary spikes in CO concentrations at the beginning of each furnace ON-cycle). The output voltage signals for CB79#6 and CB79#8 were within the same order of magnitude (i.e., 105 to 115 mV) exhibited during the Pre-Aging Phase sensitivity and in-situ testing.

CB78#3 on the other hand, exhibited voltage output signals that were not within the order of magnitude exhibited during the Pre-Aging Phase. During Pre-Aging, CB78#3 voltage output signals were in the 20 to 30 mV range. During the Aging Phase corrosion testing, CB78#3's voltage signal was typically below 1 mV, clearly a reduction in signal strength from Pre-Aging levels, suggesting that the sensor was failing. However, as shown in Graph C.1, CSA-OnSpex increased the furnace gas manifold pressure from 4.5 to 7.0 in. w.c. between October 17th and October 31st, 2007, causing the furnace to become over-fired, which would result in higher concentrations of CO. During this time frame, CB78#3 exhibited an increase in voltage output in response and to the increase in CO; CB78#3's output ranges from average daily values of XX and YY mV and a peak average daily output of ZZ mV during this period. This signifies that the sensor was not failing, but the signal strength/output was clearly, inexplicably reduced during this test phase. That CB78#3 did not experience failure is also demonstrated later during the Post-Aging Phase when it exhibited voltage signals more representative of those it exhibited during the Pre-Aging Phase testing.

NDIR CO sensors
Continued Operation
The ON cycle data for the NDIR CO sensor installed in the natural gas test furnace are presented in Graph C.2 and Table C.2 in Appendix C. Although the sensor continued to exhibit an output voltage, the sensor did not exhibit a discernible response to CO, nor did sensor output voltage change in sequence with the furnace ON/OFF cycles and the corresponding changes in CO concentration. The sensor continued to

exhibit signs that it was experiencing interference. The sensor exhibited full-scale output voltage during approximately the first 3,000 cycles and last 8,000 to 12,000 ON cycles of the furnace. The sensor exhibited minimal voltage output approximately between 3,000 and 8,000 ON cycles of the furnace. As discussed earlier during the pre-aging phase in-situ furnace testing, possible prime sources of interference were from the CO_2 or water vapor produced during the combustion process, and more development work may be required to resolve this issue.

NDIR CO_2 sensors

Continued Operation

The ON cycle data for the NDIR CO_2 sensor installed in the natural gas test furnace is presented in Graph C.2 and Table C.2. Based on the following observations, the NDIR CO_2 sensors continued to operate throughout the duration of the Corrosion Test:

1. There was no loss of sensor output voltage signal, and
2. Sensor output voltages remained responsive to and changed in sequence with the furnace ON/OFF cycles and associated increases and decreases in CO_2 concentrations.

3.1.3 In-Situ Corrosion Test Performance of Sensors in the Propane Gas Furnace

Catalytic bead CO sensors

Continued Operation

The ON cycle data for the catalytic bead CO sensors installed in the propane test furnace are presented in Graph C.3 and Table C.3 in Appendix C. As discussed in Section 3.1.2, In-Situ Corrosion Test Performance of Sensors in the Propane Gas Furnace, and earlier sections, because these sensors were not equipped with an algorithm or other means for re-zeroing or calibration, their zero offset voltages did not remain constant during corrosion testing. The data in Graph C.3 and Table C.3 is therefore presented with the zero offset voltage included.

Based on the following observations, the catalytic bead sensors continued to operate throughout the duration of the corrosion test:

1. There was no loss of output voltage signal from any of the sensors, and
2. Sensor output voltages remained responsive to and changed in sequence with the furnace ON/OFF cycles and associated increases and decreases in CO concentrations.

NDIR CO sensors

Continued Operation

The ON cycle data for the NDIR CO sensor installed in the propane test furnace are presented in Graph C.4 and Table C.4 in Appendix C. As in the case of the infrared CO sensor installed in the natural gas furnace, the infrared CO sensor installed in the propane furnace also continued to exhibit signs that it was experiencing interference. In the first 6,000 furnace ON cycles, sensor output voltage oscillated between full scale and minimum output and stayed at full scale between 6,000 and 12,000 ON cycles. As discussed earlier, possible prime sources of interference were from the CO_2 or water vapor produced during the combustion process.

NDIR CO_2 sensors

Continued Operation

The ON cycle data for the NDIR CO_2 sensor installed in the propane test furnace is presented in Graph C.4 and Table C.4 in Appendix C. Based on the following observations, the NDIR CO_2 sensors continued to operate throughout the duration of the corrosion test:

1. There was no loss of sensor output voltage signal, and
2. Sensor output voltages remained responsive to and changed in sequence with the furnace ON/OFF cycles and associated increases and decreases in CO_2 concentrations.

4. POST-AGING TEST PHASE

The objective of the tests described in the post-aging test phase was to determine whether the sensors were still operable after exposure to the aging effects of the corrosion test conditions and the harsh furnace environment. In addition, sensor performance was evaluated to determine whether it had degraded from the baseline results established during the pre-aging test phase. In order to accomplish these objectives, additional sensitivity and in-situ furnace tests were conducted. The in-situ furnace testing was performed at CSA-OnSpex at the conclusion of the corrosion testing and was conducted to determine whether the sensors were still able to exhibit proportional response to changing levels of their target gases. The sensitivity testing was performed at the combustion test facilities at CPSC's Directorate for Laboratory Sciences. The sensitivity test results were compared to those obtained during the Pre-Aging Test Phase.

The performance measures for CO sensors during the Post-Aging in-situ furnace testing were (1) whether or not the sensors were still operable; (2) whether or not the sensors were still able to detect the proposed CO shutoff level (*i.e.,* nominally 400 ppm) in the furnace; and (3) whether or not the sensors were still able to distinguish shutoff levels of CO from non-shutoff levels (*i.e.,* 300 ppm or less). The performance measures for the CO_2 sensors were (1) whether or not the sensors were still operable; (2) whether or not the sensors were still able to detect CO_2 levels that corresponded to the proposed CO shutoff level (*i.e.,* nominally 9 percent CO_2 or more); and (3) whether or not the sensors were still able to distinguish between those levels and CO_2 levels that corresponded to non-shutoff levels (*i.e.,* 8 percent CO_2 or less). The voltammetric sensors were subjected to all of the testing conducted during the post-aging phase. However, because their performance had to be evaluated using proprietary software developed by the sensor manufacturer, the test results for the voltammetric sensors were not included in this report. A summary of all post-aging phase test results is provided in Appendices D and E. A summary of all post-aging phase test objectives and whether each sensor met the objective are located in the table in Appendix F.

4.1 IN-SITU FURNACE TESTING OF SENSORS

4.1.1 In-Situ Sensor Performance in the Natural Gas Test Furnace

During post-aging in-situ testing the natural gas test furnace was operated at the same cycling rate used during corrosion testing (*i.e*., 4 minutes ON and 8 minutes OFF) and under abnormal operating conditions that included over-firing of the furnace. The furnace was over-fired by adjusting its gas manifold valve from its normal operating pressure of 3.5 inches water column (in. w.c.) to approximately 7.4 in. w.c. Carbon monoxide and carbon dioxide samples were drawn from the vertical section of vent pipe approximately 3 feet above the outlet of the inducer motor. Under this combination of conditions, furnace CO levels rose rapidly and peaked during the ON cycles. Although optimum for corrosion testing, this cycling rate did not allow the furnace to operate long enough for CO levels and, as a result, corresponding CO sensor output levels to reach steady state/equilibrium. When depicted in a scatter plot (see Graphs D.1 through D.10), furnace ON/OFF cycles, CO and CO_2 concentrations, and sensor output voltage were characterized by a repetitive, saw tooth-like pattern in which CO levels started at approximately 0 ppm, spiking to peak levels that exceeded 1045 ppm during the initial warm-up, gradually declining (but not reaching steady state) during the remainder of the ON cycles, and then rapidly dropping to 0 ppm when the furnace cycled OFF. The CO_2 levels started at 0 percent, spiking at peak levels that exceeded 10 percent. The furnace was cycled ON a total of 13 times during this test. Average CO levels within the furnace ranged from between 270 and 955 ppm through 13 ON-cycles, with peak levels reaching 1045 ppm. Average CO_2 levels ranged between 8.3 percent and 9.5 percent during the ON cycles and peaked between 10.0 percent and 10.4 percent. Average temperature during the furnace ON cycle ranged from 104 to 107^{o}F in the furnace condensate pan and from 356 to 402^{o}F in the flue collector.

Catalytic bead CO sensors
As seen in Graphs D.1 through D.3, each catalytic bead CO sensor exhibited changes in voltage output that corresponded to changes in furnace CO levels during the ON/OFF cycles. Carbon monoxide levels during furnace ON-cycles were very distinct from CO levels during OFF-cycles and corresponding sensor output at these CO levels was also very distinct (see Table D.1). Each sensor: (1) continued to exhibit output voltages proportional to the changing concentrations of CO to which they were exposed, and (2) produced voltage outputs at or near the proposed shutoff level that was distinct from voltage levels at non-shutoff CO levels. These results help establish the long-term durability of the catalytic bead CO sensors, because they continued to operate after being subjected to harsh furnace conditions and the aging effects of the corrosion test over an extended period of time.

NDIR CO sensors
As seen in Graph D.4 and Table D.1, the infrared CO sensor used in the natural gas test furnace, NDIRCO#2, continued to exhibit nonresponsive behavior to the levels of CO that changed as the furnaces cycled ON and OFF. Given this and past behavior, no further testing or analysis was conducted on this sensor.

NDIR CO_2 sensors
From Graph D.5, it can be seen that the NDIR CO_2 sensor exhibited changes in voltage output that corresponded to changes in furnace CO_2 levels during the ON/OFF cycles. Sensor output at these CO_2 levels was very distinct from sensor output at CO_2 levels below the proposed shutoff level (see Table D.1.). Each sensor: (1) continued to exhibit output voltages proportional to the changing concentrations of CO_2 to which they were exposed, and (2) produced voltage outputs at or near the proposed shutoff level that were distinct from voltage levels at non-shutoff levels of CO_2. These results help establish the long-term durability of the NDIR CO_2 sensors because they continued to operate after being subjected to harsh furnace conditions and the aging effects of the corrosion test over an extended period of time.

4.1.2 In-Situ Sensor Performance in the Propane Gas Test Furnace
The propane gas test furnace was operated under abnormal conditions, including over-fire and was cycled ON a total of 18 times at the same cycle rate used during the corrosion test (4 minutes ON and 8 minutes OFF). The furnace was over-fired by adjusting its gas manifold valve from its normal operating pressure of 7.0 inches water column (in. w.c.) to approximately 14.0 in. w.c. Carbon monoxide and carbon dioxide samples were drawn from the vertical section of vent pipe approximately 3 feet above the outlet of the inducer motor. Furnace CO levels rose rapidly, peaking at 1050 ppm under these conditions. As in the case of the natural gas test furnace, this cycling rate was optimal for corrosion testing but did not allow the furnace to operate long enough for CO levels or corresponding sensor output to reach steady state/equilibrium. When plotted against time (see Graphs D.6 through D.8, and D.10), CO levels and sensor output voltages generally exhibited a repetitive, saw tooth-like pattern with initial CO levels of 0 ppm, spiking to peak levels in excess of 1050 ppm during the initial warm-up, then gradually decreasing (without reaching steady state conditions) during the remainder of each ON cycle. At the end of the ON cycle, CO levels dropped rapidly to 0 ppm (see Table D.3.).

The peak CO levels within the propane gas test furnace reached 1050 ppm but only averaged between 246 and 287 ppm through 18 ON cycles (see Table D.2.). Average CO_2 levels ranged between 9.5 percent and 10.7 percent during the ON cycles and peaked between 11.1 percent and 11.5 percent. Sensor output at these CO levels was very distinct from sensor output at CO levels below the proposed shutoff level.

The thermocouples used to measure condensate pan and flue collector signals were inadvertently disconnected prior to this set of tests in the propane furnace, and therefore, temperature data were not recorded. However, the temperature in the condensate pan and flue collector should be within the range of those recorded during pre-aging phase in-situ propane furnace testing; 111 to 239^{o}F for the condensate pan and 342 to 643^{o}F for the flue collector. It is important to note that, unlike the pre-aging phase in-situ furnace testing, the line voltage to the furnace circulation air blower was not reduced during post-aging testing. Because the circulation air blower is designed to remove heat from the heat exchangers and circulate hot air through a household duct system, staff expects that the average temperatures in the condensate pan and flue collector was more likely closer to the lower end of the range (*i.e*., 111^{o}F for the condensate pan and 342 to 450^{o}F for the flue collector).

Catalytic bead CO sensors
Each catalytic bead CO sensor exhibited changes in voltage output that corresponded to changes in furnace CO levels during the ON/OFF cycles, as shown in Graphs D.6, D.7, and D.8. As seen in Table D.2, sensor output at these CO levels was very distinct from sensor output at CO levels below the proposed shutoff level. The test results demonstrated that, despite being exposed to harsh furnace conditions and the aging effects of the corrosion test over an extended period of time, the catalytic bead CO sensors continued to operate. Each sensor satisfied the following performance criteria: (1) it continued to exhibit output voltages proportional to the changing concentrations of CO to which they were exposed, and (2) its voltage output at or near the proposed shutoff level was distinct from voltage levels at non-shutoff CO levels. These results help establish the long-term durability of the catalytic bead CO sensors because they continued to operate after being subjected to harsh furnace conditions and the aging effects of the corrosion test over an extended period of time.

NDIR CO sensors
As shown in Graph D.9, the infrared CO sensor used in the propane test furnace, NDIRCO#1, continued to output voltages that were nonresponsive to the levels of CO that changed as the furnace cycled ON and OFF. Given this and past behavior, no further testing or analysis was conducted on this sensor.

NDIR CO_2 Sensors
Each NDIR CO_2 sensor exhibited changes in voltage output that corresponded to changes in furnace CO_2 levels during the ON/OFF cycles, as shown in Graph D.10. Sensor output at these CO_2 levels was very distinct from sensor output at CO_2 levels below the proposed shutoff level (see Table D.2.). The test results indicated that, despite being exposed to harsh furnace conditions and the aging effects of the corrosion test over an extended period of time, the NDIR CO_2 sensors continued to operate. This was evidenced by the sensors satisfying the following performance criteria: (1) continued to exhibit output voltages proportional to the changing concentrations of CO_2 to which they were exposed; and
(2) produced voltage outputs at or near the proposed shutoff level that were distinct from voltage levels at non-shutoff CO_2 levels. These results help establish the long-term durability of the NDIR CO_2 sensors, since they continued to operate after being subjected to harsh furnace conditions and the aging effects of the corrosion test over an extended period of time.

4.2 SENSITIVITY TESTING

4.2.1 Sensitivity Test Setup
All post-aging sensitivity testing was conducted in the combustion test facilities located at the CPSC's directorate for laboratory sciences in the same environmental chamber, using the same gas injection and sampling systems described earlier in section 2.1.1, sensitivity test method and setup for the pre-aging

phase. All sensors were tested at a nominal chamber temperature of 70°F and a relative humidity of 50 percent. Unlike the pre-aging phase tests, chamber gas concentrations were recorded automatically using the data acquisition system.

4.2.2 Sensitivity Test Results

Catalytic bead CO sensors

Continued Sensitivity

Sensitivity testing was conducted on the six catalytic bead CO sensors (*i.e.,* CB78#1, CB78#2, CB78#3, CB79#5, CB79#6, and CB79#8) that were subjected to the testing described in Section 3, Aging Test Phase. As was done in reporting the results of the sensitivity testing conducted during the pre-aging test phase, the zero offset voltages were again subtracted from the base or zero voltages recorded for the sensors in order to more clearly differentiate the change in voltage from the base (*i.e.,* zero) voltage.

As shown in Graphs E.1 through E.4, Appendix E, each sensor continued to exhibit sensitivity to CO; when increasing concentrations of CO were injected into the chamber, the sensors exhibited an increasing, linear voltage output in response. For the six sensors, the voltage output increased at rates that ranged from 0.1 to 0.2 mV per 100 ppm of CO and continued to exhibit high degrees of correlation to CO, demonstrated by correlation coefficient (r) values ranging from 0.77 to 0.99.

Discrimination between shutoff and non-shutoff CO levels

As seen during the pre-aging phase sensitivity testing, sensor output exhibited some overlap at successive CO concentrations. As previously stated, CPSC staff believes this overlap can be attributed to the following factors: (1) the sensors were not equipped with a calibration algorithm; (2) the magnitude of the zero offset voltages (90 to 130 mV for the CB79s and 20 to 35 mV for the CB78s) and the voltage drop across the measurement range (*i.e.,* 2 to 7 mV) were relatively small; (3) the sensors were not equipped with amplifiers to boost the voltage signals; and (4) the sensors were not equipped with filters to remove or reduce signal noise potentially introduced from the test setup and data acquisition system. Regarding their ability to distinguish between the proposed CO shutoff concentration and non-shutoff concentrations, the sensors had varied results. During Test #1 and Test #2, CB79#6 and CB78#3 output voltages exhibited a downward shift between chamber CO levels of 200 and 400 ppm, while CB78#1, CB78#2, CB79#5, and CB79#8 output voltages continued to increase and were able to show a distinct response between the two CO levels. For a full set of results, see Appendix E, Graphs E.1 through E.4 and Tables E.1 and E.2.

NDIR CO sensors

The infrared CO sensors used in the natural gas and propane test furnaces, NDIRCO#2 and NDIRCO#1, continued to output voltages that were nonresponsive to the increasing levels of CO that were injected into the environmental test chamber. Given this and past behavior, no further testing or analysis was conducted on these sensors.

NDIR CO_2 sensors

Continued Sensitivity

Sensitivity testing was conducted on the two NDIR CO_2 sensors (*i.e*., NDIRCO2 #2 and #3) that were subjected to the testing described in Section 3, Aging Test Phase. As shown in Graphs E.5 and E.6, each sensor continued to exhibit an increasing linear voltage output in response to the increasing concentrations of CO_2 injected into the chamber. For the two sensors, sensor output continued to increase at rates ranging from 0.36 to 0.37 volts for every 1 percent change in chamber CO_2 concentration and showed a high degree of correlation to CO_2, demonstrated by correlation coefficient (r) values that ranged from 0.93 to 0.95.

Discrimination between shutoff and non-shutoff CO_2 levels

Each sensor continued to distinguish between different concentrations of CO_2 up to 9 percent. The average output voltage for each sensor at chamber CO_2 concentrations of 9 percent was distinct from the output voltage at chamber CO_2 concentrations of 8 percent and lower. For a full set of results, see Appendix E, Tables E.3 and E.4 and Graphs E.5 and E.6.

5. COMPARISON OF PRE- AND POST-AGING TEST RESULTS

The primary purpose of this test program was to determine whether the sensors would still exhibit discernible operability, after being exposed to the harsh furnace environment and corrosion test conditions they were operated in. Operability was based on whether the sensors: (1) remained sensitive to their target gas; (2) continued to exhibit a linear relationship to their target gas; and (3) continued to distinguish between shutoff concentrations and non-shutoff concentrations of their target gas. Because none of the sensors was equipped with calibration algorithms, it was not unexpected that sensor voltage might change. Therefore, staff did not examine measures such as percent change or percent difference.

"Sensor sensitivity" was defined as the change in output voltage divided by the change in target gas concentration. Thus, continued sensitivity during the post-aging phase was based on whether each sensor continued to exhibit an increase in output voltage in response to increasing concentrations of its target gas. Sensitivity was illustrated by the slope of the line created from the plot of sensor output voltage versus target gas concentration.

The correlation coefficient (r) was the measure staff used to determine the strength of the linear relationship between the output voltages exhibited by sensors in response to increasing concentrations of their respective target gases. Correlation coefficient (r) values of 0.8 or higher were considered to represent strong linear relationships, while values less than 0.7 were considered to represent weak linear relationships. Thus, for a sensor to be considered to have continued to have a strong linear relationship to its target gas during the post-aging phase, its Correlation coefficient (r) values must have remained at or above 0.8. Finally, continued ability of sensors to distinguish between shutoff and non-shutoff concentrations of their target gases during the post-aging phase was based on the sensors exhibiting a positive differential between output voltages at the shutoff and non-shutoff levels.

Catalytic bead CO sensors

As seen in Graphs E.1 through E.4, all six of the catalytic bead CO sensors continued to exhibit sensitivity to CO during the post-aging phase, demonstrated by increasing output voltages in response to increasing concentrations of CO being injected into the chamber. However, as shown in Table 3 and Graphs 1 through 6, when compared to pre-aging phase test results, sensor sensitivity declined during the post-aging phase. Average sensor sensitivity ranged from 0.2 to 0.3 mV per 100 ppm of CO during pre-aging, but declined to a range of 0.1 to 0.2 mV per 100 ppm of CO during post-aging. This is shown visually by the decline in the slope of the trend line in Graphs 1–6 and numerically, by the decline in the slope of the line. Staff was uncertain what caused this decline in sensitivity (*e.g.*, exposure to the furnace operating environment and/or the corrosion test conditions, or drift caused by an absence of a calibration algorithm in the sensing electronics). This test program was not designed to examine the mechanical integrity of sensors, only the electrical operability and performance of sensors because these were the only parameters reported by a furnace manufacturer to have degraded during in-situ furnace testing of sensors they were conducting.[xi] These results warrant additional testing that would examine the mechanical integrity of sensors, pre- and post-aging, as well as performance of sensors equipped with calibration algorithms.

CB78#3 and CB79#6 exhibited a considerable amount of decline in their correlation coefficient (r) values (*i.e.,* r<0.7 in Table 3) during post-aging phase testing. The remaining four catalytic bead sensors (*i.e.*,

[xi] ESFS staff visited three furnace manufacturing facilities in 2006 to witness their proprietary testing of sensors in gas furnaces.

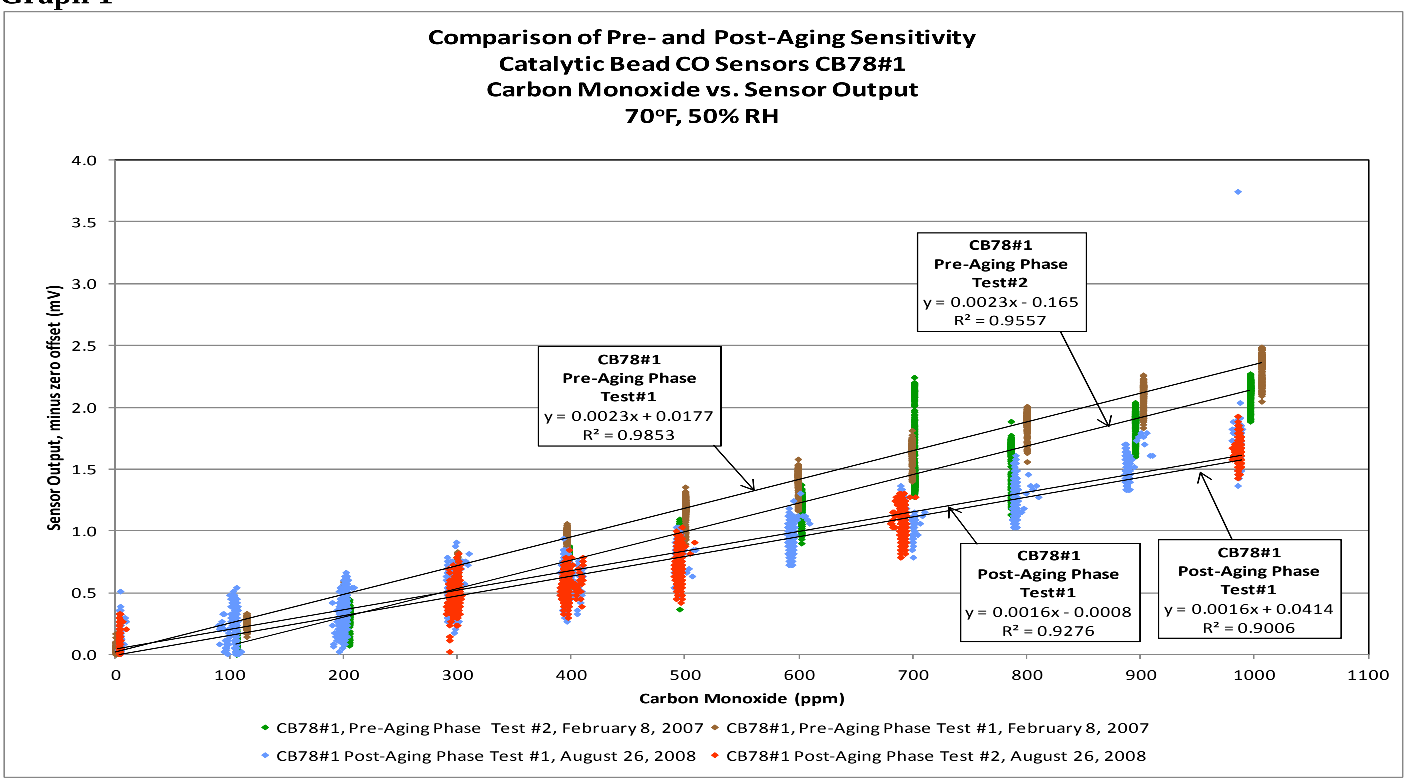
CB78#1, CB78#2, CB79#5, and CB79#8) continued to exhibit a strong linear relationship to CO, demonstrated by high correlation coefficient (r) values (*i.e.*, $r \geq 0.8$). As discussed earlier for the pre-aging sensitivity testing, this noise and its impact could have been attributed to the fact that the voltage drop across the measurement range was relatively small (*i.e.,* less than 3 mV) and the sensors were not equipped with filters to remove or reduce signal noise potentially introduced from the test environment or the data acquisition system. Any future testing of sensors with such minute voltage outputs should include a means to amplify the voltage signal and to filter out environmental noise.

Average sensor voltage ($V_{Avg.}$) at nominal chamber CO concentrations of 400 ppm, ranged from 0.6 to 1.4 mV during pre-aging sensitivity testing, but declined to a range of 0.5 to 0.8 mV at the same (nominal) concentration during post-aging sensitivity testing. Despite this change in sensor output, sensors CB78#1, CB79#5, and CB79#8 each continued to exhibit distinct voltages between shutoff (*i.e.,* 400 ppm) and non-shutoff (*i.e.,* 300 ppm and lower) CO levels during the first and second post-aging sensitivity tests. The results for CB78#2, CB78#3, and CB79#6 varied. CB782 and CB79#6 each exhibited distinct voltages during the second test, but not during the first test. CB78#3 did not exhibit a positive voltage differential during either of the tests.

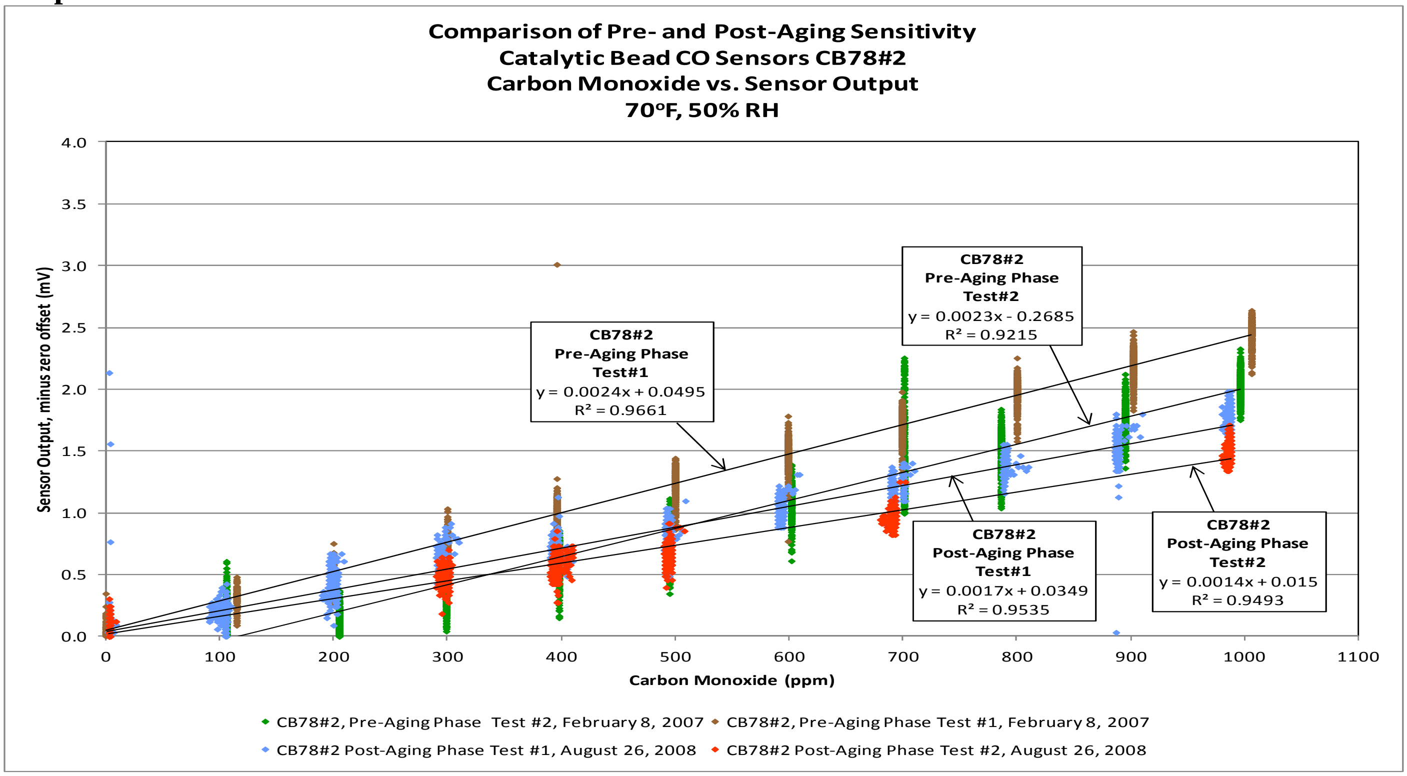
The performance data indicated that, despite the harsh furnace environment and corrosion test conditions, most of the catalytic bead CO sensors maintained their basic operability (*e.g.*, ability to produce output signals that demonstrated continued sensitivity to target gas, continued strong linear relationship, and a continued ability to distinguish between shutoff and non-shutoff CO levels). Staff believes that the types of problems exhibited by some of the sensors could have been caused by factors such as the sensors not being equipped with a calibration algorithm or filters, and not by the furnace or corrosion test conditions. The basis for this is that some of the same trends exhibited during post-aging sensitivity testing were also present during pre-aging sensitivity testing. In particular, the wide bands of raw voltage seen at each concentration of CO in Graphs E.1 through E.4 during post-aging sensitivity testing are also present in the pre-aging sensitivity testing shown in Graphs A.1 through A.5. Thus, this behavior preceded installation of the sensors into the test furnaces and exposure to the corrosion test conditions, and therefore, it would not have been caused by these conditions.

Table 3	COMPARISON OF PRE- AND POST-AGING SENSITIVITY DATA											
	CATALYTIC BEAD CO SENSORS											
	CB78#1		CB78#2		CB78#3		CB79#5		CB79#6		CB79#8	
	Test #1	Test #2	Test #1	Test #2	Test #1	Test #2	Test #1	Test #2	Test #1	Test #2	Test #1	Test #2
Sensitivity ($\Delta V/\Delta CO$)	**mV/CO**	**mV/CO**	**mV/CO**	**mV/CO**	**mV/CO**	**mV/CO**	**mV/CO**	**mV/CO**	**mV/CO**	**mV/CO**	**mV/CO**	**mV/CO**
Pre-Aging	0.0023	0.0023	0.0024	0.0025	0.0025	0.0026	0.0024	0.0025	0.0023	0.0024	0.0021	
Post-Aging	0.0016	0.0016	0.0017	0.0014	0.0014	0.0011	0.0021	0.0018	0.0010	0.0011	0.0018	0.0019
Correlation Coefficient, r												
Pre-Aging	0.9995	0.998	0.9997	0.998	0.9976	0.9976	0.9988	0.9995	0.9986	0.9996	0.9809	
Post-Aging	0.8912	0.905	0.8837	0.9215	0.5575	0.3207	0.893	0.9636	0.4494	0.3051	0.9255	0.8281
$V_{Avg@300\ ppm\ CO}$	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	
Pre-Aging	0.7	0.7	0.8	0.7	0.8	0.8	0.7	0.7	0.7	0.7	0.7	
Post-Aging	0.5	0.5	0.6	0.5	0.6	0.8	0.6	0.5	0.5	0.7	0.6	0.7
$V_{Avg@400\ PPM}$ CO	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**
Pre-Aging	0.9	0.7	1.0	0.6	1.0	1.4	0.9	1.3	0.9	1.4	1.0	
Post-Aging	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.5	0.8	0.7	0.8

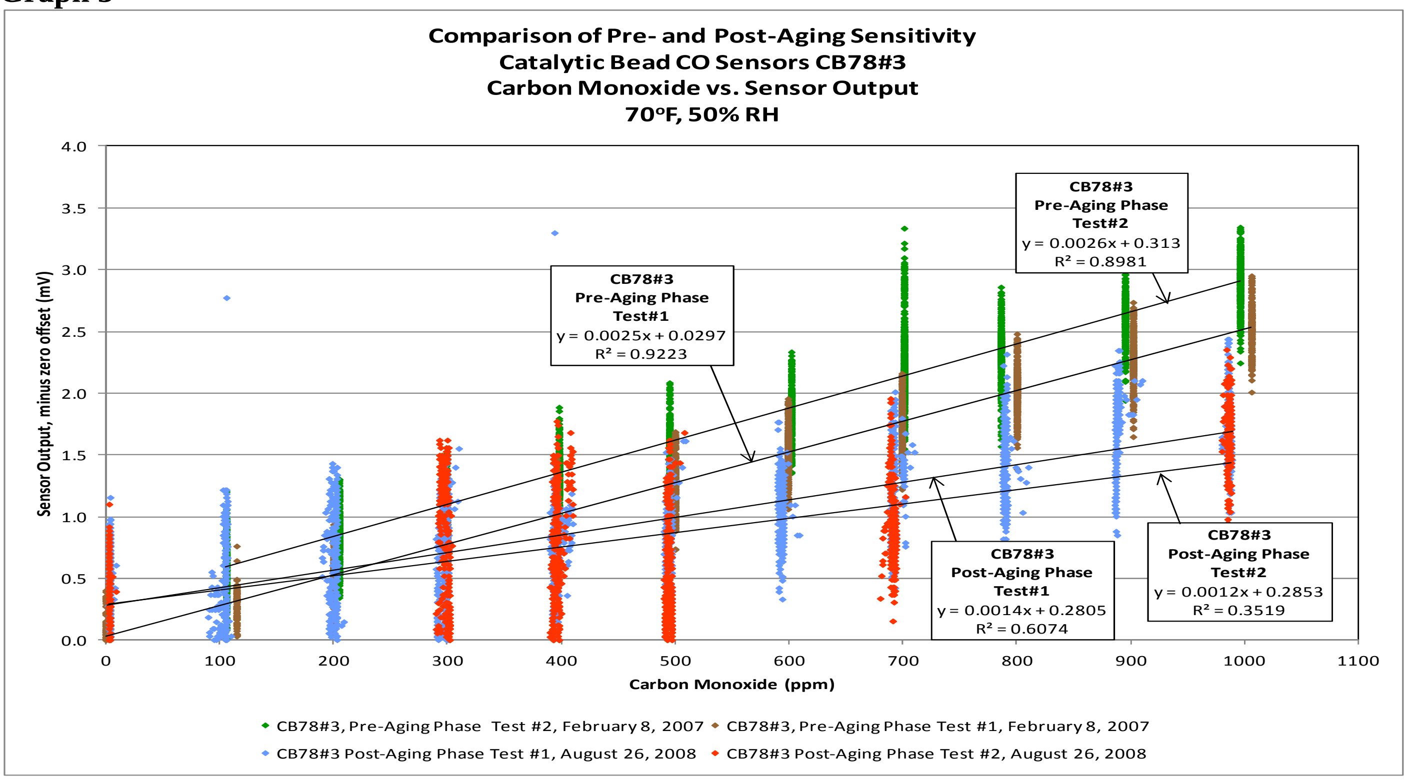
Graph 1



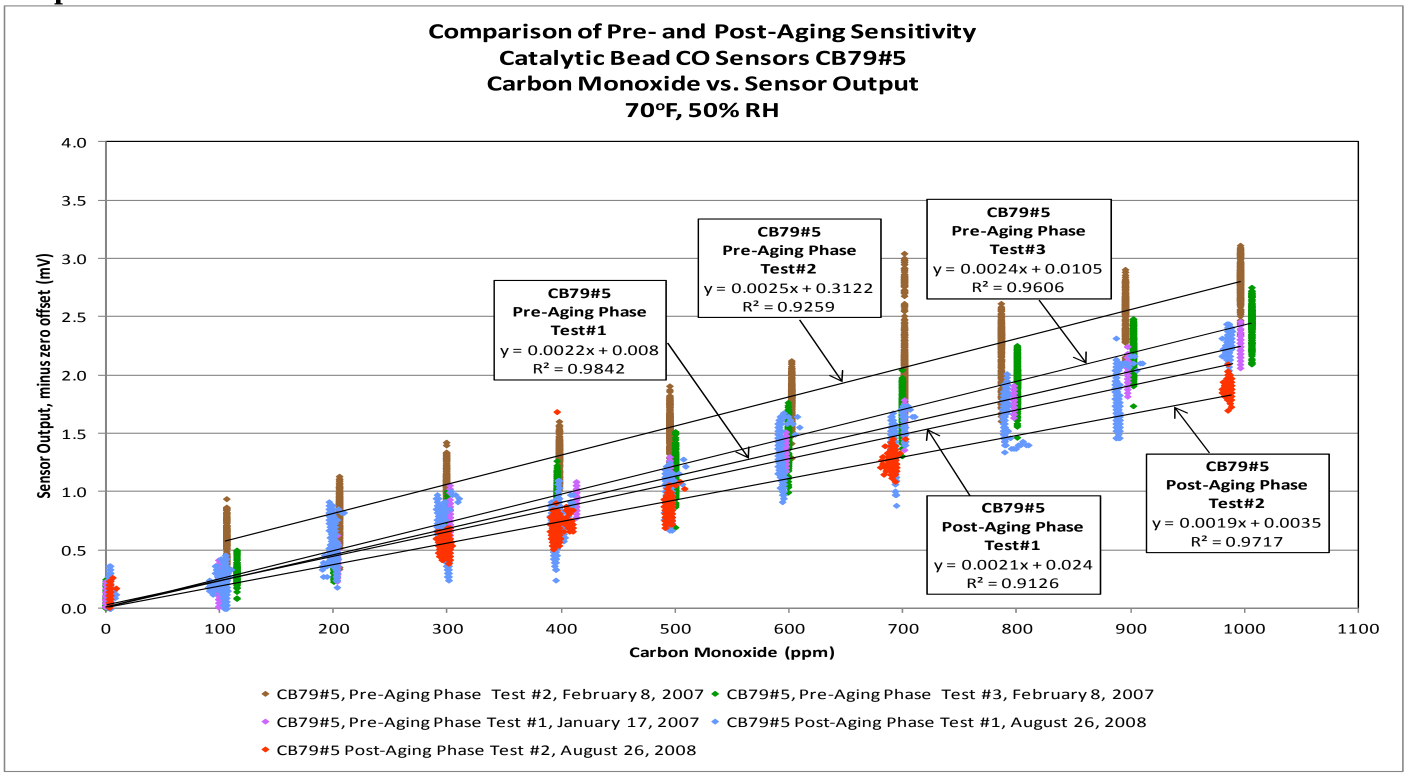
Graph 2



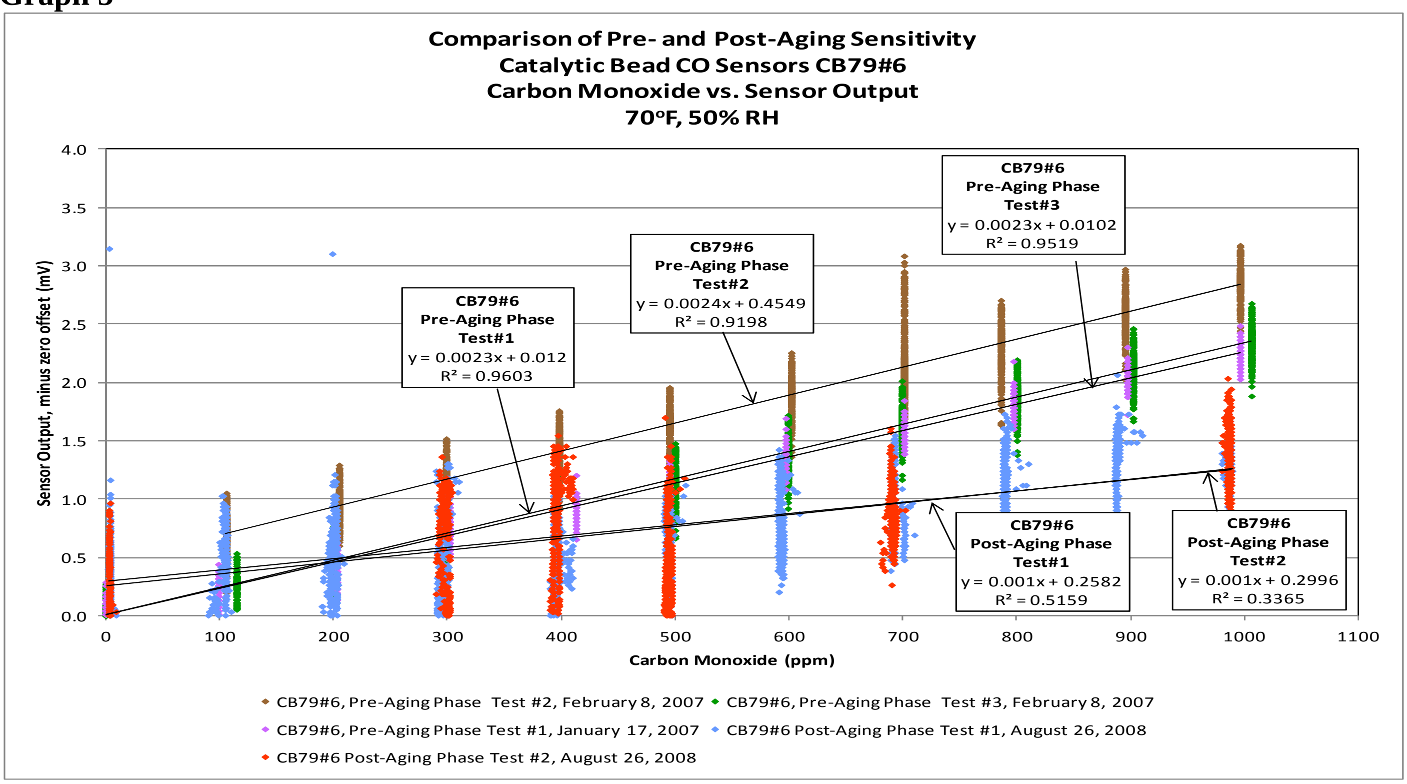
Graph 3



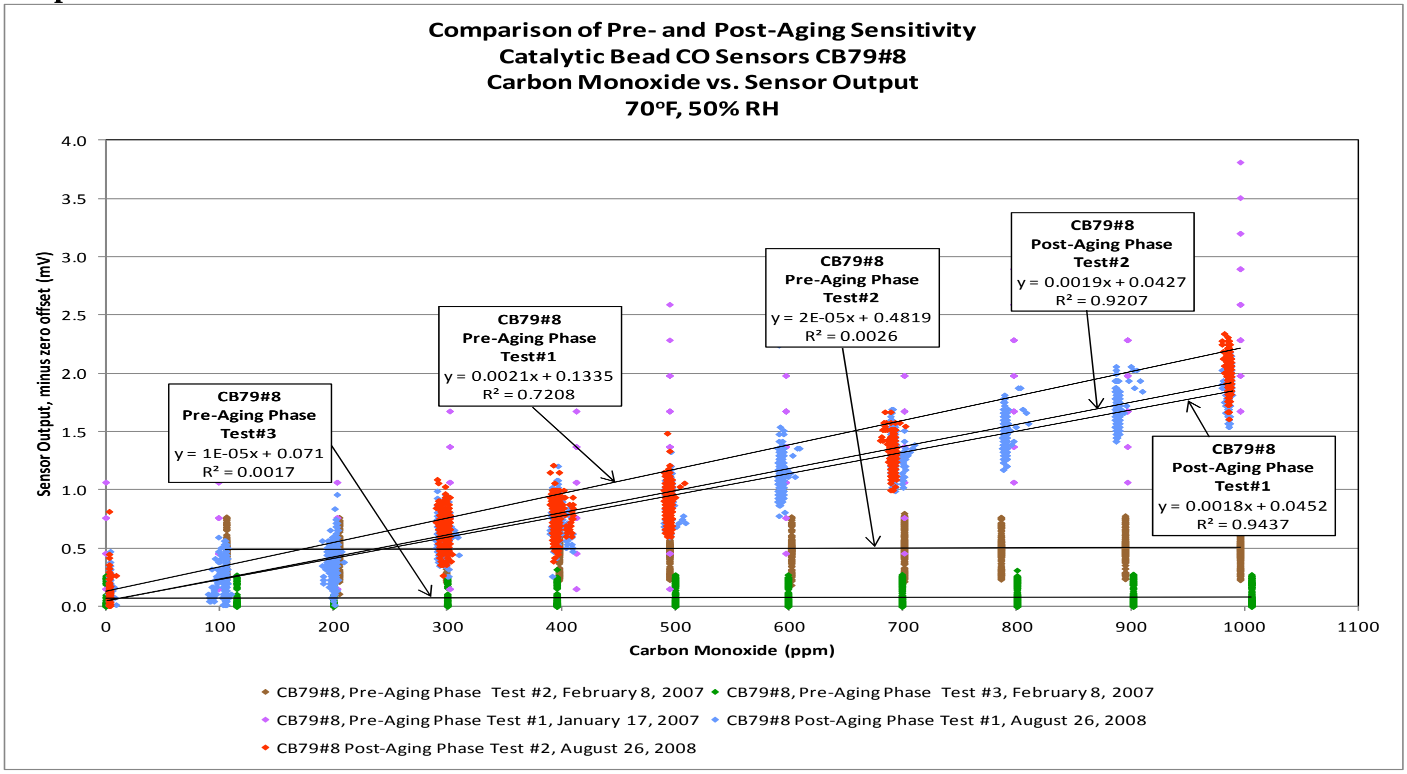
Graph 4



Graph 5



Graph 6



NDIR CO sensors

The infrared CO sensors used in the natural gas and propane test furnaces, NDIRCO#2 and NDIRCO#1, continued to output voltages that were nonresponsive to the increasing levels of CO that were injected into the environmental test chamber. Given this and past behavior, no further testing or analysis was conducted on these sensors.

