United States
Consumer Product Safety Commission
cpsc.gov | info@cpsc.gov | 800.638.2772

THIS MATTER IS NOT SCHEDULED FOR A BALLOT VOTE

A DECISIONAL MEETING FOR THIS MATTER IS SCHEDULED ON : October 11, 2023

TO: The Commission
Alberta E. Mills, Secretary

DATE: September 20, 2023

THROUGH: Austin C. Schlick, General Counsel
Jason K. Levine, Executive Director

FROM: Daniel R. Vice, Assistant General Counsel, Regulatory Affairs
David M. DiMatteo, Attorney, Regulatory Affairs

SUBJECT: Notice of Proposed Rulemaking: Safety Standard for Residential Gas Furnaces and Boilers

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Staff is forwarding to the Commission a briefing package recommending that the Commission issue a notice of proposed rulemaking (NPR), pursuant to sections 7 and 9 of the Consumer Product Safety Act, 15 U.S.C. §§ 2056 & 2058, to address the risk of carbon monoxide (CO) poisoning from residential gas furnaces and boilers. The Office of the General Counsel is providing for the Commission's consideration a draft NPR that would establish requirements to address dangerous levels of CO production from residential gas furnaces and boilers.

Please indicate your vote on the following options:

I. Approve publication of the attached notice in the *Federal Register,* as drafted.

____________________________ (Signature)   ____________________ (Date)

II. Approve publication of the attached notice in the *Federal Register,* with specified changes.

____________________________ (Signature)   ____________________ (Date)

U.S. Consumer Product Safety Commission
4330 East-West Highway
Bethesda, MD 20814

National Product Testing and Evaluation Center
5 Research Place
Rockville, MD 20850

United States
Consumer Product Safety Commission
cpsc.gov | info@cpsc.gov | 800.638.2772

III. Do not approve publication of the attached notice in the *Federal Register.*

______________________________ ______________________
(Signature) (Date)

IV. Take other action specified below.

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____
____
____

______________________________ ______________________
(Signature) (Date)

Attachment: Draft *Federal Register* Notice of Proposed Rulemaking: Safety Standard for Residential Gas Furnaces and Boilers

Billing Code 6355-01-P

CONSUMER PRODUCT SAFETY COMMISSION

16 CFR Part 1408

[CPSC Docket No. CPSC–2019-0020]

Safety Standard for Residential Gas Furnaces and Boilers

AGENCY: Consumer Product Safety Commission.

ACTION: Notice of proposed rulemaking; notice of opportunity for oral presentation of comments.

SUMMARY: The U.S. Consumer Product Safety Commission (Commission or CPSC) has determined preliminarily that there is an unreasonable risk of injury and death associated with residential gas fired central furnaces, boilers, wall furnaces, and floor furnaces (gas furnaces and boilers). To address this risk, the Commission proposes a rule to detect and prevent dangerous levels of carbon monoxide (CO) production and leakage from residential gas furnaces and boilers. The Commission is providing an opportunity for interested parties to present written and oral comments on this notice of proposed rulemaking (NPR).

DATES: *Deadline for Written Comments*: Written comments must be received by [**INSERT DATE THAT IS 60 DAYS AFTER PUBLICATION IN THE FEDERAL REGISTER**].

Deadline for Request to Present Oral Comments: Any person interested in making an oral presentation must send an e-mail indicating this intent to the Office of the Secretary at cpsc-os@cpsc.gov by [**INSERT DATE THAT IS 60 DAYS AFTER PUBLICATION IN THE FEDERAL REGISTER**].

ADDRESSES: *Written Comments*: Comments related to the Paperwork Reduction Act aspects of the proposed rule should be directed to the Office of Information and Regulatory Affairs, OMB, Attn: CPSC Desk Officer, FAX: 202-395-6974, or e-mailed to oira_submission@omb.eop.gov.

Other written comments in response to the proposed rule, identified by Docket No. CPSC-2019-0020, may be submitted by any of the following methods:

Electronic Submissions: Submit electronic comments to the Federal eRulemaking Portal at: www.regulations.gov. Follow the instructions for submitting comments. CPSC typically does not accept comments submitted by e-mail, except as described below. CPSC encourages you to submit electronic comments by using the Federal eRulemaking Portal, as described above.

Mail/hand delivery/courier Written Submissions: Submit comments by mail/hand delivery/courier to: Office of the Secretary, Consumer Product Safety Commission, 4330 East West Highway, Bethesda, MD 20814; telephone: (301) 504-7479. If you wish to submit confidential business information, trade secret information, or other sensitive or protected information that you do not want to be available to the public, you may submit such comments by mail, hand delivery, courier, or you may e-mail them to: cpsc-os@cpsc.gov.

Instructions: All submissions must include the agency name and docket number. CPSC may post all comments without change, including any personal identifiers, contact information, or other personal information provided to: www.regulations.gov. Do not submit through this website: confidential business information, trade secret information, or other sensitive or protected information that you do not want to be available to the public. If you wish to submit such information, please submit it according to the instructions for mail/hand delivery/courier written submissions.

Docket for NPR: For access to the docket to read background documents or comments received, go to: www.regulations.gov, insert the docket number CPSC–2019-0020 into the "Search" box, and follow the prompts.

FOR FURTHER INFORMATION CONTACT: Ronald A. Jordan, Directorate for Engineering Sciences, Mechanical Engineering, Consumer Product Safety Commission, National Product Testing and Evaluation Center, 5 Research Place, Rockville, MD 20850; telephone: 301-987-2219; rjordan@cpsc.gov.

SUPPLEMENTARY INFORMATION:

I. Background

On August 19, 2019, the Commission published an advance notice of proposed rulemaking (ANPR) to develop a rule to address the risk of injury associated with residential gas furnaces and boilers from CO production and leakage. 84 FR 42847. The Commission received 15 comments. The Commission is now proceeding with this proposed rulemaking.[1] The information discussed in this preamble is derived from CPSC the Staff Briefing Package for the NPR, which is available on CPSC's website at: [INSERT HYPERLINK].

II. Statutory Authority

This rulemaking falls under the authority of the CPSA, (Consumer Product Safety Act) 15 U.S.C. 2051-2089. Section 7(a) of the CPSA authorizes the Commission to promulgate a mandatory consumer product safety standard that sets forth performance or labeling requirements for a consumer product, if such requirements are reasonably necessary to prevent or reduce an unreasonable risk of injury. 15 U.S.C. 2056(a). Section 9 of the CPSA specifies the procedure that the Commission must follow to issue a consumer product safety standard under

[1] The Commission voted X-X to approve publication of this notice as drafted.

section 7 of the CPSA. In accordance with section 9, the Commission commenced this rulemaking by issuing an ANPR.

According to section 9(f)(1) of the CPSA, before promulgating a consumer product safety rule, the Commission must consider, and make appropriate findings to be included in the rule, on the following issues:

(A) The degree and nature of the risk of injury that the rule is designed to eliminate or reduce;

(B) the approximate number of consumer products, or types or classes of product, subject to the rule;

(C) the need of the public for the products subject to the rule and the probable effect the rule will have on utility, cost, or availability of such products; and

(D) the means to achieve the objective of the rule while minimizing adverse effects on competition, manufacturing, and commercial practices consistent with public health and safety.

15 U.S.C. 2058(f)(1).

Under section 9(f)(3) of the CPSA, to issue a final rule, the Commission must find that the rule is "reasonably necessary to eliminate or reduce an unreasonable risk of injury associated with such product" and that issuing the rule is in the public interest. 15 U.S.C. 2058(f)(3)(A) and (B). Additionally, if a voluntary standard addressing the risk of injury has been adopted and implemented, the Commission must find that:

- The voluntary standard is not likely to eliminate or adequately reduce the risk of injury, or
- substantial compliance with the voluntary standard is unlikely.

15 U.S.C. 2058(f)(3)(D). The Commission also must find that expected benefits of the rule bear a reasonable relationship to its costs and that the rule imposes the least burdensome requirements that would adequately reduce the risk of injury. 15 U.S.C. 2058(f)(3)(E) and (F).