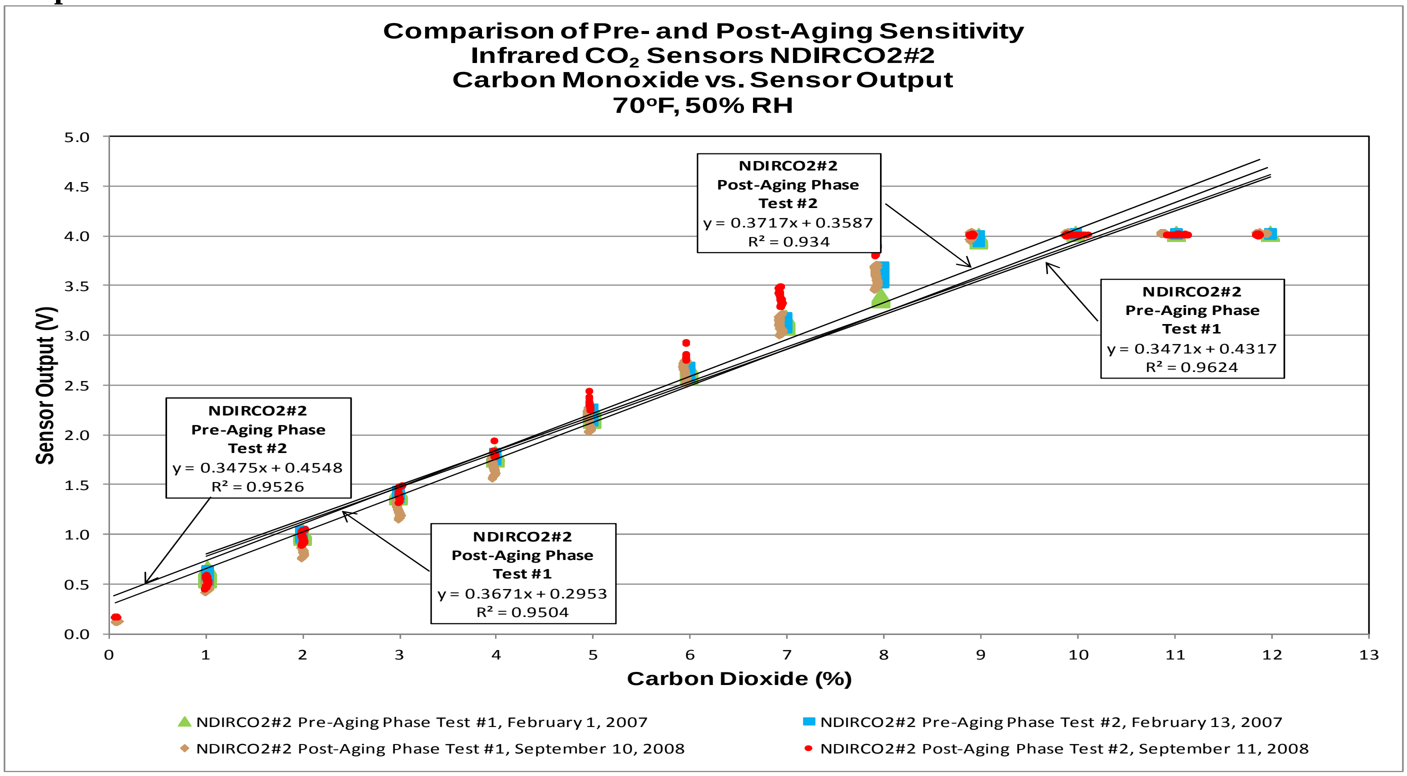
NDIR CO_2 sensors

As seen in Graphs E.5 and E.6, both of the infrared CO_2 sensors continued to exhibit sensitivity to CO_2, demonstrated by increasing output voltages in response to increasing concentrations of CO_2 being injected into the chamber. Table 4 and Graphs 7 and 8 show that when compared to pre-aging phase results, sensor sensitivity exhibited little or no change during post-aging. Average sensor sensitivity ranged from 0.345 to 0.363 volts per percent CO_2 during pre-aging and from 0.367 to 0.377 volts per percent CO_2 during post-aging. NDIRCO2#2 and NDIRCO2#3 each continued to exhibit a strong linear relationship to CO_2, demonstrated by high correlation coefficient (r) values (*i.e.*, r>0.8).

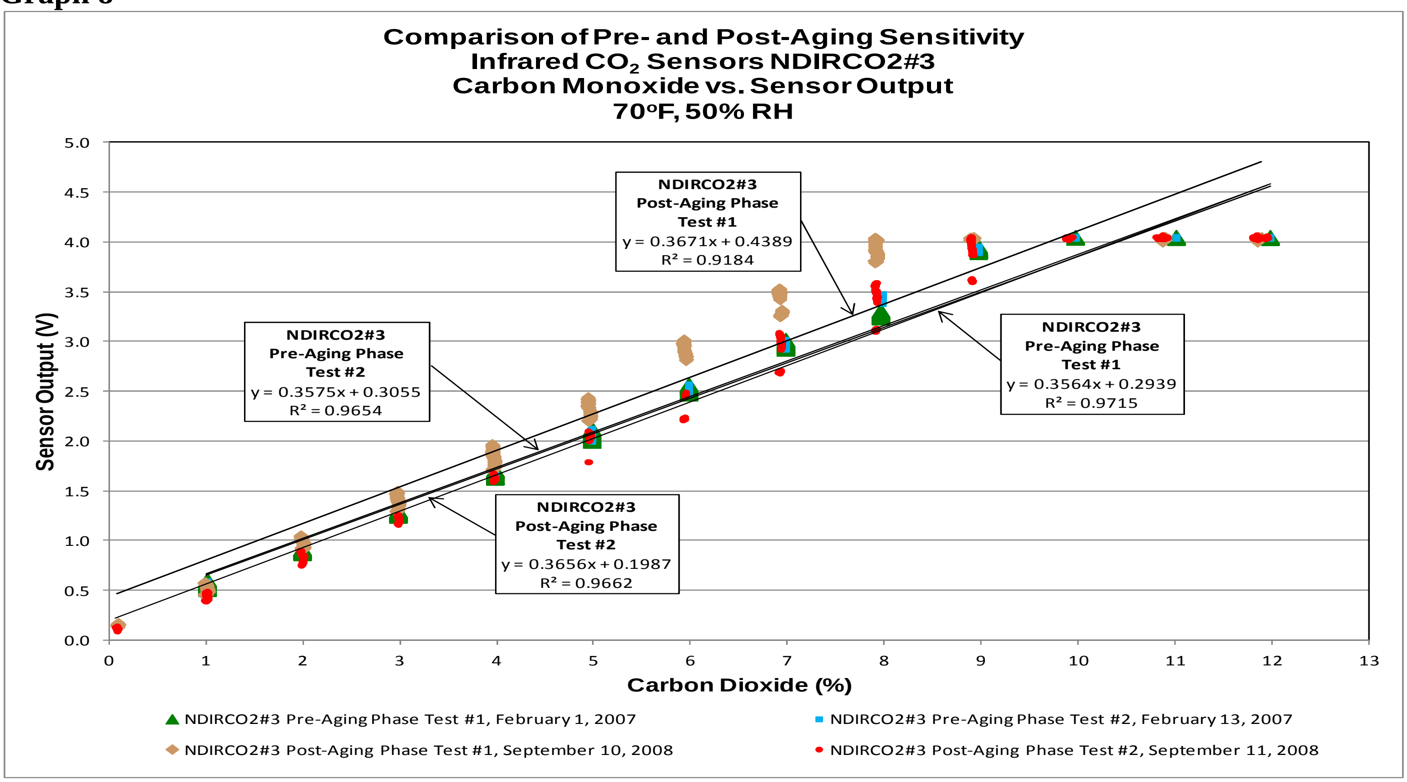
The average voltage ($V_{Avg.}$) of the sensors at nominal chamber CO_2 concentrations of 9 percent ranged between 3.9 and 4.0 volts during pre-aging and post-aging sensitivity testing. As shown in Table 4, NDIRCO2#2 and NDIRCO2#3 each continued to exhibit distinct voltages between shutoff (*i.e.*, 9 percent) and non-shutoff (*i.e.*, 8 percent) CO_2 levels during the first and second sensitivity tests, resulting in a positive differential in the average voltage (ΔV_{Avg}) between the two CO_2 levels. The performance data indicated that, despite the harsh furnace environment and corrosion test conditions, both of the infrared CO_2 sensors maintained their basic operability (*e.g.*, ability to produce output signals that demonstrated continued sensitivity to target gas, continued strong linear relationship, and a continued ability to distinguish between shutoff and non-shutoff CO_2 levels).

Table 4	COMPARISON OF PRE- AND POST-AGING SENSITIVITY DATA NDIR CO_2 SENSORS			
	NDIRCO2#2		NDIRCO2#3	
	Test #1	Test #2	Test #1	Test #2
Sensitivity ($\Delta V/\Delta CO_2$)	V/CO_2	V/CO_2	V/CO_2	V/CO_2
Pre-Aging	0.3519	0.345	0.3628	0.3557
Post-Aging	0.3727	0.3765	0.3665	0.3766
Correlation Coefficient, r				
Pre-Aging	0.9492	0.9526	0.9591	0.9654
Post-Aging	0.9578	0.9481	0.9304	0.9657
$V_{Avg@8\% CO2}$	V	V	V	V
Pre-Aging	3.4	3.6	3.3	3.4
Post-Aging	3.6	3.9	3.9	3.4
$V_{Avg@9\% CO2}$	V	V	V	V
Pre-Aging	4.0	4.0	3.9	3.9
Post-Aging	4.0	4.0	4.0	3.9

Graph 7



Graph 8



6. CONCLUSION

The results of this test program demonstrated that, despite being exposed to the operating environment of a gas furnace and the conditions of the corrosion test, the catalytic bead CO sensors and the NDIR CO_2 sensors maintained their basic electrical operability. These sensors continued to exhibit sensitivity and a strong linear relationship to their respective target gases, as well as distinct output voltages in response to exposure to the proposed shutoff and non-shutoff concentrations of these gases. Although the catalytic bead sensors exhibited some decline in sensitivity, staff believes that this could be resolved by amplifying the voltage signal and equipping the sensors with a calibration algorithm and electronic filters. The NDIR CO sensors were an exception to these findings. Based on their performance and discussions with their manufacturer, the problems encountered by the NDIR CO sensors were likely caused by interference from CO_2 or water vapor and would require additional development for this application. A summary of the objectives for this test program and whether they were met is provided in Appendix F.

This test program was only designed to examine the electrical operability of the sensors, as this was the only failure condition mentioned in limited discussions with appliance manufacturers engaged in sensor testing. An evaluation of the mechanical integrity of the sensors after aging was not part of the scope of this test program, but should be considered in future test and evaluation efforts. Additional work is warranted, but staff believes these findings address the basic durability and longevity concerns expressed by the Z21/83 Technical Committee in 2005 and demonstrate the availability of chemical sensors that are capable of withstanding the harsh operating environment of a furnace and surviving throughout the lifespan of the furnace.

ACKNOWLEDGEMENTS

The following individuals were instrumental in the completion of this sensor test program:

Randy Butturini, U.S. CPSC, Directorate for Engineering Sciences, provided technical expertise, support, and served as one of the principal engineers in the design and setup of the data acquisition system, chemical sensor preparation and operation, conduct of sensitivity and in-situ furnace testing of chemical sensors, trouble shooting of test setup and sensor operation, and analysis and reduction of test data.

Dave Tucholski, U.S. CPSC, Directorate for Laboratory Sciences, provided technical expertise and support in various aspects of the readiness and operation of environmental chambers and associated gas monitoring and sampling systems.

Chris Brown, U.S. CPSC, Directorate for Laboratory Sciences, provided technical expertise and support in various aspects of the readiness and operation of environmental chambers and associated gas monitoring and sampling systems.

John Worthington, U.S. CPSC, Directorate for Laboratory Sciences, provided technical expertise and support in design and fabrication of the mechanical fixtures used to mount chemical sensors to the test furnaces.

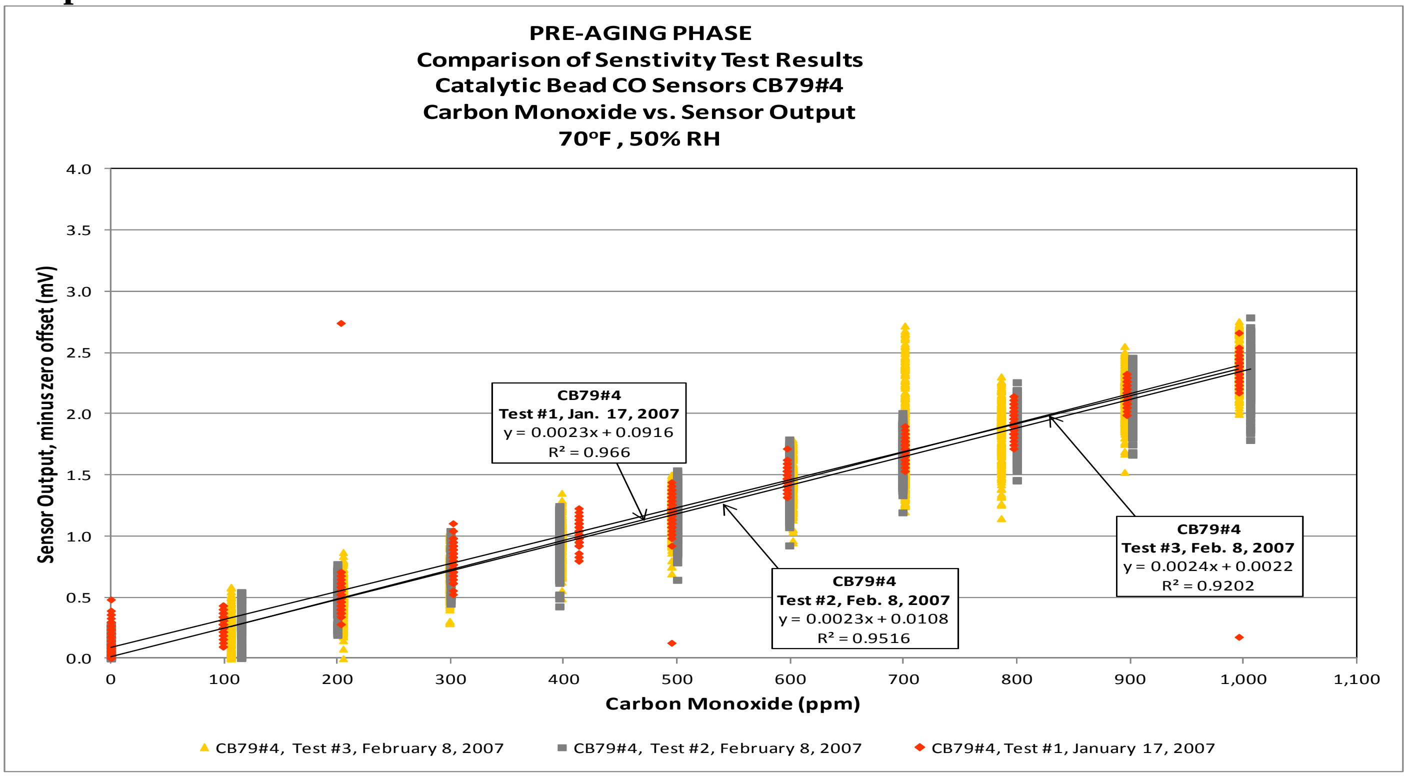
Scott Snyder, U.S. CPSC, Directorate for Laboratory Sciences, provided technical expertise and support in setup and operation of the environmental chamber's closed loop duct and heat exchanger system used to condition return and supply air provided to the test furnaces.

Dr. Michael Greene, Directorate for Epidemiology, provided technical expertise and consultation on aging test design and analysis of data.

Judd Smith, Canadian Standards Association (CSA)-OnSpex, Cleveland, Ohio, provided technical expertise under Contract Number CPSC-S-06-0080 to setup, troubleshoot, and conduct corrosion testing of two gas furnaces outfitted with an array of chemical sensors.

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.1

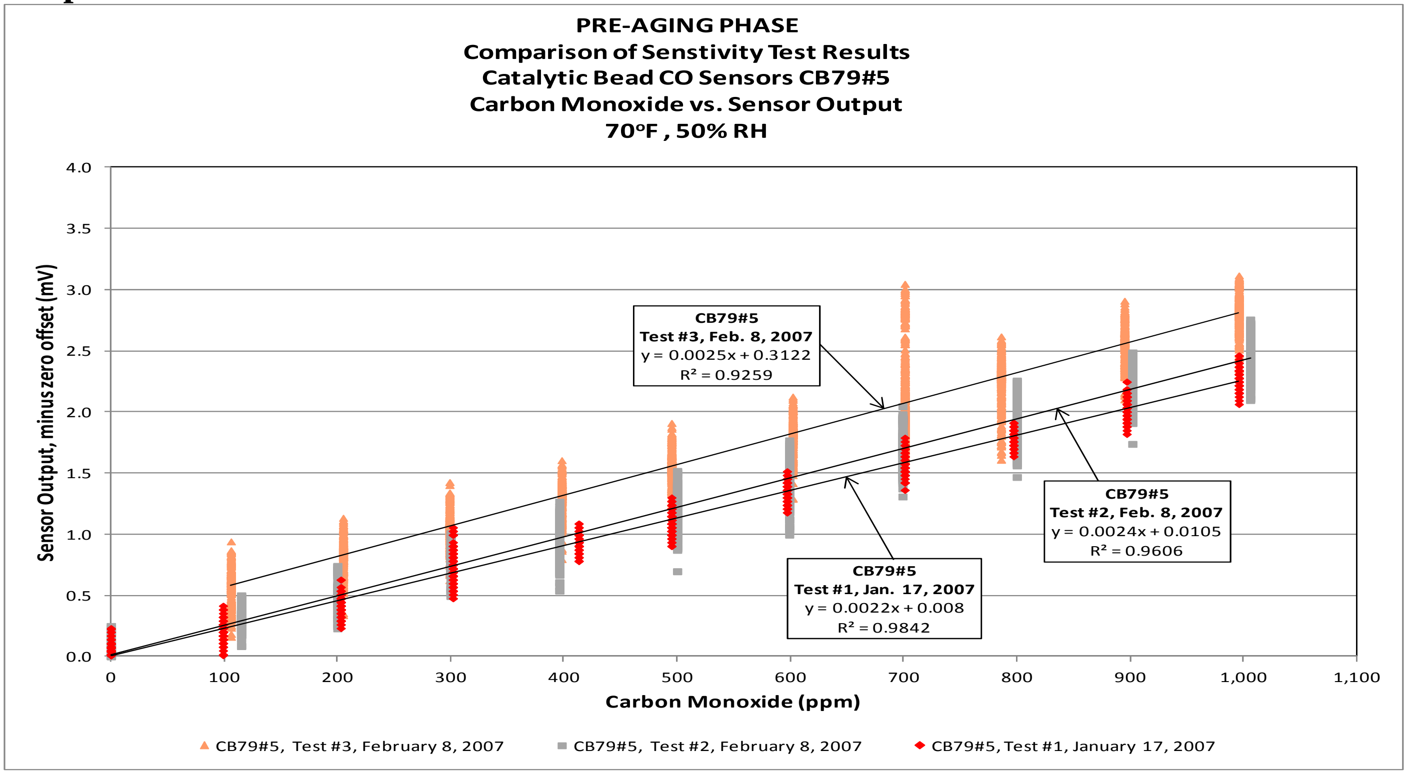


*Note that sensor voltage is presented with the zero offset voltage subtracted.

Table A.1	PRE-AGING PHASE Comparison of Sensitivity Test Results for CB79#4 (mV) 70^{o}F, 50% RH													
Test #1, January 17, 2007					Test #2, February 8, 2007					Test #3, February 8, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
0	0.1		0.5	0.0	0	0.1		0.3	0.0	----	----	----	----	----
99	0.3	0.2	0.4	0.1	115	0.3	0.2	0.5	0.0	106	0.2	----	0.6	0.0
203	0.5	0.2	2.7	0.3	200	0.5	0.2	0.8	0.2	205	0.5	0.2	0.9	0.0
302	0.8	0.3	1.1	0.5	300	0.7	0.3	1.0	0.4	299	0.7	0.2	1.0	0.3
413	1.0	0.2	1.2	0.8	396	0.9	0.2	1.2	0.4	398	1.0	0.3	1.4	0.5
495	1.2	0.2	1.4	0.1	500	1.2	0.3	1.5	0.6	495	1.2	0.2	1.5	0.7
597	1.5	0.3	1.7	1.3	599	1.4	0.2	1.8	0.9	602	1.5	0.3	1.8	0.9
701	1.7	0.2	1.9	1.5	699	1.7	0.3	2.0	1.2	701	1.7	0.2	2.7	1.2
797	1.9	0.2	2.1	1.7	800	1.9	0.2	2.3	1.5	786	1.9	0.2	2.3	1.1
897	2.2	0.2	2.3	2.0	902	2.1	0.2	2.5	1.7	895	2.1	0.3	2.6	1.5
996	2.3	0.2	2.7	0.2	1006	2.4	0.2	2.8	1.8	996	2.4	0.2	2.8	2.0

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

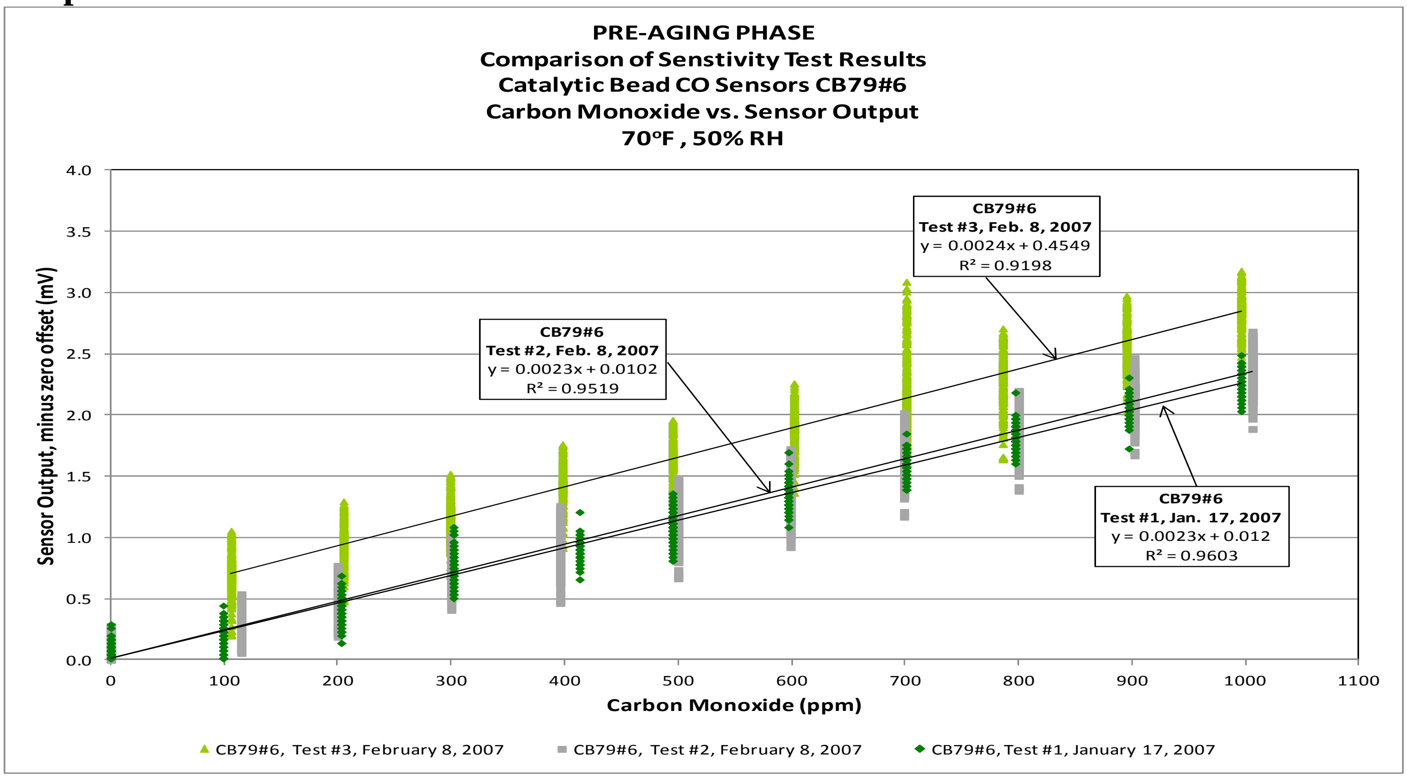
Graph A.2



*Note that sensor voltage is presented with the zero offset voltage subtracted.

Table A.2	PRE-AGING PHASE Comparison of Sensitivity Test Results for CB79#5 (mV) 70^{o}F, 50% RH													
Test #1, January 17, 2007					Test #2, February 8, 2007					Test #3, February 8, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
0	0.1		0.2	0.0	0	0.1		0.2	0.0	---	---	---	---	---
99	0.2	0.1	0.4	0.0	115	0.3	0.2	0.5	0.1	106	0.6	---	0.9	0.2
203	0.4	0.2	0.6	0.2	200	0.5	0.2	0.7	0.2	205	0.8	0.3	1.1	0.3
302	0.7	0.3	1.1	0.5	300	0.7	0.2	1.0	0.5	299	1.1	0.2	1.4	0.6
413	0.9	0.2	1.1	0.8	396	0.9	0.2	1.3	0.5	398	1.3	0.2	1.6	0.8
495	1.1	0.2	1.3	0.9	500	1.2	0.3	1.5	0.7	495	1.6	0.3	1.9	1.2
597	1.3	0.2	1.5	1.2	599	1.4	0.3	1.8	1.0	602	1.8	0.3	2.1	1.3
701	1.6	0.2	1.8	1.4	699	1.7	0.3	2.0	1.3	701	2.1	0.3	3.0	1.6
797	1.8	0.2	1.9	1.6	800	2.0	0.2	2.3	1.5	786	2.2	0.1	2.6	1.6
897	2.0	0.2	2.2	1.8	902	2.2	0.2	2.5	1.7	895	2.5	0.3	2.9	2.1
996	2.3	0.2	2.5	2.1	1006	2.5	0.3	2.8	2.1	996	2.8	0.3	3.1	2.3

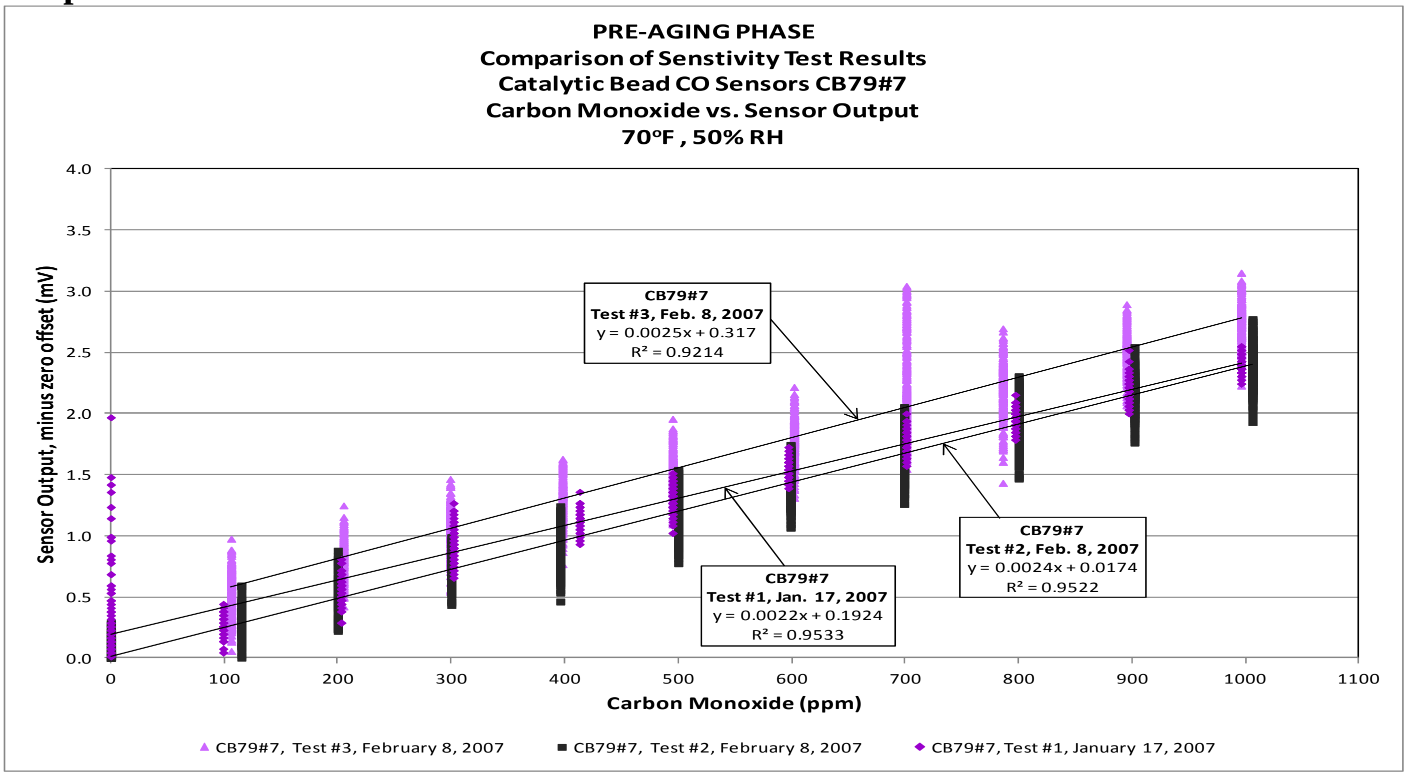
APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA
Graph A.3



*Note that sensor voltage is presented with the zero offset voltage subtracted.

Table A.3	PRE-AGING PHASE Comparison of Sensitivity Test Results for CB79#6 (mV) 70°F, 50% RH													
Test #1, January 17, 2007					Test #2, February 8, 2007					Test #3, February 8, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
0	0.1		0.3	0.0	0	0.1		0.3	0.0	---	---	---	---	---
99	0.2	0.1	0.4	0.0	115	0.3	0.2	0.5	0.1	106	0.7	---	1.1	0.2
203	0.4	0.2	0.7	0.1	200	0.5	0.2	0.8	0.2	205	1.0	0.3	1.3	0.5
302	0.8	0.3	1.1	0.5	300	0.7	0.2	1.0	0.4	299	1.2	0.2	1.5	0.7
413	0.9	0.2	1.2	0.7	396	0.9	0.2	1.3	0.5	398	1.4	0.3	1.8	0.9
495	1.1	0.2	1.4	0.8	500	1.2	0.3	1.5	0.7	495	1.6	0.2	2.0	1.1
597	1.3	0.2	1.7	1.1	599	1.4	0.2	1.7	0.9	602	1.9	0.2	2.3	1.4
701	1.6	0.3	1.8	1.4	699	1.7	0.3	2.0	1.2	701	2.2	0.3	3.1	1.6
797	1.8	0.2	2.2	1.6	800	1.9	0.2	2.2	1.4	786	2.3	0.1	2.7	1.6
897	2.0	0.2	2.3	1.7	902	2.1	0.2	2.5	1.7	895	2.6	0.3	3.0	2.0
996	2.3	0.3	5.6	2.0	1006	2.4	0.2	2.7	1.9	996	2.9	0.3	3.2	2.4

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA
Graph A.4

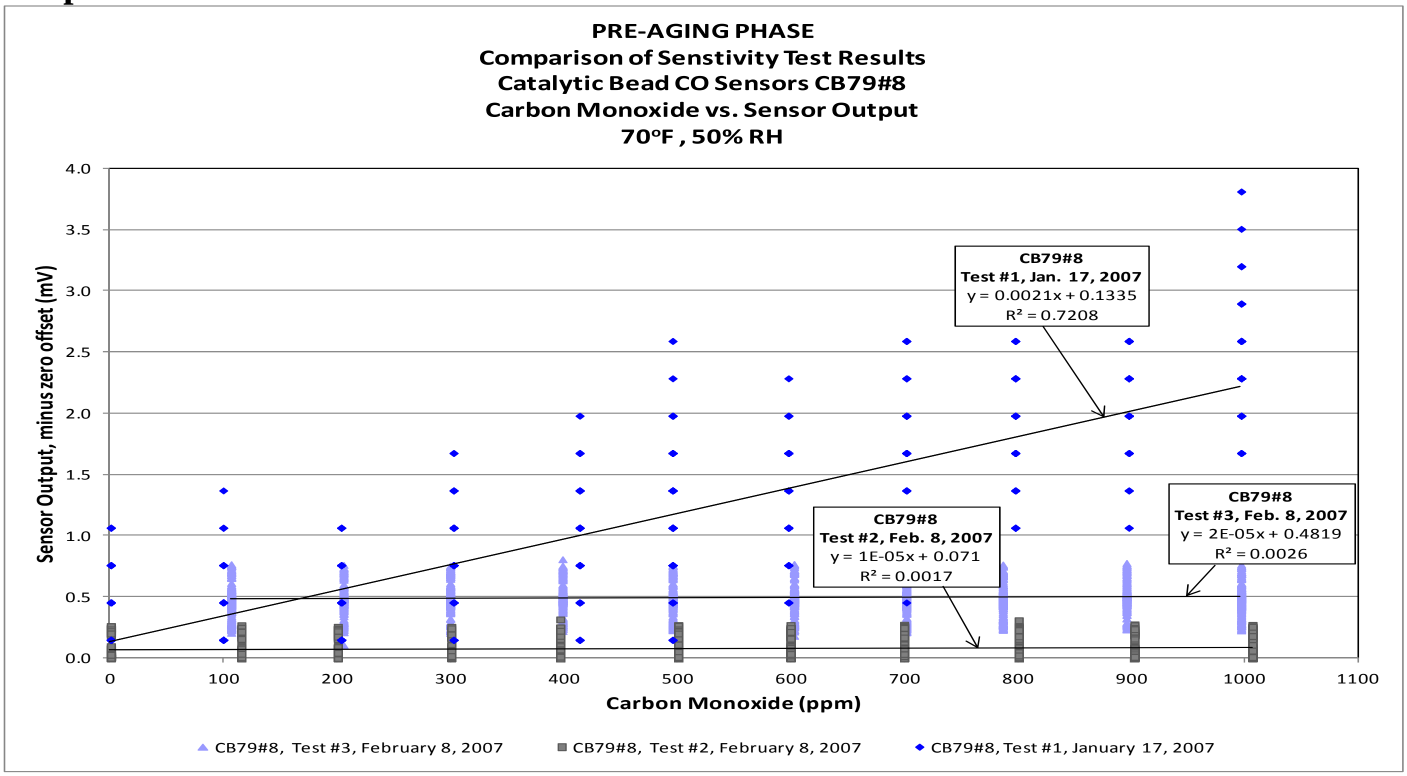


*Note that sensor voltage is presented with the zero offset voltage subtracted.

Table A.4	PRE-AGING PHASE Comparison of Sensitivity Test Results for CB79#7 (mV) 70°F, 50% RH													
Test #1, January 17, 2007					Test #2, February 8, 2007					Test #3, February 8, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
0	0.3		2.0	0.0	0	0.1		0.3	0.0	---	---	---	---	---
99	0.3	-0.1	0.4	0.0	115	0.3	0.2	0.6	0.0	106	0.5	---	1.0	0.1
203	0.6	0.3	0.8	0.3	200	0.5	0.2	0.9	0.2	205	0.8	0.3	1.2	0.4
302	0.9	0.4	1.3	0.7	300	0.7	0.2	1.0	0.4	299	1.1	0.2	1.5	0.5
413	1.1	0.2	1.4	0.9	396	0.9	0.2	1.2	0.5	398	1.3	0.2	1.6	0.8
495	1.3	0.2	1.5	1.0	500	1.2	0.3	1.5	0.8	495	1.6	0.2	2.0	1.1
597	1.5	0.2	1.7	1.4	599	1.4	0.2	1.7	1.1	602	1.8	0.2	2.2	1.3
701	1.8	0.2	2.0	1.6	699	1.7	0.3	2.1	1.3	701	2.1	0.3	3.0	1.5
797	2.0	0.2	2.2	1.8	800	1.9	0.2	2.3	1.5	786	2.2	0.1	2.7	1.4
897	2.2	0.2	2.5	2.0	902	2.2	0.3	2.5	1.8	895	2.5	0.3	2.9	2.1
996	2.4	0.2	2.5	2.2	1006	2.4	0.2	2.8	1.9	996	2.8	0.3	3.1	2.2

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.5

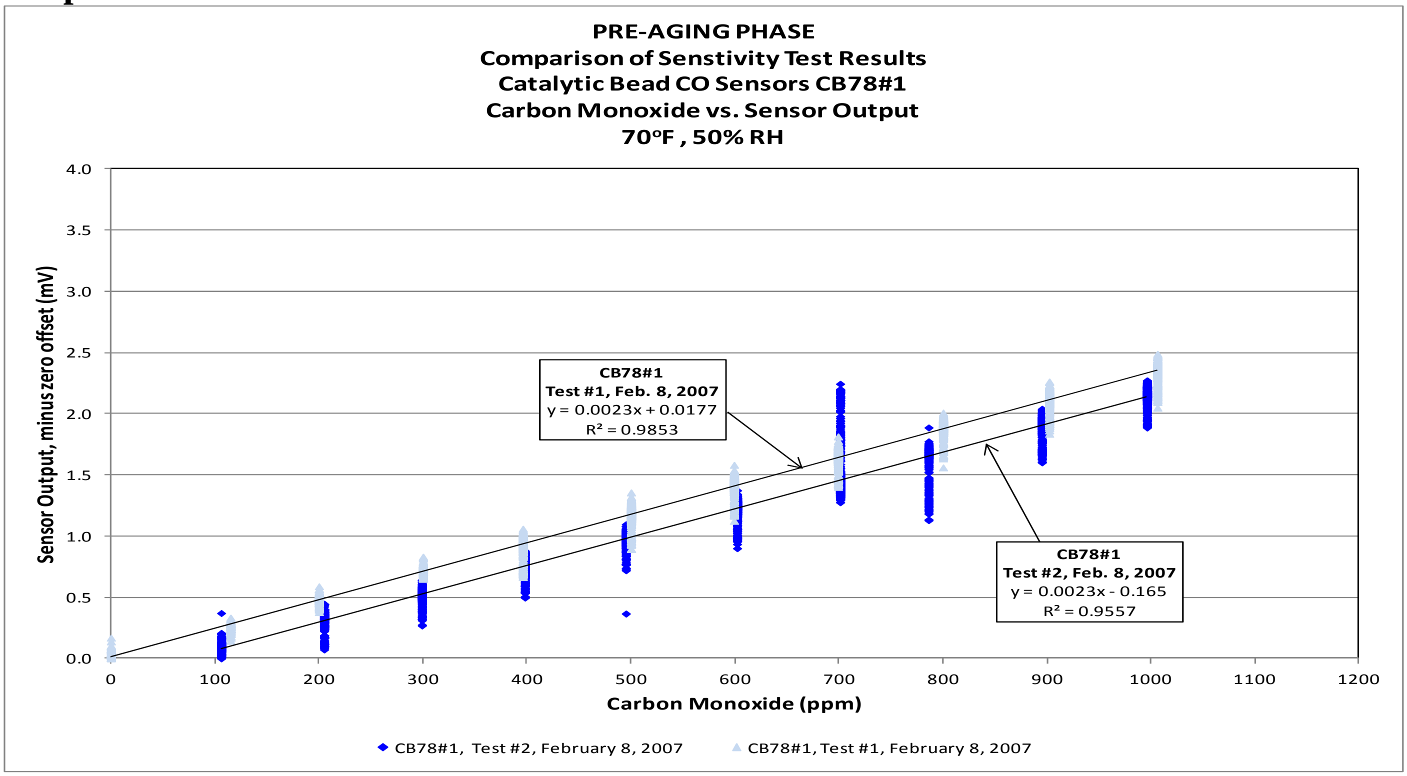


*Note that sensor voltage is presented with the zero offset voltage subtracted.

Table A.5	PRE-AGING PHASE Comparison of Sensitivity Test Results for CB79#8 (mV) 70°F, 50% RH													
Test #1, January 17, 2007					Test #2, February 8, 2007					Test #3, February 8, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
0	0.4		1.1	0.2	0	0.1		0.3	0.0	---	---	---	---	---
99	0.4	0.0	1.4	0.2	115	0.1	0.0	0.3	0.0	106	0.5	---	0.8	0.2
203	0.4	0.0	1.1	0.2	200	0.1	0.0	0.3	0.0	205	0.5	0.0	0.8	0.1
302	0.7	0.3	1.7	0.2	300	0.1	0.0	0.3	0.0	299	0.5	0.0	0.8	0.2
413	0.9	0.2	2.0	0.2	396	0.1	0.0	0.3	0.0	398	0.5	0.0	0.8	0.2
495	1.1	0.2	2.6	0.2	500	0.1	0.0	0.3	0.0	495	0.5	0.0	0.8	0.2
597	1.3	0.2	2.3	0.5	599	0.1	0.0	0.3	0.0	602	0.5	0.0	0.8	0.2
701	1.6	0.3	2.6	0.5	699	0.1	0.0	0.3	0.0	701	0.5	0.0	0.8	0.2
797	1.8	0.2	2.9	1.1	800	0.1	0.0	0.3	0.0	786	0.5	0.0	0.8	0.2
897	2.1	0.2	2.9	1.1	902	0.1	0.0	0.3	0.0	895	0.5	0.0	0.8	0.2
996	2.3	0.2	3.8	1.1	1006	0.1	0.0	0.3	0.0	996	0.5	0.0	0.8	0.2

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.6

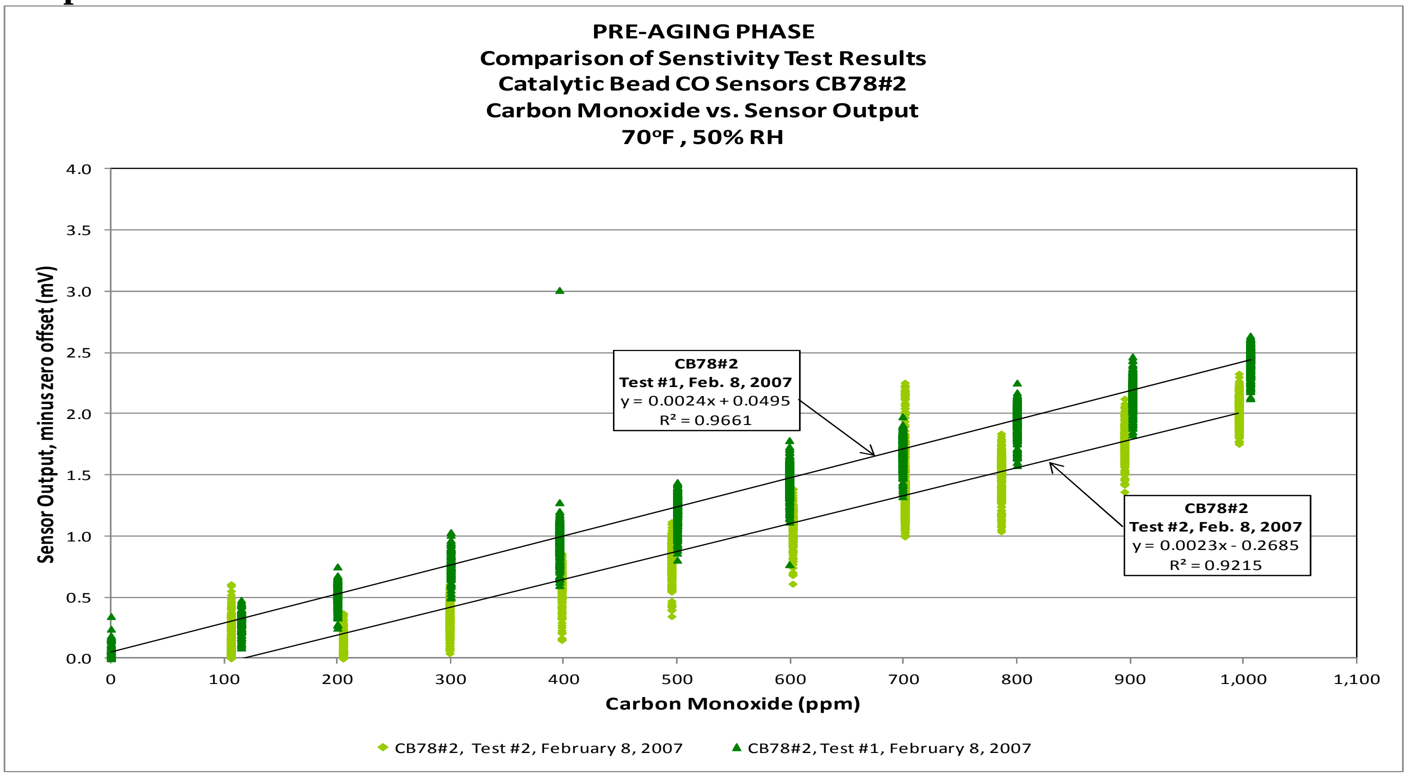


*Note that sensor voltage is presented with the zero offset voltage subtracted.

Table A.6	PRE-AGING PHASE Comparison of Sensitivity Test Results for CB78#1 (mV) 70°F, 50% RH								
Test #1, February 8, 2007					Test #2, February 8, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
0	0.1		0.2	0.0	106	0.1		0.4	0.0
115	0.3	0.2	0.3	0.1	205	0.3	0.2	0.4	0.1
200	0.5	0.2	0.6	0.4	299	0.5	0.2	0.6	0.3
300	0.7	0.2	0.8	0.7	398	0.7	0.2	0.9	0.5
396	0.9	0.2	1.1	0.7	495	1.0	0.2	1.1	0.4
500	1.2	0.3	1.4	0.9	602	1.2	0.2	1.4	0.9
599	1.4	0.2	1.6	1.1	701	1.5	0.3	2.2	1.3
699	1.7	0.2	1.8	1.4	786	1.6	0.1	1.9	1.1
800	1.9	0.2	2.0	1.6	895	1.9	0.3	2.0	1.6
902	2.1	0.2	2.3	1.8	996	2.1	0.3	2.3	1.9
1006	2.4	0.2	2.5	2.0					

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.7

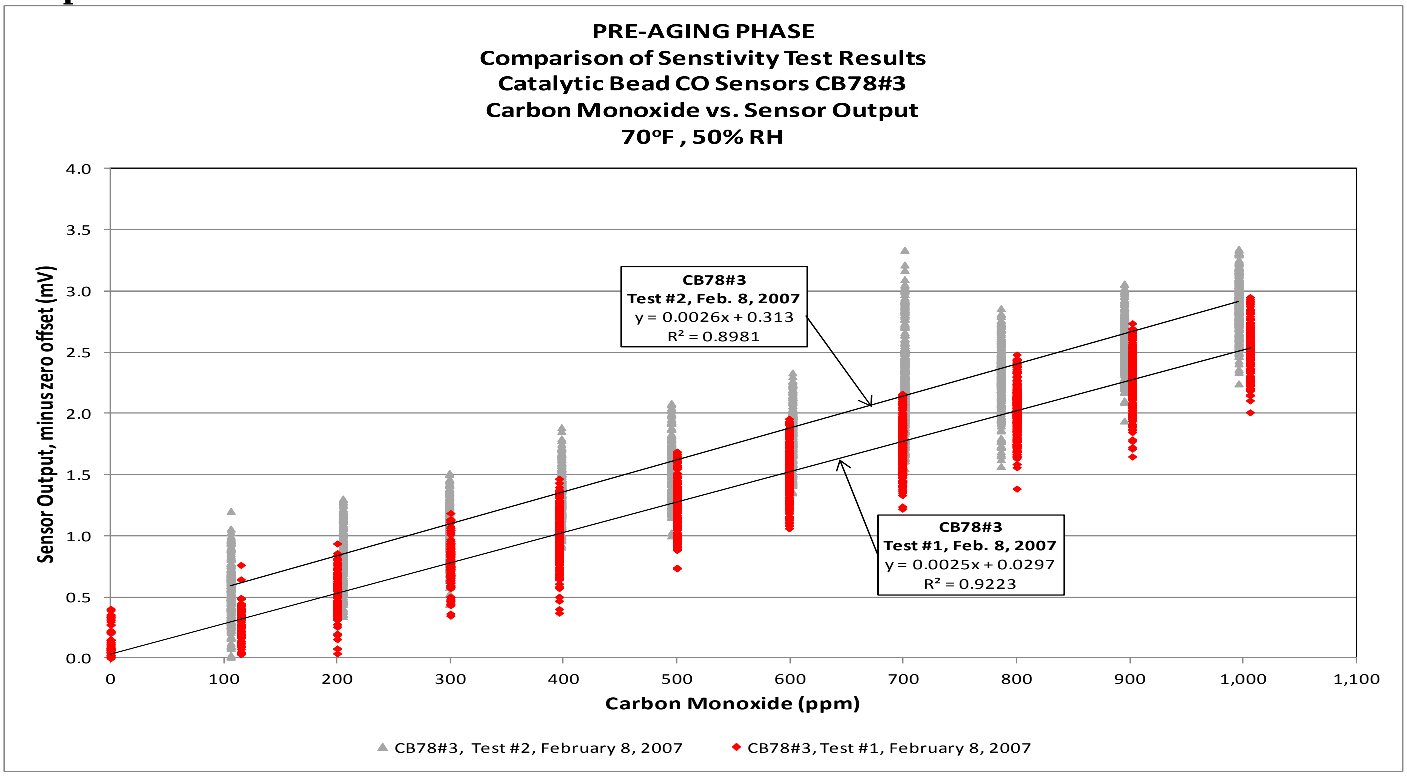


*Note that sensor voltage is presented with the zero offset voltage subtracted.

Table A.7	PRE-AGING PHASE Comparison of Sensitivity Test Results for CB78#2 (mV) 70^{o}F, 50% RH								
Test #1, February 8, 2007					Test #2, February 8, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
0	0.1		0.3	0.0	106	0.2		0.6	0.0
115	0.3	0.2	0.5	0.1	205	0.1	-0.1	0.4	0.0
200	0.5	0.2	0.8	0.3	299	0.3	0.2	0.6	0.0
300	0.8	0.2	1.0	0.5	398	0.6	0.3	0.9	0.2
396	1.0	0.2	3.0	0.6	495	0.8	0.2	1.1	0.3
500	1.2	0.2	1.4	0.8	602	1.1	0.3	1.4	0.6
599	1.5	0.3	1.8	0.8	701	1.4	0.3	2.3	1.0
699	1.7	0.2	2.0	1.3	786	1.5	0.1	1.8	1.0
800	2.0	0.3	2.3	1.6	895	1.8	0.3	2.1	1.4
902	2.2	0.2	2.5	1.8	996	2.0	0.3	2.3	1.8
1006	2.4	0.2	2.6	2.1					

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.8

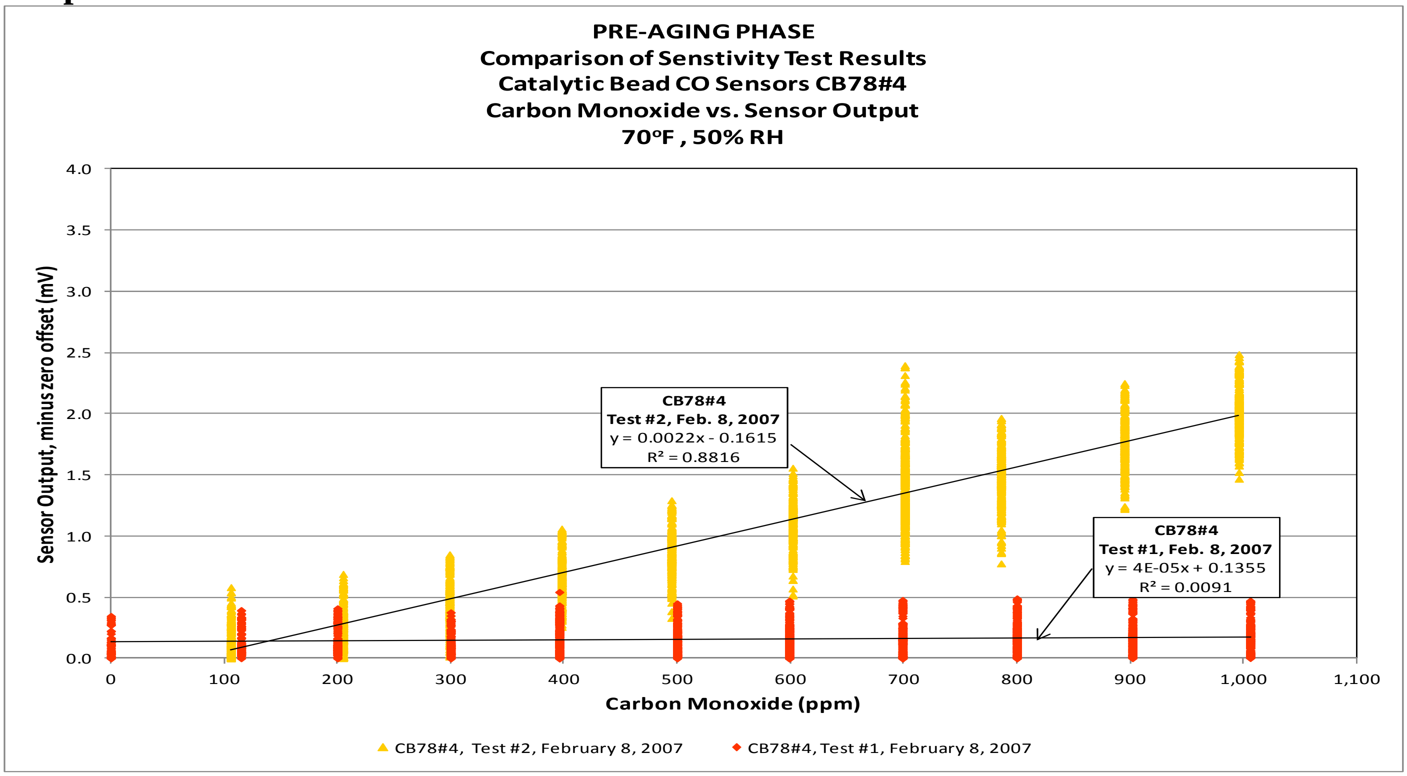


*Note that sensor voltage is presented with the zero offset voltage subtracted.

Table A.8	PRE-AGING PHASE Comparison of Sensitivity Test Results for CB78#3 (mV) 70°F, 50% RH								
Test #1, February 8, 2007					Test #2, February 8, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
0	0.1		0.4	0.0	106	0.6		1.2	0.0
115	0.3	0.1	0.8	0.0	205	0.8	0.3	1.3	0.3
200	0.5	0.2	0.9	0.0	299	1.1	0.2	1.5	0.4
300	0.8	0.3	1.2	0.3	398	1.4	0.3	1.9	0.9
396	1.0	0.2	1.5	0.4	495	1.6	0.2	2.1	1.0
500	1.3	0.3	1.7	0.7	602	1.9	0.3	2.3	1.4
599	1.5	0.3	2.0	1.1	701	2.2	0.4	3.3	1.6
699	1.8	0.2	2.2	1.2	786	2.3	0.1	2.9	1.6
800	2.0	0.3	2.5	1.4	895	2.6	0.3	3.1	1.9
902	2.3	0.2	2.7	1.6	996	2.9	0.3	3.3	2.2
1006	2.5	0.3	3.0	2.0					

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.9

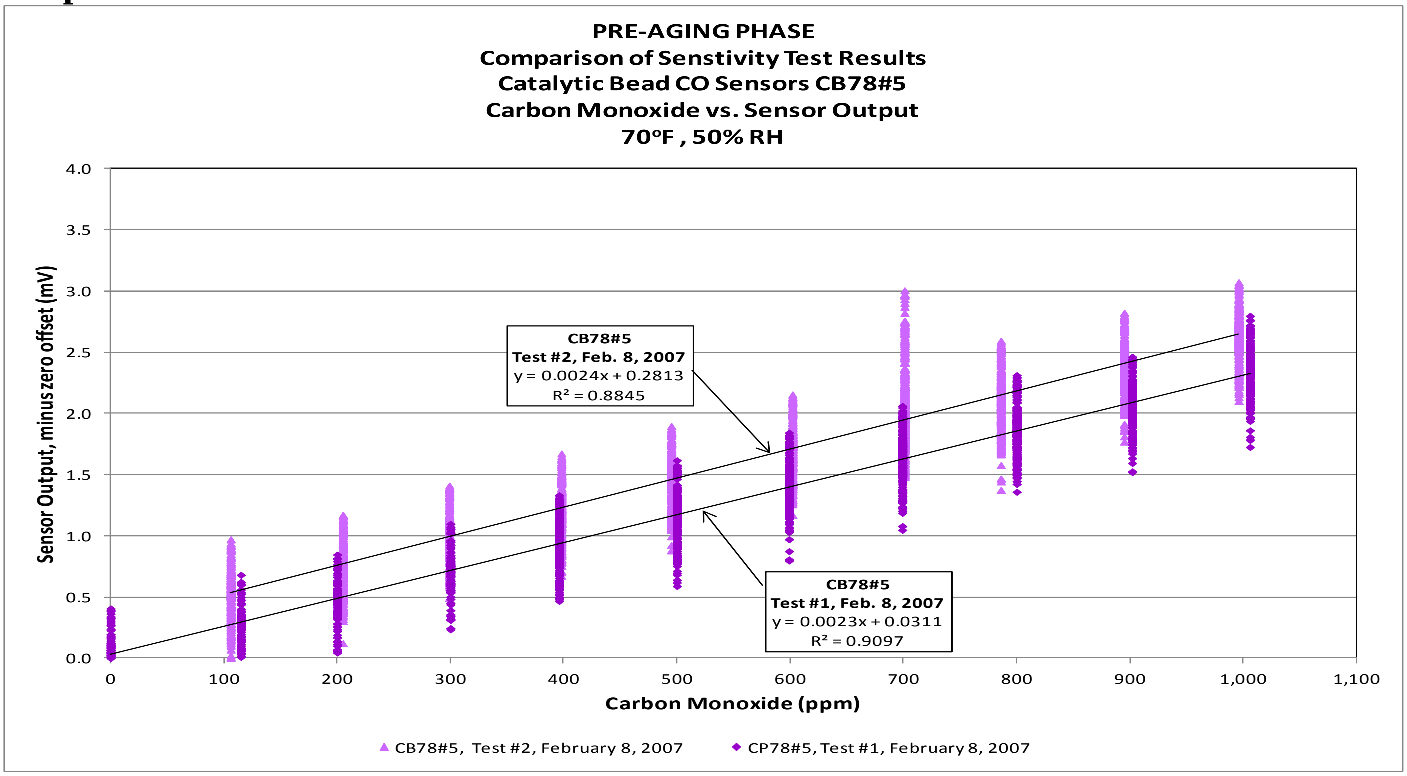


*Note that sensor voltage is presented with the zero offset voltage subtracted.

Table A.9	PRE-AGING PHASE Comparison of Sensitivity Test Results for CB78#4 (mV) 70°F, 50% RH								
Test #1, February 8, 2007					Test #2, February 8, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
0	0.1		0.3	0.0	106	0.2		0.6	0.0
115	0.2	0.0	0.4	0.0	205	0.3	0.1	0.7	0.0
200	0.1	0.0	0.4	0.0	299	0.5	0.2	0.9	0.0
300	0.1	0.0	0.4	0.0	398	0.7	0.2	1.1	0.3
396	0.2	0.0	0.5	0.0	495	0.9	0.2	1.3	0.3
500	0.2	0.0	0.5	0.0	602	1.1	0.2	1.6	0.5
599	0.2	0.0	0.5	0.0	701	1.4	0.3	2.4	0.8
699	0.2	0.0	0.5	0.0	786	1.5	0.1	2.0	0.8
800	0.2	0.0	0.5	0.0	895	1.8	0.3	2.2	1.2
902	0.2	0.0	0.5	0.0	996	2.0	0.3	2.5	1.5
1006	0.2	0.0	0.5	0.0					

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.10



*Note that sensor voltage is presented with the zero offset voltage subtracted.

Table A.10	PRE-AGING PHASE Comparison of Sensitivity Test Results for CB78#5 (mV) 70°F, 50% RH								
Test #1, February 8, 2007					Test #2, February 8, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
0	0.1		0.4	0.0	106	0.5		1.0	0.0
115	0.3	0.1	0.7	0.0	205	0.8	0.2	1.2	0.1
200	0.5	0.2	0.8	0.0	299	1.0	0.2	1.4	0.5
300	0.7	0.2	1.1	0.2	398	1.2	0.2	1.7	0.7
396	0.9	0.2	1.3	0.5	495	1.4	0.2	1.9	0.9
500	1.2	0.2	1.6	0.6	602	1.7	0.3	2.2	1.2
599	1.4	0.3	1.8	0.8	701	2.0	0.3	3.0	1.5
699	1.6	0.2	2.1	1.0	786	2.1	0.1	2.6	1.4
800	1.9	0.2	2.3	1.4	895	2.4	0.3	2.8	1.8
902	2.1	0.2	2.5	1.5	996	2.6	0.3	3.1	2.1
1006	2.3	0.3	2.8	1.7					

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.11

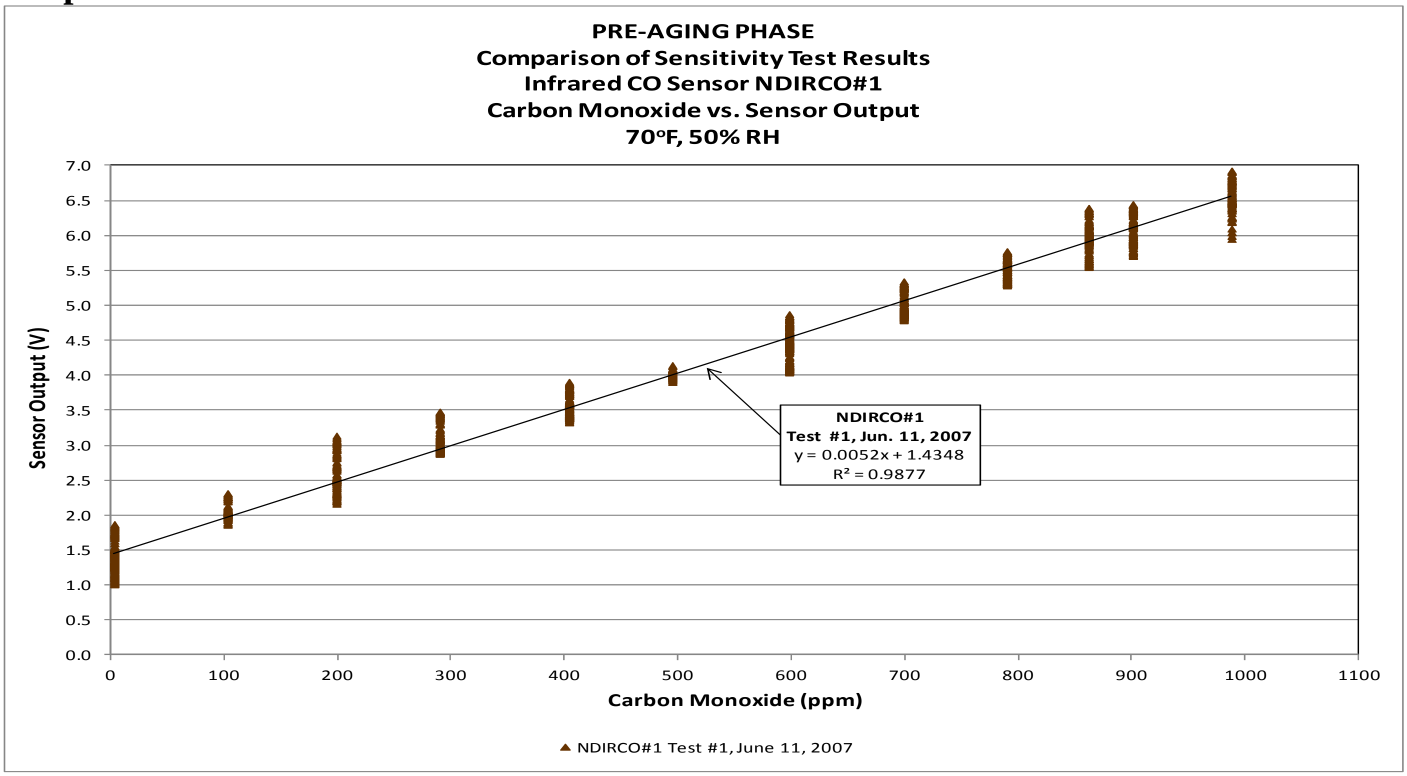


Table A.11	PRE-AGING PHASE Sensitivity Test Results for NDIRCO#1 (V) 70°F, 50% RH			
Test #1, June 11, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min
3	1.4		1.9	1.0
103	2.1	0.7	2.3	1.9
199	2.5	0.5	3.1	2.2
290	3.1	0.5	3.5	2.9
404	3.6	0.5	3.9	3.3
495	4.0	0.5	4.1	3.9
598	4.4	0.4	4.9	4.0
699	5.0	0.5	5.3	4.8
790	5.5	0.5	5.8	5.3
901	6.1	0.6	6.4	5.7
988	6.5	0.5	6.9	6.0

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.12

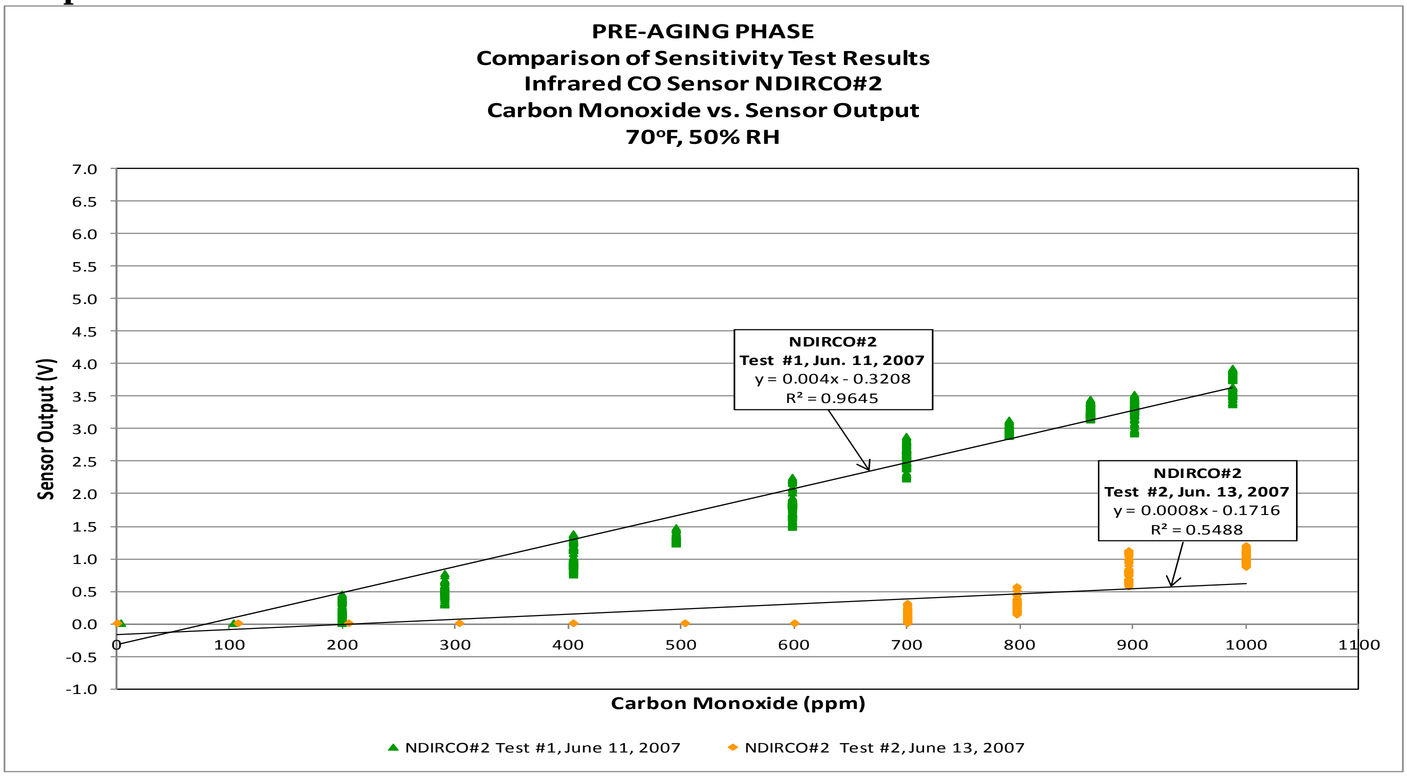


Table A.12	PRE-AGING PHASE Sensitivity Test Results for NDIRCO#2 (V) 70^{o}F, 50% RH								
Test #1, June 11, 2007					Test #2, June 13, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
3	0.0		0.0	0.0	0	0.0		0.0	0.0
103	0.0	0.0	0.0	0.0	104	0.0	0.0	0.0	0.0
199	0.2	0.2	0.5	0.0	203	0.0	0.0	0.0	0.0
290	0.5	0.3	0.8	0.3	304	0.0	0.0	0.0	0.0
404	1.0	0.5	1.4	0.8	404	0.0	0.0	0.0	0.0
495	1.3	0.3	1.5	1.2	501	0.0	0.0	0.0	0.0
598	1.8	0.5	2.3	1.5	601	0.0	0.0	0.0	0.0
699	2.6	0.7	2.9	2.2	699	0.1	0.1	0.3	0.0
790	3.0	0.4	3.1	2.9	800	0.3	0.2	0.6	0.1
901	3.3	0.3	3.5	2.9	898	0.8	0.5	1.1	0.6
988	3.7	0.4	3.9	3.4	1000	1.0	0.2	1.2	0.9

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.13

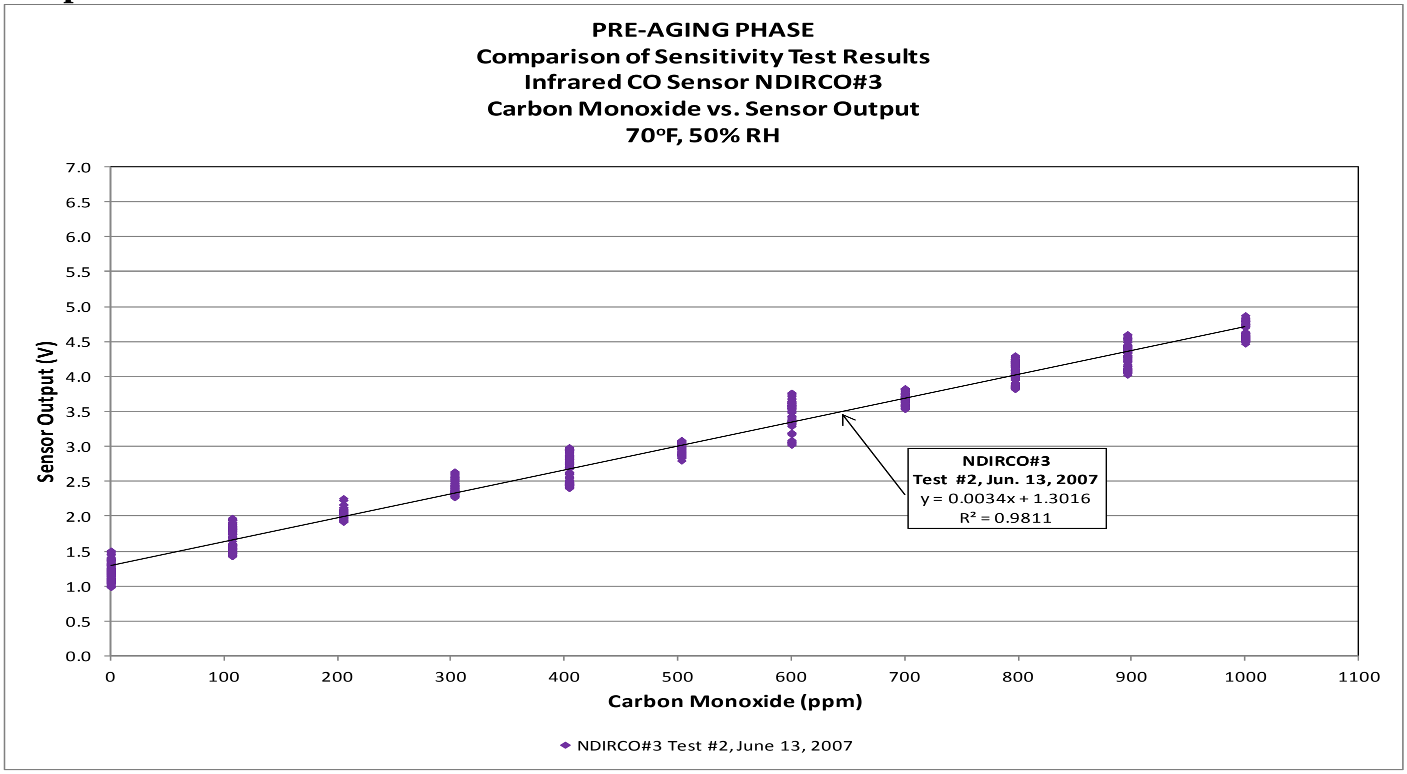


Table A.13	PRE-AGING PHASE Sensitivity Test Results for NDIRCO#3 (V) 70°F, 50% RH			
Test #2, June 13, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min
0	1.2		1.5	1.0
104	1.7	0.5	2.0	1.4
203	2.0	0.4	2.3	1.9
304	2.4	0.4	2.6	2.3
404	2.7	0.3	3.0	2.4
501	3.0	0.3	3.1	2.8
601	3.5	0.5	3.8	3.0
699	3.7	0.2	3.8	3.5
800	4.1	0.4	4.3	3.8
898	4.3	0.2	4.6	4.0
1000	4.6	0.3	4.9	4.6

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.14

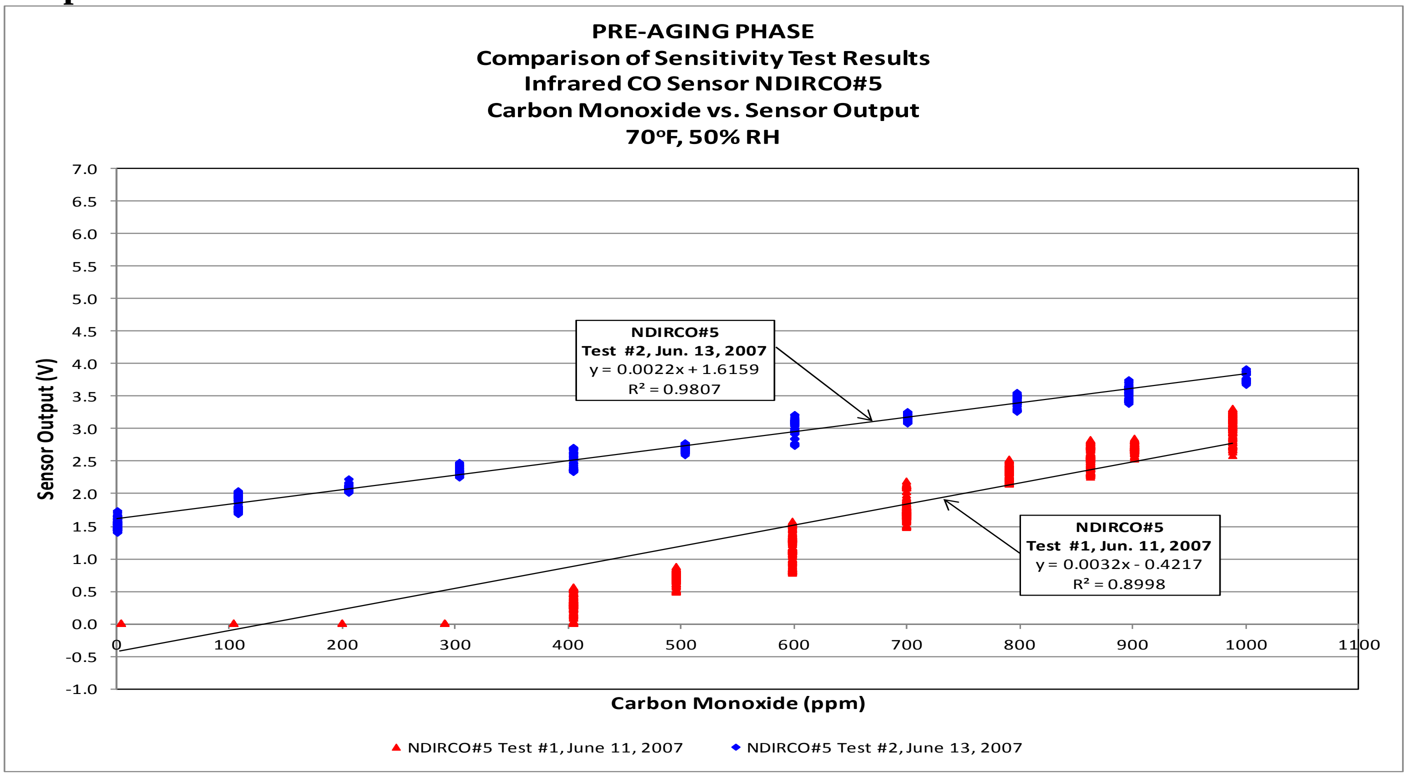


Table A.14	PRE-AGING PHASE Sensitivity Test Results for NDIRCO#5 (V) 70oF, 50% RH								
Test #1, June 11, 2007					Test #2, June 13, 2007				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
3	0.0		0.0	0.0	0	1.5		1.8	1.4
103	0.0	0.0	0.0	0.0	104	1.9	0.3	2.1	1.7
199	0.0	0.0	0.0	0.0	203	2.1	0.2	2.2	2.0
290	0.0	0.0	0.0	0.0	304	2.3	0.2	2.5	2.3
404	0.3	0.3	0.6	0.0	404	2.5	0.2	2.7	2.3
495	0.7	0.4	0.9	0.5	501	2.7	0.2	2.8	2.6
598	1.2	0.4	1.6	0.8	601	3.0	0.3	3.2	2.7
699	1.8	0.6	2.2	1.5	699	3.2	0.1	3.3	3.1
790	2.3	0.6	2.5	2.2	800	3.4	0.3	3.6	3.3
901	2.7	0.4	2.9	2.5	898	3.6	0.1	3.8	3.4
988	3.1	0.3	3.3	2.6	1000	3.8	0.2	3.9	3.7

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.15

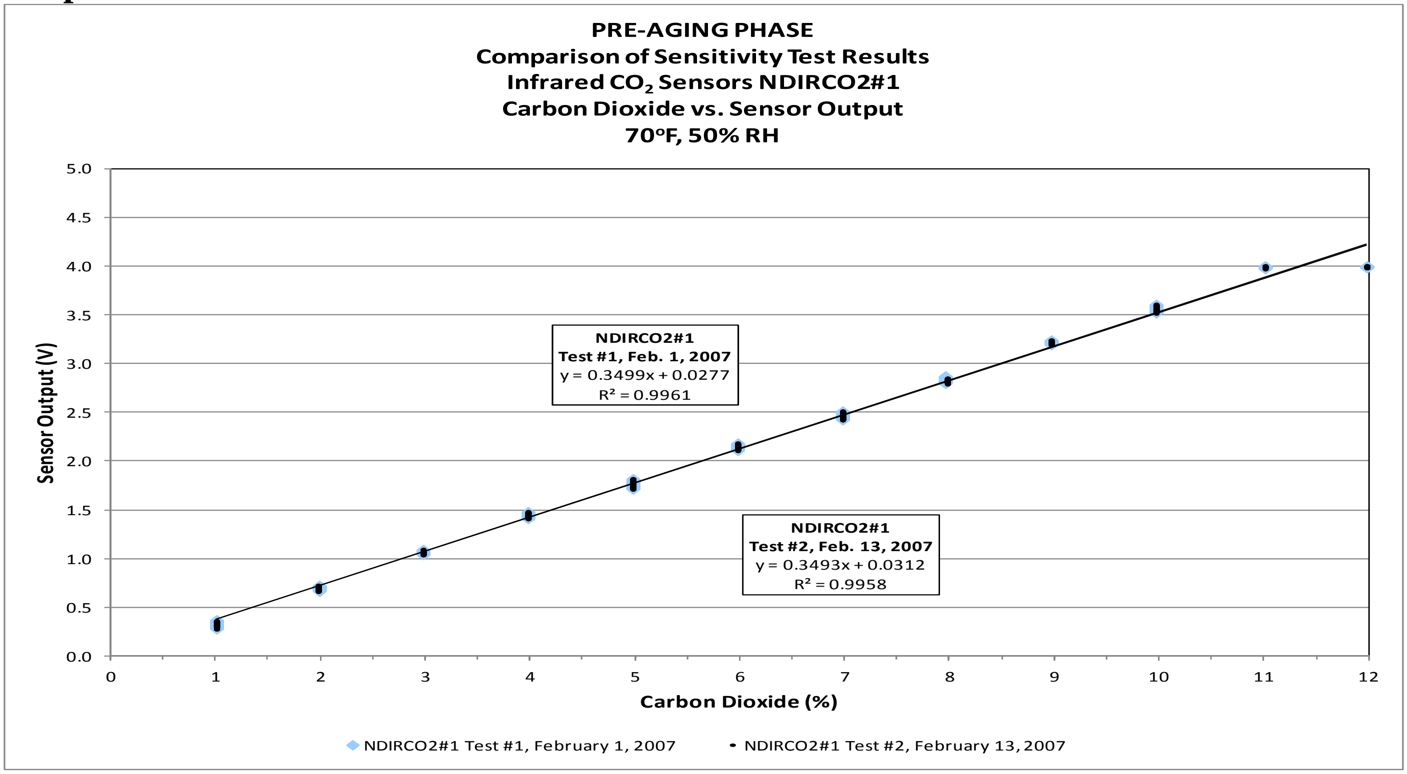


Table A.15	PRE-AGING PHASE Comparison of Sensitivity Test Results for NDIRCO2#1 (V) 70°F, 50% RH								
Test #1, February 1, 2007					Test #2, February 13, 2007				
Chamber CO_2 (%)	Avg	Diff Avg	Max	Min	Chamber CO_2 (%)	Avg	Diff Avg	Max	Min
1.0	0.3		0.4	0.3	1.0	0.4		0.7	0.3
2.0	0.7	0.4	0.7	0.7	2.0	0.9	0.4	1.1	0.7
3.0	1.1	0.4	1.1	1.0	3.0	1.3	0.4	1.4	1.1
4.0	1.4	0.4	1.5	1.4	4.0	1.6	0.3	1.8	1.4
5.0	1.8	0.3	1.8	1.7	5.0	2.0	0.4	2.2	1.8
6.0	2.2	0.4	2.2	2.1	6.0	2.3	0.3	2.5	2.2
7.0	2.5	0.3	2.5	2.4	7.0	2.7	0.3	2.8	2.5
8.0	2.8	0.4	2.9	2.8	8.0	3.0	0.3	3.2	2.8
9.0	3.2	0.4	3.2	3.2	9.0	3.3	0.4	3.6	3.2
10.0	3.6	0.3	3.6	3.5	10.0	3.8	0.4	4.0	3.5
11.0	4.0	0.4	4.0	4.0	11.0	4.0	0.2	4.0	4.0
12.0	4.0		4.0	4.0	12.0	4.0		4.0	4.0

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.16

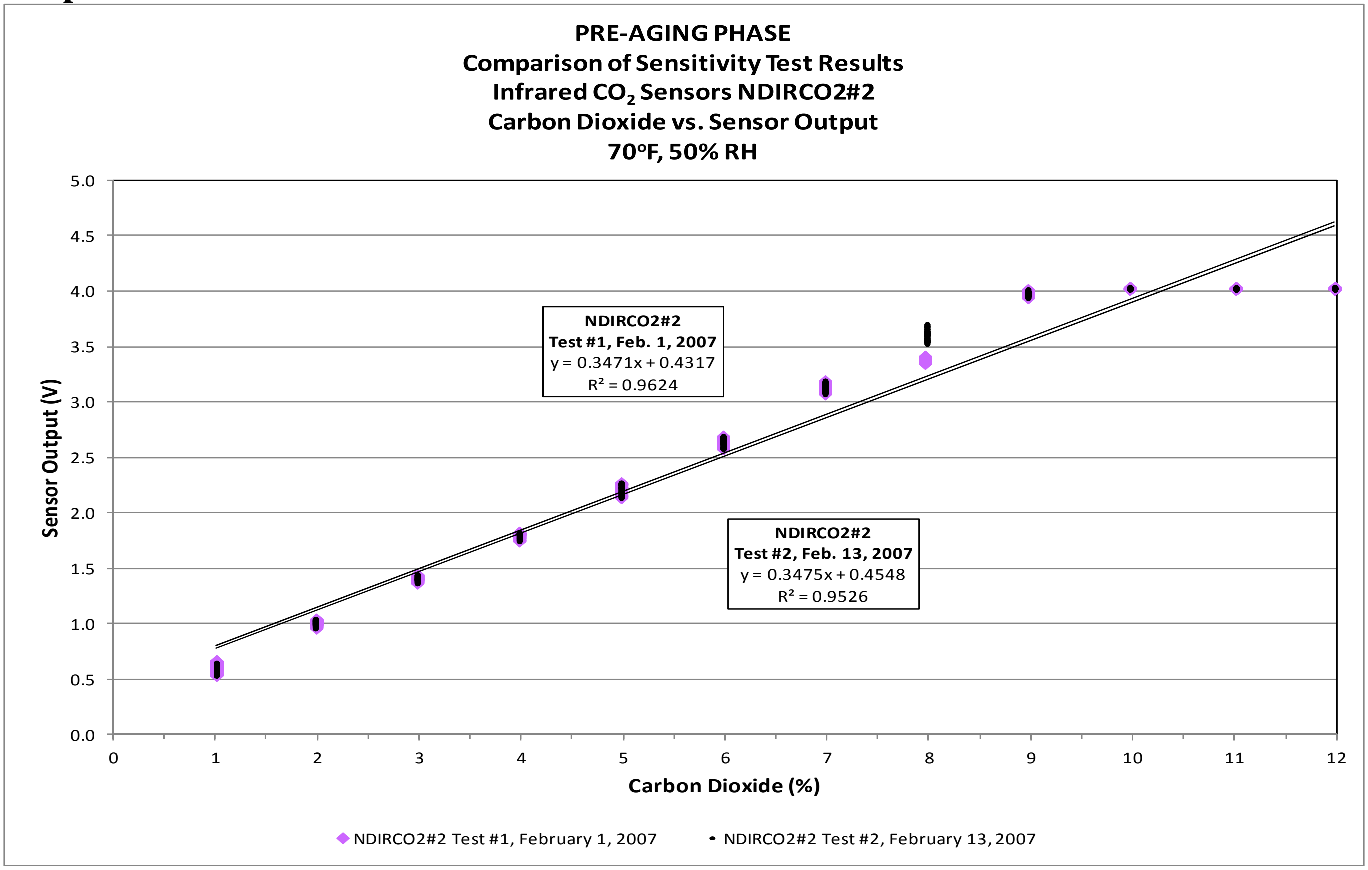


Table A.16	PRE-AGING PHASE Comparison of Sensitivity Test Results for NDIRCO2#2 (V) 70oF, 50% RH								
Test #1, February 1, 2007					Test #2, February 13, 2007				
Chamber CO_2 (%)	Avg	Diff Avg	Max	Min	Chamber CO_2 (%)	Avg	Diff Avg	Max	Min
1.0	0.6		0.7	0.5	1.0	0.7		1.0	0.5
2.0	1.0	0.4	1.0	1.0	2.0	1.2	0.5	1.4	1.0
3.0	1.4	0.4	1.4	1.4	3.0	1.6	0.4	1.8	1.4
4.0	1.8	0.4	1.8	1.7	4.0	2.0	0.4	2.2	1.8
5.0	2.2	0.4	2.3	2.1	5.0	2.4	0.4	2.6	2.2
6.0	2.6	0.4	2.7	2.6	6.0	2.9	0.5	3.1	2.6
7.0	3.1	0.5	3.2	3.1	7.0	3.4	0.5	3.6	3.1
8.0	3.4	0.3	3.4	3.3	8.0	3.8	0.4	4.0	3.6
9.0	4.0	0.6	4.0	3.9	9.0	4.0	0.2	4.0	3.9
10.0	4.0	0.1	4.0	4.0	10.0	4.0	0.0	4.0	4.0
11.0	4.0	0.0	4.0	4.0	11.0	4.0	0.0	4.0	4.0
12.0	4.0		4.0	4.0	12.0	4.0		4.0	4.0

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.17

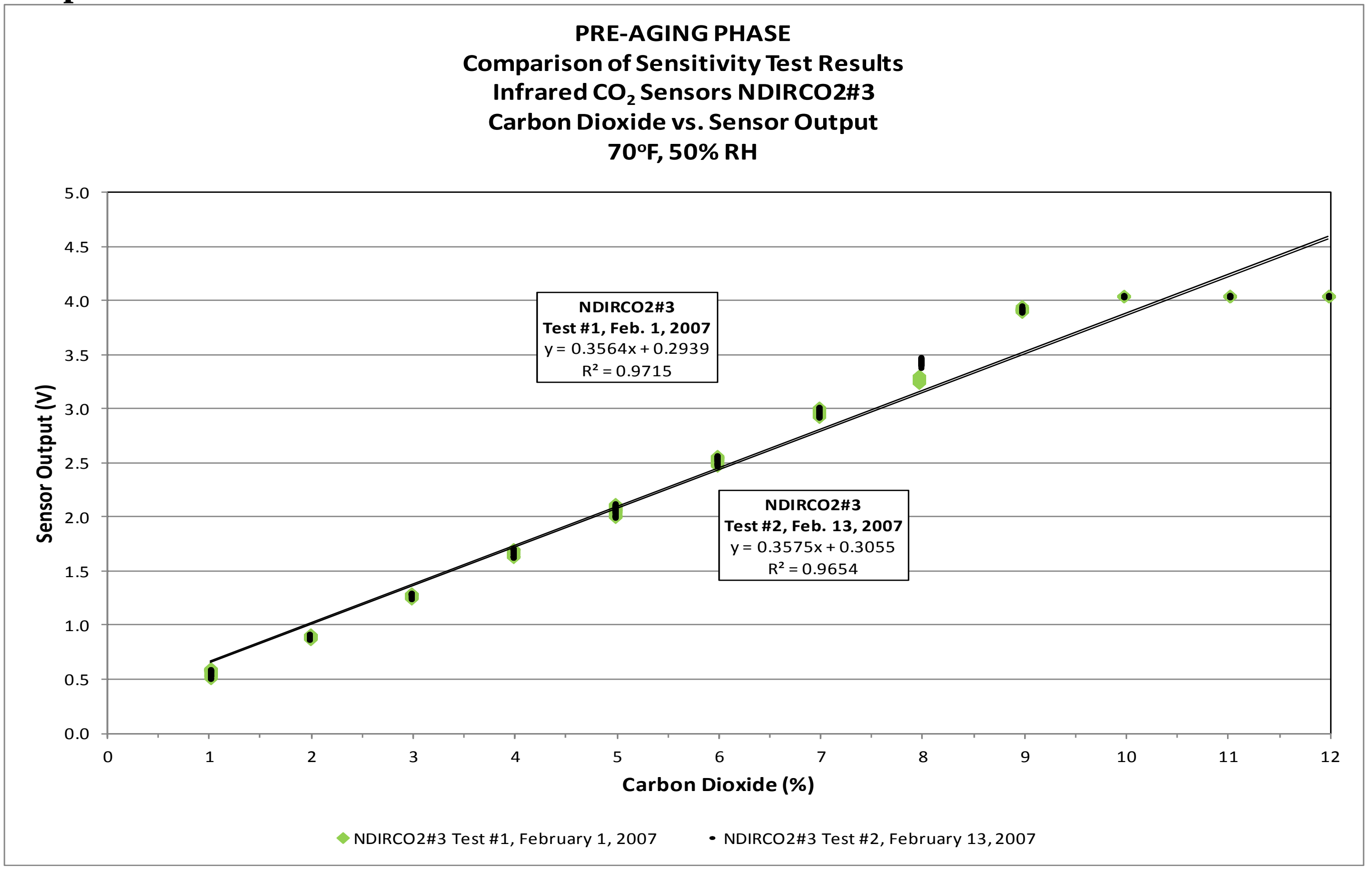


Table A.17	PRE-AGING PHASE Comparison of Sensitivity Test Results for NDIRCO2#3 (V) 70°F, 50% RH								
Test #1, February 1, 2007					Test #2, February 13, 2007				
Chamber CO_2 (%)	Avg	Diff Avg	Max	Min	Chamber CO_2 (%)	Avg	Diff Avg	Max	Min
1.0	0.6		0.6	0.5	1.0	0.7		0.9	0.5
2.0	0.9	0.3	0.9	0.9	2.0	1.1	0.4	1.3	0.9
3.0	1.3	0.4	1.3	1.2	3.0	1.5	0.4	1.7	1.3
4.0	1.7	0.4	1.7	1.6	4.0	1.9	0.4	2.1	1.7
5.0	2.1	0.4	2.1	2.0	5.0	2.3	0.4	2.6	2.1
6.0	2.5	0.5	2.6	2.5	6.0	2.7	0.4	3.0	2.5
7.0	3.0	0.4	3.0	2.9	7.0	3.2	0.5	3.5	3.0
8.0	3.3	0.3	3.3	3.2	8.0	3.6	0.4	3.9	3.4
9.0	3.9	0.6	4.0	3.9	9.0	4.0	0.3	4.1	3.9
10.0	4.0	0.1	4.1	4.0	10.0	4.0	0.1	4.1	4.0
11.0	4.0	0.0	4.1	4.0	11.0	4.0	0.0	4.1	4.0
12.0	4.0		4.1	4.0	12.0	4.0		4.1	4.0