III. The Product

Central furnaces, boilers, wall furnaces, and floor furnaces fueled by natural gas or propane (gas furnaces and boilers) are used to heat all categories of consumer dwellings. These products burn a mixture of gas and air within the combustion chamber of a heat exchanger. As the mixture of fuel and air is burned, heat is released and transferred through the wall of the heat exchanger to the medium surrounding the heat exchanger and circulated through air ducts (for central furnaces), water pipes throughout the dwelling (for boilers), or directly into the ambient air to provide heat (for wall furnaces and floor furnaces).

Burning the mixture of fuel and air results in the formation of combustion products that are typically composed of oxygen, carbon dioxide, water vapor, and CO. The combustion products are exhausted to the outdoors through a vent system, either vertically through the roof or horizontally through a side wall through the vent pipe. When the mixture of fuel and air is burned completely, the concentration of CO produced should remain relatively low. However, when issues arise with the combustion process (such as fuel-air mixtures that are not optimal), dangerous levels of CO can be produced. The combination of production of dangerous levels of CO during the combustion process and leakage of that CO through the vent system into the living space is a potentially deadly hazard pattern identified by CPSC staff.

In a gas-fired central furnace (Figure 1), air is the medium that surrounds and is heated by the heat exchanger. A large fan is used to force-circulate the heated air across the exterior surfaces of the heat exchanger, through a duct system, and then the heated air exits the duct system through warm air registers typically within the dwelling. The arrow in Figure 1 depicts the vent pipe.

In a gas boiler (Figure 2), water or steam is the medium that surrounds and is heated by the heat exchanger. The heated water or steam is circulated, using a pump to force the fluid through a piping system to radiators typically in each room in the dwelling. Living areas are heated through radiative and conductive heat transfer from the heated water or steam supplied to the radiators to the room. Gas-fired central furnaces and boilers are considered central heating appliances because they provide heat to each room of a dwelling. The arrow in Figure 2 points to the boiler's vent pipe.

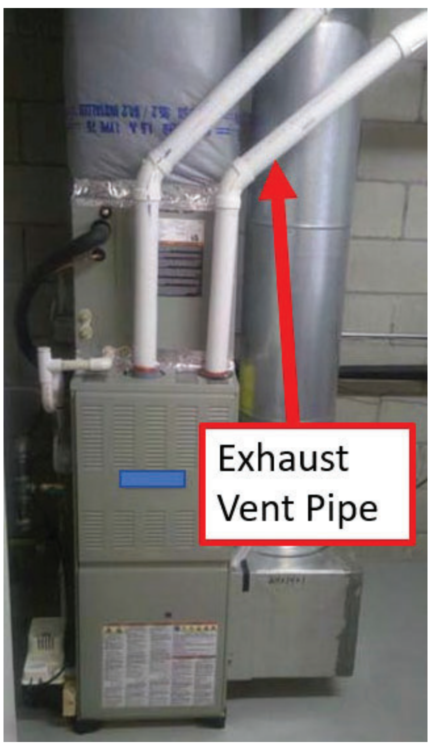


Figure 1. Gas-fired central furnace

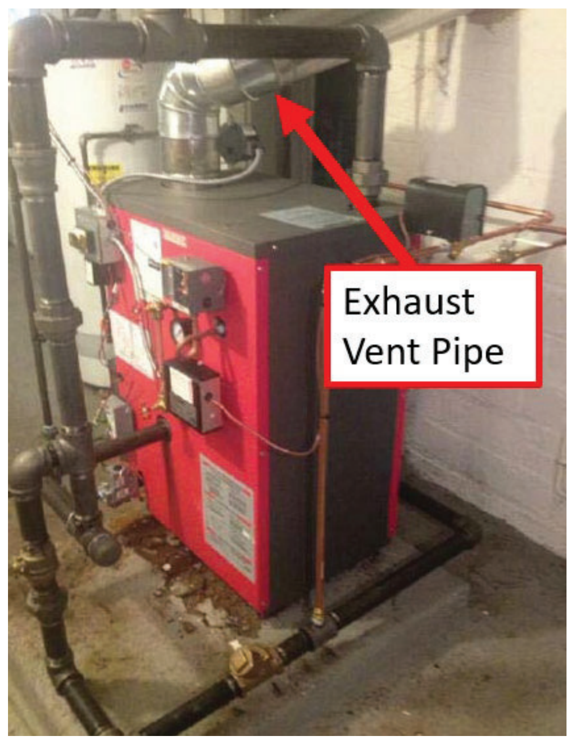


Figure 2. Gas boiler

In addition to central gas-fired furnaces and boilers, the proposed scope of the NPR also includes gas wall furnaces (Figure 3) and gas floor furnaces (Figure 4). As their names indicate, gas wall furnaces are installed in wall spaces, typically between the wall stud framing members; and floor furnaces are installed in the floor, typically between the floor joist framing members. Wall furnaces and floor furnaces provide localized heating directly to the room in which they are located, and indirectly to adjoining rooms within the dwelling. The combustion products of wall furnaces are vented to the outdoors, either vertically through the roof, or horizontally through a side wall with the vent pipe running along the length of the wall studs between which the unit is installed. The combustion products of a floor furnace are typically vented horizontally through a side wall, with the vent pipe running along the length of the floor joists between which the unit is installed and through an exterior wall.


Figure 3. Gas wall furnace


Figure 4. Gas floor furnace

IV. Risk of Injury

A. Incident Data

1. Fatalities

From the time period of 2017 to 2019 (the most recent period for which data are complete), there were annually an estimated 21 CO-related deaths associated with gas furnaces and boilers (burning liquefied petroleum, natural gas, and unspecified gas).[2] For the 20-year period, 2000 through 2019, these products were associated with a total of 539 deaths from CO poisoning. Tab A of the Staff NPR Briefing Package provides further information regarding fatalities.

2. Injury Estimates

To estimate the number of injuries associated with CO exposure from natural gas and propane furnaces and boilers, an interdisciplinary team of CPSC staff evaluated injuries reported through the National Electronic Injury Surveillance System (NEISS) (*See* Tab J of the Staff NPR Briefing Package). Staff queried NEISS for data between the years 2014 and 2018. Staff identified 236 nonfatal injuries related to CO leakages from gas furnaces and boilers that occurred during this period. Of the 236 nonfatal injuries, 18 resulted in hospital admissions via the emergency department (ED), and 218 were treated in the ED and released. Staff used NEISS incidents and the Injury Cost Model (ICM) to extrapolate and generate national estimates for injuries from CO leakages from gas furnaces and boilers treated in EDs and other settings. Staff, using the ICM, calculated that the aggregate number of nonfatal injuries from CO leakages from gas furnaces and boilers from 2014 to 2018 was 30,587. Staff estimated that of the 30,587 injuries, 22,817 were treated in an outpatient setting (*e.g.*, doctor's office, or clinic), 7,358 resulted in ED treatment, 333 resulted in hospital admissions via the ED, and 79 resulted in direct hospital admissions.

[2] *Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products 2019 Annual Estimates*. J. Topping. CPSC Directorate for Epidemiology. March 2023. https://www.cpsc.gov/s3fs-public/NonFireCarbonMonoxideDeathsAssociatedwiththeUseofConsumerProducts2019AnnualEstimates.pdf?VersionId=90WCZoH61aVUrTgDtOo16LLKZf1EeH3E.

B. Description of Hazard - Acute CO Poisoning

In Tab C of the Staff ANPR Briefing Package[3] staff described the hazard pattern for CO poisoning associated with gas furnaces and boilers; which involves (1) hazardous levels of CO from incomplete combustion of the source fuel/gas and (2) exhaust leakage of that hazardous CO into the living space through a leak in the exhaust vent system. Staff's review of the 83 incidents, in conjunction with findings from earlier in-depth investigation (IDI) reviews, identified the following factors related to the incomplete combustion and exhaust leakage hazard patterns.