APPENDIX A. PRE-AGING PHASE SENSITIVITY TEST DATA

Graph A.18

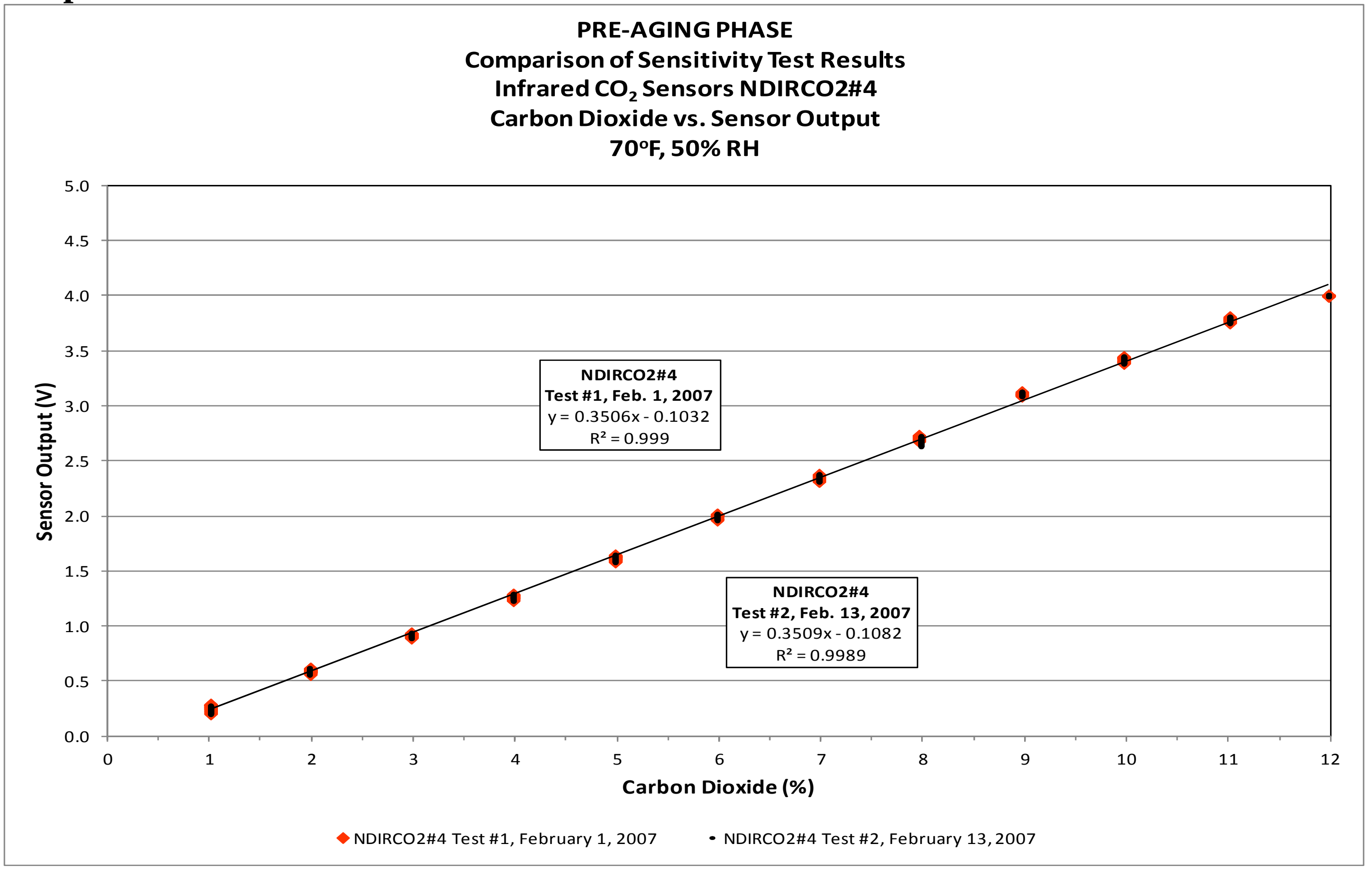
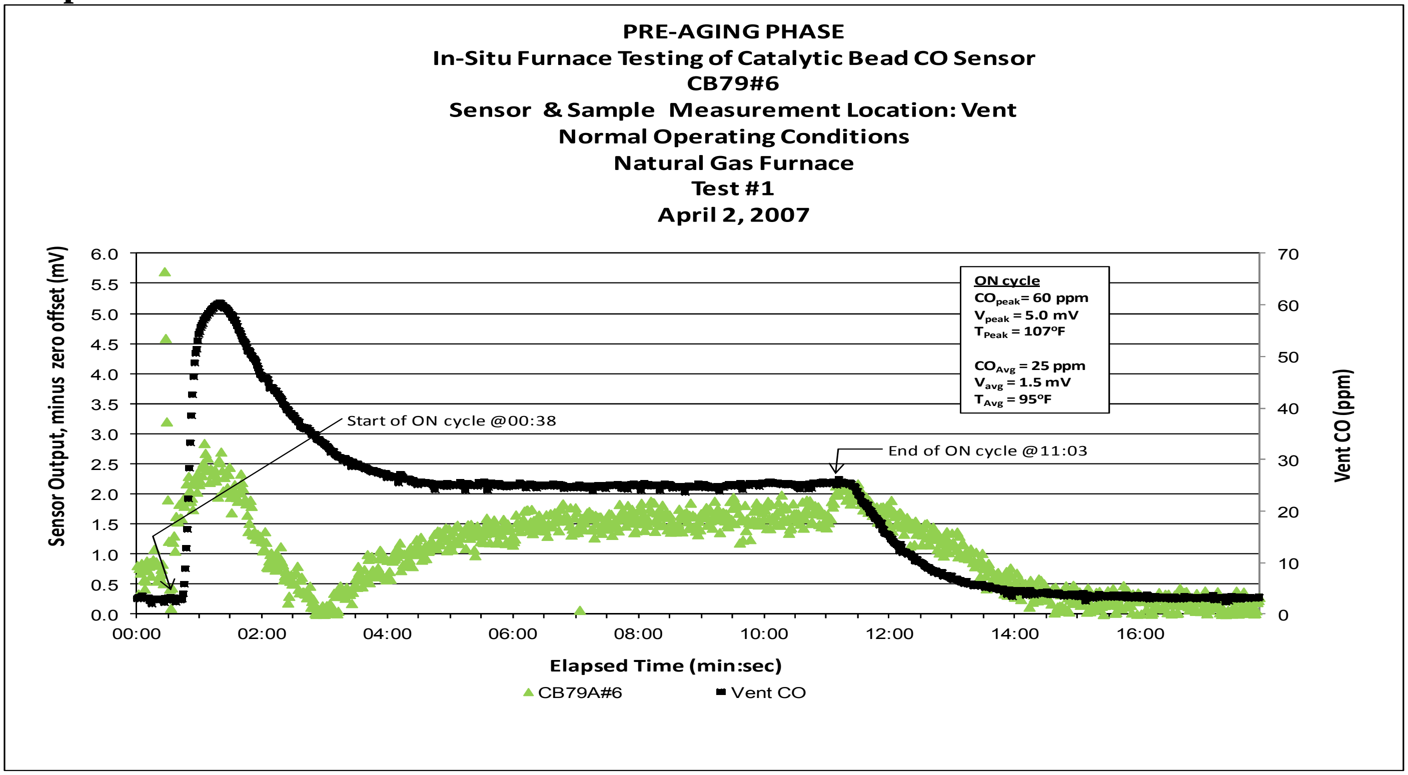


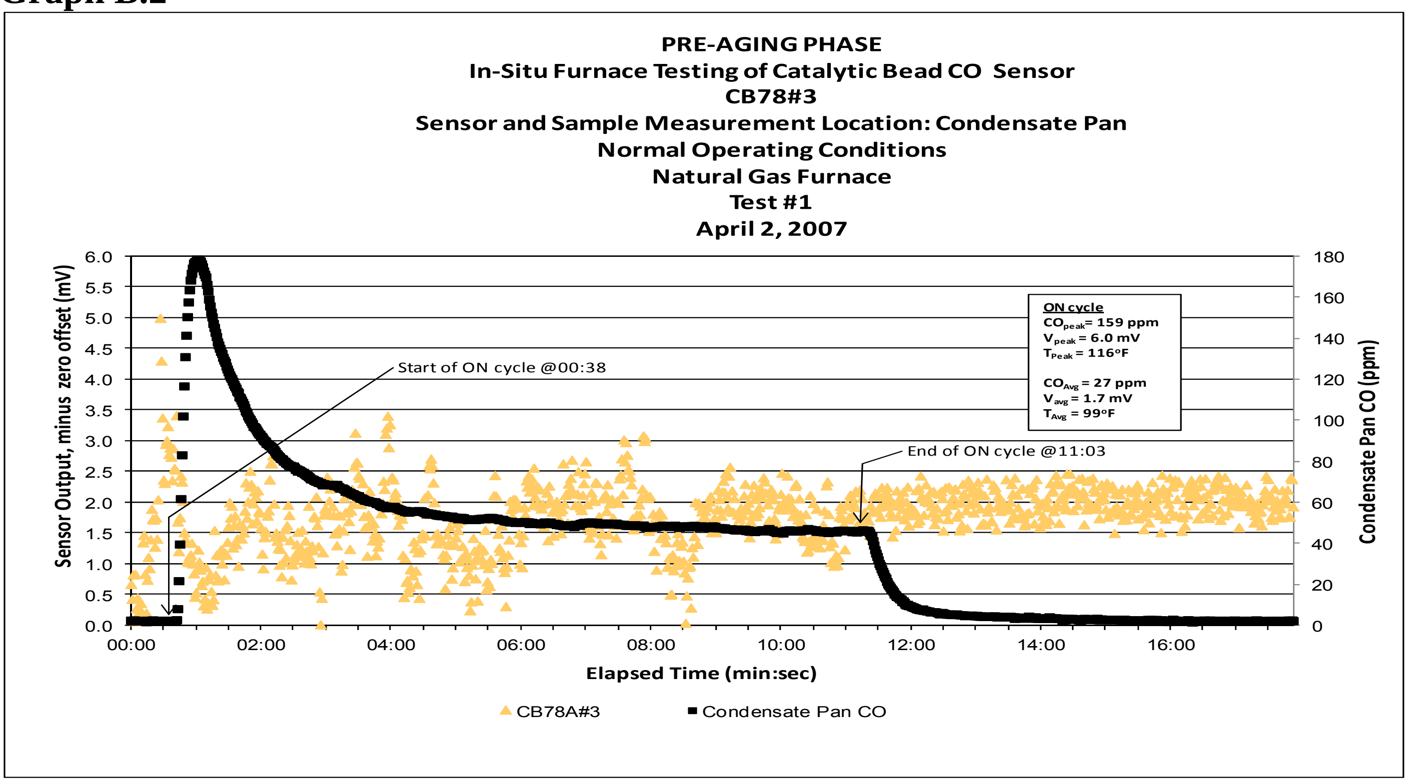
Table A.18	PRE-AGING PHASE Comparison of Sensitivity Test Results for NDIRCO2#4 (V) 70oF, 50% RH								
Test #1, February 1, 2007					Test #2, February 13, 2007				
Chamber CO_2 (%)	Avg	Diff Avg	Max	Min	Chamber CO_2 (%)	Avg	Diff Avg	Max	Min
1.0	0.3		0.3	0.2	1.0	0.4		0.6	0.2
2.0	0.6	0.3	0.6	0.6	2.0	0.8	0.4	0.9	0.6
3.0	0.9	0.3	0.9	0.9	3.0	1.1	0.3	1.3	0.9
4.0	1.3	0.3	1.3	1.2	4.0	1.4	0.4	1.6	1.3
5.0	1.6	0.4	1.6	1.6	5.0	1.8	0.4	2.0	1.6
6.0	2.0	0.4	2.0	2.0	6.0	2.2	0.4	2.4	2.0
7.0	2.4	0.4	2.4	2.3	7.0	2.5	0.3	2.7	2.4
8.0	2.7	0.4	2.7	2.7	8.0	2.9	0.4	3.1	2.7
9.0	3.1	0.4	3.1	3.1	9.0	3.2	0.4	3.4	3.1
10.0	3.4	0.3	3.4	3.4	10.0	3.6	0.4	3.8	3.4
11.0	3.8	0.4	3.8	3.8	11.0	3.9	0.3	4.0	3.8
12.0	4.0		4.0	4.0	12.0	4.0		4.0	4.0

APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: NATURAL GAS FURNACE

Graph B.1

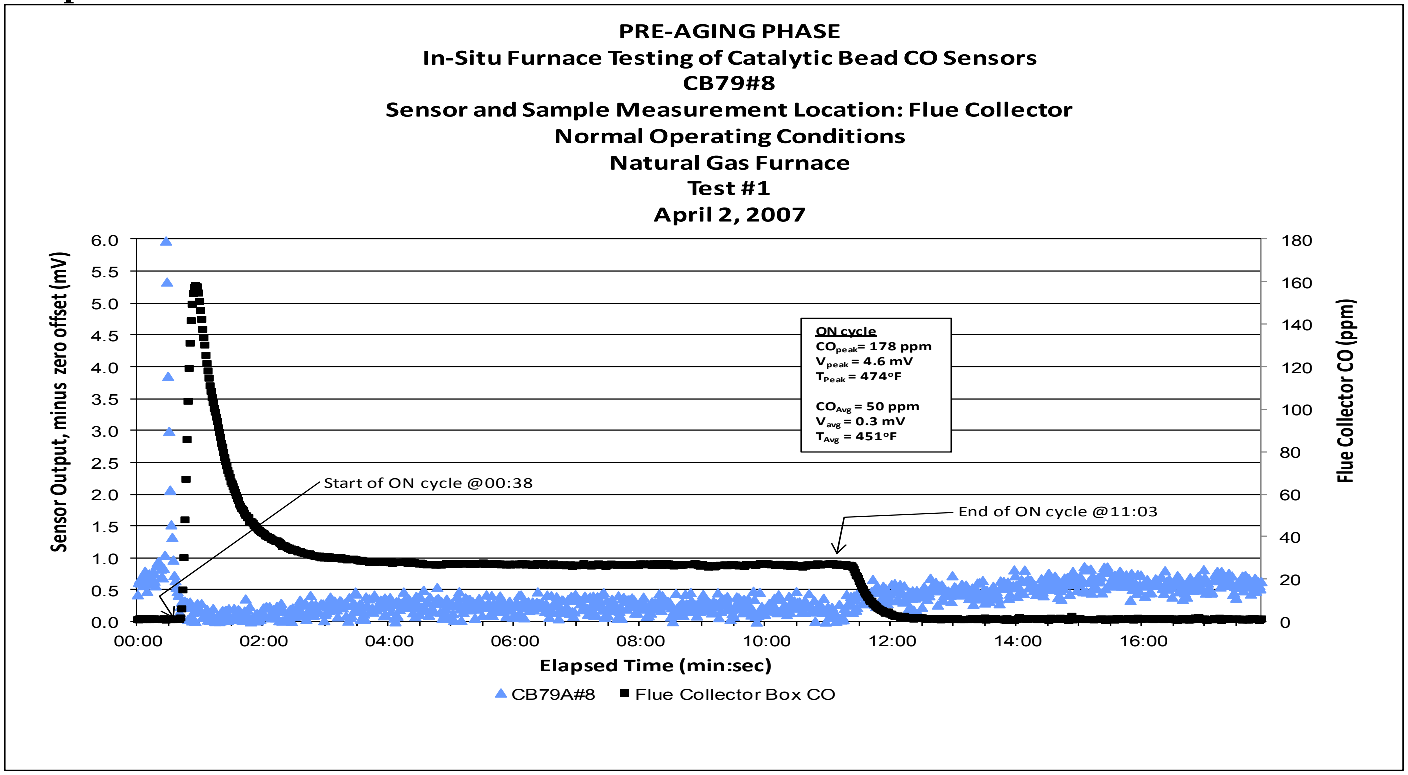


Graph B.2

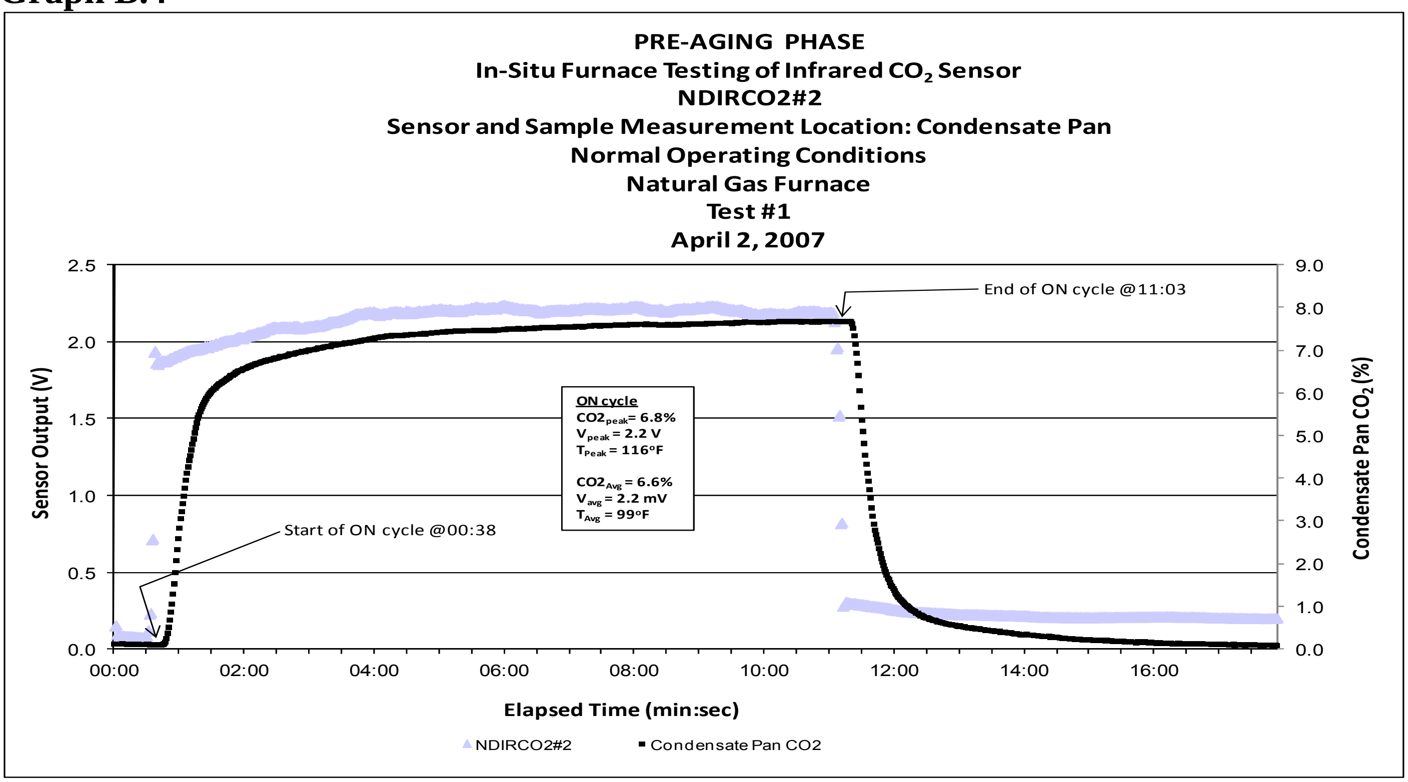


APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: NATURAL GAS FURNACE

Graph B.3

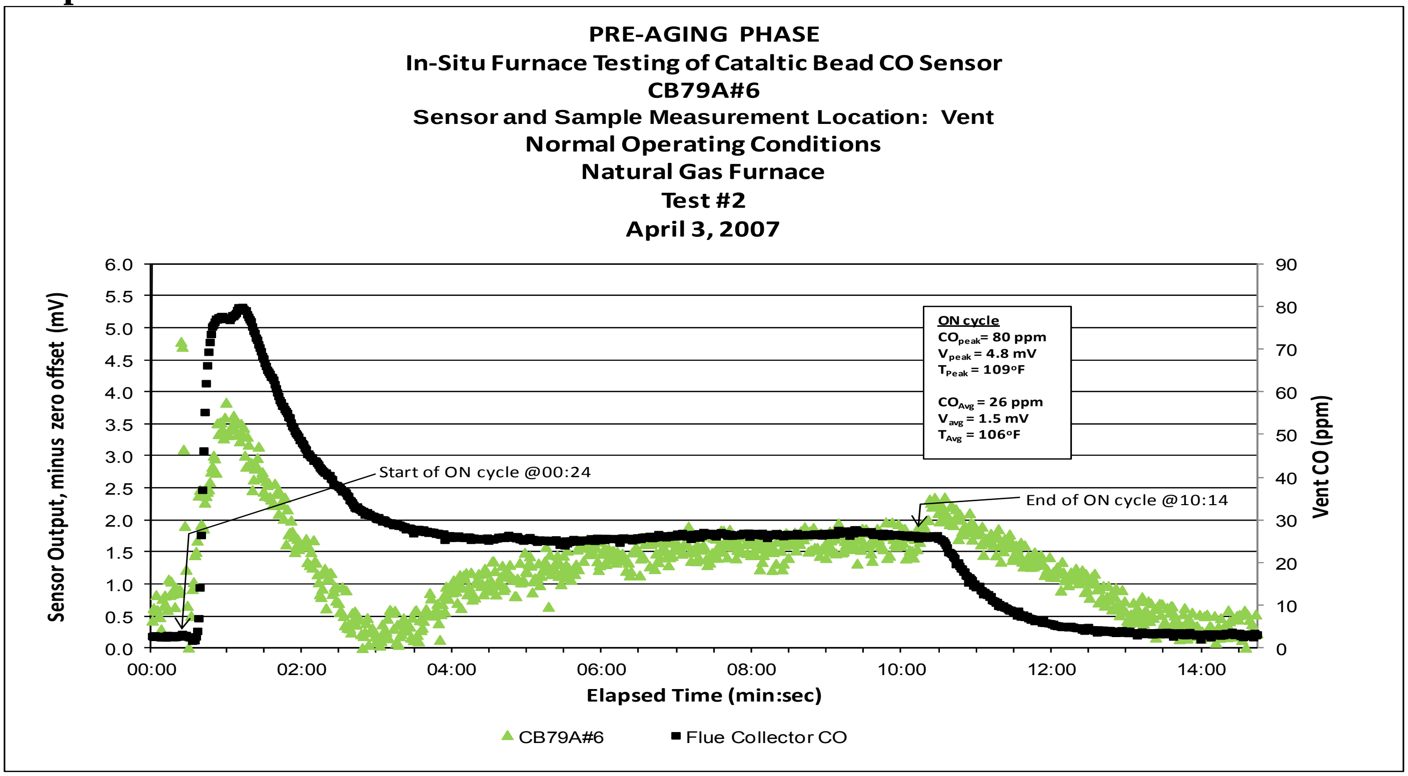


Graph B.4

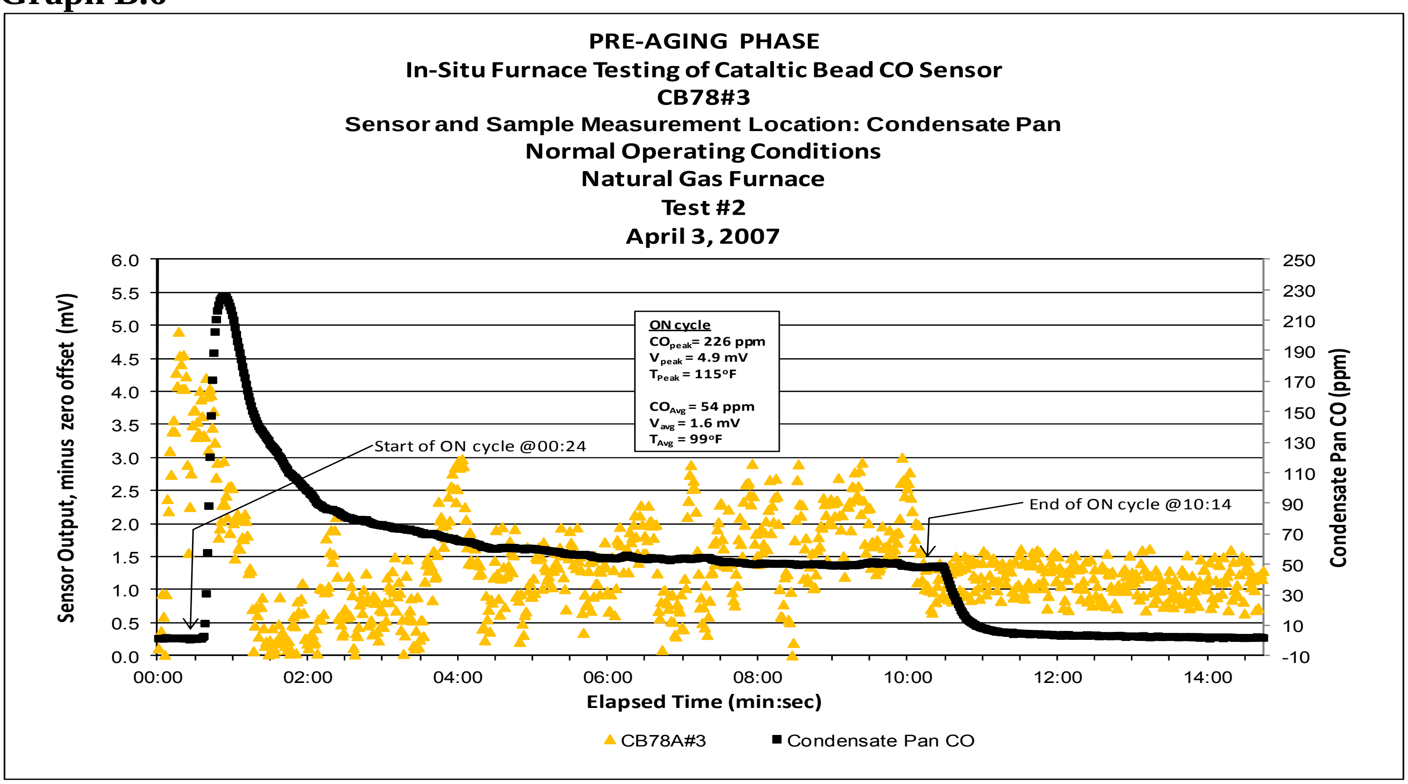


APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: NATURAL GAS FURNACE

Graph B.5

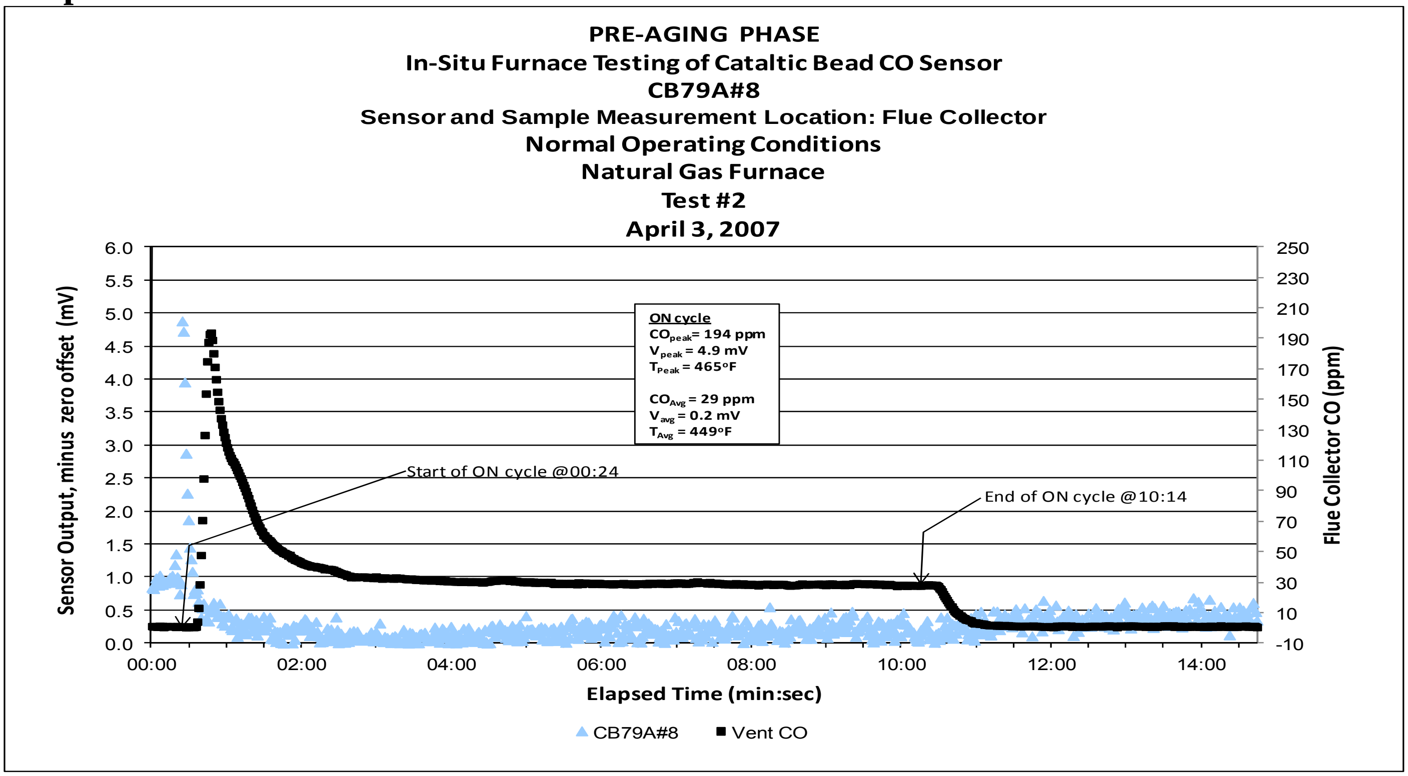


Graph B.6

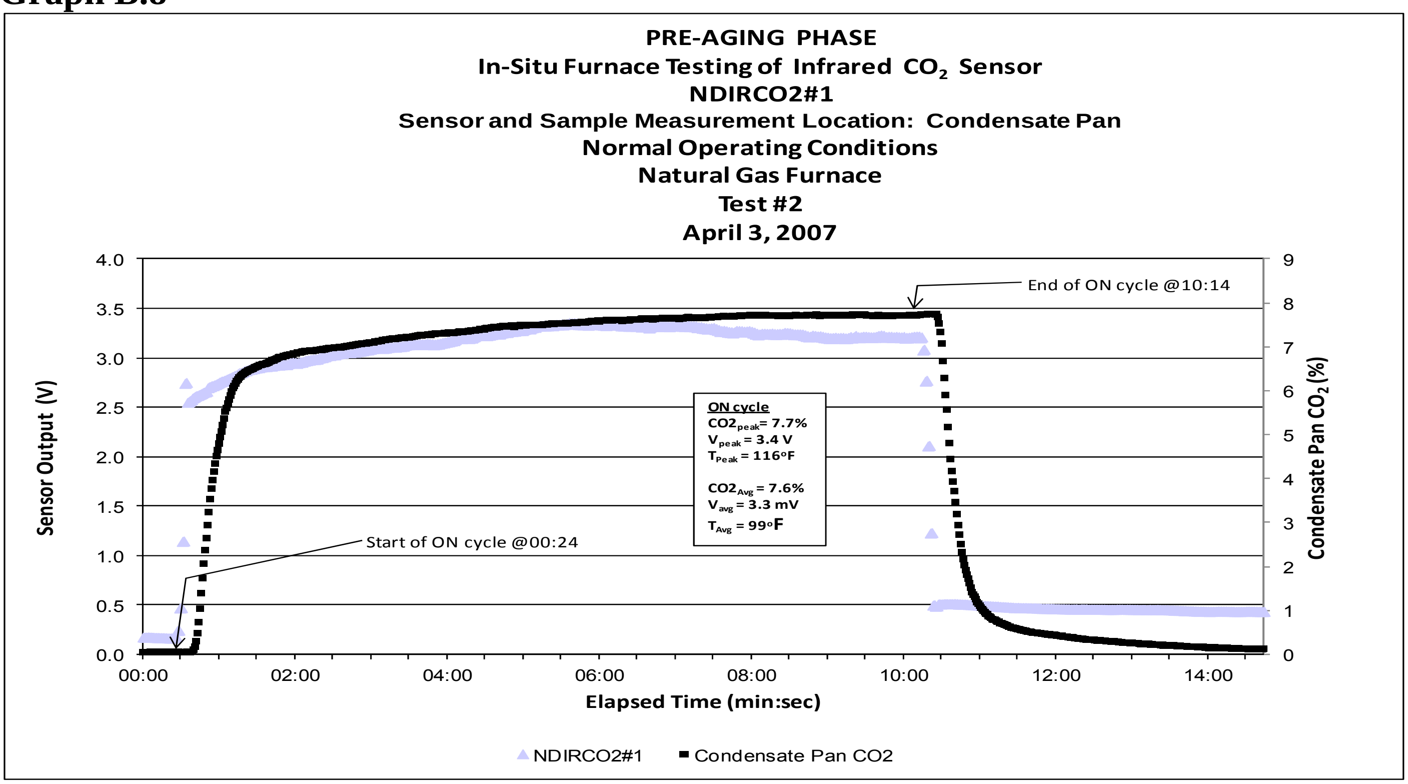


APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: NATURAL GAS FURNACE

Graph B.7



Graph B.8



APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: NATURAL GAS FURNACE

Table B.1		PRE-AGING PHASE In-Situ Furnace Sensor Response Test #1 Natural Gas Furnace (April 2, 2007) Average and Peak Values during ON-Cycle*														
Cycle #	Cycle Status ON/OFF?	Start of Cycle (min:sec)	End of Cycle (min:sec)	Cycle Duration (min:sec)	CO vent (ppm)	CO cond (ppm)	CO flue (ppm)	CO2 cond (%)	CB79#6 vent (mV)	CB78#3 cond (mV)	CB79#8 flue (mV)	NDIRCO2#2 cond (V)	Temp vent (°F)	Temp cond (°F)	Temp flue (°F)	Manifold Pressure (in. w.c.)
1	OFF	00:00	00:26	00:26	3	1	2	0.2	0.9	1.1	0.7	0.1	79.5	91.1	142.5	-0.1
	ON	00:27	11:03	10:36												
	ON_{peak}	00:27	11:03	10:36	60	159	178	6.8	4.6	5.0	6.0	2.2	107.1	116.1	473.5	4.1
	ON_{Avg}	04:00	10:00	06:00	25	27	50	6.6	1.5	1.7	0.3	2.2	104.5	99.3	451.2	4.0
	OFF	11:04	17:53	06:49	7	4	7	1.4	0.7	2.0	0.1	0.3	93.2	97.1	222.3	-0.1

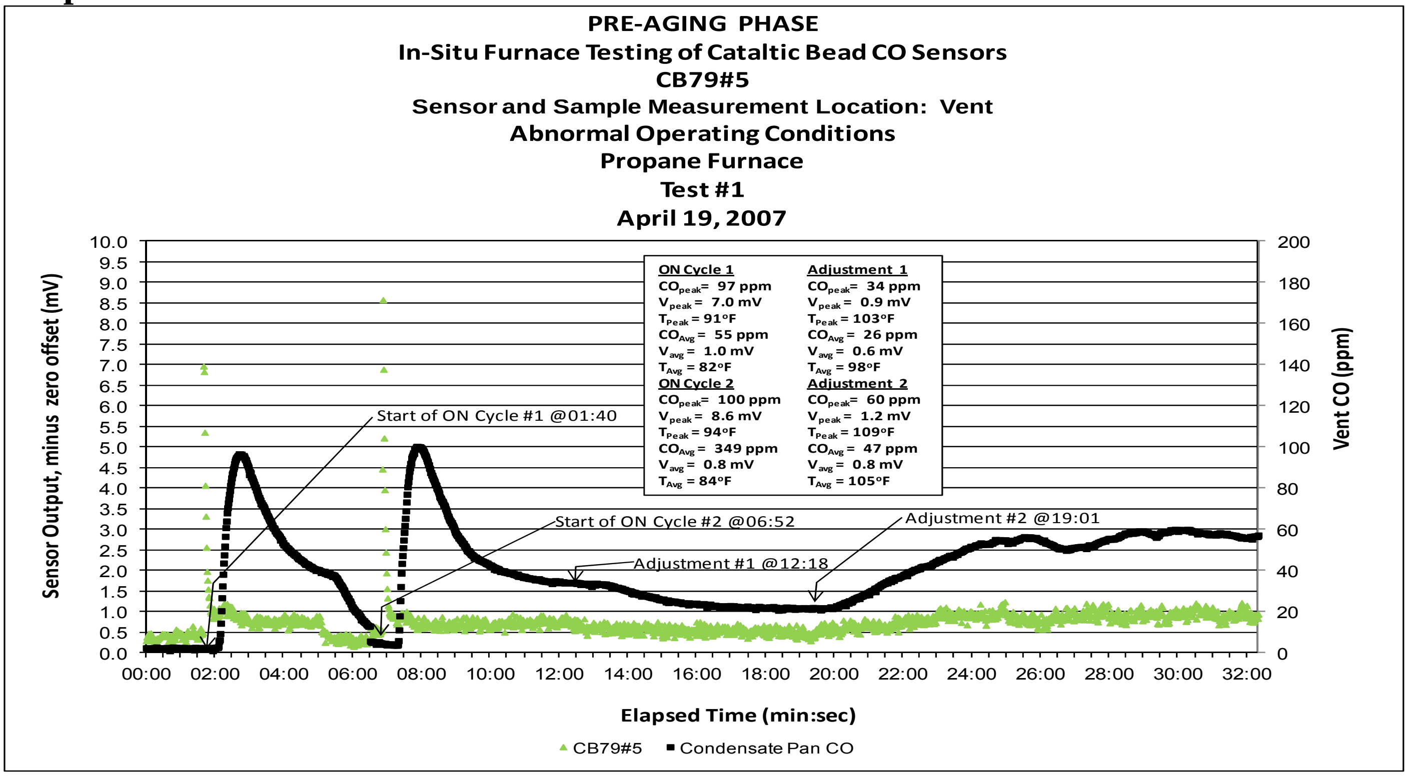
*Average values were calculated for the ON-cycle time frame (between 4 and 10 minutes) during which CO and CO_2 levels began to approach steady state and are bounded by the start and end of cycles in the ON_{Avg} row. Peak values were determined for the duration of the entire ON-Cycle.

Table B.2		PRE-AGING PHASE In-Situ Furnace Sensor Response Test #2 Natural Gas Furnace (April 3, 2007) Average and Peak Values during ON-Cycle*														
Cycle #	Cycle Status ON/OFF?	Start of Cycle (min:sec)	End of Cycle (min:sec)	Duration of Cycle (min:sec)	CO vent (ppm)	CO cond (ppm)	CO flue (ppm)	CO2 cond (%)	CB79#6 vent (mV)	CB78#3 cond (mV)	CB79#8 flue (mV)	NDIRCO2#1 cond (V)	Temp vent °F	Temp cond °F	Temp flue °F	Manifold Pressure in. w.c
1	OFF	00:00	00:25	00:25	3	2	1	0.1	1.1	2.7	1.3	0.2	75	56	48	-0.1
	ON	00:26	10:13	09:47												
	ON_{Peak}	00:24	10:13	09:47	80	226	194	7.7	4.8	4.9	4.9	3.4	109	116	465	4.1
	ON_{Avg}	04:00	10:00	06:00	26	54	29	7.6	1.5	1.6	0.2	3.3	105	99	449	4.0
	OFF	10:14	14:44	04:30	8	8	4	1.1	1.1	1.1	0.3	0.5	96	93	258	-0.1

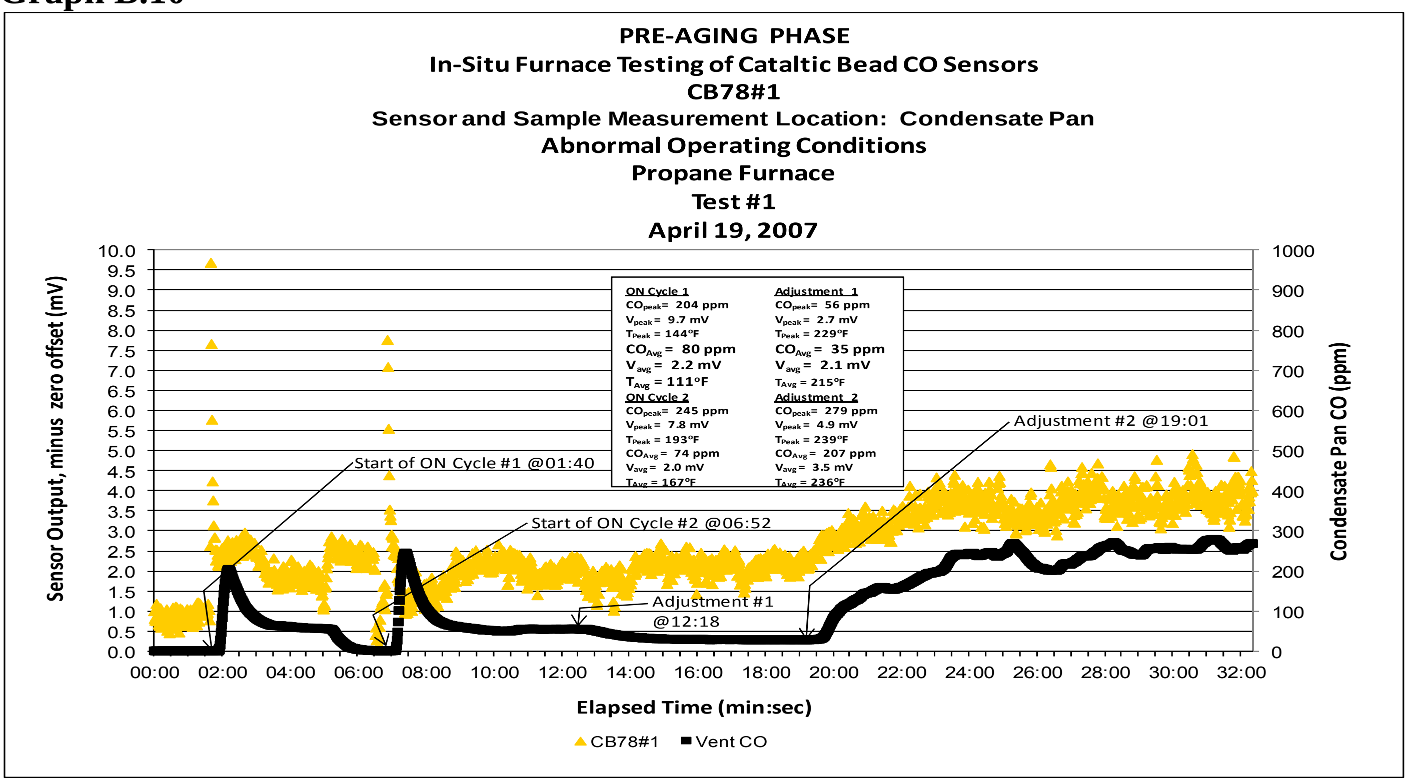
*Average values were calculated for the ON-cycle time frame (between 4 and 10 minutes) during which CO and CO2 levels began to approach steady state levels and are bounded by the start and end of cycles in the ON_{Avg} row. Peak values were determined for the duration of the entire ON-Cycle.

APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: PROPANE FURNACE

Graph B.9

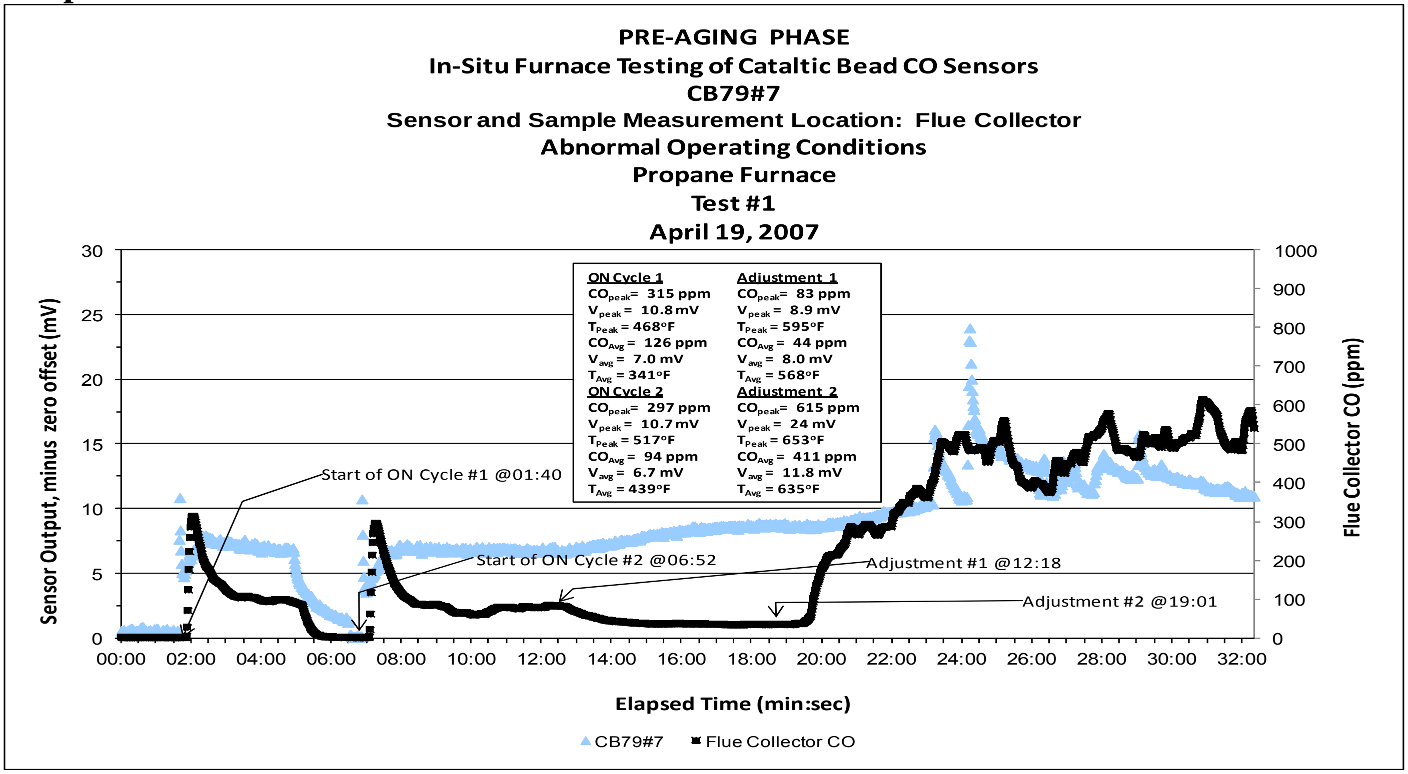


Graph B.10

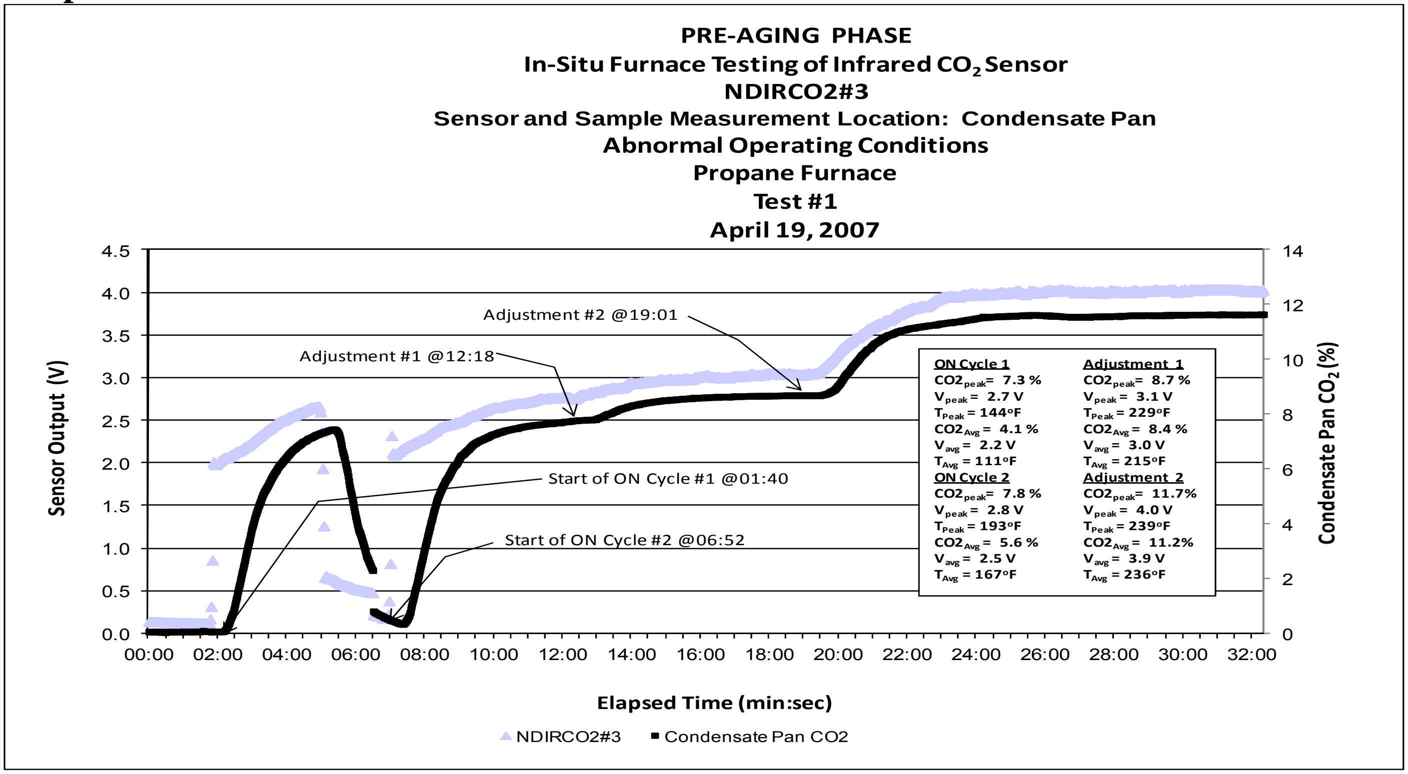


APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: PROPANE FURNACE

Graph B.11

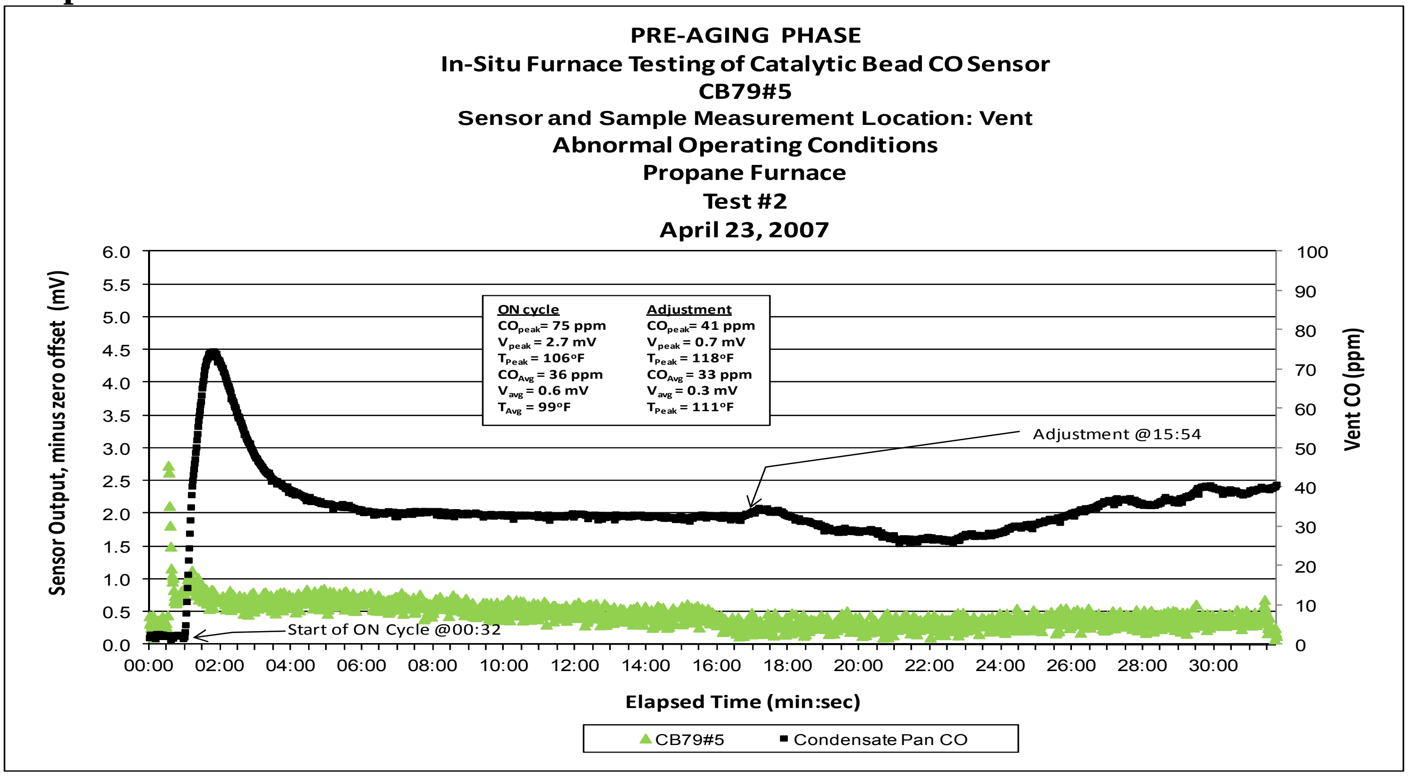


Graph B.12

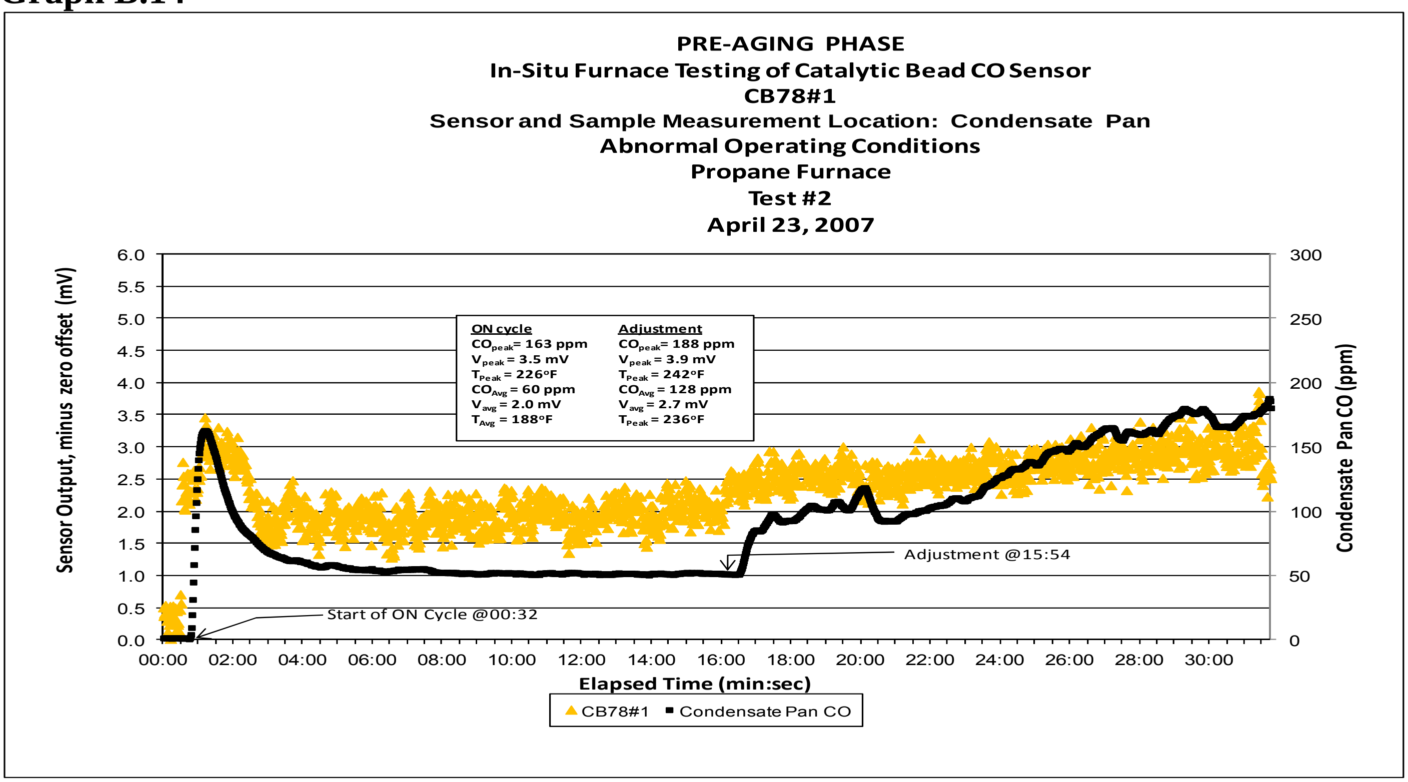


APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: PROPANE FURNACE

Graph B.13

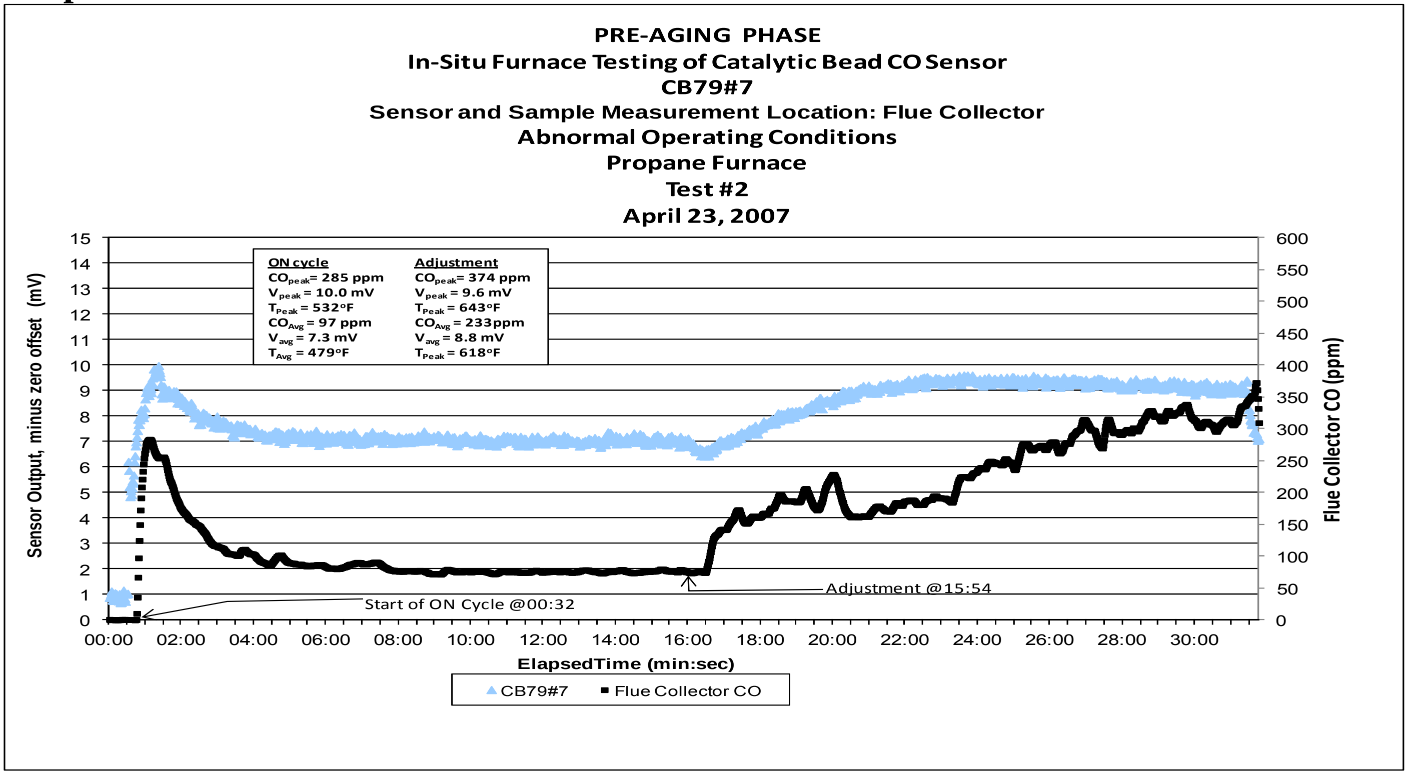


Graph B.14

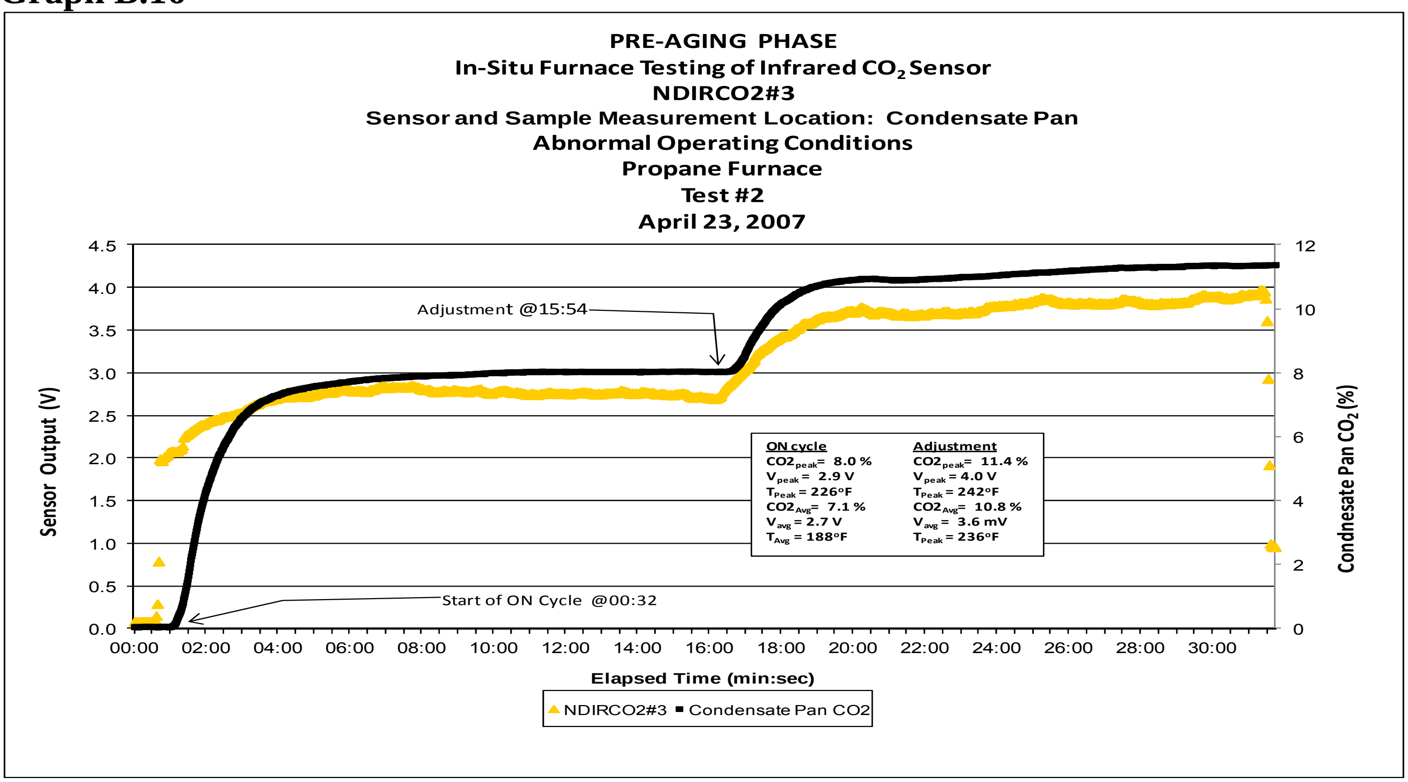


APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: PROPANE FURNACE

Graph B.15



Graph B.16



APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: PROPANE FURNACE

Table B.3

PRE-AGING PHASE
In-Situ Furnace Sensor Response Test #1
Propane Furnace (April 19, 2007)
Peak and Steady State Levels during Cycling

Cycle #	Cycle Status ON/OFF?	Start of Cycle (min:sec)	End of Cycle (min:sec)	Duration of Cycle (min:sec)	CO vent (ppm)	CO cond (ppm)	CO flue (ppm)	CO2 cond (%)	CB79#5 vent (mV)	CB78#1 cond (mV)	CB79#7 flue (mV)	NDIRCO2#3 cond (V)	Temp vent °F	Temp cond °F	Temp flue °F	Manifold Pressure in. w.c
1	OFF	00:00	01:40	01:40	2	1	1	0.1	0.5	1.0	0.7	0.1	60.4	65.4	61.3	-0.1
	ON$_{Avg}$	01:40	04:58	03:18	55	80	126	4.1	1.0	2.2	7.0	2.2	82.4	111.3	341.1	9.9
	ON$_{Peak}$	01:40	04:58	03:18	97	204	315	7.3	7.0	9.7	10.8	2.7	91.1	144.1	467.7	10.2
2	OFF	04:59	07:16	02:17	21	21	32	3.8	0.7	2.3	2.6	0.7	73.6	134.4	304.5	1.6
	ON$_{Avg}$	06:52	12:17	05:25	49	74	94	5.6	0.8	2.0	6.7	2.5	84.6	167.9	438.8	10.1
	ON$_{Peak}$	06:52	12:17	05:25	100	245	297	7.8	8.6	7.8	10.7	2.8	94.2	193.2	516.8	10.2
	ON$_{Adjustment_1\ Avg}$	12:18	19:00	06:42	26	35	44	8.4	0.6	2.1	8.0	3.0	98.4	215.0	567.7	10.2
	ON$_{Adjustment_1\ Peak}$	12:18	19:00	06:42	34	56	83	8.7	0.8	2.7	8.9	3.1	102.7	228.9	595.0	10.2
	ON$_{Adjustment_2\ Avg}$	19:01	32:00	12:59	47	207	411	11.2	0.8	3.5	11.8	3.9	104.7	235.6	634.9	10.2
	ON$_{Adjustment_2\ Peak}$	19:01	32:00	12:59	60	279	615	11.7	1.2	4.9	24.0	4.0	109.4	239.2	652.6	10.3

*During ON Cycle #1, average and peak values were calculated for the time frame between 1:40 and 4:58 minutes.
*During ON Cycle #2, average and peak values were calculated for the time frame between 6:52 and 12:17 minutes.
*Adjustment #1 was made at 12:18 minutes and average and peak values were calculated between 12:18 and 19:00 minutes.
*Adjustment #2 was made at 19:01 minutes and average and peak values were calculated between 19:01 and 32:00 minutes.

Table B.4

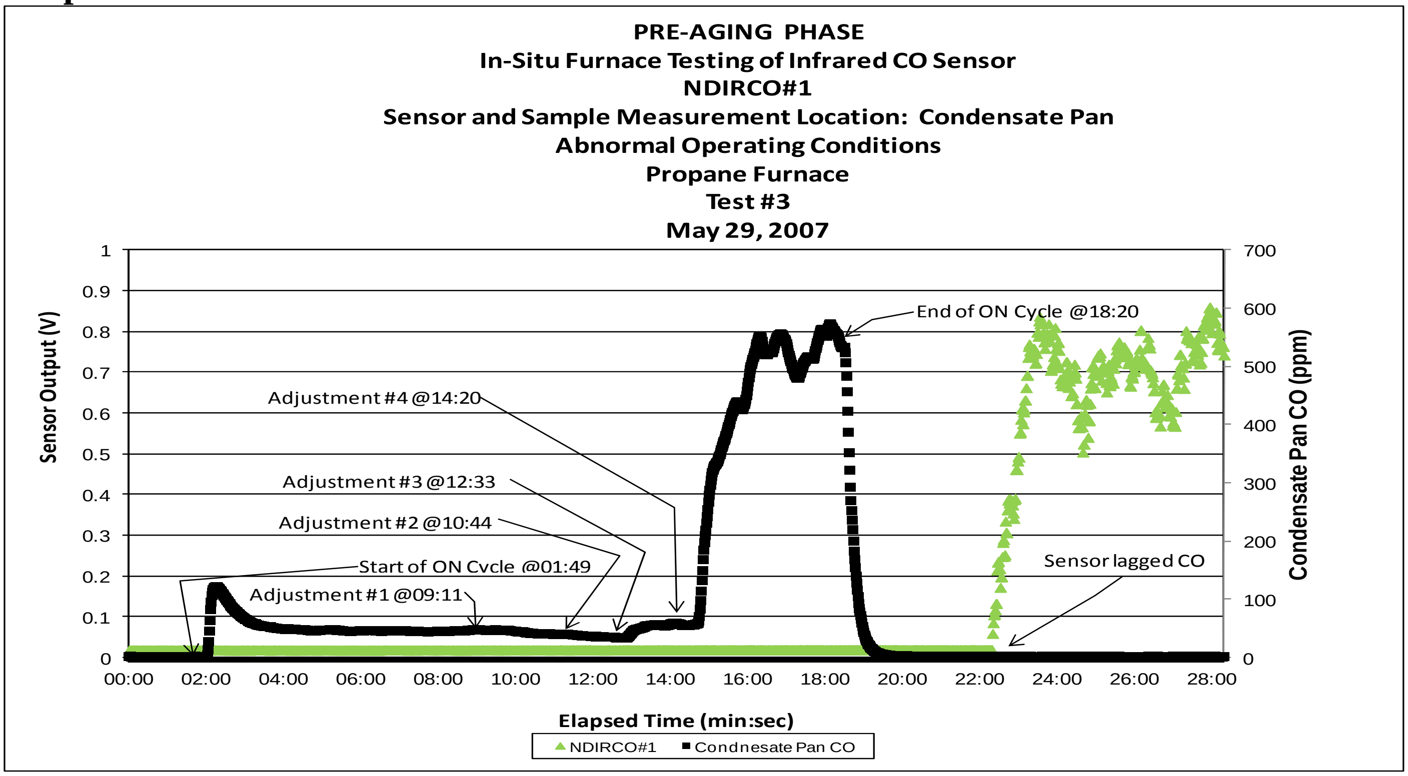
PRE-AGING PHASE
In-Situ Furnace Sensor Response Test #2
Propane Furnace (April 23, 2007)
Peaks and Steady State levels during Cycling

Cycle #	Cycle Status Status ON/OFF?	Start of Cycle (min:sec)	End of Cycle (min:sec)	Duration of Cycle (min:sec)	CO vent (ppm)	CO cond (ppm)	CO flue (ppm)	CO2 cond (%)	CB79#5 vent (mV)	CB78#1 cond (mV)	CB79#7 flue (mV)	NDIRCO2#3 cond (V)	Temp vent °F	Temp cond °F	Temp flue °F	Manifold Pressure Pressure in. w.c
1	OFF	00:00	00:31	00:31	2	2	2	0.0	0.3	0.4	1.1	0.1	57.7	63.4	56.0	-0.1
	ON$_{Avg}$	00:32	15:53	15:21	36	60	97	7.1	0.6	2.0	7.3	2.7	98.9	187.7	479.1	10.1
	ON$_{Peak}$	00:32	15:53	15:21	75	163	285	8.0	2.7	3.5	10.0	2.9	105.8	225.7	532.1	10.2
	ON$_{Adjustment\ Avg}$	15:54	31:45	15:51	33	128	233	10.8	0.3	2.7	8.8	3.6	110.7	236.3	618.2	10.0
	ON$_{Adjustment\ Peak}$	15:54	31:45	15:51	41	188	374	11.4	0.7	3.9	9.6	4.0	118.1	242.3	643.4	10.2

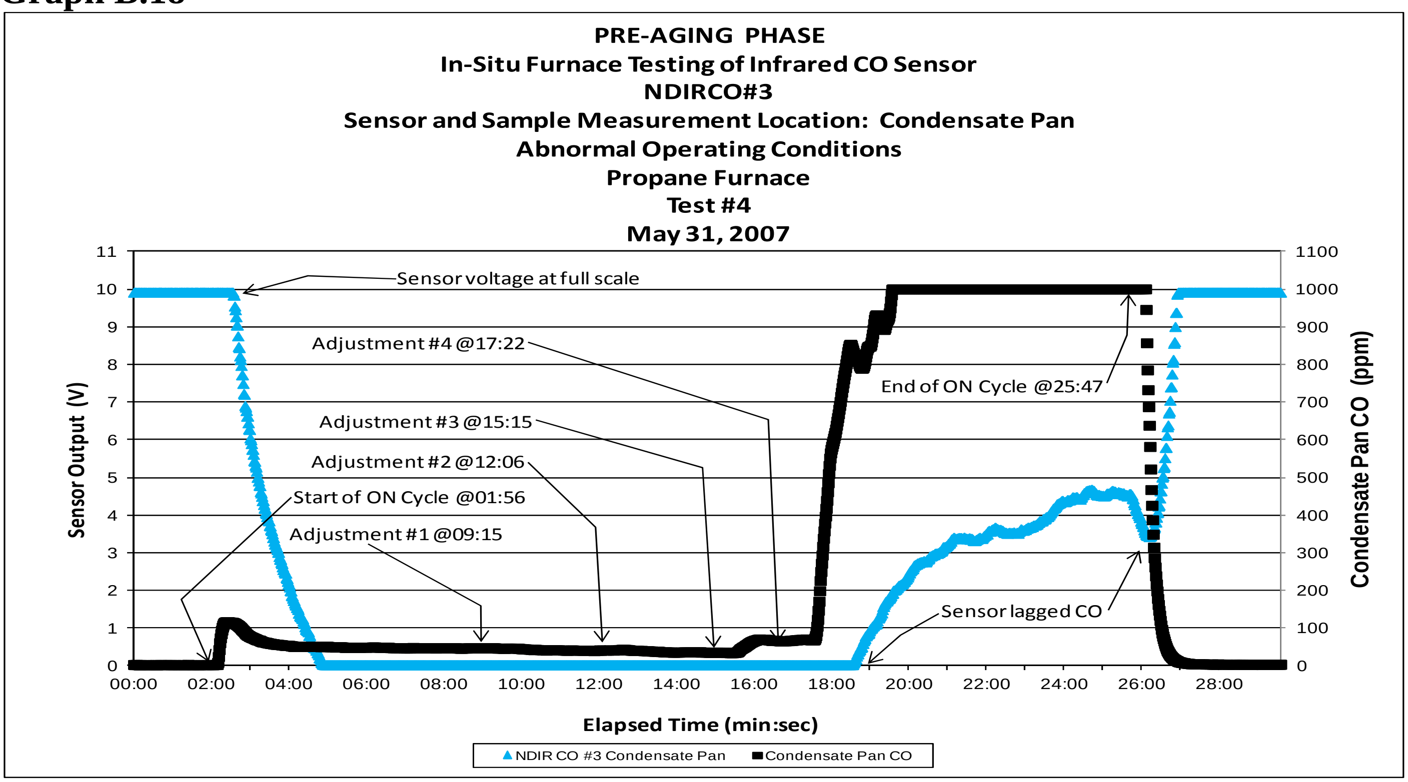
*During the ON Cycle, average and peak values were calculated for the time frame between 00:32 and 15:53 minutes.
*An adjustment was made at 16:31 minutes and average and peak values were calculated between 15:54 and 31:45 minutes.

APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: PROPANE FURNACE

Graph B.17



Graph B.18



APPENDIX B. PRE-AGING PHASE IN-SITU TEST DATA: PROPANE FURNACE

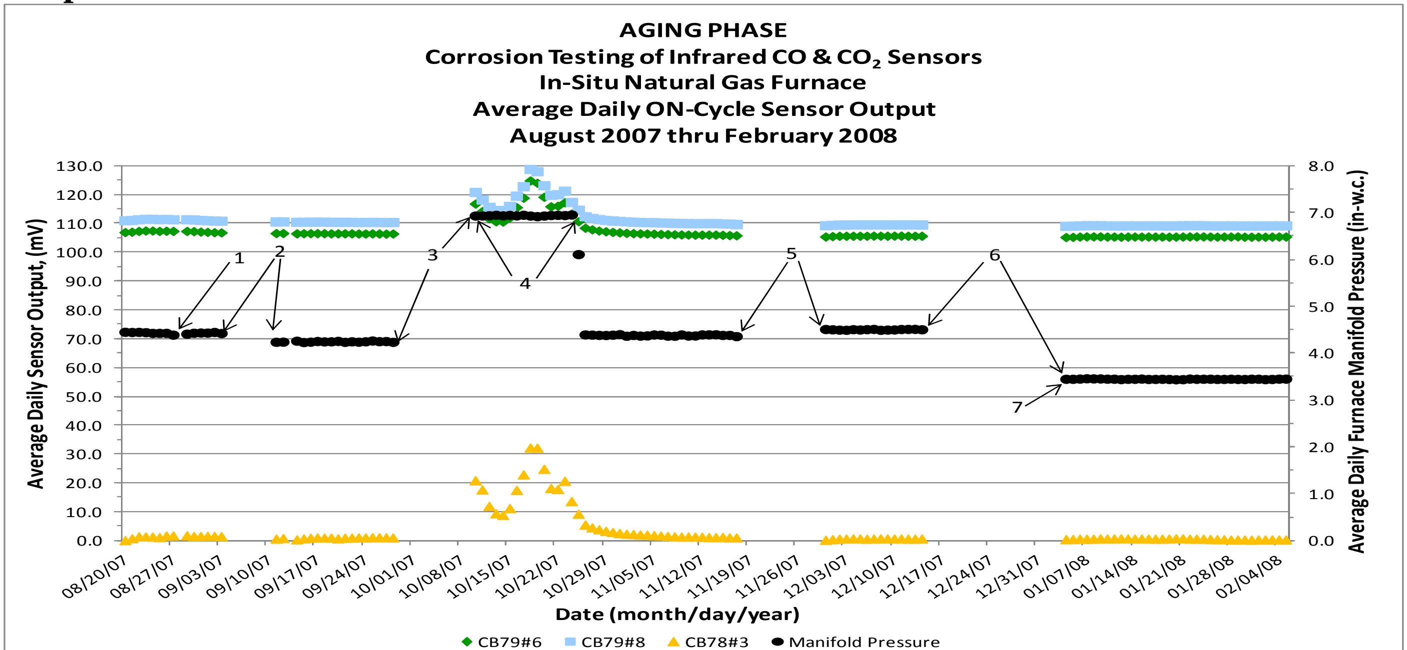
Table B.5		PRE-AGING PHASE In-Situ Furnace Sensor Response Test #3 Propane Furnace (May 29, 2007)						
Cycle #	Cycle Status ON/OFF?	Start of Cycle (min:sec)	End of Cycle (min:sec)	Duration (min:sec)	CO (cond)(ppm)	NDIRCO#1 (V)	Temp (cond) °F	Manifold Pressure (in. w.c.)
1	OFF	00:00	01:49	01:49	2	0.0	72.7	-0.1
	ON	01:50	18:19	16:29	139	0.7	81.4	10.1
	ONmax	01:50	18:19	16:29	573	0.9	86.6	10.2
	OFF	18:20	28:18	09:58	23	---	---	---

Table B.6		PRE-AGING PHASE In-Situ Furnace Sensor Response Test #4 Propane Furnace (May 31, 2007)						
Cycle #	Cycle Status ON/OFF?	Start of Cycle (min:sec)	End of Cycle (min:sec)	Duration (min:sec)	CO (cond) (ppm)	NDIRCO#3 (V)	Temp* (cond) °F	Manifold Pressure (in. w.c.)
1	OFF	00:00	01:56	01:56	2	9.9	------	0
	ON	01:57	25:46	23:49	359	1.7	------	9.7
	ON_{max}	01:57	25:46	23:49	1000	9.9	------	10.2
	OFF	25:47	29:34	03:47	4	9.9	------	0

*Condensate pan temperature data not recorded during this test due to disconnected thermocouple wire.

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: NATURAL GAS FURNACE

Graph C.1



Note: Discontinuity of data in the graph reflects time frames during which CSA-On Spex shutdown furnace or data acquisition system for test equipment maintenance or servicing, or adjusted furnace manifold pressure, and were as follows: 1) shutdown on 8/28/07; 2) shutdown from 9/4/07 to 9/10/07; 3) shutdown from 9/29/07 to 10/9/07; 4) increased manifold pressure from approximately 4.5 to 7.0 in. w.c. from 10/10/07 to 10/31/07; 5) shutdown from 11/18/07 to 11/29/07; 6) shutdown from 12/15/07 to 1/3/08; 7) decreased manifold pressure from 4.5. to 3.5 in. w.c. on 01/04/08.

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: NATURAL GAS FURNACE

Table C.1	AGING PHASE Corrosion test ON-cycle data for catalytic bead CO sensors in-situ in a natural gas furnace (August 2007 through February 2008)												
	CB79#6				CB79#8				CB78#3				Manifold Pressure
	mV				mV				mV				in. w.c.
Date	**Avg**	**Max**	**Min**	**Std**	**Avg**	**Max**	**Min**	**Std**	**Avg**	**Max**	**Min**	**Std**	**Avg**
08/20/07	106.9	107.4	106.3	0.3	111.0	111.5	110.4	0.2	0.1	1.5	-1.4	0.4	4.5
08/21/07	107.1	107.6	106.4	0.3	111.1	111.7	110.5	0.2	0.8	2.1	-0.4	0.4	4.4
08/22/07	107.3	107.9	106.6	0.3	111.4	111.9	110.7	0.3	1.4	2.4	0.1	0.4	4.5
08/23/07	107.5	107.9	106.4	0.3	111.5	111.9	110.4	0.3	1.4	2.7	-0.1	0.4	4.4
08/24/07	107.5	107.9	106.5	0.3	111.5	111.9	110.6	0.3	1.3	2.3	-0.4	0.4	4.4
08/26/07	107.3	107.9	106.7	0.3	111.4	112.0	110.7	0.3	1.2	2.5	-0.8	0.5	4.4
08/27/07	107.4	107.9	106.7	0.3	111.5	112.0	110.7	0.3	1.7	2.7	0.0	0.4	4.4
08/28/07	107.3	107.9	106.6	0.3	111.4	111.9	110.7	0.3	1.7	2.8	0.0	0.5	4.4
08/29/07	107.3	107.9	106.6	0.3	111.4	112.0	110.6	0.3	1.8	2.6	0.1	0.4	4.4
08/30/07	107.3	107.9	106.4	0.3	111.3	112.0	110.5	0.3	1.5	2.5	-0.5	0.5	4.4
08/31/07	107.1	107.7	106.3	0.3	111.2	111.8	110.3	0.3	1.6	2.7	-0.4	0.4	4.4
09/01/07	107.0	108.0	106.2	0.3	111.0	112.2	110.2	0.3	1.6	2.9	-0.3	0.4	4.4
09/02/07	106.9	107.5	106.2	0.3	110.9	111.5	110.2	0.3	1.6	2.5	-0.1	0.4	4.4
09/03/07	106.8	107.4	106.1	0.3	110.9	111.4	110.1	0.3	1.5	2.3	-0.2	0.4	4.4
09/11/07	106.6	107.0	106.1	0.2	110.6	111.2	110.1	0.2	0.6	1.5	-1.0	0.3	4.2
09/12/07	106.6	107.1	105.8	0.2	110.6	111.2	109.7	0.2	0.8	1.6	-0.3	0.3	4.2
09/14/07	106.5	106.9	106.0	0.2	110.5	111.0	110.0	0.2	0.4	1.2	-1.4	0.4	4.3
09/15/07	106.5	107.1	106.0	0.2	110.5	111.1	110.0	0.2	0.7	1.6	-0.2	0.3	4.2
09/16/07	106.6	107.0	106.0	0.2	110.6	111.2	110.0	0.2	1.0	1.7	0.0	0.3	4.2
09/17/07	106.6	107.1	106.0	0.2	110.6	111.1	110.0	0.2	1.0	1.8	0.1	0.3	4.3
09/18/07	106.5	107.1	105.9	0.2	110.5	111.0	109.9	0.2	1.0	1.8	-0.1	0.3	4.2
09/19/07	106.5	106.9	106.0	0.2	110.5	111.0	109.9	0.2	1.0	1.8	0.2	0.3	4.2
09/20/07	106.5	106.9	106.0	0.2	110.5	111.0	109.9	0.2	0.7	1.5	-0.8	0.4	4.3
09/21/07	106.5	107.0	106.0	0.2	110.5	111.1	109.9	0.2	0.9	1.7	0.0	0.3	4.2
09/22/07	106.5	106.9	106.0	0.2	110.5	111.0	110.0	0.2	1.0	1.8	-0.1	0.3	4.3
09/23/07	106.5	106.9	105.9	0.2	110.4	111.0	109.9	0.2	1.0	2.1	-0.1	0.3	4.2
09/24/07	106.4	106.8	105.9	0.2	110.4	110.9	109.9	0.2	1.1	1.8	0.1	0.3	4.3
09/25/07	106.5	106.9	105.9	0.2	110.5	111.0	109.9	0.2	1.1	1.9	0.3	0.3	4.3
09/26/07	106.5	106.9	105.9	0.2	110.4	111.1	109.9	0.2	1.1	1.9	0.2	0.3	4.3
09/27/07	106.4	111.6	105.9	0.3	110.4	115.6	109.8	0.3	1.1	9.1	0.2	0.4	4.3
09/28/07	106.4	118.1	104.5	0.8	110.4	122.1	108.4	0.8	1.1	1.9	0.3	0.3	4.2
10/10/07	116.8	139.5	105.3	7.8	120.8	143.3	109.7	7.8	20.9	54.3	-2.9	12.6	6.9

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: NATURAL GAS FURNACE

Table C.1	AGING PHASE Corrosion test ON-cycle data for catalytic bead CO sensors in-situ in a natural gas furnace (August 2007 through February 2008)												
	CB79#6				CB79#8				CB78#3				Manifold Pressure
	mV				mV				mV				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
10/11/07	114.2	139.5	108.1	5.7	118.2	143.6	112.3	5.7	17.7	54.5	2.5	10.6	6.9
10/12/07	111.7	131.5	108.1	3.6	115.7	135.4	112.4	3.6	12.0	47.3	3.0	7.3	6.9
10/13/07	110.6	121.5	107.9	2.5	114.6	125.2	112.2	2.5	9.4	36.0	3.4	5.0	6.9
10/14/07	110.6	120.6	107.8	2.5	114.6	124.6	112.0	2.5	8.9	27.5	3.1	4.6	6.9
10/15/07	112.0	131.1	107.8	4.1	116.0	134.8	112.0	4.1	11.2	45.3	3.3	7.1	6.9
10/16/07	115.6	136.1	108.2	5.6	119.6	141.0	112.3	5.7	17.5	51.3	4.1	10.0	6.9
10/17/07	118.9	139.7	108.7	7.0	122.9	144.5	112.9	7.1	22.9	56.0	4.7	11.8	7.0
10/18/07	124.8	145.3	109.9	8.3	128.9	149.1	114.0	8.3	32.2	60.1	6.8	12.8	6.9
10/19/07	124.0	144.9	110.4	7.8	128.1	149.4	114.6	7.8	32.2	61.9	8.3	12.6	6.9
10/20/07	119.2	138.5	110.0	6.0	123.2	142.3	114.2	6.1	24.8	58.3	8.2	10.9	6.9
10/21/07	115.9	128.0	109.8	3.5	119.9	131.8	113.9	3.6	18.2	41.9	7.3	6.7	6.9
10/22/07	116.1	133.0	109.4	4.1	120.1	137.2	113.7	4.2	17.8	51.6	6.8	7.2	6.9
10/23/07	117.3	135.8	109.2	4.8	121.3	139.7	113.4	4.9	20.7	53.8	7.2	8.9	6.9
10/24/07	113.4	125.1	108.7	2.4	117.3	129.0	113.1	2.4	13.7	39.8	6.1	4.8	7.0
10/25/07	110.7	119.0	108.5	1.9	114.7	122.9	112.5	1.9	9.3	23.4	5.4	3.1	6.1
10/26/07	108.4	111.0	107.8	0.3	112.4	115.0	111.7	0.3	5.5	9.4	4.5	0.4	4.4
10/27/07	107.9	109.3	107.3	0.2	111.8	113.3	111.3	0.2	4.5	6.9	3.8	0.3	4.4
10/28/07	107.5	108.1	106.8	0.2	111.4	112.2	110.8	0.2	3.9	4.8	3.1	0.3	4.4
10/29/07	107.2	107.7	106.6	0.2	111.2	111.8	110.7	0.2	3.3	4.2	2.2	0.3	4.4
10/30/07	107.0	107.6	106.3	0.2	111.0	111.6	110.4	0.2	2.9	3.9	2.0	0.3	4.4
10/31/07	106.8	107.6	106.2	0.2	110.8	111.7	110.3	0.2	2.6	3.6	1.8	0.2	4.4
11/01/07	106.7	107.2	106.0	0.2	110.7	111.3	110.2	0.2	2.3	3.4	0.8	0.2	4.4
11/02/07	106.6	108.8	105.9	0.2	110.5	112.9	110.1	0.2	2.2	5.9	1.4	0.3	4.4
11/03/07	106.5	107.1	105.9	0.2	110.4	111.1	110.0	0.2	2.1	3.0	1.4	0.2	4.4
11/04/07	106.4	107.0	105.8	0.2	110.4	111.1	109.9	0.2	2.0	2.9	1.3	0.2	4.4
11/05/07	106.4	109.4	105.6	0.2	110.3	113.4	109.8	0.2	1.8	6.7	0.5	0.3	4.4
11/06/07	106.3	106.8	105.6	0.2	110.3	110.9	109.8	0.2	1.7	2.6	0.9	0.2	4.4
11/07/07	106.2	109.7	105.6	0.2	110.2	113.7	109.8	0.2	1.6	11.0	0.6	0.4	4.4
11/08/07	106.2	107.9	105.5	0.2	110.1	112.0	109.7	0.2	1.5	3.6	0.5	0.2	4.4
11/09/07	106.1	107.2	105.6	0.2	110.1	111.7	109.7	0.2	1.4	4.5	0.6	0.3	4.4
11/10/07	106.1	106.7	105.6	0.2	110.0	110.7	109.7	0.2	1.4	2.2	0.7	0.2	4.4
11/11/07	106.0	106.6	105.6	0.2	110.0	110.6	109.6	0.2	1.3	2.2	0.7	0.3	4.4
11/12/07	106.1	109.0	105.6	0.2	110.0	113.1	109.6	0.2	1.3	6.4	0.7	0.3	4.4

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: NATURAL GAS FURNACE

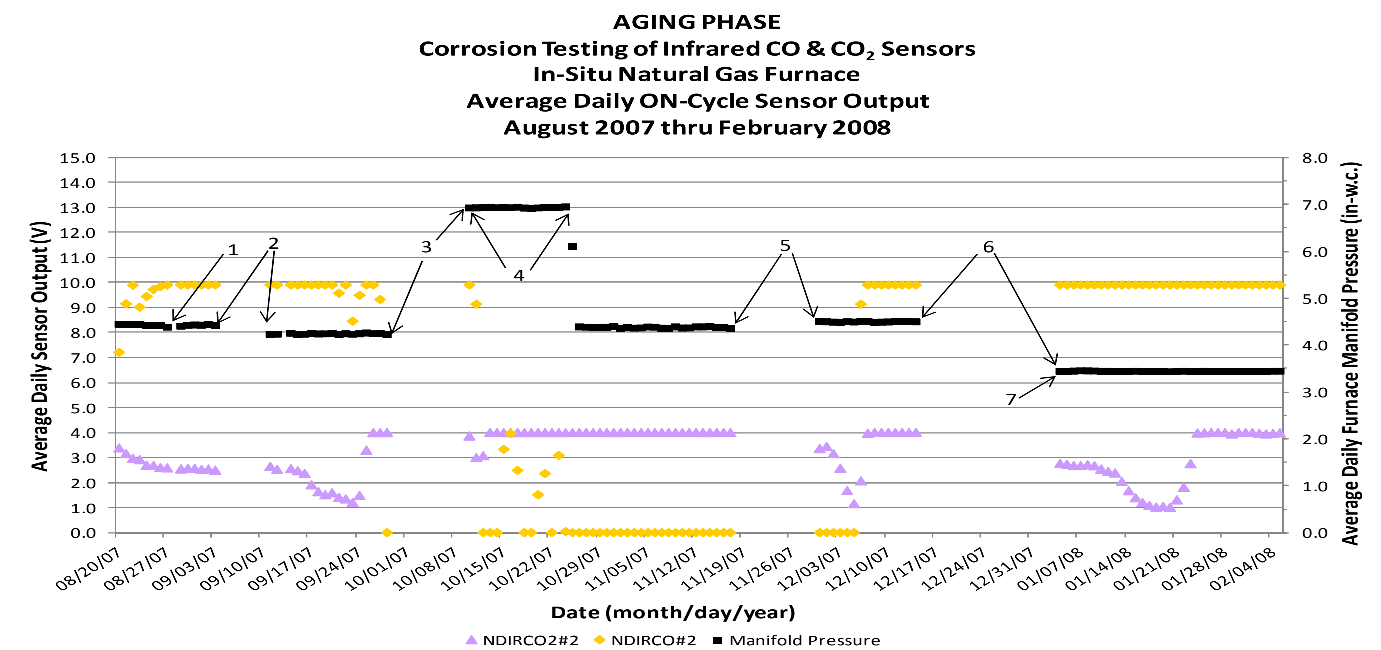
Table C.1	AGING PHASE Corrosion test ON-cycle data for catalytic bead CO sensors in-situ in a natural gas furnace (August 2007 through February 2008)												
	CB79#6				CB79#8				CB78#3				Manifold Pressure
	mV				mV				mV				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
11/13/07	106.1	106.6	105.5	0.2	110.0	110.7	109.6	0.2	1.2	2.0	0.1	0.2	4.4
11/14/07	106.1	107.2	105.4	0.2	110.0	111.2	109.6	0.2	1.2	2.7	0.0	0.3	4.4
11/15/07	106.0	110.5	105.4	0.2	109.9	114.4	109.5	0.3	1.2	9.5	-0.4	0.4	4.4
11/16/07	105.9	106.5	105.3	0.2	109.9	110.5	109.5	0.2	1.1	1.9	-0.3	0.2	4.4
11/17/07	105.8	106.4	104.9	0.2	109.7	110.5	109.0	0.3	1.1	1.9	0.2	0.2	4.4
11/30/07	105.4	105.9	104.7	0.2	109.3	110.0	108.8	0.2	0.2	1.1	-0.9	0.3	4.5
12/01/07	105.5	106.2	105.0	0.2	109.4	110.1	109.0	0.2	0.5	1.4	-0.1	0.3	4.5
12/02/07	105.6	106.2	105.1	0.2	109.6	110.2	109.2	0.2	0.6	1.5	0.0	0.2	4.5
12/03/07	105.6	106.1	105.1	0.2	109.5	110.1	109.2	0.2	0.7	1.8	-0.1	0.2	4.5
12/04/07	105.7	106.2	105.1	0.2	109.6	110.2	109.2	0.2	0.7	1.6	-0.4	0.2	4.5
12/05/07	105.7	106.2	105.1	0.2	109.6	110.3	109.2	0.2	0.7	1.7	-0.2	0.2	4.5
12/06/07	105.7	106.2	105.2	0.2	109.6	110.2	109.2	0.2	0.6	1.6	0.0	0.2	4.5
12/07/07	105.7	106.2	105.1	0.2	109.6	110.3	109.2	0.2	0.7	1.6	-0.7	0.2	4.5
12/08/07	105.7	106.3	105.2	0.2	109.6	110.3	109.2	0.2	0.7	1.6	0.0	0.2	4.5
12/09/07	105.7	106.2	105.1	0.2	109.6	110.3	109.2	0.2	0.7	1.9	0.1	0.2	4.5
12/10/07	105.7	106.3	105.1	0.2	109.6	110.3	109.2	0.2	0.7	1.9	0.0	0.2	4.5
12/11/07	105.7	106.2	105.1	0.2	109.6	110.2	109.2	0.2	0.7	1.5	0.0	0.2	4.5
12/12/07	105.7	106.2	105.1	0.2	109.6	110.2	109.2	0.2	0.6	1.6	-0.1	0.2	4.5
12/13/07	105.7	106.1	105.0	0.2	109.6	110.2	109.1	0.2	0.6	1.6	-0.5	0.2	4.5
12/14/07	105.7	106.2	105.0	0.2	109.6	110.2	108.8	0.2	0.7	1.5	0.1	0.2	4.5
01/04/08	105.2	105.8	105.0	0.2	109.1	109.8	108.8	0.2	0.5	1.0	-0.7	0.2	3.5
01/05/08	105.3	105.9	105.0	0.2	109.2	109.9	108.9	0.2	0.5	1.5	-0.1	0.3	3.5
01/06/08	105.4	106.0	105.1	0.2	109.3	109.9	109.0	0.2	0.6	1.8	0.0	0.3	3.5
01/07/08	105.4	106.0	105.1	0.2	109.3	110.0	109.0	0.2	0.6	1.8	-0.1	0.2	3.5
01/08/08	105.5	106.3	105.1	0.2	109.3	110.4	109.0	0.2	0.6	1.9	0.0	0.2	3.5
01/09/08	105.4	112.8	105.1	0.3	109.3	116.6	108.9	0.3	0.7	18.6	0.0	0.6	3.5
01/10/08	105.4	106.0	105.0	0.2	109.3	110.0	109.0	0.2	0.7	2.0	-0.1	0.3	3.5
01/11/08	105.4	106.2	105.2	0.2	109.3	110.2	109.0	0.2	0.7	2.0	-0.3	0.3	3.5
01/12/08	105.4	105.9	105.1	0.2	109.2	109.9	108.9	0.2	0.7	1.6	0.2	0.2	3.4
01/13/08	105.4	105.9	105.1	0.2	109.3	109.9	108.9	0.2	0.7	1.8	0.0	0.2	3.4
01/14/08	105.4	106.0	105.1	0.2	109.3	110.0	109.0	0.2	0.7	1.9	0.0	0.3	3.5
01/15/08	105.4	106.0	105.1	0.2	109.3	110.0	108.9	0.2	0.7	1.7	-0.1	0.3	3.5
01/16/08	105.4	106.0	105.1	0.2	109.3	109.9	109.0	0.2	0.7	1.7	-0.3	0.3	3.4

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: NATURAL GAS FURNACE

Table C.1	AGING PHASE Corrosion test ON-cycle data for catalytic bead CO sensors in-situ in a natural gas furnace (August 2007 through February 2008)												
	CB79#6				CB79#8				CB78#3				Manifold Pressure
	mV				mV				mV				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
01/17/08	105.4	106.0	105.0	0.2	109.3	109.9	108.9	0.2	0.6	1.8	-0.2	0.3	3.4
01/18/08	105.4	106.0	105.1	0.2	109.3	110.0	108.9	0.2	0.6	1.6	0.0	0.3	3.5
01/19/08	105.4	106.0	105.1	0.1	109.2	109.9	108.9	0.2	0.7	1.6	0.0	0.2	3.4
01/20/08	105.4	105.9	105.0	0.2	109.3	109.9	108.9	0.2	0.8	1.9	0.0	0.2	3.4
01/21/08	105.4	105.9	105.1	0.2	109.3	110.0	108.9	0.2	0.7	1.8	-0.4	0.3	3.4
01/22/08	105.4	106.0	105.2	0.1	109.3	110.0	109.0	0.2	0.6	2.0	-0.1	0.3	3.5
01/23/08	105.4	105.9	105.0	0.1	109.3	110.0	108.9	0.2	0.6	1.8	-0.1	0.3	3.5
01/24/08	105.4	105.9	105.1	0.1	109.3	109.9	109.0	0.2	0.6	1.6	-0.8	0.3	3.5
01/25/08	105.4	105.9	105.1	0.2	109.3	109.9	108.9	0.2	0.5	1.6	-0.1	0.3	3.5
01/26/08	105.4	105.9	105.1	0.2	109.2	109.9	108.9	0.2	0.5	1.3	-0.2	0.2	3.4
01/27/08	105.4	105.9	105.1	0.2	109.3	109.9	108.9	0.2	0.4	1.5	-0.2	0.2	3.4
01/28/08	105.4	106.0	105.1	0.2	109.3	110.0	108.9	0.2	0.3	1.3	-0.3	0.2	3.5
01/29/08	105.4	106.1	105.0	0.2	109.3	110.0	109.0	0.2	0.4	1.4	-0.4	0.2	3.4
01/30/08	105.3	105.9	105.1	0.2	109.2	109.9	109.0	0.2	0.3	1.5	-0.4	0.3	3.4
01/31/08	105.4	105.9	105.0	0.2	109.2	110.0	108.8	0.2	0.3	1.3	-1.1	0.2	3.5
02/01/08	105.4	105.9	105.0	0.2	109.2	109.9	108.9	0.2	0.3	1.4	-0.3	0.2	3.5
02/02/08	105.3	105.9	105.1	0.2	109.2	109.9	108.9	0.2	0.4	1.3	-0.4	0.2	3.4
02/03/08	105.4	105.9	105.0	0.2	109.2	109.9	108.9	0.2	0.4	1.3	-0.2	0.2	3.4
02/04/08	105.4	105.9	105.1	0.1	109.3	109.9	109.0	0.2	0.4	1.4	-0.1	0.2	3.5
02/05/08	105.4	105.9	105.1	0.1	109.3	109.9	108.9	0.2	0.3	1.2	-0.2	0.2	3.5

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: NATURAL GAS FURNACE

Graph C.2



Note: Discontinuity of data on the graph reflects time frames during which CSA-On Spex shutdown furnace or data acquisition system for test equipment maintenance or servicing, or adjusted furnace manifold pressure, and were as follows: 1) shutdown on 8/28/07; 2) shutdown from 9/4/07 to 9/10/07; 3) shutdown from 9/29/07 to 10/9/07; 4) increased manifold pressure from approximately 4.5 to 7.0 in. w.c. from 10/10/07 to 10/31/07; 5) shutdown from 11/18/07 to 11/29/07; 6) shutdown from 12/15/07 to 1/3/08; 7) decreased manifold pressure from 4.5. to 3.5 in. w.c. on 01/04/08.