1. Production of Dangerous Levels of CO from Incomplete Combustion

Complete combustion of hydrocarbon fuels, such as natural gas or liquefied petroleum gas (LP-gas or propane), requires a proper mixture of air and fuel, as well as an adequate amount of heat to ignite the combustion air-fuel mixture. Incomplete combustion of the fuel supplied to gas appliances can lead to production of hazardous levels of CO. Incomplete combustion can occur when there is inadequate combustion of air (for instance when air openings to the appliance combustion chamber or burner assembly, or the exhaust outlet from the appliance is blocked); too much fuel is supplied to the appliance burner (*i.e.*, over-firing); or the burner flame temperature falls below the ignition temperature of the combustion air-fuel mixture (*i.e.*, flame quenching). Depending on the severity and duration, all these conditions can result in incomplete combustion of the fuel; which, in turn, can result in the gas furnace or boiler producing dangerous levels of CO. Staff's ongoing review of IDIs confirms that these

[3] Draft Advance Notice of Proposed Rulemaking: Performance Requirements for Residential Gas Furnaces and Boilers. Retrieved at: https://cpsc.gov/s3fs-public/Draft%20ANPR%20-%20Performance%20Requirements%20for%20Residential%20Gas%20Furnaces%20and%20Boilers.pdf

hazard patterns have not changed since publication of the ANPR.

2. Exhaust leakage

Combustion products produced by a gas furnace or boiler are normally vented to remove them from the home through a properly functioning vent system. A potential CO hazard in a home can arise if the combustion system of a gas furnace or boiler malfunctions and produces hazardous levels of CO, which a compromised exhaust system then allows to leak into the occupied space of the home. Typical exhaust failure leakage paths include a totally or partially blocked vent, chimney, heat exchanger, or a disconnected or hole in the vent pipe.

Another potential leakage mechanism occurs when an exhaust fan or fireplace is installed near a gas furnace or boiler. The operation of an exhaust fan or a warm chimney created by a fireplace can pull air out of the room in which the gas furnace or boiler is installed. This can depressurize the room, resulting in reverse flow of the combustion products through the gas furnace or boiler vent system or flue passageways. Instead of being vented safely to the outdoors, depressurization can cause CO to spill into the living space. Other mechanisms that can lead to spillage include venting that is inadequate for the gas furnace or boiler connected to it. This can be caused by total or partial vent blockage, installation of a vent pipe that is too small for the gas furnace or boiler, or the connection of too many appliances to the vent.

V. Assessment of Relevant Existing Voluntary Standards

A. U.S. Voluntary Standards

1. Description of Existing U.S. Voluntary Standards for Gas Furnaces and Boilers

In the United States, the four types of gas furnaces and boilers within the scope of the proposed rule are covered by the following ANSI Z21 voluntary standards:

- ANSI Z21.13-2022, *Standard for Gas-fired low pressure steam and hot water boilers*: This standard specifies construction and performance requirements for gas-fired, low-pressure steam and hot water boilers with input ratings of less than 12,500,000 Btu/hr (3,663 kW). The first edition of the standard was published in 1934, and the standard has been revised several times, with the latest edition published in 2022.
- ANSI Z21.47-2021, *Standard for Gas-fired central furnaces*: This standard specifies construction and performance requirements for gas-fired central furnaces with input ratings up to and including 400,000 Btu/hr (117 kW) for installation in residential, commercial, and industrial structures including furnaces for direct vent, recreational vehicle, outdoor, and manufactured (mobile) homes. The requirements for gas-fired central furnaces were initially included in ANSI Z21.13, before becoming a separate standard in 1964. From 1978 through 1993, a separate standard for direct vent central furnaces (ANSI Z21.64) was in place before being consolidated into a single standard and harmonized with Canadian standard requirements in 1993, with the latest edition of ANSI Z21.47 published in 2021.
- ANSI Z21.86-2016, *Standard for Vented gas-fired space heating appliances*: This standard specifies construction and performance requirements for vented gas-fired space heating appliances with input ratings up to and including 400,000 Btu/hr (117 kW), including gravity and fan type direct-vent wall furnaces and gravity and fan-type floor furnaces. The ANSI Z21.86 standard was first published in 1998, with the latest edition published in 2016.

All three ANSI standards have the following relevant requirements for gas furnaces and boilers:

- must not produce CO in excess of 400 ppm (under prescribed laboratory test conditions);

- shut off when vent or flue is fully blocked;
- shut off when blower door is not sealed properly (gas-fired central furnaces only); and
- shut off if flames issue outside of the burner compartment.

2. CPSC Voluntary Standards Activity

In 2000, CPSC staff proposed voluntary standard provisions that would require a gas furnace (ANSI Z21/83 Technical Committee subsequently extended the consideration of the proposed standards provisions to all vented heating appliances including boilers):

- to shut down if the vent pipe became disconnected; and
- to shut down if the vent pipe became totally or partially blocked; or
- to have a means to prevent CO emissions from exceeding the standard limits once installed in the field; and
- to have a means, once installed in the field, to shut down if CO emissions exceeded the standard limits.

In 2002, the ANSI Z21/83 Technical Committee (TC) established a working group to evaluate the feasibility of using CO and combustion sensor technology to implement CPSC staff's CO shutoff/response proposal. CPSC staff participated in that working group from 2002 through 2005. ANSI disbanded this working group in 2005 because manufacturers expressed concerns that there were no sensors commercially available that had the durability or longevity to operate within a gas furnace or boiler for their expected 20-year lifespan. CPSC staff conducted additional sensor testing from 2007 to 2008 to evaluate and assess the ANSI ZS21/83 TC's and working group's concerns.

In 2014, the Commission published a request for information (79 FR 21442) and hosted a Carbon Monoxide/Combustion Sensor Forum to gather more information on the availability and feasibility of CO and combustion sensors for use in gas furnaces and boilers.

In 2015, the Z21/83 TC established another working group to evaluate a new CPSC staff proposal to add performance requirements for CO Shutoff/Reponses to the voluntary standards for gas-fired central furnaces and, boilers, wall furnaces, and floor furnaces. The Z21/83 Technical Committee assessed that the technology required to meet the performance requirements was not feasible. The working group disbanded in 2019 without proposing any revisions to the voluntary standard that would adequately mitigate the CO hazard associated with gas furnaces and boilers.

In Tab D of the 2019 Staff ANPR Briefing Package, staff analyzed the three ANSI voluntary standards and concluded that none of the existing voluntary standards included requirements to protect against many of the known failure modes or conditions that have been associated with production and leakage of CO into living spaces. Since publication of the ANPR in August 2019, none of the existing ANSI voluntary standards discussed above have been revised to address the known failure modes or conditions associated with CO poisoning, such as disconnection, breach, or partial blocking of flues, vents, and chimneys.

B. International Standards

Existing Japanese and European gas appliance voluntary standards include CO shutoff or combustion control[4] requirements, with reliance on gas sensing technologies to implement those standards' requirements.

[4] Combustion control refers to a means to control the combustion of a gas/air mixture to ensure complete combustion of the gas/air mixture and to limit the production of carbon monoxide.

1. Japan

The primary gas heating appliances used in Japan are gas water heaters, gas boilers, and gas space heaters. Based on staff's review of the Japanese gas appliance market, instantaneous tankless gas water heaters[5] (Figure 6) are more common than traditional gas water heaters with storage tanks.

Figure 6. Japanese tankless gas water heater

The governing voluntary performance and safety standards in Japan are:

- JIS-S-2109 - Gas-burning water heaters for domestic use;
- JIS S 2112 - Gas hydronic[6] heating appliances for domestic use; and
- JIS S 2122 - Gas-burning space heaters for domestic use.