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: NATURAL GAS FURNACE

Table C.2	AGING PHASE Corrosion test ON-cycle data for non-dispersive infrared CO_2 and CO sensors in-situ in a natural gas furnace (August 2007 through February 2008)								
	NDIRCO2#2				NDIRCO#2				Manifold Pressure
	V				V				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
08/20/07	3.4	3.8	3.0	0.1	7.2	9.9	2.9	2.1	4.5
08/21/07	3.2	3.8	2.7	0.1	9.2	9.9	5.2	1.4	4.4
08/22/07	3.0	3.3	2.6	0.1	9.9	9.9	9.1	0.1	4.5
08/23/07	2.9	3.3	0.1	0.2	9.0	9.9	5.6	0.9	4.4
08/24/07	2.7	3.0	0.1	0.2	9.5	9.9	5.9	0.6	4.4
08/26/07	2.7	3.1	0.1	0.2	9.7	9.9	6.9	0.3	4.4
08/27/07	2.6	2.9	0.1	0.1	9.9	9.9	7.5	0.2	4.4
08/28/07	2.6	3.0	0.1	0.2	9.9	9.9	8.8	0.1	4.4
08/29/07	2.6	2.8	0.1	0.2	9.9	9.9	9.9	0.0	4.4
08/30/07	2.6	2.9	0.1	0.3	9.9	9.9	9.9	0.0	4.4
08/31/07	2.6	2.9	0.0	0.3	9.9	9.9	9.9	0.0	4.4
09/01/07	2.6	2.9	0.0	0.3	9.9	9.9	9.9	0.0	4.4
09/02/07	2.6	2.9	0.0	0.2	9.9	9.9	9.9	0.0	4.4
09/03/07	2.5	2.8	0.0	0.3	9.9	9.9	9.9	0.0	4.4
09/11/07	2.7	2.9	0.1	0.3	9.9	9.9	9.9	0.0	4.2
09/12/07	2.5	2.9	0.1	0.2	9.9	9.9	9.9	0.0	4.2
09/14/07	2.6	2.9	0.1	0.3	9.9	9.9	9.9	0.0	4.3
09/15/07	2.5	2.8	0.0	0.3	9.9	9.9	9.9	0.0	4.2
09/16/07	2.4	2.7	0.0	0.2	9.9	9.9	9.9	0.0	4.2
09/17/07	1.9	2.5	0.0	0.2	9.9	9.9	9.9	0.0	4.3
09/18/07	1.7	2.0	0.0	0.2	9.9	9.9	9.9	0.0	4.2
09/19/07	1.5	1.7	0.0	0.1	9.9	9.9	9.9	0.0	4.2
09/20/07	1.6	1.9	0.0	0.2	9.9	9.9	9.9	0.0	4.3
09/21/07	1.4	1.7	0.0	0.2	9.6	9.9	0.0	1.8	4.2
09/22/07	1.4	1.6	0.0	0.1	9.9	9.9	9.9	0.0	4.3
09/23/07	1.2	1.4	0.0	0.1	8.5	9.9	0.0	3.5	4.2
09/24/07	1.5	1.9	0.0	0.2	9.5	9.9	0.0	2.0	4.3
09/25/07	3.3	4.0	0.0	1.0	9.9	9.9	9.9	0.0	4.3
09/26/07	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	4.3
09/27/07	4.0	4.0	4.0	0.0	9.3	9.9	0.0	2.3	4.3
09/28/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.2

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: NATURAL GAS FURNACE

Table C.2	AGING PHASE Corrosion test ON-cycle data for non-dispersive infrared CO_2 and CO sensors in-situ in a natural gas furnace (August 2007 through February 2008)								
	NDIRCO2#2				NDIRCO#2				Manifold Pressure
	V				V				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
10/10/07	3.9	4.0	0.1	0.6	9.9	9.9	9.9	0.0	6.9
10/11/07	3.0	4.0	0.0	0.9	9.2	9.9	0.0	2.6	6.9
10/12/07	3.1	4.0	0.0	1.2	0.0	0.0	0.0	0.0	6.9
10/13/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	6.9
10/14/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	6.9
10/15/07	4.0	4.0	4.0	0.0	3.4	9.9	0.0	4.7	6.9
10/16/07	4.0	4.0	4.0	0.0	4.0	9.9	0.0	4.9	6.9
10/17/07	4.0	4.0	4.0	0.0	2.5	9.9	0.0	4.3	7.0
10/18/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	6.9
10/19/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	6.9
10/20/07	4.0	4.0	4.0	0.0	1.5	9.9	0.0	3.6	6.9
10/21/07	4.0	4.0	4.0	0.0	2.4	9.9	0.0	4.2	6.9
10/22/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	6.9
10/23/07	4.0	4.0	4.0	0.0	3.1	9.9	0.0	4.6	6.9
10/24/07	4.0	4.0	4.0	0.0	0.1	9.9	0.0	0.6	7.0
10/25/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	6.1
10/26/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
10/27/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
10/28/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
10/29/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
10/30/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
10/31/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/01/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/02/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/03/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/04/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/05/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/06/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/07/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/08/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/09/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/10/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: NATURAL GAS FURNACE

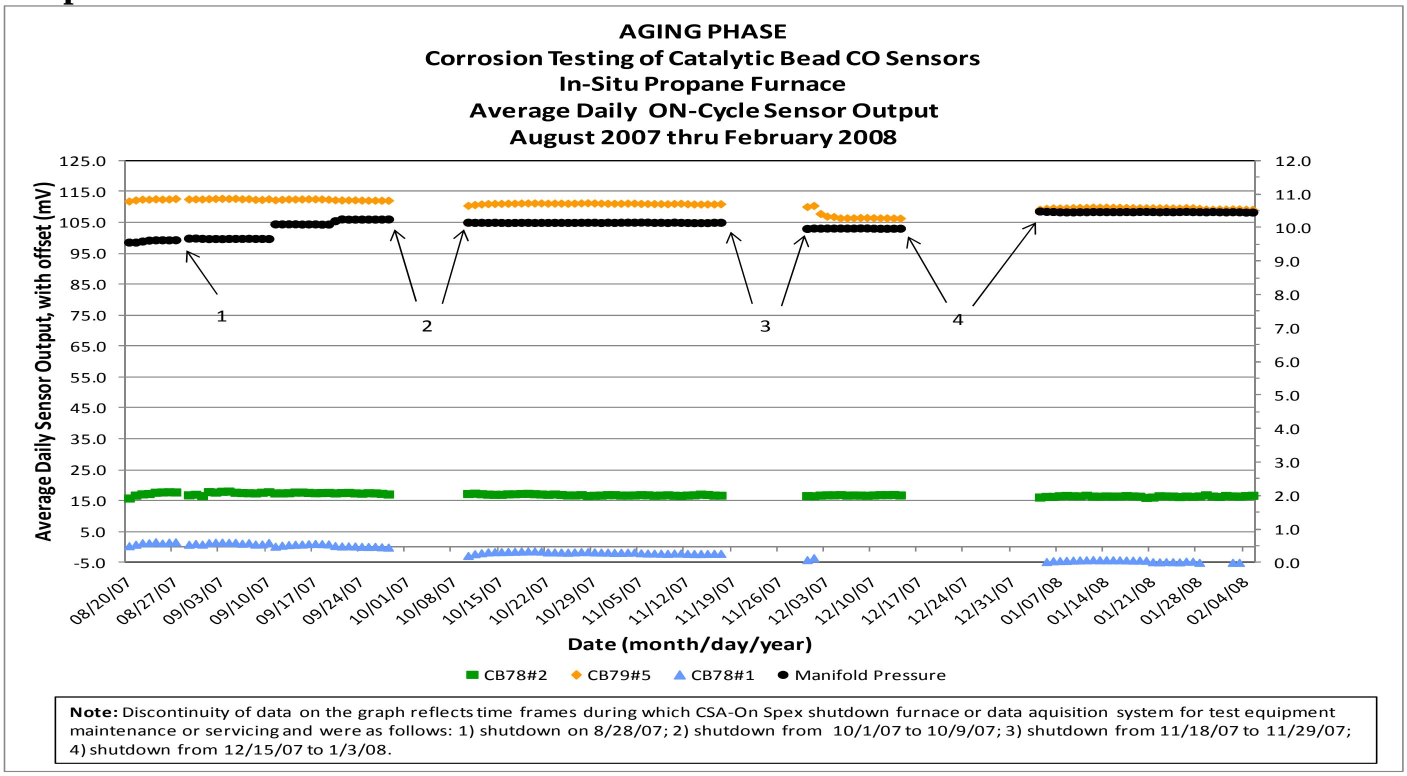
Table C.2	AGING PHASE Corrosion test ON-cycle data for non-dispersive infrared CO_2 and CO sensors in-situ in a natural gas furnace (August 2007 through February 2008)								
	NDIRCO2#2				NDIRCO#2				Manifold Pressure
	V				V				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
11/11/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/12/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/13/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/14/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/15/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/16/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/17/07	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	4.4
11/30/07	3.4	4.0	0.2	0.5	0.0	0.0	0.0	0.0	4.5
12/01/07	3.5	4.0	0.2	0.4	0.0	0.0	0.0	0.0	4.5
12/02/07	3.2	3.9	0.1	0.4	0.0	0.0	0.0	0.0	4.5
12/03/07	2.6	3.4	0.1	0.4	0.0	0.0	0.0	0.0	4.5
12/04/07	1.7	2.6	0.0	0.4	0.0	0.0	0.0	0.0	4.5
12/05/07	1.2	1.6	0.0	0.2	0.0	0.0	0.0	0.0	4.5
12/06/07	2.1	4.0	0.0	0.6	9.2	9.9	0.0	2.6	4.5
12/07/07	4.0	4.0	0.4	0.2	9.9	9.9	9.9	0.0	4.5
12/08/07	4.0	4.0	3.4	0.0	9.9	9.9	9.9	0.0	4.5
12/09/07	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	4.5
12/10/07	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	4.5
12/11/07	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	4.5
12/12/07	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	4.5
12/13/07	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	4.5
12/14/07	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	4.5
01/04/08	2.8	3.1	0.2	0.2	9.9	9.9	9.9	0.0	3.5
01/05/08	2.8	3.1	0.2	0.2	9.9	9.9	9.9	0.0	3.5
01/06/08	2.7	3.1	2.3	0.1	9.9	9.9	9.9	0.0	3.5
01/07/08	2.7	3.0	0.1	0.2	9.9	9.9	9.9	0.0	3.5
01/08/08	2.7	3.1	0.1	0.2	9.9	9.9	9.9	0.0	3.5
01/09/08	2.7	3.0	0.2	0.2	9.9	9.9	9.9	0.0	3.5
01/10/08	2.6	3.0	0.1	0.2	9.9	9.9	9.9	0.0	3.5
01/11/08	2.5	2.8	0.1	0.1	9.9	9.9	9.9	0.0	3.5
01/12/08	2.4	2.8	0.1	0.2	9.9	9.9	9.9	0.0	3.4
01/13/08	2.1	2.4	1.7	0.1	9.9	9.9	9.9	0.0	3.4

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: NATURAL GAS FURNACE

Table C.2	AGING PHASE Corrosion test ON-cycle data for non-dispersive infrared CO_2 and CO sensors in-situ in a natural gas furnace (August 2007 through February 2008)								
	NDIRCO2#2				NDIRCO#2				Manifold Pressure
	V				V				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
01/14/08	1.7	2.1	0.0	0.2	9.9	9.9	9.9	0.0	3.5
01/15/08	1.4	1.7	1.1	0.1	9.9	9.9	9.9	0.0	3.5
01/16/08	1.2	1.5	0.0	0.1	9.9	9.9	9.9	0.0	3.4
01/17/08	1.1	1.4	0.0	0.1	9.9	9.9	9.9	0.0	3.4
01/18/08	1.0	1.2	0.0	0.1	9.9	9.9	9.9	0.0	3.5
01/19/08	1.1	1.2	0.8	0.1	9.9	9.9	9.9	0.0	3.4
01/20/08	1.0	1.3	0.0	0.1	9.9	9.9	9.9	0.0	3.4
01/21/08	1.3	1.8	0.0	0.2	9.9	9.9	9.9	0.0	3.4
01/22/08	1.8	2.3	1.3	0.2	9.9	9.9	9.9	0.0	3.5
01/23/08	2.8	4.0	0.1	0.5	9.9	9.9	9.9	0.0	3.5
01/24/08	4.0	4.0	0.7	0.1	9.9	9.9	9.9	0.0	3.5
01/25/08	4.0	4.0	1.9	0.1	9.9	9.9	9.9	0.0	3.5
01/26/08	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	3.4
01/27/08	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	3.4
01/28/08	4.0	4.0	3.8	0.0	9.9	9.9	9.9	0.0	3.5
01/29/08	4.0	4.0	1.1	0.3	9.9	9.9	9.9	0.0	3.4
01/30/08	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	3.4
01/31/08	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	3.5
02/01/08	4.0	4.0	4.0	0.0	9.9	9.9	9.9	0.0	3.5
02/02/08	4.0	4.0	2.3	0.2	9.9	9.9	9.9	0.0	3.4
02/03/08	4.0	4.0	2.3	0.3	9.9	9.9	9.9	0.0	3.4
02/04/08	4.0	4.0	2.5	0.2	9.9	9.9	9.9	0.0	3.5
02/05/08	4.0	4.0	3.1	0.1	9.9	9.9	9.9	0.0	3.5

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: PROPANE GAS FURNACE

Graph C.3



APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: PROPANE GAS FURNACE

Table C.3	AGING PHASE Corrosion test ON-cycle data for catalytic bead CO sensors in-situ in a propane furnace (August 2007 through February 2008)												
	CB78A#2				CB79A#5				CB78A#1				Manifold Pressure
	mV				mV				mV				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
08/20/07	15.9	26.3	12.6	3.4	112.0	112.6	111.7	0.2	0.5	2.3	-0.4	0.5	9.6
08/21/07	16.8	28.0	13.7	3.5	112.3	113.0	111.9	0.2	0.9	3.3	-0.4	0.6	9.6
08/22/07	17.2	31.3	14.2	3.4	112.6	113.4	112.3	0.1	1.5	4.2	0.1	0.5	9.6
08/23/07	17.4	25.9	14.7	3.2	112.5	112.9	112.4	0.1	1.4	2.6	0.7	0.4	9.6
08/24/07	17.8	50.7	14.8	3.9	112.7	130.9	112.4	1.3	1.8	40.5	0.2	2.8	9.6
08/25/07	17.9	33.6	15.2	3.4	112.6	114.9	111.4	0.2	1.3	6.1	0.2	0.6	9.6
08/26/07	17.9	37.1	15.3	3.5	112.6	118.2	112.4	0.3	1.6	19.8	0.2	1.1	9.6
08/27/07	17.9	44.0	14.8	3.7	112.8	122.3	112.5	0.5	1.7	28.8	0.4	1.5	9.6
08/29/07	17.0	26.4	14.2	3.5	112.6	112.9	112.4	0.1	1.0	2.5	0.4	0.4	9.7
08/30/07	17.1	53.4	13.7	4.5	112.7	122.7	112.4	0.8	1.2	37.8	-0.2	2.6	9.7
08/31/07	16.7	33.7	13.6	3.4	112.6	116.0	112.4	0.2	1.0	6.9	0.1	0.5	9.7
09/01/07	18.0	54.5	14.7	4.1	112.7	136.0	112.4	0.9	1.5	47.4	0.2	2.3	9.7
09/02/07	17.8	60.9	14.5	4.2	112.8	136.0	112.5	1.1	1.6	63.9	0.2	3.4	9.7
09/03/07	18.1	66.7	14.7	4.2	112.8	147.9	112.5	1.6	1.6	69.0	0.4	3.1	9.7
09/04/07	18.1	62.6	14.5	4.6	112.8	129.4	112.0	0.9	1.6	33.9	0.6	2.0	9.7
09/05/07	17.8	53.9	14.4	4.6	112.8	140.7	112.4	1.6	1.6	57.4	0.1	3.0	9.7
09/06/07	17.7	39.3	14.2	4.2	112.7	122.3	112.3	0.8	1.3	19.3	0.2	1.5	9.7
09/07/07	17.6	50.9	13.9	4.9	112.7	140.9	112.3	2.3	1.5	61.5	0.4	4.9	9.7
09/08/07	17.6	66.9	13.9	4.5	112.5	142.2	112.1	1.6	1.0	78.8	0.4	4.3	9.7
09/09/07	17.8	34.5	14.5	3.8	112.5	115.5	112.3	0.2	1.1	8.2	0.4	0.5	9.7
09/10/07	18.0	73.1	14.5	5.3	112.7	141.0	112.4	1.9	1.5	91.6	0.6	6.1	9.7
09/11/07	17.6	25.5	14.5	3.1	112.4	112.8	112.2	0.1	0.4	1.3	-0.2	0.2	10.1
09/12/07	17.5	25.6	14.7	3.1	112.5	112.9	112.3	0.1	0.7	1.7	0.2	0.2	10.1
09/13/07	17.6	25.6	14.7	3.1	112.6	113.0	112.4	0.1	0.9	1.8	0.6	0.2	10.1
09/14/07	17.8	25.9	15.3	3.1	112.6	112.9	112.4	0.1	1.0	1.8	0.7	0.2	10.1
09/15/07	17.8	25.6	15.3	3.1	112.6	113.0	112.5	0.1	1.0	1.8	0.7	0.2	10.1
09/16/07	17.7	25.6	15.2	3.1	112.7	113.0	112.5	0.1	1.1	2.1	0.7	0.3	10.1
09/17/07	17.6	25.6	15.2	3.1	112.7	113.1	112.4	0.1	1.2	2.1	0.7	0.2	10.1
09/18/07	17.7	25.6	15.2	3.1	112.6	113.2	112.4	0.1	1.2	2.3	0.7	0.2	10.1
09/19/07	17.7	25.5	15.2	3.1	112.5	112.8	112.4	0.1	1.1	2.1	0.9	0.3	10.1
09/20/07	17.6	25.5	14.2	3.1	112.4	112.8	112.1	0.1	0.5	2.1	-0.1	0.4	10.2
09/21/07	17.6	25.5	14.8	3.1	112.3	112.6	112.2	0.1	0.4	1.3	0.1	0.2	10.3

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: PROPANE GAS FURNACE

Table C.3	AGING PHASE Corrosion test ON-cycle data for catalytic bead CO sensors in-situ in a propane furnace (August 2007 through February 2008)												
	CB78A#2				CB79A#5				CB78A#1				Manifold Pressure
	mV				mV				mV				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
09/22/07	17.7	25.6	15.2	3.1	112.4	112.5	112.2	0.0	0.4	1.2	0.2	0.2	10.3
09/23/07	17.5	25.6	14.8	3.1	112.3	112.6	112.2	0.1	0.4	1.3	0.1	0.2	10.3
09/24/07	17.5	25.6	14.7	3.1	112.3	112.5	112.1	0.1	0.3	1.2	0.1	0.1	10.3
09/25/07	17.6	25.6	14.8	3.1	112.2	112.5	112.1	0.1	0.2	0.9	0.1	0.2	10.3
09/26/07	17.6	25.5	14.8	3.1	112.2	112.5	112.1	0.1	0.3	1.2	0.1	0.2	10.3
09/27/07	17.4	25.5	14.7	3.1	112.2	112.5	112.1	0.1	0.1	1.2	-0.2	0.2	10.3
09/28/07	17.2	25.5	14.7	3.2	112.2	112.4	112.1	0.1	0.0	0.7	-0.2	0.2	10.3
10/10/07	17.4	25.6	14.4	3.1	110.6	110.9	110.4	0.1	-2.7	-1.5	-3.3	0.3	10.2
10/11/07	17.5	25.5	14.8	3.2	110.8	111.2	110.6	0.1	-2.1	-1.2	-2.5	0.2	10.2
10/12/07	17.3	25.6	14.7	3.2	111.0	111.4	110.9	0.1	-1.8	-0.7	-2.1	0.2	10.2
10/13/07	17.2	25.5	14.5	3.2	111.1	111.4	111.0	0.1	-1.5	-0.4	-2.0	0.2	10.2
10/14/07	17.1	25.5	14.4	3.2	111.2	111.5	111.1	0.1	-1.4	-0.4	-1.7	0.2	10.2
10/15/07	17.1	25.3	14.5	3.2	111.2	111.6	111.1	0.1	-1.4	-0.4	-1.7	0.2	10.2
10/16/07	17.2	25.6	14.4	3.2	111.3	111.5	110.9	0.1	-1.4	-0.4	-2.0	0.2	10.2
10/17/07	17.3	25.6	14.7	3.2	111.3	111.5	111.1	0.1	-1.3	-0.4	-1.7	0.2	10.2
10/18/07	17.4	25.6	14.7	3.2	111.3	111.6	111.1	0.1	-1.2	-0.2	-1.5	0.3	10.2
10/19/07	17.4	25.8	14.7	3.2	111.3	111.6	111.2	0.1	-1.2	-0.1	-1.5	0.2	10.2
10/20/07	17.3	25.5	14.8	3.2	111.3	111.6	111.2	0.1	-1.2	-0.2	-1.5	0.2	10.2
10/21/07	17.2	25.5	14.5	3.2	111.3	111.6	111.2	0.1	-1.3	-0.2	-1.5	0.2	10.2
10/22/07	17.1	25.5	14.5	3.2	111.3	111.6	111.1	0.1	-1.6	-0.4	-2.1	0.4	10.2
10/23/07	17.2	25.3	14.5	3.2	111.3	111.5	111.2	0.1	-1.5	-0.6	-2.0	0.3	10.2
10/24/07	17.0	25.3	14.4	3.2	111.3	111.5	111.1	0.1	-1.6	-0.6	-2.0	0.2	10.2
10/25/07	16.9	25.0	14.2	3.2	111.2	111.4	111.0	0.1	-1.6	-1.0	-2.1	0.2	10.2
10/26/07	16.9	25.3	14.4	3.2	111.3	111.5	111.2	0.0	-1.5	-0.7	-2.0	0.2	10.2
10/27/07	17.0	25.3	14.4	3.2	111.4	111.5	111.2	0.0	-1.4	-0.6	-1.7	0.2	10.2
10/28/07	16.7	25.0	14.2	3.3	111.4	111.6	111.3	0.0	-1.4	-0.6	-1.7	0.2	10.2
10/29/07	16.8	25.3	14.2	3.3	111.3	111.5	111.1	0.1	-1.5	-0.6	-2.0	0.2	10.2
10/30/07	16.9	25.0	14.2	3.2	111.3	111.5	111.0	0.1	-1.6	-0.7	-2.0	0.2	10.2
10/31/07	17.0	25.3	14.4	3.2	111.2	111.4	111.1	0.1	-1.6	-0.7	-2.0	0.2	10.2
11/01/07	17.0	25.0	14.4	3.2	111.2	111.4	111.0	0.0	-1.7	-1.0	-2.1	0.2	10.2
11/02/07	16.8	25.0	14.2	3.2	111.2	111.4	111.1	0.1	-1.7	-1.0	-2.0	0.2	10.2
11/03/07	16.9	25.0	14.4	3.2	111.3	111.4	111.2	0.0	-1.6	-1.0	-2.0	0.1	10.2

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: PROPANE GAS FURNACE

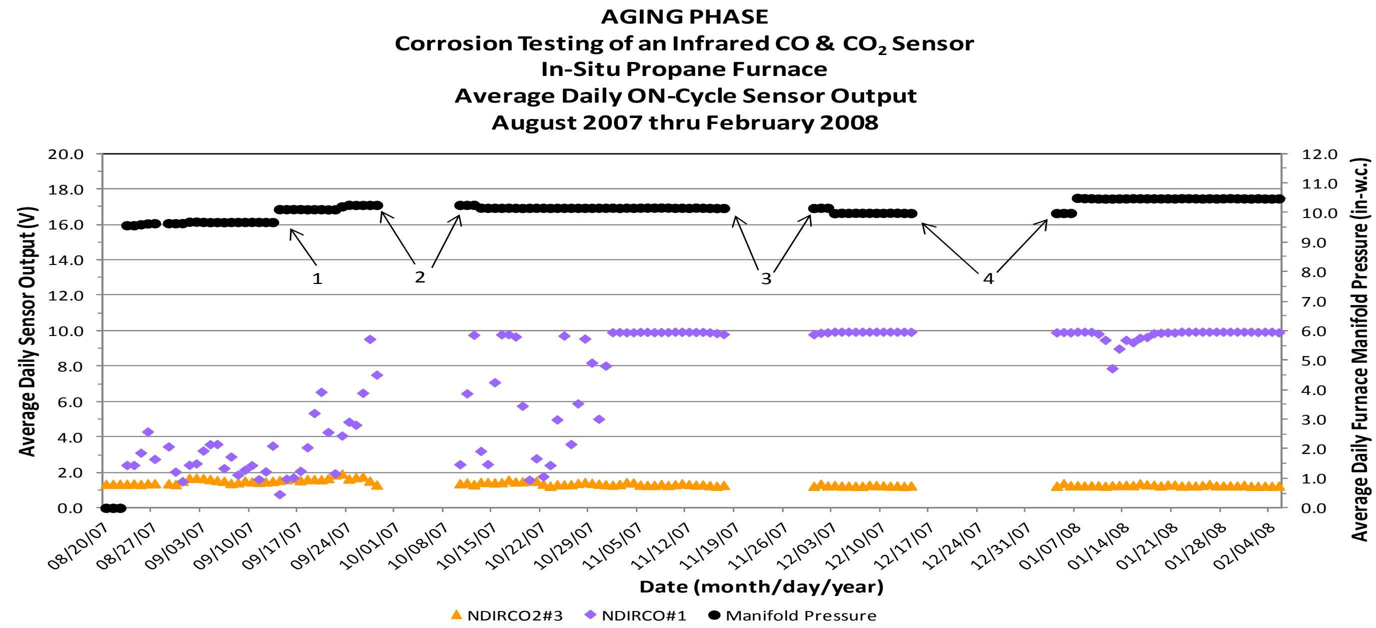
Table C.3	AGING PHASE Corrosion test ON-cycle data for catalytic bead CO sensors in-situ in a propane furnace (August 2007 through February 2008)												
	CB78A#2				CB79A#5				CB78A#1				Manifold Pressure
	mV				mV				mV				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
11/04/07	16.9	25.0	14.4	3.2	111.3	111.4	111.2	0.0	-1.6	-1.0	-2.0	0.1	10.2
11/05/07	17.0	25.0	14.4	3.2	111.2	111.4	111.0	0.1	-1.8	-1.0	-2.1	0.2	10.2
11/06/07	16.9	25.0	14.4	3.2	111.2	111.3	111.0	0.1	-1.9	-1.2	-2.1	0.2	10.2
11/07/07	16.8	25.3	14.2	3.2	111.1	111.3	110.9	0.1	-1.9	-1.2	-2.1	0.2	10.2
11/08/07	16.8	25.0	14.2	3.2	111.1	111.3	110.9	0.1	-1.9	-1.2	-2.3	0.2	10.2
11/09/07	17.0	25.0	14.4	3.2	111.1	111.2	110.9	0.1	-2.0	-1.2	-2.1	0.2	10.2
11/10/07	16.8	25.0	14.2	3.2	111.2	111.3	111.1	0.0	-1.9	-1.2	-2.1	0.2	10.2
11/11/07	16.8	25.0	14.2	3.2	111.2	111.4	111.1	0.0	-1.9	-1.2	-2.1	0.2	10.2
11/12/07	16.9	25.3	14.4	3.2	111.1	111.3	110.9	0.1	-2.0	-1.2	-2.3	0.2	10.2
11/13/07	16.9	25.0	14.5	3.2	111.0	111.2	110.8	0.1	-2.1	-1.5	-2.3	0.1	10.2
11/14/07	17.1	25.3	14.5	3.2	111.0	111.1	110.8	0.1	-2.0	-1.3	-2.3	0.2	10.2
11/15/07	17.0	25.3	14.5	3.2	111.0	111.2	110.8	0.1	-2.0	-1.3	-2.3	0.2	10.2
11/16/07	16.8	25.3	14.4	3.2	111.0	111.3	110.8	0.1	-2.0	-1.2	-2.1	0.2	10.2
11/17/07	16.8	24.8	14.4	3.2	111.1	111.2	111.0	0.0	-2.0	-1.3	-2.1	0.2	10.2
11/30/07	16.7	29.3	13.7	3.3	110.2	110.4	109.3	0.1	-4.0	-3.3	-6.3	0.3	10.0
12/01/07	16.7	24.7	13.9	3.2	110.5	110.7	110.3	0.1	-3.4	-2.6	-3.7	0.2	10.0
12/02/07	16.8	25.0	14.2	3.2	107.9	110.8	105.9	1.6	-5.8	-2.5	-7.5	1.5	10.0
12/03/07	17.0	25.3	14.4	3.2	107.1	107.2	106.8	0.1	-6.7	-6.0	-7.1	0.1	10.0
12/04/07	16.9	25.0	14.4	3.2	106.9	107.2	106.6	0.2	-6.9	-6.1	-7.4	0.2	10.0
12/05/07	17.0	25.3	14.5	3.2	106.5	106.8	106.2	0.1	-7.3	-6.6	-7.5	0.2	10.0
12/06/07	16.8	25.0	14.2	3.2	106.5	106.6	106.3	0.1	-7.4	-6.7	-7.5	0.1	10.0
12/07/07	16.9	25.0	14.4	3.2	106.6	106.7	106.3	0.1	-7.3	-6.6	-7.5	0.1	10.0
12/08/07	16.8	25.0	14.2	3.2	106.6	106.8	106.5	0.0	-7.3	-6.6	-7.4	0.2	10.0
12/09/07	16.8	25.3	14.2	3.2	106.6	106.8	106.5	0.0	-7.3	-6.6	-7.5	0.2	10.0
12/10/07	16.9	25.0	14.4	3.2	106.6	106.8	106.3	0.1	-7.4	-6.6	-7.5	0.1	10.0
12/11/07	17.0	25.3	14.2	3.2	106.5	106.7	106.3	0.1	-7.4	-6.7	-8.0	0.1	10.0
12/12/07	17.0	25.3	14.5	3.2	106.5	106.6	106.2	0.1	-7.4	-6.7	-7.5	0.1	10.0
12/13/07	17.0	25.3	14.4	3.2	106.5	106.6	106.2	0.1	-7.5	-6.7	-8.0	0.1	10.0
12/14/07	16.9	25.3	14.4	3.2	106.4	106.6	106.2	0.1	-7.5	-6.7	-8.0	0.1	10.0
01/04/08	16.2	24.7	13.3	3.3	109.3	109.5	109.0	0.1	-5.2	-4.5	-6.0	0.2	10.5
01/05/08	16.4	24.8	13.7	3.3	109.6	109.8	109.4	0.1	-4.6	-4.0	-5.0	0.2	10.5
01/06/08	16.4	24.7	13.7	3.2	109.7	109.9	109.6	0.0	-4.4	-3.7	-4.5	0.1	10.5

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: PROPANE GAS FURNACE

Table C.3	AGING PHASE Corrosion test ON-cycle data for catalytic bead CO sensors in-situ in a propane furnace (August 2007 through February 2008)												
	CB78A#2				CB79A#5				CB78A#1				Manifold Pressure
	mV				mV				mV				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
01/07/08	16.7	24.8	13.9	3.2	109.7	109.9	109.5	0.1	-4.3	-3.7	-4.5	0.1	10.5
01/08/08	16.8	25.3	13.9	3.2	109.7	109.9	109.6	0.1	-4.3	-3.7	-4.4	0.1	10.5
01/09/08	16.7	24.8	13.9	3.2	109.8	110.1	109.6	0.1	-4.2	-3.6	-4.4	0.1	10.5
01/10/08	16.6	24.8	13.9	3.2	109.9	110.1	109.6	0.1	-4.1	-3.4	-4.4	0.1	10.5
01/11/08	16.8	25.0	14.2	3.2	109.9	110.1	109.7	0.1	-4.1	-3.6	-4.2	0.1	10.5
01/12/08	16.5	24.8	13.9	3.3	110.0	110.1	109.9	0.0	-4.0	-3.4	-4.2	0.2	10.5
01/13/08	16.5	24.8	13.9	3.2	110.0	110.1	109.8	0.1	-4.0	-3.4	-4.2	0.2	10.5
01/14/08	16.6	24.8	13.9	3.2	110.0	110.1	109.8	0.1	-4.0	-3.4	-4.2	0.2	10.5
01/15/08	16.5	24.8	13.9	3.2	109.9	110.1	109.6	0.1	-4.1	-3.4	-4.4	0.1	10.5
01/16/08	16.6	25.5	13.7	3.2	109.9	110.2	109.7	0.1	-4.1	-3.4	-4.4	0.2	10.5
01/17/08	16.7	25.5	13.9	3.2	109.9	110.2	109.6	0.1	-4.1	-3.3	-4.4	0.1	10.5
01/18/08	16.6	24.7	13.9	3.2	109.8	110.0	109.5	0.1	-4.2	-3.4	-4.4	0.1	10.5
01/19/08	16.5	24.8	13.6	3.3	109.8	109.9	109.7	0.0	-4.2	-3.4	-4.4	0.2	10.5
01/20/08	16.1	24.8	13.6	3.3	109.8	110.0	109.6	0.1	-4.2	-3.4	-4.4	0.1	10.5
01/21/08	16.2	24.7	13.4	3.2	109.8	109.9	109.5	0.1	-4.7	-3.7	-5.3	0.4	10.5
01/22/08	16.7	24.8	14.2	3.2	109.8	109.9	109.5	0.1	-4.7	-4.4	-5.2	0.2	10.5
01/23/08	16.6	24.8	13.9	3.2	109.8	109.9	109.5	0.1	-4.7	-4.2	-5.0	0.1	10.5
01/24/08	16.5	24.8	13.7	3.2	109.7	109.9	109.4	0.1	-4.7	-4.0	-5.0	0.1	10.5
01/25/08	16.4	24.7	13.7	3.2	109.7	109.9	109.3	0.1	-4.7	-4.0	-5.2	0.2	10.5
01/26/08	16.5	24.8	13.9	3.3	109.8	109.9	109.7	0.0	-4.5	-3.7	-4.7	0.2	10.5
01/27/08	16.5	24.8	13.9	3.2	109.8	110.0	109.6	0.1	-4.5	-3.7	-4.7	0.1	10.5
01/28/08	16.6	24.8	13.9	3.2	109.6	109.9	109.2	0.2	-4.9	-4.0	-5.3	0.3	10.5
01/29/08	17.0	25.3	14.2	3.1	109.4	109.6	109.1	0.1	-5.1	-4.4	-5.3	0.2	10.5
01/30/08	16.5	25.3	13.4	3.2	109.3	109.5	109.0	0.1	-5.2	-4.4	-5.6	0.2	10.5
01/31/08	16.4	24.7	13.7	3.2	109.4	109.5	109.1	0.1	-5.1	-4.2	-5.3	0.2	10.5
02/01/08	16.7	24.8	14.2	3.2	109.4	109.6	109.1	0.1	-5.0	-4.2	-5.3	0.2	10.5
02/02/08	16.6	24.8	13.9	3.2	109.5	109.6	109.3	0.0	-4.9	-4.0	-5.2	0.2	10.5
02/03/08	16.5	24.8	13.7	3.2	109.4	109.6	109.2	0.0	-4.9	-4.0	-5.2	0.2	10.5
02/04/08	16.7	25.0	13.9	3.2	109.3	109.5	109.0	0.1	-5.0	-4.2	-5.3	0.2	10.5
02/05/08	16.8	25.0	14.4	3.2	109.3	109.4	109.0	0.1	-5.1	-4.2	-5.3	0.2	10.5

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: PROPANE GAS FURNACE

Graph C.4



Note: Discontinuity of data in the graph reflects time frames during which CSA-On Spex shutdown furnace or data aquisition system for test equipment maintenance or servicing and were as follows: 1) shutdown on 8/28/07; 2) shutdown from 10/1/07 to 10/9/07; 3) shutdown from 11/18/07 to 11/29/07; 4) shutdown from 12/15/07 to 1/3/08.