These Japanese Industrial Standards (JIS) have explicit performance requirements for vented gas water heaters, gas boilers, and gas space heaters that require shutoff of the appliance in response to CO levels above a certain threshold (*i.e.*, 300 ppm CO). The CO detection

[5] Instantaneous tankless gas water heaters provide heated water on demand and therefore, do not require the use of a large storage tank, whereas traditional gas storage water heaters include a large storage tank used to store heated water.
[6] "Hydronic" denotes a cooling or heating system in which heat is transported using circulating water. A boiler is a type of appliance that provides this capability.

strategies Japanese manufacturers use to comply with JIS include detection of CO within the combustion chamber of the appliance and shutoff or combustion control in response to detection of hazardous levels of CO.

2. Europe

The relevant Committee for European Standardization (CEN) standards for residential gas boilers (depicted in Figure 7 below) are:

- EN 15502 -1, Gas-fired heating boilers, Part 1: General requirements and tests;
- EN 15502-2-1, Gas-fired central heating boilers, Part 2-1: Specific standard for type C appliances and type B2, B3 and B5 appliances of a nominal heat input not exceeding 1 000 kW; and
- EN 15502-2-2, Gas-fired central heating boilers, Part 2-2: Specific standard for type B1 appliances.

Figure 7. European gas boiler

These CEN standards include explicit performance requirements for gas boilers to either shut down before the CO concentration inside the flue exceeds 2,000 ppm or not start if the CO concentration exceeds 1,000 ppm.

C. Staff Assessment of Voluntary Standards

Based on staff's analysis of the relevant ANSI standards, staff concludes that the current ANSI Z21.13-2022, ANSI Z21.47-2021, and ANSI Z21.86-2016 standards do not contain performance requirements to protect against the known failure modes or conditions identified by the Commission. Specifically, the current ANSI standards lack requirements (1) that protect against known conditions that cause or contribute to CO exposure and (2) for the appliance to monitor and manage CO production to prevent the introduction of hazardous levels of CO in the appliance's exhaust vent system. Currently, deaths and injuries can and do occur from CO poisoning even when the furnace or boiler complies with all applicable existing voluntary standards in the U.S. Based on the above discussion and the analysis in the Staff NPR Briefing Package, the Commission concludes that the existing ANSI standards for gas furnaces and boilers are inadequate to address the hazards identified by CPSC.

In addition, staff has researched international standards that required the same or similar performance requirements as staff's 2000 and 2015 proposals to the Z21/83 Technical Committee. Staff identified several gas-sensing technologies that were being used for CO shutoff or combustion control of residential gas appliances used in Japan and Europe to correspond with the respective standards. The CO-detection strategies used by Japanese manufacturers include detection of CO within the combustion chamber of the appliance and shutoff or combustion control in response.

In Europe, residential gas boilers are required to meet certain European combustion-efficiency requirements, as well as CO safety requirements. The combustion-control strategies used by European gas boiler manufacturers to comply with the standards are often accomplished by monitoring the gas/air mixture, the combustion flame, or the concentration of CO, oxygen, or carbon dioxide within the combustion products. The combustion-control strategies are also used to detect CO, but rather than causing shut-down of the appliance, CO production is either prevented or limited by modulating the appliance's operation. The Japanese and European standards do not specify a minimum lifespan for sensing devices used to implement their respective CO safety and combustion efficiency requirements. However, adoption of the European and Japanese standards for U.S. gas furnaces and boilers would not be appropriate because of the design differences between European and Japanese products and U.S. gas furnaces and boilers, as well as the different regulations and standards requirements (other than CO safety related requirements) that European and Japanese appliances are required to comply with that would not apply to appliances made and sold in the U.S.

VI. Technical Justification for the Proposed Performance Requirements

A. Testing and Evaluation Conducted by Contractors

Tab C of the Staff NPR Briefing Package includes links to the contractor reports regarding the research and testing conducted to assist in developing staff's proposed mandatory performance requirements. In 2019, a CPSC contract was awarded to Guidehouse (formerly Navigant, Inc.) to study the impact of CO/combustion sensors used in residential gas boilers and water heaters in Europe and Japan and to gain a better understanding of the use of CO sensors in gas appliances in other parts of the world and their impact in mitigating CO risks associated with gas appliances. This contract work also was commissioned to assess industry concerns about the feasibility of using sensors in the exhaust flue of gas furnaces and boilers. Work on this contract concluded in 2021 and the findings are documented in a contractor report titled, "Review of Combustion Control and Carbon Monoxide Sensors in Europe and Japan," dated June 28, 2021. The Guidehouse report is included as attachment 3 of Tab C of the staff NPR Briefing Package.

The Guidehouse report found that in Europe, gas appliance safety is governed by European Union (EU) Regulation 2016/426 on appliances burning gaseous fuels, and compliance with the applicable standard published by the CEN is generally considered a means to demonstrate compliance with the regulation. In Japan, the Gas Business Act and the Act on the Securing of Safety and the Optimization of Transaction of Liquefied Petroleum Gas require that a manufacturer or importer ensure that the gas-fired equipment conforms to the technical standards established by an Ordinance of the Ministry of Economy, Trade and Industry (METI). European and Japanese manufacturers limit CO production with combustion safety systems, combustion control systems, direct CO sensing in the exhaust path, or a combination of these approaches. The available data revealed that CO deaths and injuries in the EU and Japan were declining. However, the Guidehouse report noted that additional factors, such as other CO alarm usage and education and market changes, likely played a role in these reductions of CO deaths and injuries as well.

The Guidehouse report also found the designs used in U.S. residential heating and water heating appliances differ significantly from those used in Japan and Europe. In Europe and Japan, gas boilers are commonly used for space heating and the market has transitioned almost entirely to condensing systems that utilize premix power burners. The Guidehouse report also found that appliances with design platforms based on premix power burners are better suited to incorporate combustion control because they typically have a single burner, a single heat exchanger cell, and a single flame ionization sensor to monitor the burner flame.

CPSC also procured two contracts with ANSYS, Inc. (formerly DfR Solutions, Inc.) to estimate the expected lifespans of CO/combustion sensors while operating in a gas furnace or boiler application. The report titled "Performance and Accelerated Life Testing of Carbon Monoxide and Combustion Sensors," dated May 28, 2019, is included as attachment 1 of Tab C of the Staff NPR Briefing Package. The report titled "Performance and Accelerated Life Testing of Redesigned Carbon Monoxide and Combustion Gas Sensors," dated February 25, 2022, is included as attachment 2 of Tab C of the Staff NPR Briefing Package. The ANSYS report demonstrated that CO/combustion sensors are currently commercially available for use in gas appliances; the CO/combustion sensors that were tested had expected lifespans ranging from 6.4 to 10 years operating under conditions that replicate the main stress conditions expected within a gas appliance.

B. Justification for Proposed Performance Requirements

The proposed performance requirements are reasonably necessary and feasible for the following reasons:

- The gas furnaces and boilers under consideration are associated with an estimated 21 deaths per year, on average (2017-2019), and an estimated total of 539 CO deaths from 2000 to 2019;
- the existing voluntary standards do not include provisions that would protect consumers from a number of conditions described in section IV of the preamble that are known to cause or contribute to the production, leakage into, and accumulation of dangerous concentrations of CO in the living space of a dwelling;
- there is no indication that the Z21/83 Technical Committee or any of the technical Subcommittees for gas furnaces and boilers intend to address this hazard; and

- continuous monitoring of the combustion process or the concentration of carbon monoxide within the combustion gases can be accomplished using commercially available CO/combustion sensing or combustion control technology.

The proposed performance requirements described in this section of the preamble are intended to reduce the occurrence of CO-related deaths, injuries, and exposures associated with gas furnaces and boilers. Specifically, gas furnaces and boilers would continuously monitor CO emissions and shut down or modulate combustion if any of the average CO ranges specified in Table 1.[7] are detected in the gas furnaces and boilers flue gases for the durations listed.