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: PROPANE GAS FURNACE

Table C.4	AGING PHASE Corrosion test ON-cycle data for non-dispersive infrared CO_2 and CO sensors in-situ in a propane furnace (August 2007 through February 2008)								
	NDIRCO2#3				NDIRCO#1				Manifold Pressure
	V				V				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
08/20/07	1.4	1.6	1.2	0.1	2.4	1.5	1.5	1.3	9.6
08/21/07	1.4	1.6	1.2	0.1	2.4	1.5	1.5	1.3	9.6
08/22/07	1.4	1.6	1.2	0.1	3.1	0.2	0.2	1.1	9.6
08/23/07	1.4	1.6	1.2	0.1	4.3	1.8	1.8	1.5	9.6
08/24/07	1.4	1.6	0.1	0.1	2.8	1.4	1.4	1.2	9.6
08/25/07	1.3	1.6	0.1	0.1	3.5	0.9	0.9	1.8	9.6
08/26/07	1.4	1.7	0.1	0.1	2.0	0.8	0.8	0.5	9.6
08/27/07	1.4	1.7	0.1	0.1	1.5	0.0	0.0	0.7	9.6
08/29/07	1.4	1.6	1.2	0.1	2.4	1.3	1.3	1.4	9.7
08/30/07	1.3	1.8	0.1	0.2	2.5	0.8	0.8	2.4	9.7
08/31/07	1.5	2.1	0.8	0.2	3.2	0.5	0.5	1.8	9.7
09/01/07	1.7	2.3	0.1	0.2	3.6	0.9	0.9	2.2	9.7
09/02/07	1.7	2.3	0.1	0.2	3.6	1.2	1.2	2.2	9.7
09/03/07	1.7	2.3	0.1	0.2	2.2	0.7	0.7	2.3	9.7
09/04/07	1.6	2.1	0.1	0.3	2.9	1.3	1.3	1.5	9.7
09/05/07	1.6	1.9	0.1	0.2	1.9	0.9	0.9	1.2	9.7
09/06/07	1.5	2.1	0.1	0.2	2.1	0.9	0.9	1.2	9.7
09/07/07	1.4	1.9	0.1	0.2	2.4	0.7	0.7	1.4	9.7
09/08/07	1.4	1.9	0.1	0.2	1.6	0.6	0.6	0.8	9.7
09/09/07	1.5	2.0	0.2	0.1	2.1	1.0	1.0	1.3	9.7
09/10/07	1.5	2.0	0.1	0.2	3.5	1.8	1.8	1.3	9.7
09/11/07	1.5	1.9	1.2	0.1	0.8	0.5	0.5	0.1	10.1
09/12/07	1.5	1.9	1.2	0.1	1.6	0.8	0.8	1.6	10.1
09/13/07	1.5	1.9	1.3	0.1	1.7	0.8	0.8	0.9	10.1
09/14/07	1.6	2.2	1.3	0.1	2.1	0.9	0.9	1.4	10.1
09/15/07	1.6	2.1	1.3	0.1	3.4	0.9	0.9	2.1	10.1
09/16/07	1.7	2.1	1.4	0.1	5.4	2.5	2.5	1.9	10.1
09/17/07	1.6	2.2	1.2	0.2	6.5	2.3	2.3	2.3	10.1
09/18/07	1.6	2.4	1.4	0.2	4.3	1.7	1.7	2.3	10.1
09/19/07	1.6	2.1	1.3	0.2	1.9	1.1	1.1	0.8	10.1

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: PROPANE GAS FURNACE

Table C.4	AGING PHASE Corrosion test ON-cycle data for non-dispersive infrared CO_2 and CO sensors in-situ in a propane furnace (August 2007 through February 2008)								
	NDIRCO2#3				NDIRCO#1				Manifold Pressure
	V				V				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
09/20/07	1.6	2.5	1.2	0.2	4.1	1.1	1.1	2.4	10.2
09/21/07	1.7	2.5	1.4	0.2	4.9	1.6	1.6	2.7	10.3
09/22/07	1.9	2.5	1.5	0.2	4.7	2.4	2.4	1.6	10.3
09/23/07	1.9	2.5	1.5	0.2	6.5	1.8	1.8	3.2	10.3
09/24/07	1.7	2.4	1.2	0.2	9.5	7.8	7.8	0.4	10.3
09/25/07	1.7	2.5	1.4	0.3	7.5	3.9	3.9	1.7	10.3
09/26/07	1.8	2.5	1.3	0.3	2.5	1.2	1.2	1.2	10.3
09/27/07	1.5	2.5	1.0	0.3	6.5	1.1	1.1	4.2	10.3
09/28/07	1.3	1.6	0.9	0.1	9.8	9.3	9.3	0.1	10.3
10/10/07	1.4	2.2	1.0	0.2	3.2	0.2	0.2	2.3	10.2
10/11/07	1.4	2.2	1.1	0.2	2.5	1.0	1.0	1.2	10.2
10/12/07	1.3	2.1	1.0	0.1	7.1	2.3	2.3	2.3	10.2
10/13/07	1.5	2.2	1.1	0.2	9.8	8.6	8.6	0.2	10.2
10/14/07	1.5	2.0	1.1	0.2	9.8	9.1	9.1	0.1	10.2
10/15/07	1.4	1.9	1.0	0.2	9.7	8.5	8.5	0.3	10.2
10/16/07	1.4	2.1	1.0	0.2	5.8	2.0	2.0	2.0	10.2
10/17/07	1.6	2.3	1.0	0.3	1.6	0.8	0.8	0.8	10.2
10/18/07	1.5	2.2	1.0	0.2	2.8	1.1	1.1	1.5	10.2
10/19/07	1.5	2.1	1.1	0.2	1.8	0.7	0.7	1.2	10.2
10/20/07	1.5	2.0	1.2	0.2	2.4	0.8	0.8	1.6	10.2
10/21/07	1.5	2.0	1.1	0.2	5.0	1.2	1.2	2.8	10.2
10/22/07	1.4	2.0	1.1	0.2	9.7	9.0	9.0	0.2	10.2
10/23/07	1.2	2.1	0.8	0.2	3.6	1.1	1.1	2.1	10.2
10/24/07	1.3	2.2	1.0	0.2	5.9	1.3	1.3	2.9	10.2
10/25/07	1.3	2.1	1.0	0.2	9.6	7.2	7.2	0.6	10.2
10/26/07	1.3	1.9	1.0	0.2	8.2	4.8	4.8	1.7	10.2
10/27/07	1.4	2.1	1.0	0.3	5.0	3.4	3.4	0.9	10.2
10/28/07	1.5	2.1	1.0	0.3	8.0	3.4	3.4	2.0	10.2
10/29/07	1.4	2.0	1.1	0.2	9.9	9.8	9.8	0.0	10.2
10/30/07	1.4	1.9	1.0	0.2	9.9	9.8	9.8	0.0	10.2

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: PROPANE GAS FURNACE

Table C.4	AGING PHASE Corrosion test ON-cycle data for non-dispersive infrared CO_2 and CO sensors in-situ in a propane furnace (August 2007 through February 2008)								
	NDIRCO2#3				NDIRCO#1				Manifold Pressure
	V				V				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
10/31/07	1.3	1.9	1.0	0.2	9.9	9.8	9.8	0.0	10.2
11/01/07	1.3	1.8	1.1	0.1	9.9	9.8	9.8	0.0	10.2
11/02/07	1.3	2.0	1.0	0.2	9.9	9.8	9.8	0.0	10.2
11/03/07	1.4	2.0	1.1	0.2	9.9	9.8	9.8	0.0	10.2
11/04/07	1.4	1.9	1.1	0.1	9.9	9.8	9.8	0.0	10.2
11/05/07	1.3	1.8	1.0	0.1	9.9	9.8	9.8	0.0	10.2
11/06/07	1.3	1.8	1.0	0.1	9.9	9.8	9.8	0.0	10.2
11/07/07	1.3	1.8	1.0	0.1	9.9	9.8	9.8	0.0	10.2
11/08/07	1.3	1.9	1.1	0.2	9.9	9.8	9.8	0.0	10.2
11/09/07	1.3	1.7	1.1	0.1	9.9	9.8	9.8	0.0	10.2
11/10/07	1.3	1.9	1.0	0.2	9.9	9.8	9.8	0.0	10.2
11/11/07	1.4	1.9	1.0	0.1	9.9	9.8	9.8	0.0	10.2
11/12/07	1.3	1.8	1.0	0.1	9.9	9.8	9.8	0.0	10.2
11/13/07	1.3	1.9	1.1	0.1	9.9	9.6	9.6	0.1	10.2
11/14/07	1.3	1.8	1.1	0.1	9.8	9.3	9.3	0.1	10.2
11/15/07	1.3	1.8	1.0	0.1	9.8	9.0	9.0	0.1	10.2
11/16/07	1.2	1.4	1.0	0.1	9.9	9.7	9.7	0.1	10.2
11/17/07	1.3	1.8	1.1	0.1	9.9	9.8	9.8	0.0	10.2
11/30/07	1.2	1.8	0.1	0.1	9.9	9.9	9.9	0.0	10.0
12/01/07	1.4	1.9	1.1	0.2	9.9	9.9	9.9	0.0	10.0
12/02/07	1.3	1.7	1.1	0.1	9.9	9.9	9.9	0.0	10.0
12/03/07	1.3	1.8	1.0	0.1	9.9	9.8	9.8	0.0	10.0
12/04/07	1.3	1.7	1.1	0.1	9.9	9.8	9.8	0.0	10.0
12/05/07	1.3	1.7	1.1	0.1	9.9	9.9	9.9	0.0	10.0
12/06/07	1.2	1.7	1.0	0.1	9.9	9.8	9.8	0.0	10.0
12/07/07	1.2	1.8	1.0	0.1	9.9	9.9	9.9	0.0	10.0
12/08/07	1.3	1.7	1.0	0.1	9.9	9.8	9.8	0.0	10.0
12/09/07	1.3	1.9	1.1	0.1	9.9	9.7	9.7	0.0	10.0
12/10/07	1.3	1.8	1.1	0.1	9.9	9.8	9.8	0.0	10.0
12/11/07	1.2	1.8	1.1	0.1	9.9	9.8	9.8	0.0	10.0

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: PROPANE GAS FURNACE

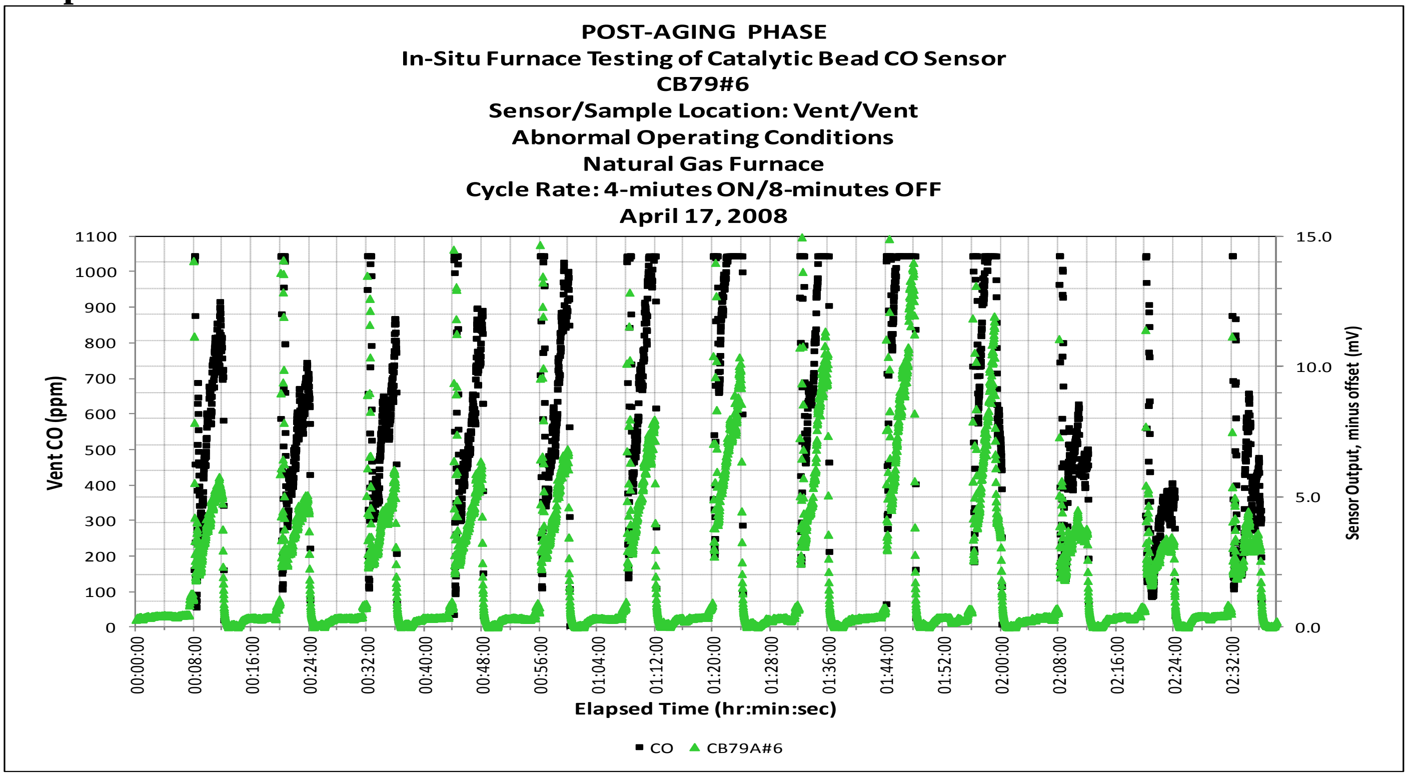
Table C.4	AGING PHASE Corrosion test ON-cycle data for non-dispersive infrared CO_2 and CO sensors in-situ in a propane furnace (August 2007 through February 2008)								
	NDIRCO2#3				NDIRCO#1				Manifold Pressure
	V				V				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
12/12/07	1.3	1.6	1.0	0.1	9.9	9.7	9.7	0.1	10.0
12/13/07	1.2	1.4	1.1	0.1	9.9	9.6	9.6	0.1	10.0
12/14/07	1.3	1.4	1.1	0.1	9.9	9.6	9.6	0.1	10.0
01/04/08	1.2	1.4	1.1	0.1	9.9	9.9	9.9	0.0	10.5
01/05/08	1.4	1.8	1.1	0.2	9.9	9.9	9.9	0.0	10.5
01/06/08	1.3	1.5	1.0	0.1	9.9	9.8	9.8	0.0	10.5
01/07/08	1.3	1.9	1.0	0.1	9.8	9.2	9.2	0.1	10.5
01/08/08	1.3	1.5	1.0	0.1	9.5	7.6	7.6	0.4	10.5
01/09/08	1.3	1.7	1.1	0.1	7.9	4.7	4.7	1.7	10.5
01/10/08	1.3	1.7	1.0	0.1	9.0	4.7	4.7	1.4	10.5
01/11/08	1.2	1.6	1.0	0.1	9.5	7.5	7.5	0.5	10.5
01/12/08	1.3	1.6	1.0	0.1	9.3	7.9	7.9	0.5	10.5
01/13/08	1.3	1.7	1.1	0.1	9.6	7.9	7.9	0.4	10.5
01/14/08	1.3	1.8	1.0	0.1	9.6	7.7	7.7	0.4	10.5
01/15/08	1.3	1.8	1.1	0.1	9.9	9.4	9.4	0.1	10.5
01/16/08	1.4	2.0	1.1	0.2	9.9	9.7	9.7	0.1	10.5
01/17/08	1.3	1.8	1.1	0.1	9.9	9.7	9.7	0.1	10.5
01/18/08	1.3	1.8	1.1	0.1	9.9	9.7	9.7	0.1	10.5
01/19/08	1.3	1.6	1.0	0.1	9.9	9.8	9.8	0.0	10.5
01/20/08	1.3	1.5	1.1	0.1	9.9	9.9	9.9	0.0	10.5
01/21/08	1.3	2.0	1.1	0.1	9.9	9.9	9.9	0.0	10.5
01/22/08	1.3	1.8	1.1	0.1	9.9	9.9	9.9	0.0	10.5
01/23/08	1.3	1.7	1.1	0.1	9.9	9.9	9.9	0.0	10.5
01/24/08	1.3	1.6	1.0	0.1	9.9	9.9	9.9	0.0	10.5
01/25/08	1.3	1.8	1.0	0.1	9.9	9.9	9.9	0.0	10.5
01/26/08	1.3	1.8	1.1	0.1	9.9	9.9	9.9	0.0	10.5
01/27/08	1.3	1.4	1.0	0.1	9.9	9.9	9.9	0.0	10.5
01/28/08	1.3	1.7	1.1	0.1	9.9	9.9	9.9	0.0	10.5
01/29/08	1.3	1.8	1.0	0.1	9.9	9.9	9.9	0.0	10.5
01/30/08	1.3	1.7	1.0	0.1	9.9	9.8	9.8	0.0	10.5

APPENDIX C. AGING PHASE IN-SITU CORROSION TEST DATA: PROPANE GAS FURNACE

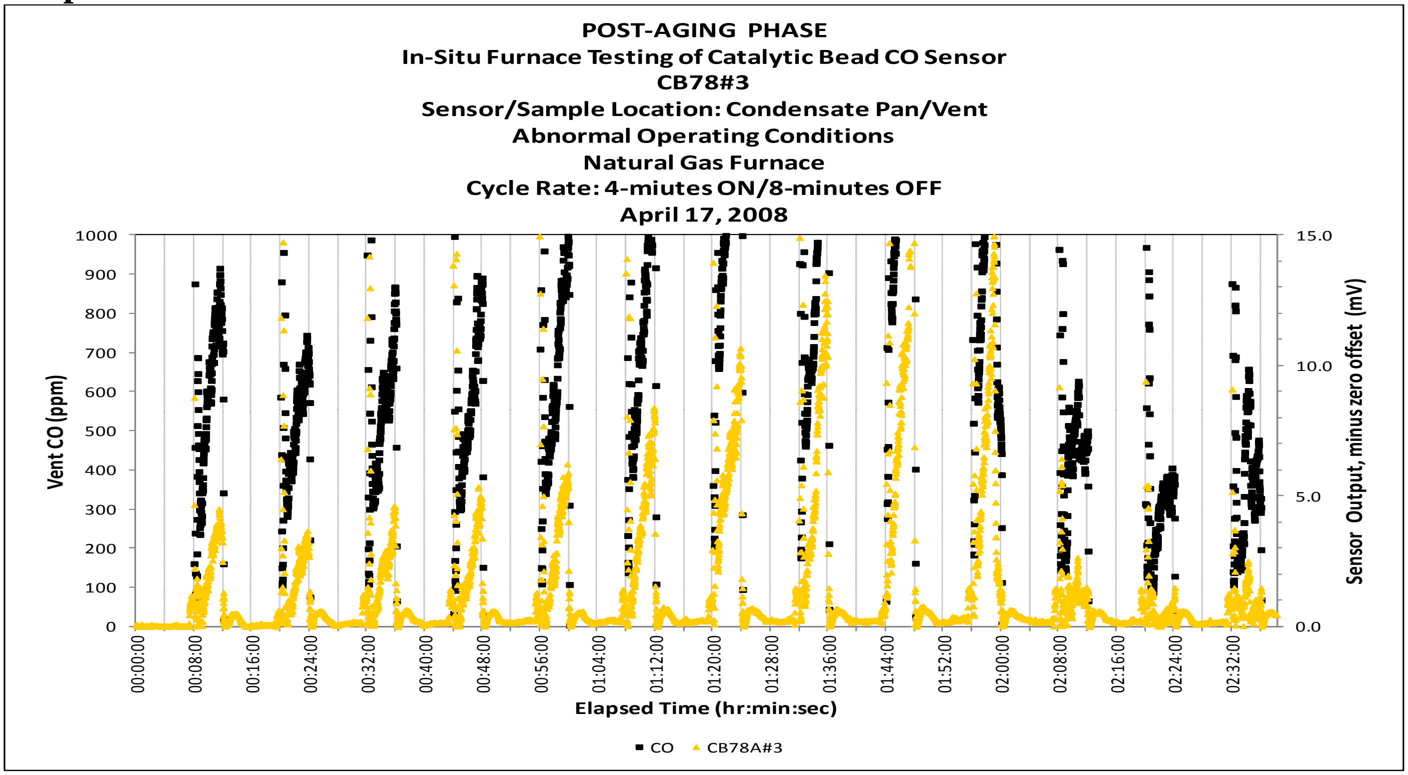
Table C.4	AGING PHASE Corrosion test ON-cycle data for non-dispersive infrared CO_2 and CO sensors in-situ in a propane furnace (August 2007 through February 2008)								
	NDIRCO2#3				NDIRCO#1				Manifold Pressure
	V				V				in. w.c.
Date	Avg	Max	Min	Std	Avg	Max	Min	Std	Avg
01/31/08	1.3	1.8	1.1	0.1	9.9	9.8	9.8	0.0	10.5
02/01/08	1.2	1.8	1.0	0.1	9.9	9.8	9.8	0.0	10.5
02/02/08	1.2	1.4	1.0	0.1	9.9	9.8	9.8	0.0	10.5
02/03/08	1.2	1.6	1.0	0.1	9.9	9.7	9.7	0.1	10.5
02/04/08	1.2	1.5	1.0	0.1	9.9	9.7	9.7	0.1	10.5
02/05/08	1.3	1.5	1.0	0.1	9.8	8.4	8.4	0.2	10.5

APPENDIX D. POST-AGING PHASE IN-SITU TEST DATA: NATURAL GAS FURNACE

Graph D.1

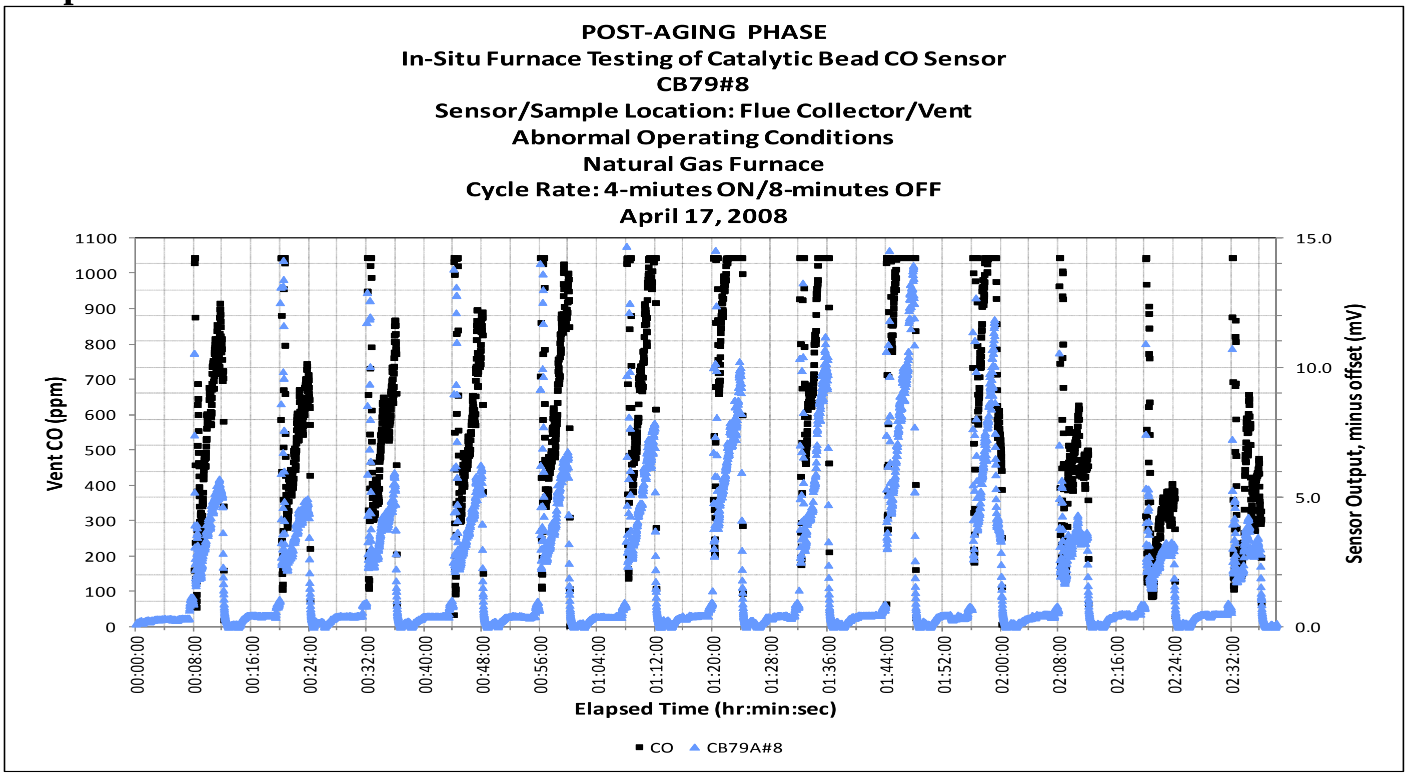


Graph D.2

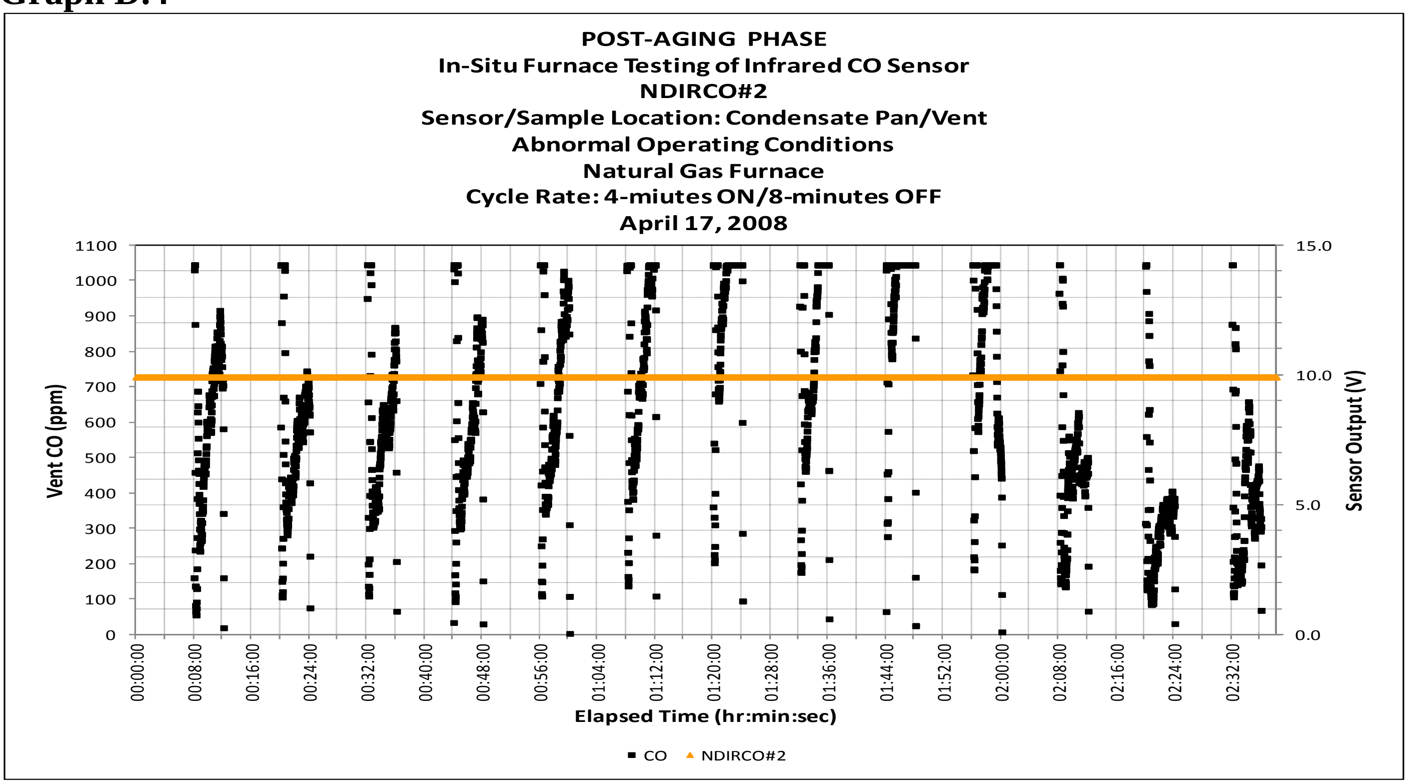


APPENDIX D. POST-AGING PHASE IN-SITU TEST DATA: NATURAL GAS FURNACE

Graph D.3

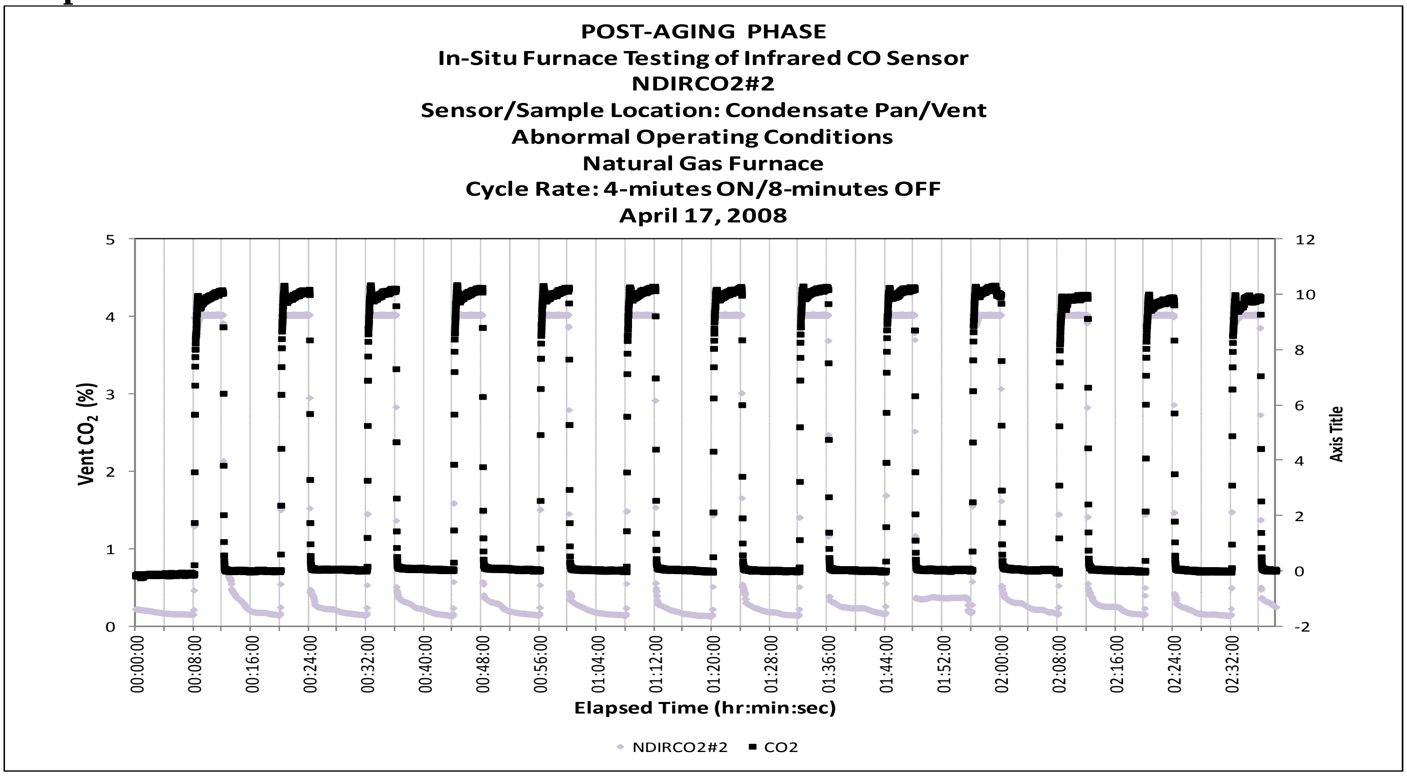


Graph D.4



APPENDIX D. POST-AGING PHASE IN-SITU TEST DATA: NATURAL GAS FURNACE

Graph D.5

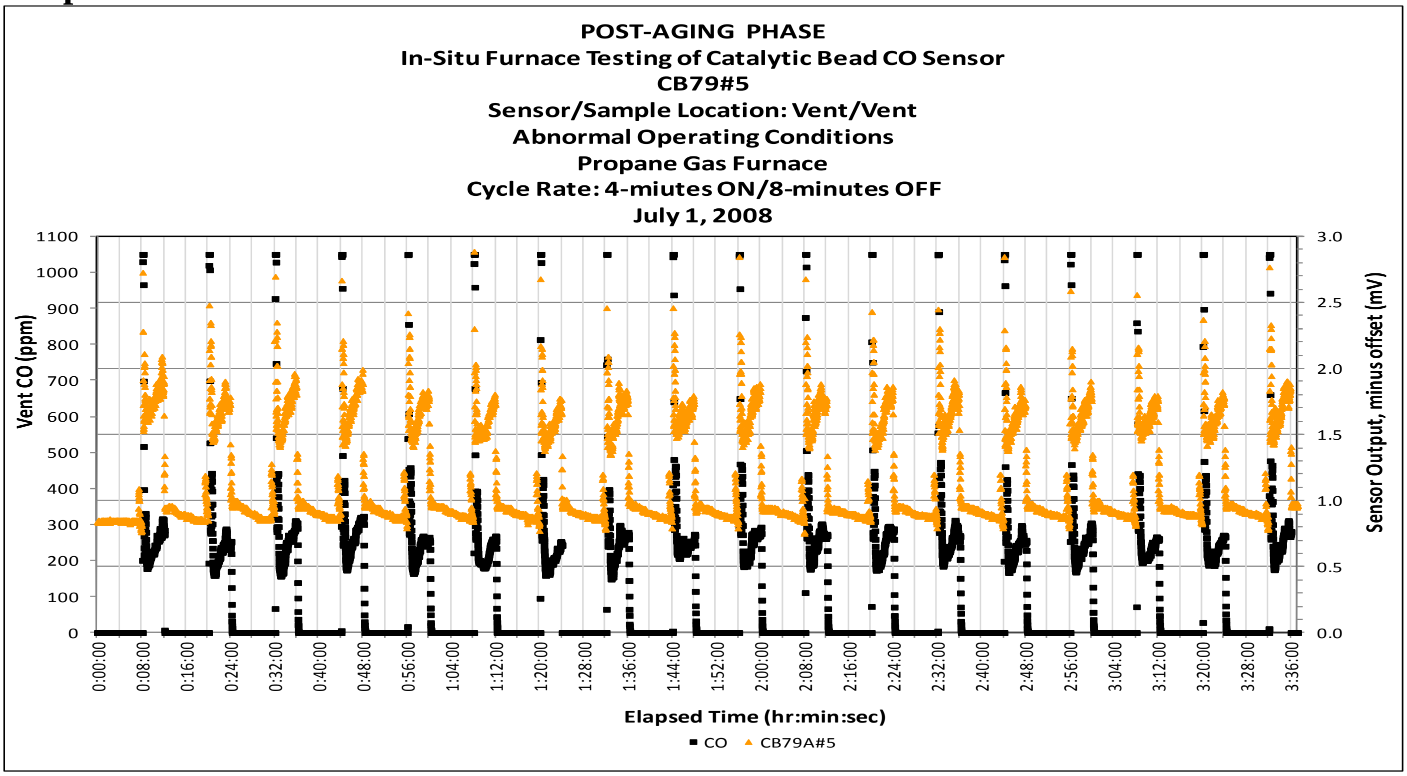


APPENDIX D. POST-AGING PHASE IN-SITU TEST DATA: NATURAL GAS FURNACE

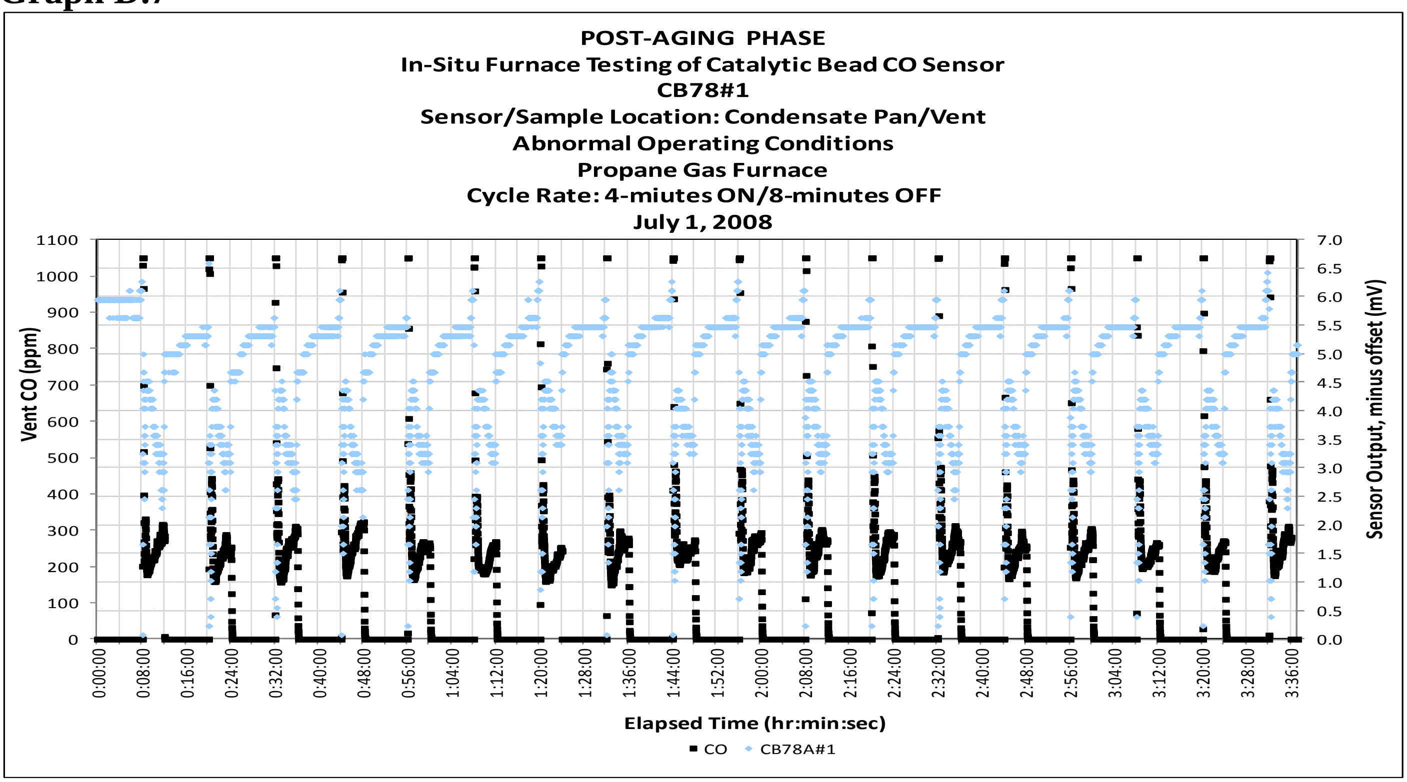
Table D.1		POST-AGING PHASE In-Situ Furnace Sensor Response Testing Natural Gas Furnace (April 17, 2008) Averages during Cycling (4-minutes ON & 8-minutes OFF)													
Cycle #	**Cycle Status ON/OFF?**	**Start of Cycle (hr:min:sec)**	**End of Cycle (hr:min:sec)**	**Duration (hr:min:sec)**	**CO (ppm)**	**CO_2 (%)**	**CB79#6 (mV)**	**CB79#8 (mV)**	**CB78#3 (mV)**	**NDIRCO2#2 (V)**	**NDIRCO#2 (V)**	**Temp (flue) (^oF)**	**Temp (cond) (^oF)**	**Manifold Pressure (in. w.c.)**
1	OFF	0:00:00	0:07:58	0:07:58	0	0.1	0.5	0.3	0.1	0.2	9.9	97	77	0.3
	ON	0:07:59	0:12:00	0:04:01	568	9.3	4.4	4.2	3.2	3.9	9.9	356	104	7.4
2	OFF	0:12:01	0:19:59	0:07:58	0	0.3	0.4	0.4	0.2	0.4	9.9	284	94	0.3
	ON	0:20:00	0:23:59	0:03:59	532	9.4	4.7	4.4	3.6	3.9	9.9	401	106	7.4
3	OFF	0:24:00	0:31:59	0:07:59	0	0.3	0.4	0.4	0.3	0.3	9.9	292	95	0.3
	ON	0:32:00	0:36:00	0:04:00	539	9.4	4.7	4.5	3.6	3.8	9.9	401	106	7.4
4	OFF	0:36:01	0:43:59	0:07:58	0	0.3	0.4	0.4	0.3	0.3	9.9	292	96	0.3
	ON	0:44:00	0:47:59	0:03:59	557	9.5	4.9	4.8	3.9	3.9	9.9	402	106	7.4
5	OFF	0:48:00	0:55:59	0:07:59	0	0.3	0.4	0.4	0.4	0.3	9.9	294	96	0.3
	ON	0:56:00	1:00:00	0:04:00	635	9.5	5.4	5.3	4.6	3.8	9.9	402	106	7.4
6	OFF	1:00:01	1:08:00	0:07:59	0	0.3	0.3	0.4	0.4	0.3	9.9	293	96	0.3
	ON	1:08:01	1:12:00	0:03:59	738	9.5	6.2	5.9	6.0	3.9	9.9	400	106	7.4
7	OFF	1:12:01	1:19:59	0:07:58	0	0.3	0.4	0.4	0.4	0.3	9.9	291	97	0.3
	ON	1:20:00	1:24:00	0:04:00	922	9.5	7.7	7.6	8.0	3.9	9.9	401	107	7.4
8	OFF	1:24:01	1:31:59	0:07:58	0	0.3	0.4	0.4	0.5	0.3	9.9	293	97	0.3
	ON	1:32:00	1:36:00	0:04:00	804	9.5	7.6	7.5	8.1	3.8	9.9	401	106	7.4
9	OFF	1:36:01	1:43:59	0:07:58	0	0.3	0.4	0.4	0.4	0.3	9.9	292	96	0.3
	ON	1:44:00	1:47:59	0:03:59	955	9.5	9.6	9.5	11.4	3.9	9.9	400	106	7.4
10	OFF	1:48:00	1:55:59	0:07:59	0	0.3	0.4	0.5	0.5	0.4	9.9	292	96	0.3
	ON	1:56:00	2:00:00	0:04:00	840	9.5	7.7	7.6	8.9	3.8	9.9	398	106	7.3
11	OFF	2:00:01	2:08:00	0:07:59	0	0.3	0.3	0.4	0.4	0.3	9.9	292	96	0.3
	ON	2:08:01	2:12:00	0:03:59	445	9.3	3.9	3.8	2.7	3.9	9.9	392	106	6.9
12	OFF	2:12:01	2:19:59	0:07:58	0	0.3	0.4	0.4	0.4	0.3	9.9	288	96	0.3
	ON	2:20:00	2:23:59	0:03:59	270	8.3	3.0	2.9	1.9	3.5	9.9	399	106	5.9
13	OFF	2:24:00	2:31:59	0:07:59	0	0.3	0.4	0.4	0.3	0.3	9.9	285	97	0.3
	ON	2:32:00	2:36:00	0:04:00	371	9.2	3.6	3.5	2.4	3.8	9.9	388	106	7.0

APPENDIX D. POST-AGING PHASE IN-SITU TEST DATA: PROPANE GAS FURNACE

Graph D.6

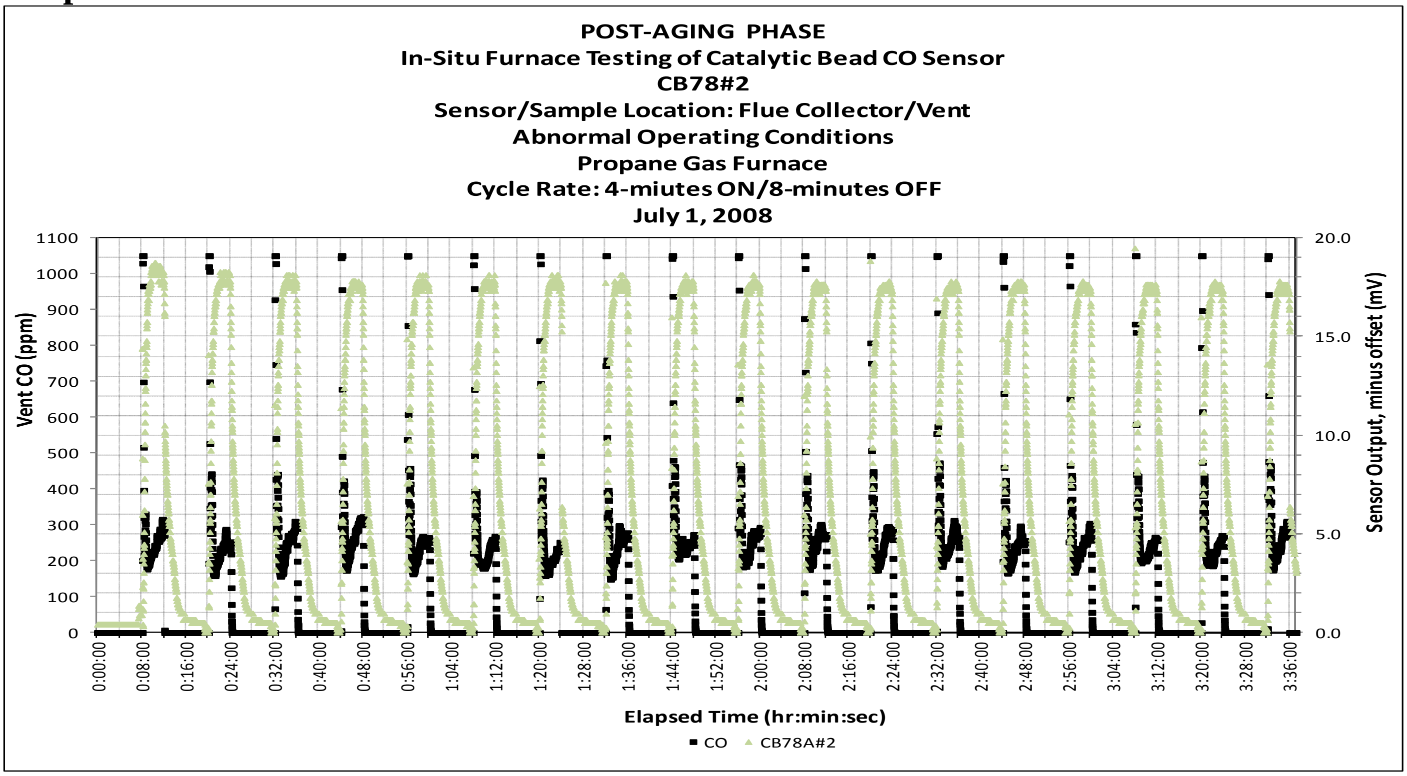


Graph D.7

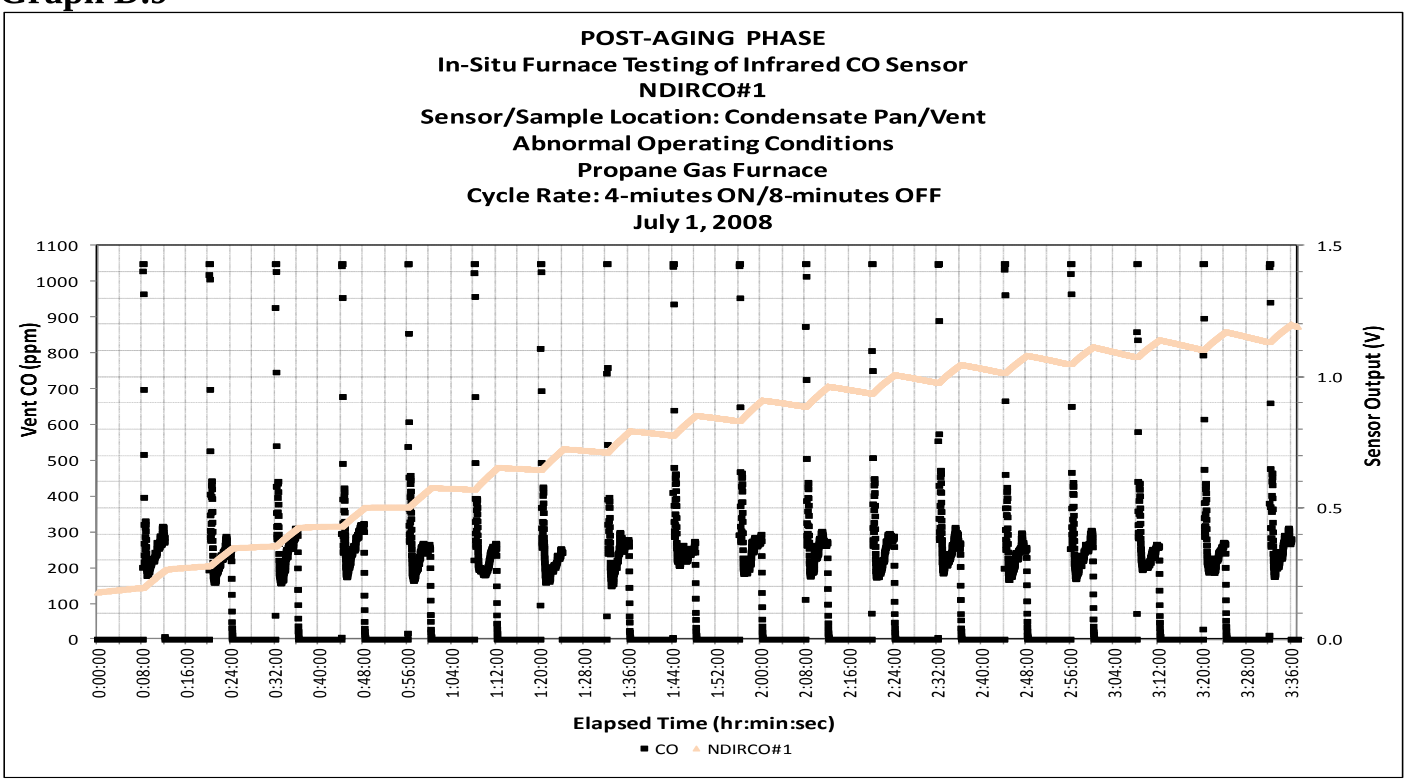


APPENDIX D. POST-AGING PHASE IN-SITU TEST DATA: PROPANE GAS FURNACE

Graph D.8

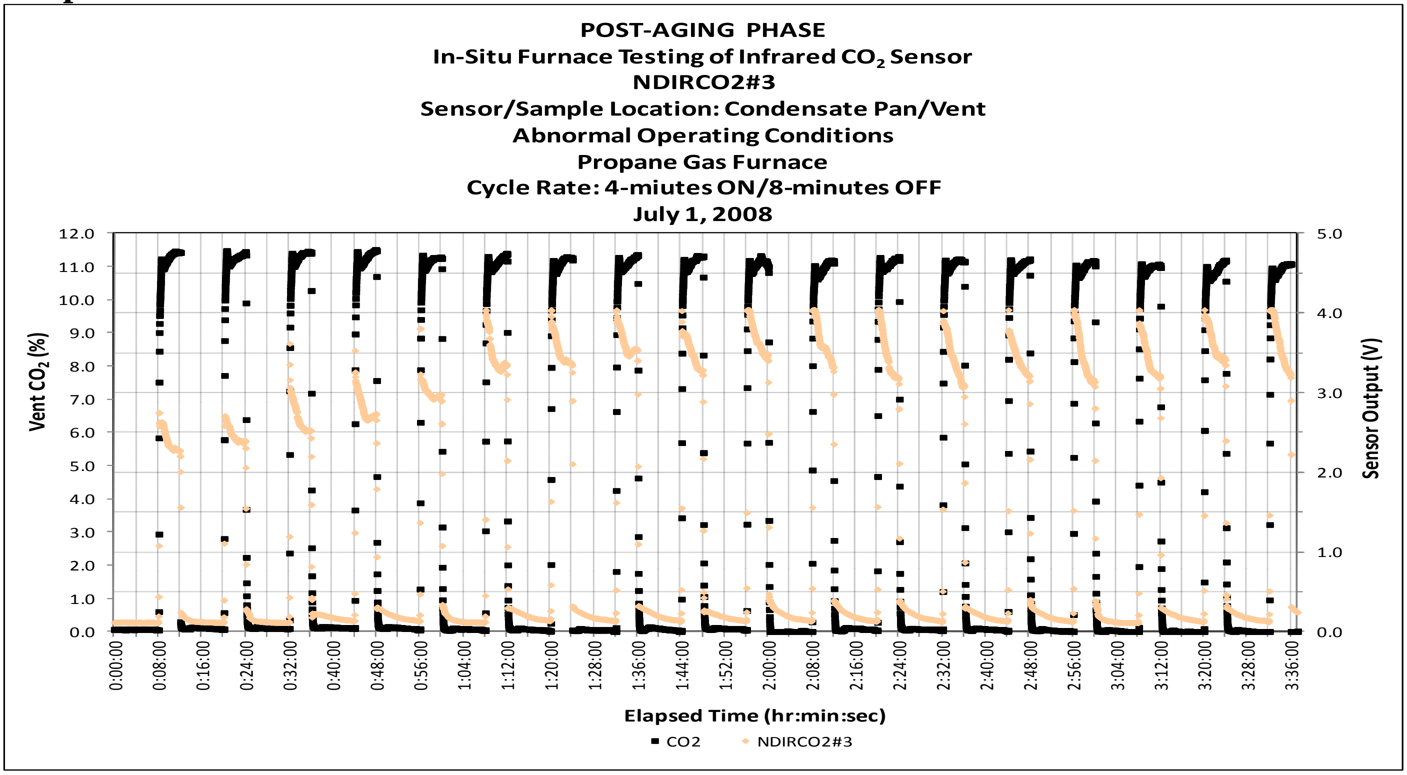


Graph D.9



APPENDIX D. POST-AGING PHASE IN-SITU TEST DATA: PROPANE GAS FURNACE

Graph D. 10



APPENDIX D. POST-AGING PHASE IN-SITU TEST DATA: PROPANE GAS FURNACE

Table D.2	POST-AGING PHASE In-Situ Furnace Sensor Response Testing Propane Gas Furnace (July 1, 2008) Averages during Cycling (4-minutes ON & 8-minutes OFF)													
Cycle No.	Cycle Status ON/OFF?	Start of Cycle (hr:min:sec)	End of Cycle (hr:min:sec)	Duration (hr:min:sec)	CO (ppm)	CO_2 (%)	CB78#2 (mV)	CB79#5 (mV)	CB78#1 (mV)	NDIRCO2#3 (V)	NDIRCO#1 (V)	Temp (flue)* (^oF)	Temp (cond)* (^oF)	Manifold Pressure (in. w.c.)
1	OFF	0:00:00	0:07:59	0:07:59	0	0.1	0.5	0.8	5.9	0.1	0.2	n/a	n/a	0.3
	ON	0:08:00	0:12:00	0:04:00	268	10.7	16.4	2.5	5.0	2.3	0.2	n/a	n/a	14.0
2	OFF	0:12:01	0:20:00	0:07:59	6	0.3	2.2	0.9	5.2	0.2	0.3	n/a	n/a	0.3
	ON	0:20:01	0:24:04	0:04:03	263	10.7	16.0	2.4	4.8	2.4	0.3	n/a	n/a	13.9
3	OFF	0:24:00	0:32:00	0:08:00	9	0.4	2.6	0.9	5.1	0.2	0.4	n/a	n/a	0.3
	ON	0:32:01	0:36:00	0:03:59	272	10.7	15.9	2.5	5.0	2.6	0.4	n/a	n/a	13.9
4	OFF	0:36:01	0:43:59	0:07:58	10	0.4	2.5	0.9	5.2	0.2	0.4	n/a	n/a	0.3
	ON	0:44:00	0:48:00	0:04:00	287	10.7	15.8	2.6	4.8	2.7	0.5	n/a	n/a	14.0
5	OFF	0:48:01	0:55:59	0:07:58	11	0.4	2.5	0.9	5.2	0.3	0.5	n/a	n/a	0.3
	ON	0:56:00	1:00:00	0:04:00	267	10.5	16.0	2.5	4.8	2.9	0.5	n/a	n/a	13.9
6	OFF	1:00:02	1:07:59	0:07:57	9	0.4	2.5	0.9	5.3	0.2	0.6	n/a	n/a	0.3
	ON	1:08:00	1:11:59	0:03:59	255	10.5	15.7	2.3	4.9	3.4	0.6	n/a	n/a	13.9
7	OFF	1:12:00	1:20:00	0:08:00	9	0.4	2.5	0.9	5.3	0.3	0.7	n/a	n/a	0.3
	ON	1:20:01	1:24:00	0:03:59	246	10.5	15.8	2.4	5.2	3.4	0.7	n/a	n/a	13.9
8	OFF	1:24:01	1:31:59	0:07:58	5	0.3	1.6	0.9	5.4	0.2	0.7	n/a	n/a	0.3
	ON	1:32:00	1:36:00	0:04:00	266	10.5	15.9	2.5	5.2	3.5	0.8	n/a	n/a	13.9
9	OFF	1:36:01	1:43:59	0:07:58	9	0.4	2.5	0.9	5.4	0.3	0.8	n/a	n/a	0.3
	ON	1:44:00	1:48:00	0:04:00	275	10.5	15.7	2.4	5.0	3.4	0.8	n/a	n/a	14.0
10	OFF	1:48:01	1:55:59	0:07:58	10	0.4	2.5	0.9	5.4	0.3	0.8	n/a	n/a	0.3
	ON	1:56:00	2:00:00	0:04:00	276	10.4	15.6	2.4	4.8	3.5	0.9	n/a	n/a	13.9
11	OFF	2:00:01	2:08:00	0:07:59	10	0.3	2.5	0.9	5.4	0.3	0.9	n/a	n/a	0.3
	ON	2:08:01	2:11:59	0:03:58	281	10.4	15.6	2.4	4.9	3.5	0.9	n/a	n/a	13.9
12	OFF	2:12:00	2:20:00	0:08:00	8	0.3	2.4	0.9	5.4	0.3	1.0	n/a	n/a	0.3
	ON	2:20:01	2:23:59	0:03:58	274	9.5	15.2	2.1	5.1	3.0	1.0	n/a	n/a	12.0
13	OFF	2:24:00	2:31:59	0:07:59	10	0.4	2.5	0.9	5.4	0.3	1.0	n/a	n/a	0.3
	ON	2:32:00	2:36:00	0:04:00	285	10.4	15.8	2.5	4.9	3.3	1.0	n/a	n/a	13.9
14	OFF	2:36:01	2:43:59	0:07:58	9	0.4	2.5	0.9	5.4	0.3	1.0	n/a	n/a	0.3

APPENDIX D. POST-AGING PHASE IN-SITU TEST DATA: PROPANE GAS FURNACE

Table D.2	POST-AGING PHASE In-Situ Furnace Sensor Response Testing Propane Gas Furnace (July 1, 2008) Averages during Cycling (4-minutes ON & 8-minutes OFF)													
Cycle No.	Cycle Status ON/OFF?	Start of Cycle (hr:min:sec)	End of Cycle (hr:min:sec)	Duration (hr:min:sec)	CO (ppm)	CO_2 (%)	CB78#2 (mV)	CB79#5 (mV)	CB78#1 (mV)	NDIRCO2#3 (V)	NDIRCO#1 (V)	Temp (flue)* (^oF)	Temp (cond)* (^oF)	Manifold Pressure (in. w.c.)
	ON	2:44:00	2:48:00	0:04:00	261	10.3	15.6	2.3	4.9	3.3	1.0	n/a	n/a	13.9
15	OFF	2:48:01	2:55:59	0:07:58	9	0.3	2.5	0.9	5.4	0.2	1.1	n/a	n/a	0.3
	ON	2:56:00	2:59:59	0:03:59	268	10.3	15.5	2.4	5.3	3.3	1.1	n/a	n/a	14.0
16	OFF	3:00:00	3:08:00	0:08:00	10	0.3	2.5	0.9	5.4	0.2	1.1	n/a	n/a	0.3
	ON	3:08:01	3:11:59	0:03:58	271	10.3	15.5	2.5	4.9	3.3	1.1	n/a	n/a	13.9
17	OFF	3:12:00	3:19:59	0:07:59	9	0.3	2.5	0.9	5.4	0.3	1.1	n/a	n/a	0.3
	ON	3:20:00	3:24:00	0:04:00	267	10.2	15.8	2.5	4.9	3.5	1.1	n/a	n/a	14.0
18	OFF	3:24:01	3:31:59	0:07:58	10	0.3	2.5	0.9	5.4	0.2	1.2	n/a	n/a	0.3
	ON	3:32:00	3:36:00	0:04:00	281	10.3	15.4	2.4	4.7	3.5	1.2	n/a	n/a	14.0

*The thermocouples used to measure condensate pan and flue collector signals were inadvertently disconnected prior to this set of tests in the propane furnace and therefore, temperature data was not recorded.