Table 1. CO ranges and durations for shut-down or modulation

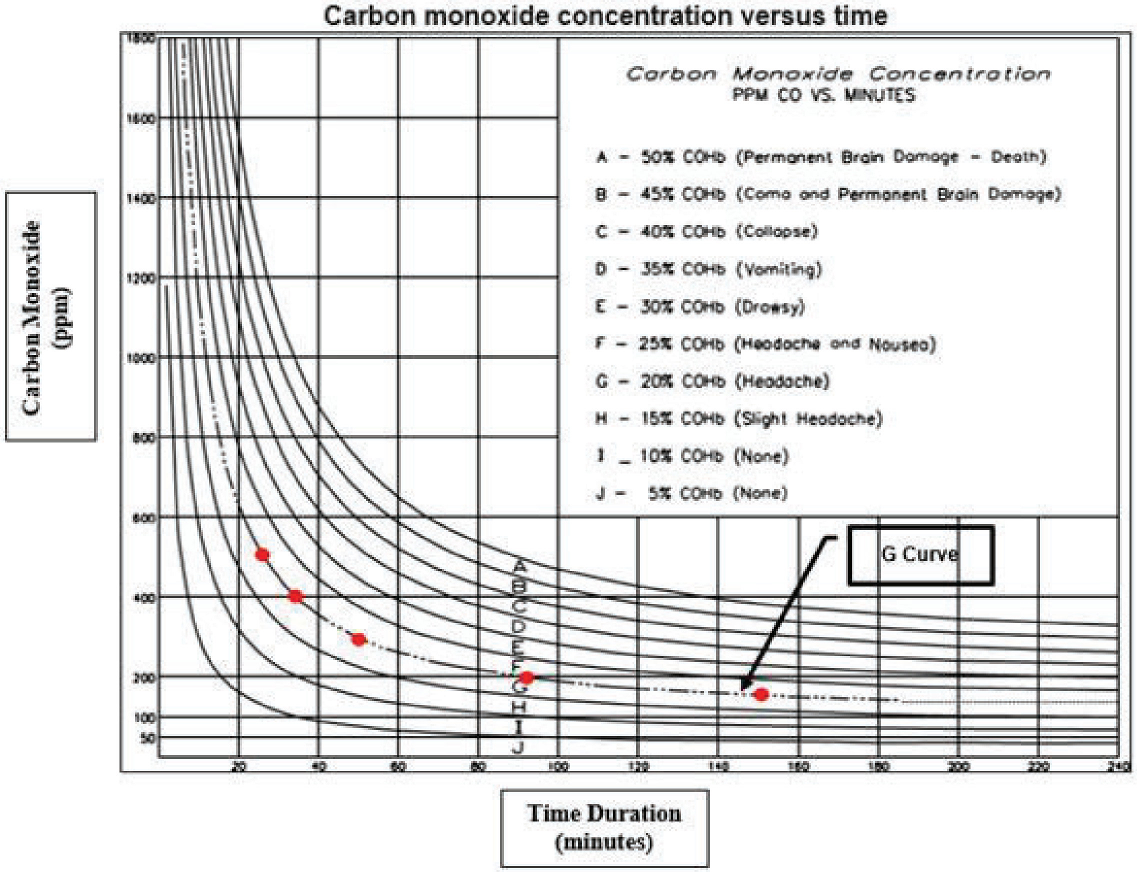
Average CO (ppm)	**Duration (minutes)**
500 or above	15
400-499	30
300-399	40
200-299	50
150-199	60

The average CO ranges in Table 1 are the proposed setpoints and durations at which a gas furnace or boiler must either shut down or begin modulation. These CO ranges are based on

[7] The proposed CO range setpoints and durations reflected in Table 1 are derived from UL 2034, Standard for Safety Single and Multiple Station Carbon Monoxide Alarms, 4th Edition, (2017), the voluntary standard for in-home carbon monoxide alarms. UL 2034 provides requirements for electrically operated single and multi-station CO alarms intended for protection in ordinary indoor locations of dwelling units. Section 41.1 of UL 2034 provides the levels at which a carbon monoxide alarm must trigger. Section 1.2 of UL 2034 covers carbon monoxide alarms intended to respond to the presence of carbon monoxide from various sources, including the abnormal operation of fuel-fired appliances.

Curve G of the CO Concentration vs. Time graph (Figure 41.1 from UL 2034) in Figure 8 which indicates what an individual's carboxyhemoglobin (COHb) levels would be if exposed to various CO concentrations and the time of exposure needed to reach that COHb level. Curve G represents a 20 percent COHb level and the onset of health effects in individuals (*i.e.*, a headache). The values on the y-axis represent CO exposure levels in parts per million (ppm) from zero ppm CO to 1800 ppm CO. The values on the x-axis represents the time durations (in minutes) of exposure to the CO concentrations presented on the y-axis. The curves A through J on the graph represent the various carboxyhemoglobin levels an individual can reach when exposed to CO (y-axis) over a period of time (x-axis).

Figure 8 (Based on Figure 41.1 in UL 2034)
Carbon monoxide concentration versus time



To interpret the graph in Figure 8, begin at a given CO concentration on the y-axis and extend a horizontal line to the right until the line intersects a COHb curve. At the point of intersection, extend a vertical line downwards to the x-axis. The time value at this point of intersection represents the amount of time, at the selected CO concentration, at which an individual would reach a certain COHb level. For example, at a 400 ppm CO concentration, it would take approximately 35 minutes for an individual to reach a COHb of 20 percent. At a CO concentration of 300 ppm, it would take approximately 50 minutes to reach a COHb of 20 percent. The dots on the graph in Figure 8 illustrate that the entire proposed CO response range (*i.e.,* 150 - 400 and above) all fall on Curve G. A performance requirement that requires shutdown or modulation of a gas furnace or boiler at this range of CO levels provides protection to consumers from the onset of the more serious CO-related health effects, such as vomiting, coma, and death. The proposed performance requirement for the range and time period for CO exposure is consistent with the existing UL 2034 standard for consumer carbon monoxide alarms, which uses similar requirements to protect consumers from CO exposure in the home.

Manufacturers may comply with the performance requirements under the proposed rule by using an option for either shut down or modulation of the gas furnace or boiler if the average CO level reaches 150 ppm over a 15-minute duration. This option simplifies the performance requirement to a single CO setpoint rather than multiple setpoints as described above. It provides the same level of protection as the multiple setpoint approach described above because the gas furnace or boiler would be required to shut down or modulate at the lowest threshold of CO production (150 ppm) that can result in low-level health effects (*i.e.,* headache per the 20 percent COHb curve). The shorter time duration (15 minutes) is protective at higher CO concentrations of 200 ppm or more that can begin to cause the onset of health effects (*i.e.,* a headache per the 20 percent COHb curve).

The proposed performance requirements described in section VIII of the preamble are also based, in part on, on the definitions and performance requirements in ANSI Z21.47, *Standard for Gas-fired central furnaces*; ANSI Z21.13, *Standard for Gas-fired low pressure steam and hot water boilers*, and ANSI Z21.86, *Standard for Vented gas-fired space heating appliances*, as well as performance requirements from CEN[8,9] standards for domestic gas boilers, and CEN standards for safety and control devices for gas appliances[10,11] and gas/air ratio controls for gas appliances,[12] and JIS standard for domestic gas water heaters, boilers and space heaters.[13,14,15] The CEN and JIS standards were given weight when developing the proposed performance requirements because the provisions in these standards are similar to the proposed performance requirements for gas furnaces and boilers in this NPR and are readily applicable to U.S. gas furnaces and boilers. In addition, although there are significant differences between the design platforms of European and Japanese gas boilers (*i.e.,* predominantly premix power burner designs) and U.S. gas furnaces and boilers (*i.e.,* predominantly induced draft and some atmospheric vent designs), the basic operating environment parameters (e.g., temperature, humidity, and combustion gases) within the heat exchangers and flues of European and Japanese gas boilers and U.S. gas furnaces and boilers are similar. The European and Japanese

[8] EN 15502-2-1, *Gas-fired central heating boilers, Part 2-1: Specific standard for type C appliances and Type B2, B3 and B5 appliances of a nominal heat input not exceeding 1 000 kW.*
[9] EN 15502-2-2, *Gas-fired central heating boilers Part 2-2: Specific standard for type B 1 appliances.*
[10] BS EN 13611, Safety and control devices for burners and appliances burning gaseous and/or liquid fuels — General requirements.
[11] BS EN 16340, Safety and control devices for burners and appliances burning gaseous or liquid fuels — Combustion product sensing devices.
[12] Gas/air ratio controls for gas burners and gas burning appliances — Part 2: Electronic types
[13] JIS-S-2109, *Gas burning water heaters for domestic use*.
[14] JIS-S-2112. *Gas hydronic heating appliances for domestic use.*
[15] JIS-S-2122, *Gas burning space heaters for domestic use*.

circumstances demonstrate the commercial availability of CO/combustion sensors and combustion controls that: (1) provide CO/combustion sensor-based shutoff or reduced CO through combustion control; (2) are durable enough to survive in heat exchangers or flues of gas appliances; and (3) can be applied for use in U.S. gas furnaces and boilers.

The proposed rule provides test methods to introduce a simulated 400 ppm, 300 ppm, 200 ppm, and 150 ppm CO emission level into the exhaust gas to determine if the safety system passes or fails the proposed performance requirements.

As explained in Tab B of the Staff NPR Briefing Package, staff assesses that the proposed rule would be 90 to 100 percent effective in preventing CO deaths and injuries associated with gas furnaces and boilers, because CO production at the gas furnace and boiler would be limited to levels that produce a headache in exposed consumers. Staff's assessment is based on the following key metrics used to assess the capability of the performance requirement in protecting consumers from the identified CO exposure risks:

- <u>Detecting CO at the source of production:</u> This provides a greater level of protection to consumers than residential CO alarms because it detects CO at the source of production within the gas furnace or boiler, before it leaks into a dwelling space, and allows for an earlier response time to protect consumers.
- <u>Prevents or limits production of harmful levels of CO</u>: Shutoff or modulation of the gas furnace or boiler directly addresses harmful CO production.
- <u>Selecting CO response concentrations that fall on the 20 Percent COHb curve</u>: Selecting multiple CO response concentrations or a single, threshold CO concentration (150 ppm or higher) limits the severity of any potential health effects to a headache (*i.e.,* the 20 percent COHb curve).

- Addresses all known hazard patterns: Although the performance requirements do not prevent combustion product (including CO) leakage, the requirements do protect against serious harm from leakage of combustion products by limiting/preventing CO production.

VII. Response to Comments

In response to the Commission's 2019 ANPR regarding residential gas furnaces and boilers, CPSC received 15 comments from the public, divided between supporters and opponents of the proposal. Opposing comments came primarily from the gas appliance industry. The comments can be found under docket number CPSC-2019-0020, at: www.regulations.gov. Below is summary of the comments and CPSC's responses by topic area.

Alternatives to Performance Requirements

Comment: Nine commenters (A.O Smith, Carrier, Crown, Rheem, US Boiler Co. Edward Johan (USBC EJ), US Boiler Co. John Busse (USBC JB), Air Conditioning, Heating, and Refrigeration Institute (AHRI), Strauch, and Stanonik) asserted that rulemaking is not necessary because residential CO alarms will prevent CO poisoning from gas appliances. One commenter (Stanonik) further claimed that information from CPSC's IDI reports show that CO alarms are effective in protecting participants from exposure to hazardous levels of CO and that a survey being conducted by CPSC should be completed before rulemaking occurs. Four commenters (Crown, USBC EJ, USBC JB, and AHRI) supported changing the ANSI gas appliance standards and/or building codes to require CO alarm installation.

Response: CPSC lacks statutory authority to mandate that consumers install CO alarms in their homes. Although the Commission urges use of residential CO alarms, not all homes are equipped with functioning and maintained CO alarms, and fewer still have them in all occupied spaces into which CO may leak from a gas furnace or boiler. Despite CPSC, state and local governments, and the private section information and education campaigns to increase the use of CO alarms, injuries and fatalities that occur annually are evidence that this hazard continues to kill and injure consumers, supporting the view that effective performance requirements for gas appliances are critical to consumer safety.

Comment: USBC JB stated that a CO monitor in the equipment room or living space would provide a better solution than a CO monitor on the appliance.

Response: A monitoring system located within the equipment room or living space would not necessarily detect CO at all foreseeable points of potential leakage along the length of the vent system. In contrast, detecting excessive CO leakage at the point of production on the appliance would protect consumers from CO exposure, regardless of the point or mechanism of leakage, or the cause of elevated CO production.

Comment: USBC JB stated that CPSC should sponsor and provide funding for a multi-functional task force to develop solutions to reduce and eliminate CO poisoning caused by residential gas furnaces and boilers.

Response: CPSC has contributed extensively to the development of proposed solutions to the CO hazard from gas furnaces and boilers. Staff's memorandum in Tab D of the Staff ANPR Briefing Package summarizes CPSC staff's efforts from 2000 to 2019 to work with the ANSI Z21/T83 Technical Committee to address carbon monoxide poisoning that was continuing to occur despite revisions to the gas appliance standards. CPSC staff conducted research and shared the results of that research, along with incident reports, with the Committee. Staff also submitted two proposals to the Technical Committee (in 2000 and 2015) requesting that the relevant voluntary standards add requirements to address the production of hazardous levels of

CO and the risk of that CO entering the living space of a dwelling. Despite staff's efforts over two decades, as well as the developments of voluntary standard requirements in Japan and Europe, the U.S. voluntary standards community has not adequately addressed the CO risk at the source of production in gas appliances. Indeed, in 2019 the Technical Committee disbanded the working group assessing possible revisions to the standards.

Comment: USBC JB predicted that gas furnaces and boilers will eventually be replaced with electric heating appliances because current and future efforts to reduce carbon emissions will eliminate or restrict the availability of natural gas for residential appliances.

Response: Gas appliances and boilers continue to be sold in large numbers for residential heating in the United States, without an effective voluntary solution to the CO hazard. Therefore, the Commission preliminarily concludes that mandatory performance requirements to address CO production by gas furnaces and boilers are necessary to reduce deaths and injuries from CO exposure that otherwise will continue to occur.

Comment: USBC JB referred to periodic inspection and service of gas appliances and asked if CPSC's data addresses whether "formalized inspection and service requirements would reduce carbon monoxide poisoning." Two other commenters (Crown and AHRI) asserted that a formal program to check installation, service, and maintenance will reduce carbon monoxide incidents.

Response: CPSC lacks statutory authority to mandate homeowners' spending for maintenance services. Further, CPSC staff is not aware of data indicating that maintenance alone can address the deadly CO hazard from gas furnaces and boilers. Manufacturers already recommend routine maintenance of furnaces and boilers, yet injuries and deaths continue to occur for the reasons described above.

Comment: Crown and USBC JB asserted that CPSC should rely on recalls to prevent/reduce CO incidents involving gas boilers and furnaces.

Response: When a product is subject to a CPSC recall, the product already may have been involved in an incident, in this case a CO exposure incident that may have caused serious injury or death. The CPSC will continue to utilize the CPSA section 15 recall process, independent of this this rulemaking, but it is not a substitute for the proposed rule, which addresses elevated CO levels that may be unrelated to a defect in the furnace or boiler itself.

<u>Rely on Consumer or Installer Education</u>

Comment: Carrier, Crown, Rheem, USBC EJ, and USBC JB stated that information and education programs for consumers, installers, and maintenance personnel will adequately address CO poisoning hazards.

Response: Information and education campaigns currently exist, and yet numerous deaths and injuries continue to occur due to CO poisoning from gas furnaces and boilers demonstrating that these campaigns do not adequately address the hazard.

Warnings rely on educating consumers about the hazard and persuading consumers to alter their behavior in some way to avoid the hazard. To be effective, warnings also depend on consumers noticing or otherwise receiving the message, attending to the message, remembering the recommended behaviors when needed, and behaving consistently, regardless of situational or contextual factors that influence precautionary behavior, such as fatigue, stress, or social influences. Thus, providing warnings and instructions about hazards is less effective than either designing the hazard out of a product or guarding the consumer from the hazard. .