APPENDIX E. POST-AGING PHASE SENSITIVITY TEST DATA

Graph E.1

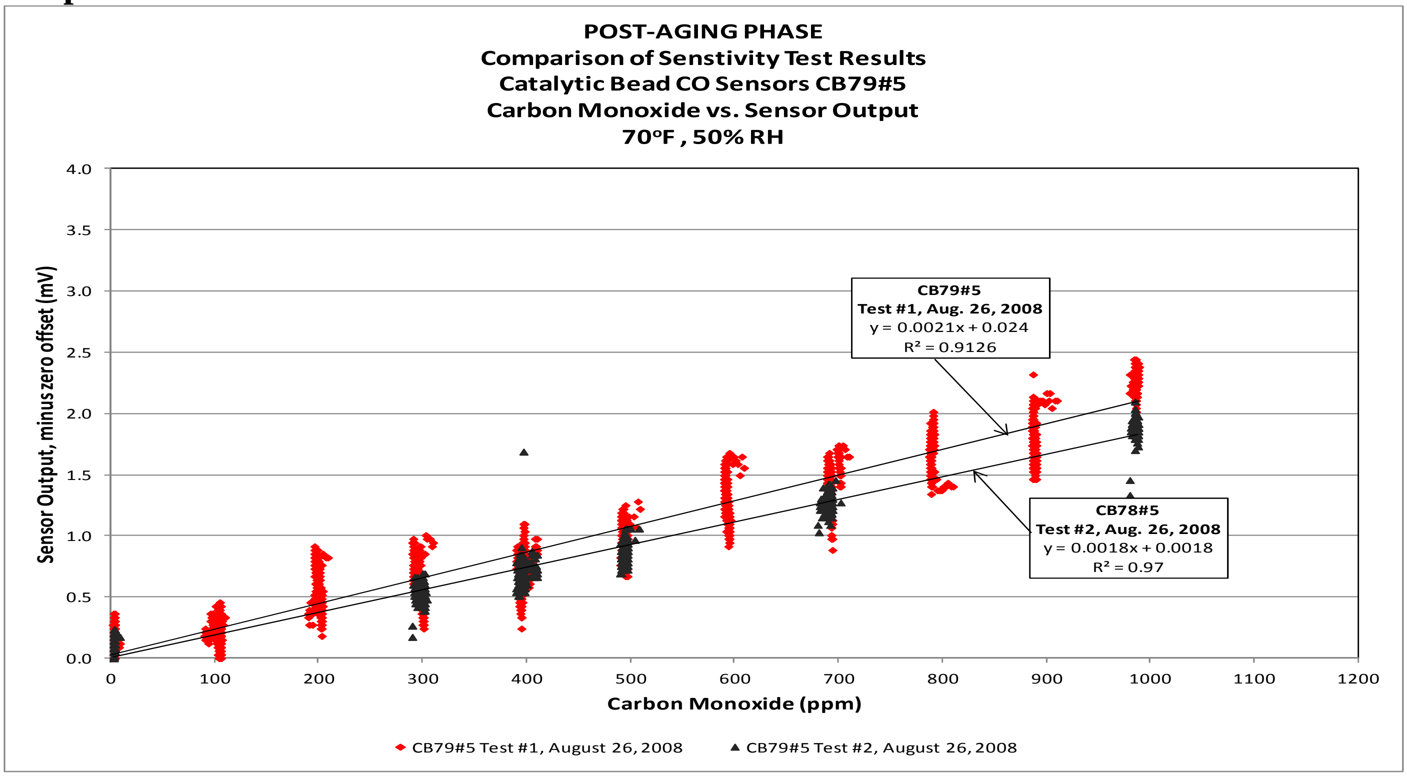


Table E.1	POST-AGING PHASE Comparison of Sensitivity Test Results for CB79#5 (mV) 70°F, 50% RH								
Test #1, August 26, 2008					Test #2, August 26, 2008				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
19	0.1		0.4	0.0	3	0.1		0.3	0.0
125	0.2	0.1	0.5	0.0	298	0.5	0.4	0.7	0.4
218	0.5	0.3	0.9	0.2	396	0.7	0.1	1.7	0.5
315	0.6	0.1	5.1	0.2	494	0.9	0.2	1.1	0.7
408	0.7	0.1	1.1	0.2	690	1.3	0.4	1.5	1.1
512	1.0	0.3	1.3	0.7	986	1.9	0.6	2.1	1.7
612	1.3	0.3	1.7	0.9					
709	1.4	0.1	1.7	0.9					
808	1.7	0.3	2.0	1.3					
909	1.8	0.1	2.3	1.5					
986	2.3	0.5	2.4	2.0					

APPENDIX E. POST-AGING PHASE SENSITIVITY TEST DATA

Graph E.2

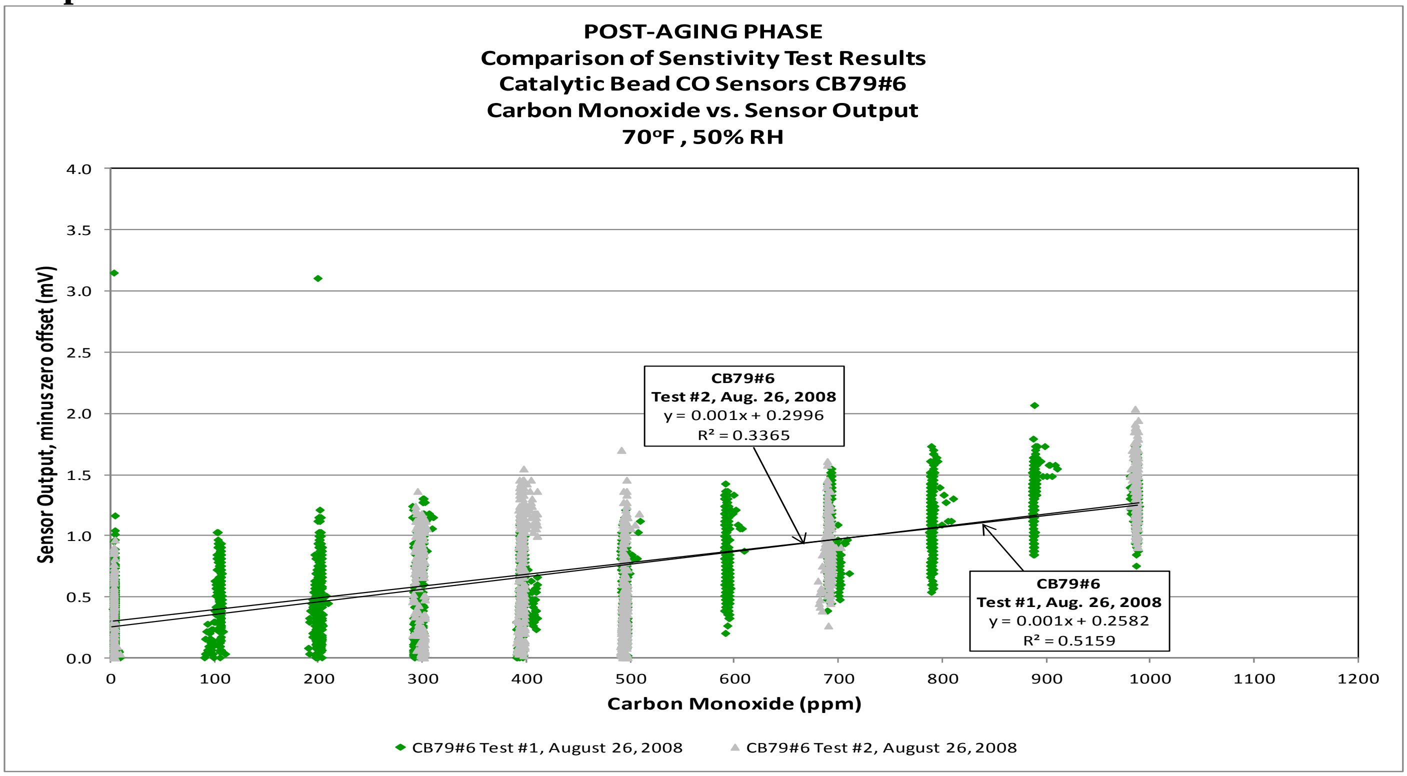


Table E.2	POST-AGING PHASE Comparison of Sensitivity Test Results for CB79#6 (mV) 70°F, 50% RH								
Test #1, August 26, 2008					Test #2, August 26, 2008				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
25	0.4		3.2	0.0	3	0.4		1.0	0.0
132	0.5	0.1	1.0	0.0	298	0.7	0.3	1.4	0.0
224	0.5	0.1	3.1	0.0	396	0.8	0.2	1.5	0.0
321	0.5	0.0	1.3	0.0	494	0.5	-0.4	1.7	0.0
412	0.5	0.0	1.2	0.0	690	0.9	0.4	1.6	0.3
518	0.6	0.2	1.2	0.0	986	1.4	0.5	2.0	0.9
618	0.8	0.2	1.4	0.2					
715	1.0	0.1	1.5	0.4					
815	1.1	0.2	1.7	0.5					
916	1.3	0.2	2.1	0.8					
986	1.3	-0.1	1.7	0.8					

APPENDIX E. POST-AGING PHASE SENSITIVITY TEST DATA

Graph E.3

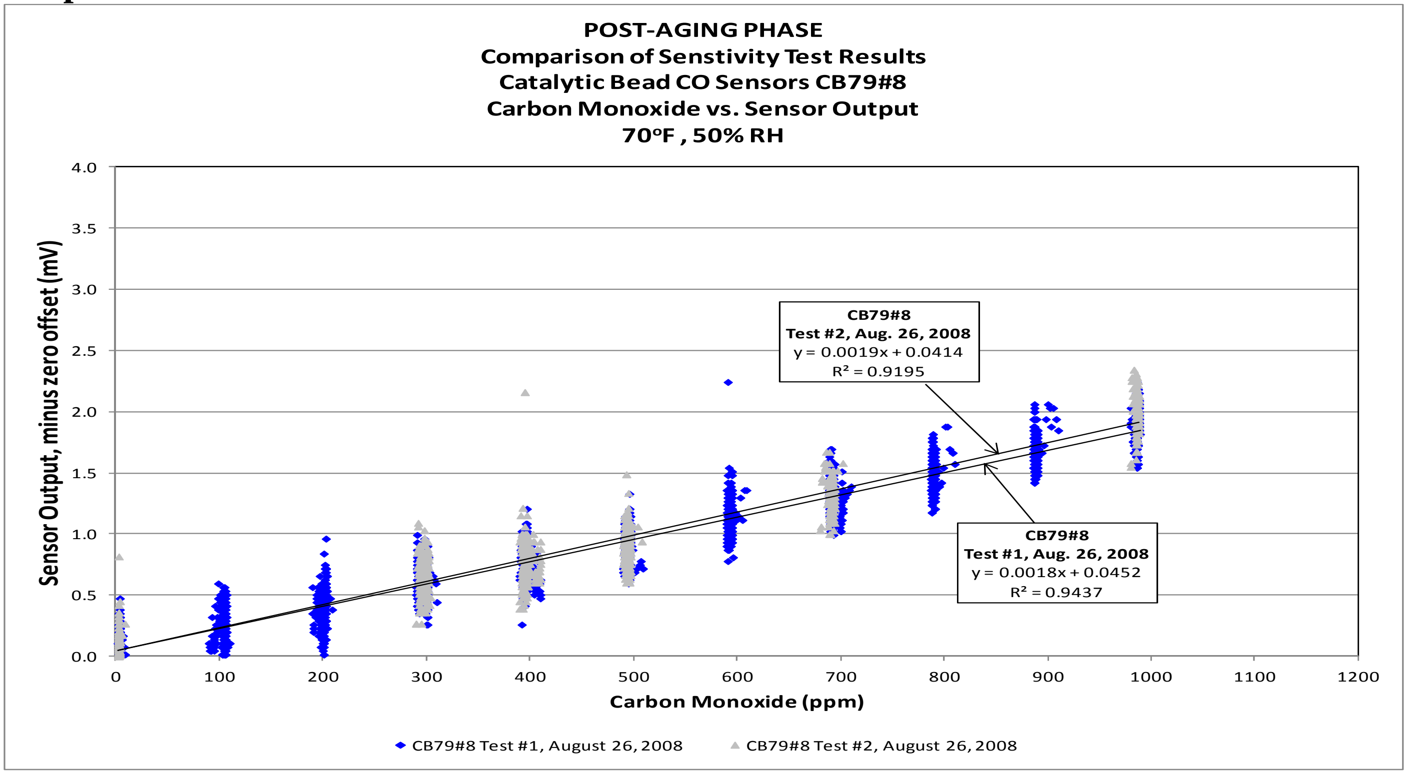


Table E.3	POST-AGING PHASE Comparison of Sensitivity Test Results for CB79#8 (mV) 70°F, 50% RH								
Test #1, August 26, 2008					Test #2, August 26, 2008				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
30	0.1		0.5	0.0	3	0.1		0.8	0.0
139	0.2	0.1	0.6	0.0	298	0.7	0.5	1.1	0.3
230	0.4	0.2	1.0	0.0	396	0.8	0.1	2.2	0.4
326	0.6	0.2	1.0	0.3	494	0.9	0.1	1.5	0.6
416	0.7	0.1	1.2	0.3	690	1.3	0.4	1.7	1.0
524	0.9	0.2	1.3	0.6	986	2.0	0.7	2.3	1.6
624	1.1	0.2	2.2	0.8					
721	1.3	0.2	1.7	1.0					
821	1.5	0.2	1.9	1.2					
923	1.7	0.2	2.1	1.4					
986	1.9	0.2	2.2	1.5					

APPENDIX E. POST-AGING PHASE SENSITIVITY TEST DATA

Graph E.4

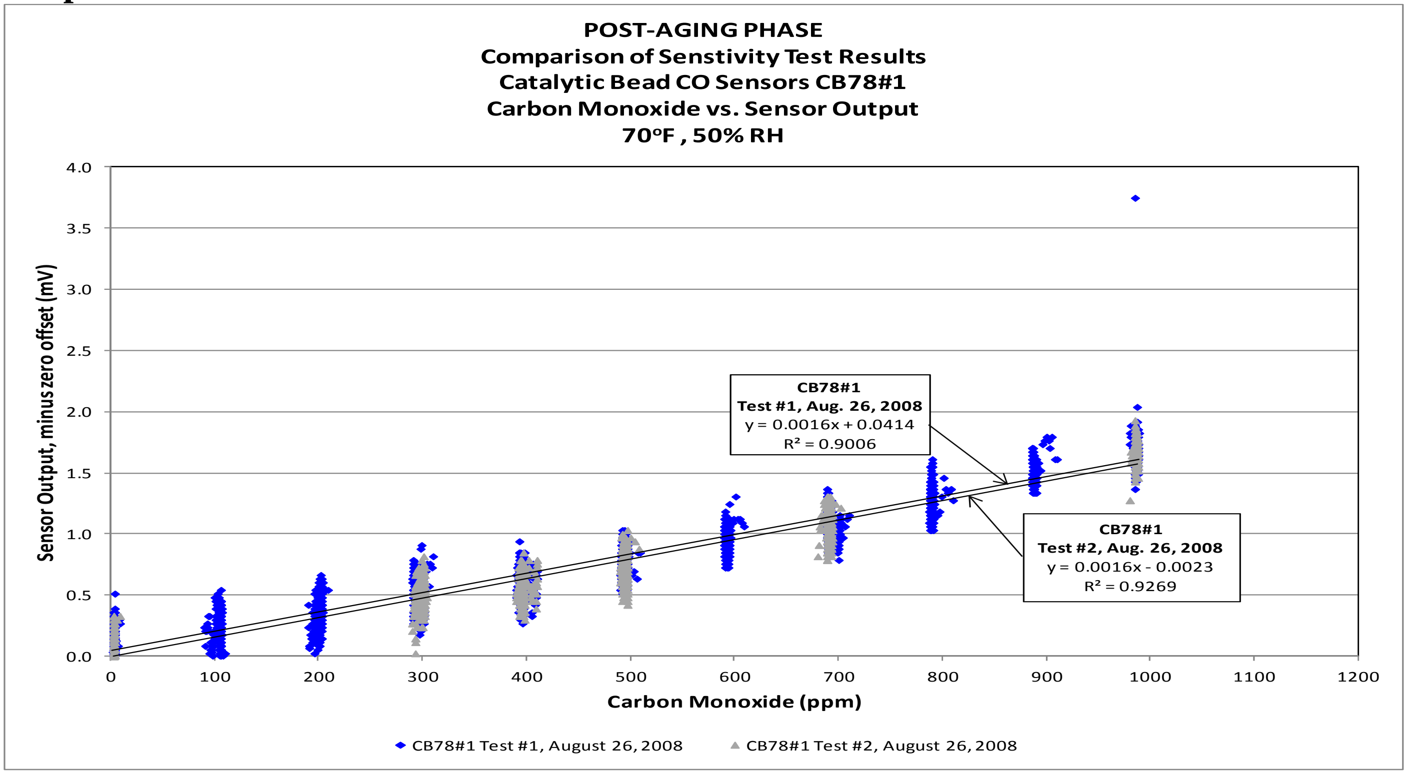


Table E.4	POST-AGING PHASE Comparison of Sensitivity Test Results for CB78#1 (mV) 70^{o}F, 50% RH								
Test #1, August 26, 2008					Test #2, August 26, 2008				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
4	0.1		0.5	0.0	3	0.1		0.3	0.0
104	0.2	0.1	0.5	0.0	298	0.5	0.3	0.8	0.0
200	0.4	0.1	5.3	0.0	396	0.6	0.1	0.8	0.3
297	0.5	0.1	0.9	0.2	494	0.7	0.1	1.0	0.4
396	0.6	0.1	0.9	0.3	690	1.1	0.4	1.3	0.8
494	0.8	0.2	1.0	0.5	986	1.7	0.6	1.9	1.4
593	1.0	0.2	1.3	0.7					
692	1.1	0.1	1.4	0.8					
790	1.3	0.2	1.6	1.0					
888	1.5	0.2	1.8	1.3					
986	1.7	0.2	3.7	1.4					

APPENDIX E. POST-AGING PHASE SENSITIVITY TEST DATA

Graph E.5

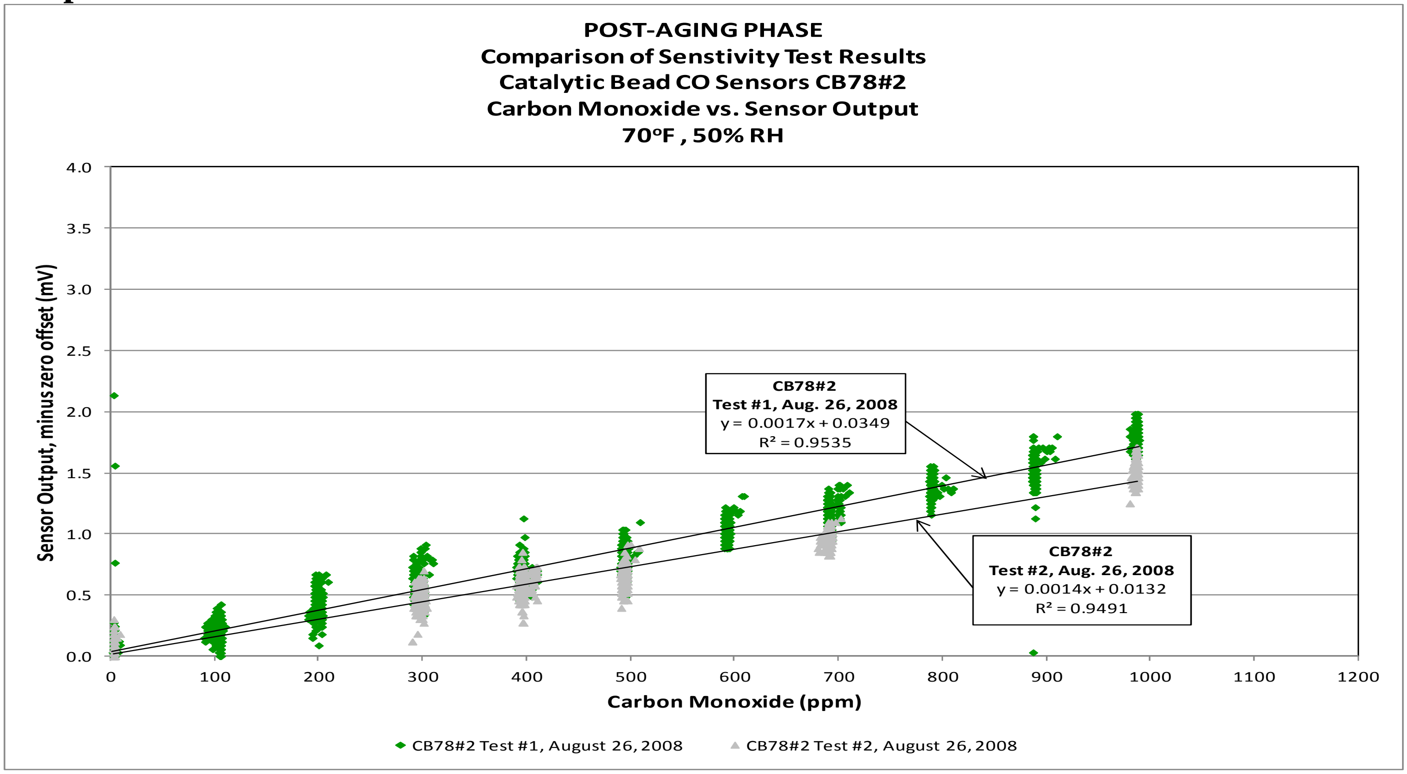


Table E.5	POST-AGING PHASE Comparison of Sensitivity Test Results for CB78#2 (mV) 70°F, 50% RH								
Test #1, August 26, 2008					Test #2, August 26, 2008				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
4	0.1		2.1	0.0	3	0.1		0.3	0.0
104	0.2	0.1	0.4	0.0	298	0.5	0.4	0.7	0.2
200	0.4	0.2	0.7	0.1	396	0.6	0.1	0.9	0.3
297	0.6	0.2	0.9	0.3	494	0.6	0.1	0.9	0.4
396	0.6	0.1	1.1	0.5	690	1.0	0.3	1.3	0.8
494	0.8	0.2	1.1	0.5	986	1.5	0.5	1.7	1.3
593	1.0	0.2	1.3	0.9					
692	1.2	0.1	1.4	0.9					
790	1.4	0.2	1.6	1.2					
888	1.5	0.1	1.8	0.0					
986	1.8	0.3	2.0	1.6					

APPENDIX E. POST-AGING PHASE SENSITIVITY TEST DATA

Graph E.6

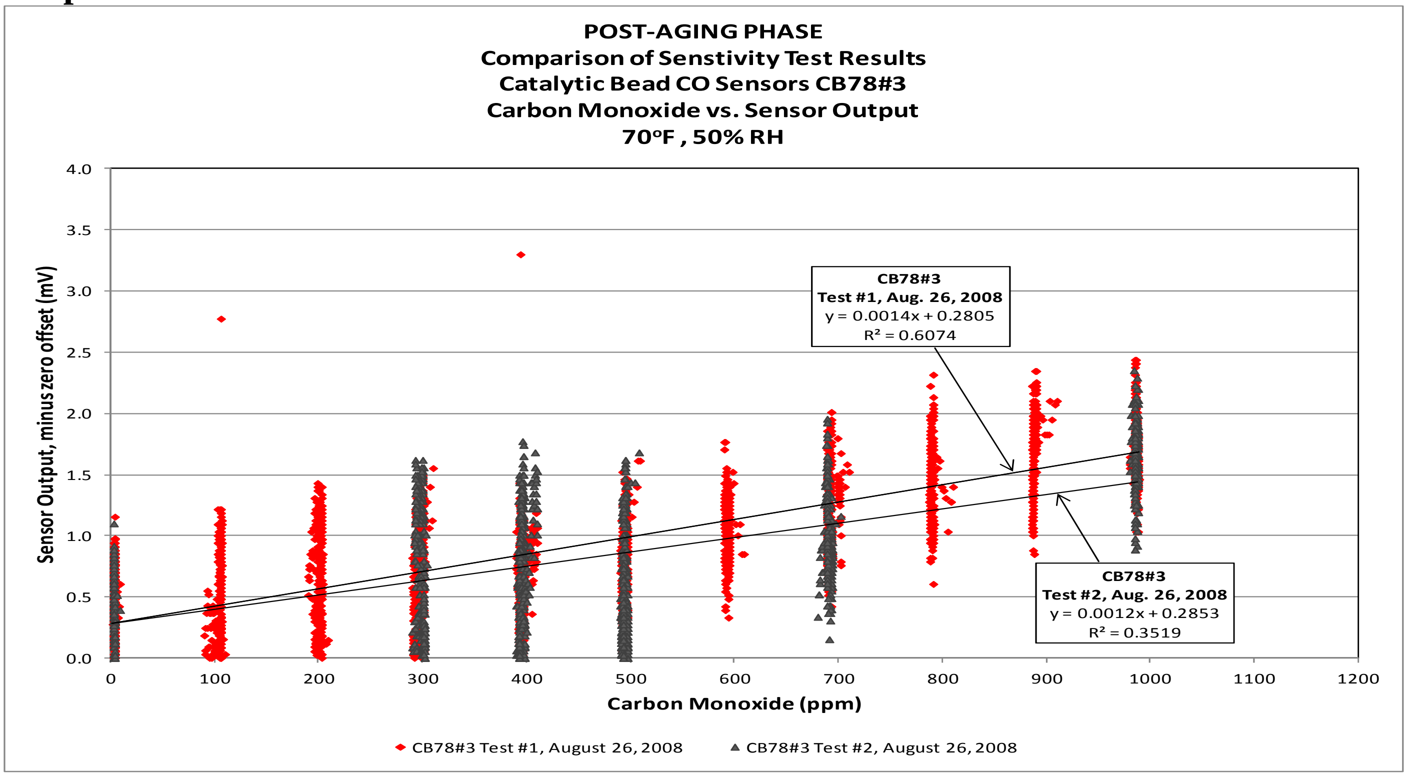


Table E.6	POST-AGING PHASE Comparison of Sensitivity Test Results for CB78#3 (mV) 70^{o}F, 50% RH								
Test #1, August 26, 2008					Test #2, August 26, 2008				
Chamber CO (ppm)	Avg	Diff Avg	Max	Min	Chamber CO (ppm)	Avg	Diff Avg	Max	Min
14	0.4		1.2	0.0	3	0.4		1.1	0.0
118	0.5	0.1	2.8	0.0	298	0.8	0.3	1.6	0.0
212	0.7	0.2	1.4	0.0	396	0.8	0.0	1.8	0.0
309	0.6	-0.1	1.6	0.0	494	0.6	-0.2	1.7	0.0
404	0.6	0.0	3.3	0.0	690	1.0	0.4	2.0	0.2
506	0.8	0.2	1.6	0.1	986	1.6	0.7	2.4	0.9
605	1.1	0.3	1.8	0.3					
704	1.3	0.2	2.0	0.4					
802	1.5	0.2	2.3	0.6					
902	1.7	0.3	2.3	0.9					
986	1.7	0.0	2.4	1.0					

APPENDIX E. POST-AGING PHASE SENSITIVITY TEST DATA

Graph E.7

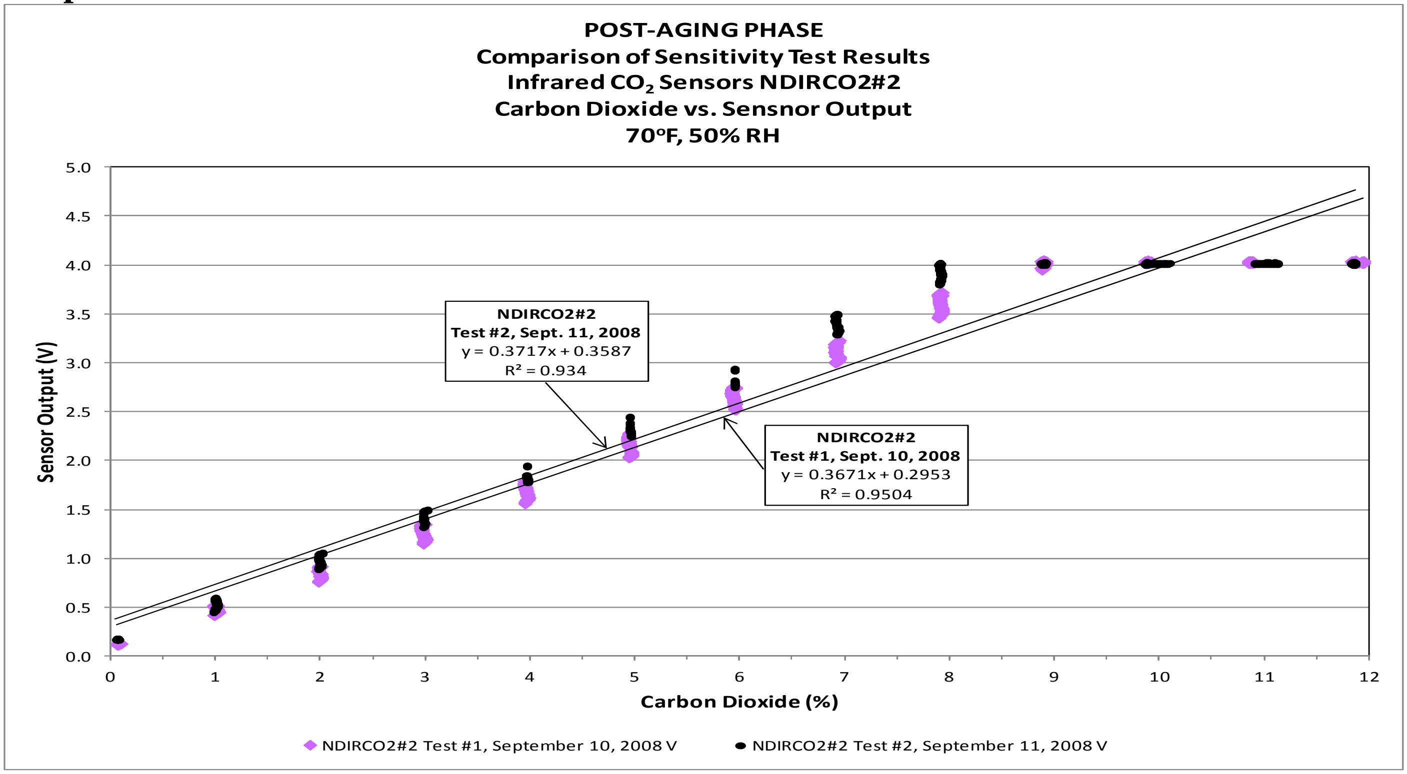


Table E.7	POST-AGING PHASE Comparison of Sensitivity Test Results for NDIRCO2#2 (V) 70°F, 50% RH								
Test #1, September 10, 2008					Test #2, September 11, 2008				
Chamber CO_2 (%)	Avg	Diff Avg	Max	Min	Chamber CO_2 (%)	Avg	Diff Avg	Max	Min
0.1	0.1		0.1	0.1	0.1	0.2		0.2	0.2
1.0	0.5	0.4	0.5	0.4	1.0	0.5	0.4	0.6	0.5
2.0	0.8	0.4	0.9	0.8	2.0	1.0	0.4	1.1	0.9
3.0	1.3	0.4	1.4	1.2	3.0	1.4	0.4	1.5	1.3
4.0	1.7	0.4	1.8	1.6	4.0	1.8	0.4	2.0	1.8
4.9	2.2	0.5	2.3	2.0	5.0	2.3	0.5	2.5	2.3
5.9	2.7	0.5	2.8	2.5	6.0	2.8	0.5	2.9	2.8
6.9	3.1	0.5	3.2	3.0	6.9	3.4	0.6	3.5	3.3
7.9	3.6	0.5	3.7	3.5	7.9	3.9	0.5	4.0	3.8
8.9	4.0	0.4	4.1	4.0	8.9	4.0	0.1	4.0	4.0
9.9	4.0	0.0	4.1	4.0	9.9	4.0	0.0	4.0	4.0
10.9	4.0	0.0	4.0	4.0	11.0	4.0	0.0	4.0	4.0
11.9	4.0	0.0	4.1	4.0	11.9	4.0	0.0	4.0	4.0

APPENDIX E. POST-AGING PHASE SENSITIVITY TEST DATA

Graph E.8

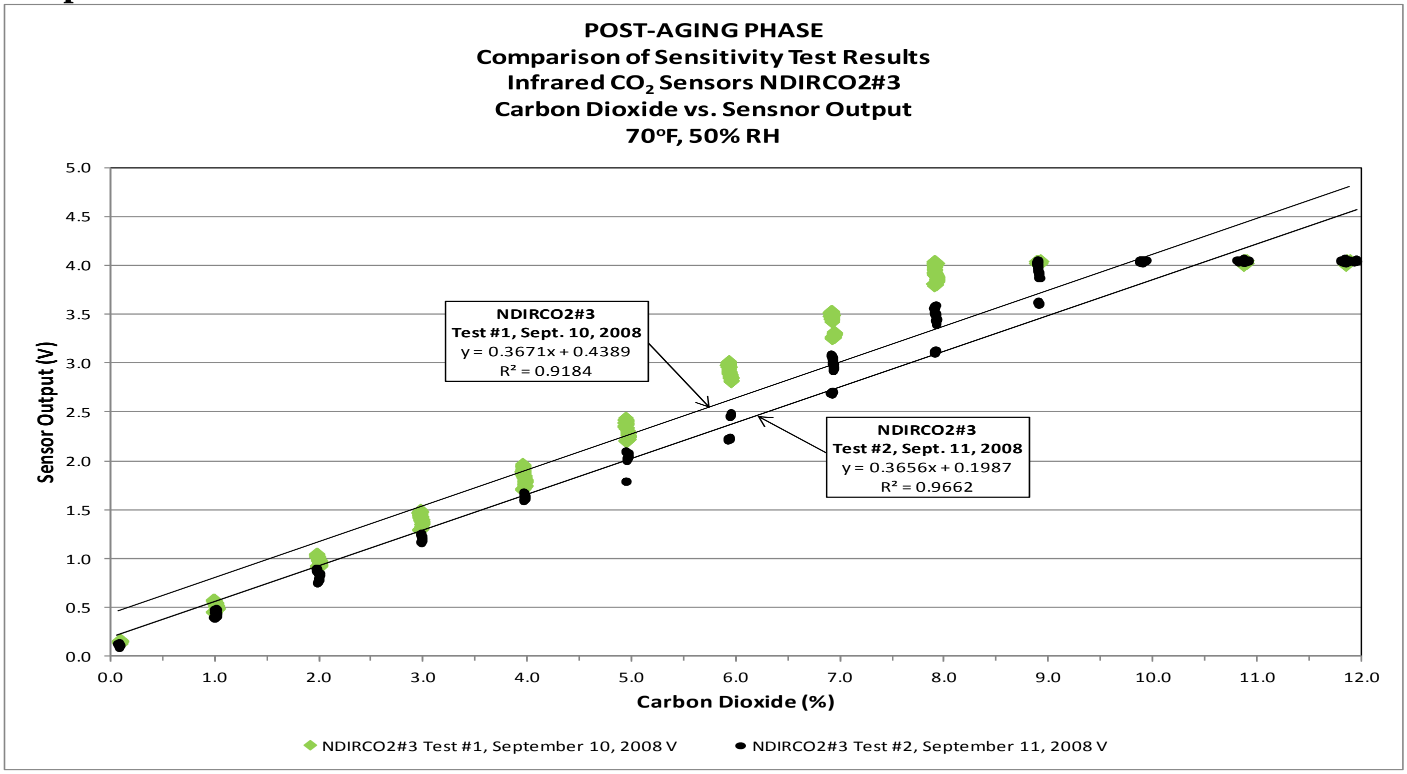


Table E.8	POST-AGING PHASE Comparison of Sensitivity Test Results for NDIRCO2#3 (V) 70°F, 50% RH								
Test #1, September 10, 2008					Test #2, September 11, 2008				
Chamber CO_2 (%)	Avg	Diff Avg	Max	Min	Chamber CO_2 (%)	Avg	Diff Avg	Max	Min
0.1	0.2		0.2	0.1	0.1	0.1		0.1	0.1
1.0	0.5	0.4	0.6	0.5	1.0	0.4	0.3	0.5	0.4
2.0	1.0	0.5	1.1	0.9	2.0	0.8	0.4	0.9	0.8
3.0	1.4	0.4	1.5	1.3	3.0	1.2	0.4	1.3	1.2
4.0	1.9	0.4	2.0	1.7	4.0	1.6	0.4	1.7	1.6
4.9	2.3	0.5	2.4	2.2	5.0	2.0	0.4	2.1	1.8
5.9	2.9	0.6	3.0	2.8	5.9	2.4	0.3	2.5	2.2
6.9	3.4	0.5	3.5	3.3	6.9	3.0	0.6	3.1	2.7
7.9	3.9	0.5	4.0	3.8	7.9	3.4	0.5	3.6	3.1
8.9	4.0	0.1	4.1	4.0	8.9	3.9	0.5	4.1	3.6
10.9	4.0	0.0	4.1	4.0	9.9	4.0	0.1	4.1	4.0
11.9	4.0	0.0	4.1	4.0	10.9	4.0	0.0	4.1	4.0
					11.9	4.0	0.0	4.1	4.0

APPENDIX F. SUMMARY OF TEST PROGRAM OBJECTIVES

Table F	Summary of Sensor Durability and Longevity Test Program Objectives													
	Catalytic Bead CO						Infrared CO				Infrared CO_2			
	CB78#:			CB79#			NDIRCO#				NDIRCO2#			
Evaluation Criteria	**1**	**2**	**3**	**5**	**6**	**8**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Pre-Aging Phase Sensitivity Test Criteria/Measure														
1. Confirm nature of response	√	√	√	√	√	√	√	√	√	√	√	√	√	√
2. Establish sensitivity	√	√	√	√	√	√	√	√	√	√	√	√	√	√
3. Establish $V_{Avg.}$ @400 ppm CO	√	√	√	√	√	√	√	√	√	√	n/a	n/a	n/a	n/a
4. Distinct $V_{Avg.}$ @400 and ≤200 ppm CO	√	√	√	√	√	√	√	√	√	√	n/a	n/a	n/a	n/a
5. Establish $V_{Avg.}$ @9% CO_2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	yes	yes	yes	yes
6. Distinct $V_{Avg.}$ @ 9% and ≤8% CO_2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	yes	yes	yes	yes
In-Situ Furnace Test Criteria														
1. Operable in furnace	√	√	√	√	√	√	limited	limited	limited	limited	√	√	√	√
2. Proportional response to changing target gas	√	√	√	√	√	√	initially	initially	initially	initially	√	√	√	√
3. Detect 400 ppm CO	√	√	√	√	√	√	initially	initially	initially	initially	n/a	n/a	n/a	n/a
4. Distinct $V_{Avg.}$ @400 and ≤200 ppm CO	√	√	√	√	√	√	initially	initially	initially	initially	n/a	n/a	n/a	n/a
5. Detect 9% CO_2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	yes	yes	yes	yes
6. Distinct $V_{Avg.}$ @9% and ≤8% CO_2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	yes	yes	yes	yes
Aging Phase Corrosion Test Criteria Durability														
1. Continued proportional response to ΔCO or ΔCO_2 during ON & OFF cycles	√	√	√	√	√	√	no	no	no	no	√	√	√	√
2. Continued distinct $V_{Avg.}$ @400 and ≤200 ppm CO	√	√	√	√	√	√	no	no	no	no	n/a	n/a	n/a	n/a
3. Continued distinct $V_{Avg.}$ @9% and ≤8% CO_2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	√	√	√	√
Longevity														
1. Continued to meet durability criteria (1) & (2) or (3)	√	√	√	√	√	√	no	no	no	no	√	√	√	√

APPENDIX F. SUMMARY OF TEST PROGRAM OBJECTIVES

Table F	Summary of Sensor Durability and Longevity Test Program Objectives													
	Catalytic Bead CO						Infrared CO				Infrared CO_2			
	CB78#:			CB79#			NDIRCO#				NDIRCO2#			
Evaluation Criteria	1	2	3	5	6	8	1	2	3	4	1	2	3	4
@100 days														
Post-Aging Phase In-Situ Furnace Test Criteria														
1. Operable in furnace	√	√	√	√	√	√	no	no	no	no	√	√	√	√
2. Continued proportional response to ΔCO or ΔCO_2	√	√	√	√	√	√	no	no	no	no	√	√	√	√
3. Continued detect 400 ppm CO	√	√	√	√	√	√	no	no	no	no	n/a	n/a	n/a	n/a
4. Continued distinct Vout @400 and ≤200 ppm CO	√	√	√	√	√	√	no	no	no	no	n/a	n/a	n/a	n/a
5. Continued detect 9% CO_2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	√	√	√	√
6. Continued distinct Vout @9% and ≤8% CO_2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	√	√	√	√
Sensitivity Test Criteria/Measure														
1. Nature of response same	√	√	√	√	√	√	no	no	no	no	√	√	√	√
2. Continued sensitivity	√	√	√	√	√	√	no	no	no	no	√	√	√	√
3. Continued $V_{Avg.}$ @400 ppm CO	√	√	√	√	√	√	no	no	no	no	n/a	n/a	n/a	n/a
4. Continued distinct $V_{Avg.}$ @400 and ≤200 ppm CO	√	√	√	√	√	√	no	no	no	no	n/a	n/a	n/a	n/a
5. Continued $V_{Avg.}$ @9% CO_2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	√	√	√	√
6. Continued distinct $V_{Avg.}$ @ 9% and ≤8% CO_2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	√	√	√	√

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