<u>Rely on Voluntary Standards</u>

Comment: Commenters A.O. Smith, Rheem and the National Propane Gas Association

(NPGA) stated that the CPSC should work with voluntary standards organizations to address the hazard.

Response: Tab D of the Staff ANPR Briefing Package summarizes CPSC staff's efforts from 2000 to 2019 to work with the ANSI Z21/T83 Technical Committee to address carbon monoxide poisoning incidents. As described above, despite staff's efforts, the voluntary standards organizations have not adopted adequate performance requirements to address the hazard.

Comment: Carrier and AHRI noted that current appliance designs certified to the applicable ANSI/CSA Z21 safety standards already incorporate several safety features that reduce the risk of carbon monoxide production. These include blocked vent/intake switches, draft hood spill switches, and flame roll-out switches. Another commenter (USBC JB) stated that the ANSI standard for direct and non-direct vent boilers includes a test method to limit CO levels when the flue outlet is blocked or partially blocked, which USBC JB believes addresses the impact of snow blocking the vent. Stanonik stated that two-pipe or direct vent systems have fewer CO risks and some atmospherically vented appliances are not susceptible to depressurizing and back drafting that lead to CO exposure in the living space, and that these features, combined with the proper installation, service, and maintenance of the appliances, would eliminate the CO risk.

Response: Blocked vent/intake pressure switches, draft hood spill switches, and flame rollout switches are all requirements that were added to and became effective in the standards between 1987 and 1993. Yet injuries and deaths from CO poisoning have continued to occur despite the existence of these voluntary standards provisions. Indeed, as discussed in Tab B of the Staff NPR Briefing Package, the particular voluntary standards provisions cited by these commenters have failed to prevent deaths and injuries in real-world scenarios.

<u>Adverse/Unintended consequences of shut-off triggered by CO sensor</u>

Comment: Six commenters (Carrier, Crown, USBC EJ, USG JB, AHRI, and Strauch) stated that improper shut-down of a gas appliance by a CO sensor will cause a no-heat hazard for consumers.

Response: In response to these comments and other staff analyses, the proposed rule would require a fail-safe provision that would operate for the life of the appliance. If a CO sensor, combustion sensor, combustion control system, or other device designed to meet these requirements, fails to operate properly or at all, then the appliance shall shutdown and restart after 15 minutes, repeating this cycle and continuing to provide heat until the failed component is replaced, while also alerting the consumer of the hazard. For the life of the gas furnace or boiler, the proposed fail-safe provision would be required to notify consumers and service technicians of device failure by either a flashing light, or other appropriate code on the appliance control board, that corresponds to the device failure.

Comment: Crown stated that a shut-down central heating appliance may encourage the use of less safe heating alternatives.

Response: Shut-off devices on gas furnaces and boilers (e.g., BVSS, flame rollout switches, and over temperature limit switches) have been required by the ANSI Z21 standards for 25 to 30 years. However, we are not aware of any trends of consumers using less safe heating alternatives as the result of these other safety shut-down devices on these products. Furthermore, the proposed rule has a fail-safe provision, as described above, which provides warning to consumers of a CO sensor issue without complete loss of functionality of the gas furnace or boiler.

<u>Carbon monoxide sensor – Sensitivity and Durability</u>

Comment: American Gas Association (AGA) and USBC JB asserted that measuring "air-free" CO concentrations benchmarked to the ANSI-recognized "safe" concentration of 400 ppm would be complex because a carbon monoxide monitor measures "raw" CO concentrations which includes the "air-free" carbon monoxide concentration multiplied by the ratio of air that was not used in combustion. Consequently, the air-free CO will always be lower than the measured CO.

Response: CPSC staff agrees that an air-free measurement calculation would be more complex since it would require the measurement of carbon dioxide or oxygen as well, and the proposed rule does not require this calculation.

Comment: USBC JB stated that the performance of existing CO sensors has not been established at the 400 ppm level and lower.

Response: In general, sensor manufacturers specify the maximum and minimum concentration range that a sensor can detect, as well as whether the sensor provides a linear output voltage in response to the gas (*i.e.*, CO) it's designed to detect. For example, if a manufacturer specifies that their sensor has a linear response range of 0 to 10,000 ppm of CO, then the sensor can detect between 0 and 10,000 ppm CO, including 400 ppm CO or lower. CPSC staff has identified multiple CO sensors with an advertised linear response range that extends below 400 ppm.

Comment: Strauch asserted that research does not show that CO sensors are durable enough to last for 15 to 20 years. Another (USBC JB) stated that performance requirements normally address device tolerances to allow conformance at prescribed conditions and avoid nuisance issues.

Response: We do not agree with the premise that CO sensors must have a 15-to-20 year lifespan in order for the proposed rule to be effective. Many parts may fail during the lifetime of a gas furnace or boiler, resulting in the need for replacement or a service call to fix or replace the part. CO sensors would be expected to be treated in this same manner as other parts that need to be replaced during the lifespan of the product. The costs of such services are included in the preliminary regulatory analysis in section IX of the preamble. Regarding the comment about tolerances, manufacturers will need to select appropriate sensors and other equipment to ensure that their furnaces and boilers comply with the proposed standard.

Requirements in International Standards

Comment: Crown and USBC JB asserted that there is no widespread use of CO sensors in gas appliances in Europe and Japan. One commenter (AHRI) observed that "the EN standards (EN 15502-1, EN 15502-2-1 and EN 15502-2-2) do not require manufacturers to incorporate a CO-sensor shut-off device within the appliance." In addition, that commenter stated none of the U.S. or international standards, including JIS S 2019, specifically require a CO sensor within the appliance. AHRI stated that the most commonly used CO sensor, manufactured by Nemoto Sensor Engineering, Ltd., is designed to work when carbon monoxide levels exceed 1000 ppm.

Response: While the Japanese standard, JIS S 2019, and the European standards, EN 15502-2-1 and EN 15502-2-2, do not specifically require a CO sensor in-situ (*i.e.*, within the heater exchanger or flue passage ways of the appliance), each standard includes an option that allows for CO and combustion sensors in-situ if the manufacturer chooses to use that approach to meet the requirements of the respective standards. Some European and Japanese gas boilers products certified to those standards are equipped with CO sensor shutoff capability. More generally, the existence of the option to use CO sensors incorporated in-situ to meet the requirements of respective standards reinforces that such sensors are feasible. Regarding Nemoto sensors, the published Nemoto product literature (NAP-78SU --Nemoto Sensor Engineering for Gas Sensors) indicates that the CO sensors in question have a linear response range of zero to 10,000 ppm CO; thus the sensors in question are represented by Nemoto to have the capability to provide an output voltage response to all of the CO levels within that range, including 400 ppm CO and lower.

Feasibility of performance requirements with existing CO/Combustion technology

Comment: Carrier and AHRI stated that "a minimum of 20 years is needed to replace existing residential gas appliances with a carbon monoxide sensor-equipped appliances" based on the anticipated lifespan of an appliance. USBC JB stated that it would take a minimum of two to three years to develop and validate performance requirements and then revise the voluntary standards through the consensus process.

Response: We agree that it will take time for existing gas furnaces and boilers to be replaced by newly installed equipment that meets the requirements of the proposed rule mandating additional safety features for future gas furnaces and boilers; inasmuch as the proposed rule does not require replacement of existing installed gas furnaces and boilers and would only apply to the future manufacture of gas furnaces and boilers. This is reflected in the preliminary regulatory analysis in Section IX of the preamble. Approximately two million gas furnaces and 800,000 gas boilers without CO sensors are sold each year, thus prolonging the time it would take to replace old stock. As a result, each year of further delay in instituting safety features to address the CO hazard will result in millions of units without these features being sold and installed and remaining in homes for multiple decades, risking additional preventable deaths and injuries.

Comment: Carrier and AHRI stated that CO sensors will not detect leakage from the venting system.

Response: The proposed rule focuses on the source rather than leakage points throughout the exhaust path because of the extent, variability, and potential inaccessibility of the exhaust path in homes. We agree that a CO sensor will not detect leakage from a venting system. However, CO detection at the source of production would provide protection to consumers regardless of the location of downstream leakage. For these reasons, we disagree with AHRI's assertion that a CO sensor-equipped appliance would be ineffective against a compromised vent.

Comment: A.O. Smith stated that CO sensors in a gas appliance cannot easily be replaced in the field.

Response: The commenter provided no technical evidence to support the claim that CO sensors cannot be installed so that they are easily replaced in the field. CPSC staff is aware of and has access to gas appliances that utilize CO sensors, air/fuel ratio sensors, and other combustion control devices within the combustion chamber of flue passageways to provide CO safety and/or energy efficiency. CO sensors are no more complex and do not present any greater difficulty in gaining access to the devices for maintenance or replacement than other safety devices, such as pressure switches, flame sensors, and flame rollout switches, currently required by the ANSI standards for gas appliances. Sensors are comprised of a sensing element covered by shielding and a mounting flange. Typically, the shielded, sensing element is inserted through an access hole through the bulkhead of a combustion chamber, plenum, or flue passageway. The sensor is generally mounted to the bulkhead with two screws with a heat-resistant gasket between the mounting flange and the bulkhead. We assess that CO sensors in a gas appliance could be replaced in consumer homes in a manner similar to other existing gas furnace or boiler components that are currently serviced and replaced in consumer homes.

Comment: Rheem asserted that some of the referenced/observed failure modes in the ANPR cannot be addressed through appliance design alone.

Response: We do not agree with the assertion that failure mode issues cannot be addressed through appliance design. By ensuring that harmful levels of CO are not produced in the gas furnace or boiler, the proposed requirements remove the need to provide protection throughout the entire exhaust vent system.

Comment: Stanonik stated that the document "Findings from CPSC's 2014 Carbon Monoxide/Combustion Sensor Forum and Request for Information" (https://www.cpsc.gov/s3fs-public/pdfs/blk_pdf_Findings-from-the-FY14-Sensor-Forum-and-RFI.pdf) indicates that a specific sensor technology that appeared to address durability and longevity concerns is very expensive and reflected the "significant process" involved in developing durable and reliable sensor products.

Response: We agree that the cost the commenter referenced would be high. However, the sensing technology in question was an evaluation unit, not a full-scale production unit, and came with electronic controls necessary to operate and evaluate the sensor, resulting in elevated costs for that particular sensing technology. The cost per unit typically goes down with large scale production. CPSC staff estimates costs for volume purchases in the range of approximately $5 to $15 per unit. The preliminary regulatory analysis in section IX of the preamble provides further analysis of potential costs and benefits.

VIII. Description of the Proposed Rule

The proposed rule would create a new part 1408, "Safety Standard for Residential Gas Furnaces and Boilers." The provisions of the proposed rule are described below.

A. Proposed section 1408.1 Scope, purpose, and effective date

Proposed section 1408.1 provides that new part 1408 establishes a consumer product safety standard that would provide performance requirements for residential gas furnaces and boilers that are consumer products used to heat dwellings. The purpose of these requirements is to reduce the occurrence of carbon monoxide-related deaths, injuries, and exposures associated with gas furnaces, boilers, and wall and floor furnaces. All requirements of the proposed rule apply to all residential gas furnaces, boilers, and wall and floor furnaces that are manufactured after the proposed effective date, which is 18 months after publication of the final rule in the *Federal Register.*

B. Proposed section 1408.2 Definitions

Proposed section 1408.2 provides definitions that apply for purposes of part 1408. Proposed section1408.2 provides definitions for the covered categories of furnaces and boilers. The proposed definitions are based on the definitions used in ANSI Z21.47-2021, ANSI Z21.13-2022, and ANSI Z21.47-2016 for the same product types.

C. Proposed section 1408.3 Performance requirements for gas furnaces and boilers

Proposed section 1408.3 provides general requirements, performance requirements, test configuration, and test methods for all residential gas furnaces and boilers. Section VII.B of the preamble provides the technical justification for these proposed requirements.

1. Proposed section 1408.3(a) (general requirements)

Proposed section 1408.3(a) provides that all residential gas furnaces and boiler must have a means to either directly or indirectly monitor the concentration of carbon monoxide produced during the combustion process and shut down or modulate combustion to reduce average CO concentrations to below the CO levels for the durations of time specified in proposed section

1408.3(b). The gas furnace or boiler must either shut down or modulate combustion to reduce average CO emissions to below 150 ppm if the average CO emissions reach or exceed the CO limits and time durations specified in section 1408.3(b).

Proposed section 1408.3(a) also states that indirect monitoring and control of CO emissions can be accomplished by monitoring and controlling other combustion parameter(s) that accurately correlate to the production of CO. Proposed section 1408.3(a) provides examples of parameters that can serve as a proxy for CO production such as carbon dioxide (CO_2), oxygen (O_2), the Gas/Air Ratio, and the flame ionization current produced by the burner flame.

2. Proposed section 1408.3(b) (performance requirements)

Proposed section 1408.3(b) provides a performance requirement that a gas furnace or boiler must be equipped with a means to continuously monitor CO emission and must meet the requirements described in either proposed section 1408.3(b)(1) or (b)(2) (direct means to monitor CO emissions) or (b)(3) or (4) (indirect means to monitor CO emissions) when tested using the test method described in proposed section 1408.3(d). Proposed subparagraphs 1408.3(b)(1) and (2) provides two options for gas furnaces and boilers manufacturers to use direct means to monitor CO emissions that must either cause either shut-down or modulation of the gas furnace or boiler combustion, based on conditions within the gas furnace or boiler for a range of specified average CO concentrations for the specified time frames. Proposed section 1408.3(b)(3) provides two options for gas furnace and boiler manufacturers to use an indirect means to monitor CO emissions that must either cause shut-down of the gas furnace or boiler or cause modulation of combustion of the gas furnace or boiler, based on conditions within the gas furnace or boiler for a range of specified average CO concentrations for the specified time frames described.

Proposed section 1408.3(b)(4) provides a fail-safe requirement that during the life of the gas furnace or boiler, if a CO sensor, combustion sensor, combustion control system, or other device designed to meet these requirements fails to operate properly or at all, then the gas furnace or boiler must shutdown and restart after 15 minutes and repeat this cycle until the failed component is replaced. The requirement mandates that consumers and service technicians must be notified of device failure by either a flashing light, or other appropriate code on the gas furnace or boiler control board, that corresponds to the device failure.

3. Proposed section 1408.3(c) (test configuration)

Proposed section 1408.3(c) describes the requirements that gas furnace or boilers must be configured in accordance with the provisions of the combustion sections of the respective voluntary standards (section 5.8.1 of ANSI Z21.47-2021 for gas furnaces; section 5.5.1 of ANSI Z21.13-2022 for gas boilers; and sections 9.3.1, 11.2.1, and 13.3.1, of ANSI Z21.86-2016 for gas wall and floor furnaces) with respective instruction on how products are to be configured before testing to proposed section 1408.3(d).

4. Proposed section 1408.3(d) (test procedure)

Proposed section 1408.3(d) provides the test procedure to be used to test a gas furnace or boiler after the product has been configured pursuant to proposed section 1408.3(b) to demonstrate compliance with the performance requirements provided in proposed section 1408.3(b).

D. Proposed section 1408.4 Incorporation by reference

Proposed section 1408.4 incorporates by reference ANSI Z21.47-2021, ANSI Z21.13-2022, and ANSI Z21.47-2016 regarding the test setup cited in proposed section 1408.3 and provides information on where the standards are available.

E. Proposed section 1408.5 Prohibited stockpiling

Pursuant to section 9(g)(2) of the CPSA, 15 U.S.C. 2058(g)(2), the proposed rule would prohibit a manufacturer from "stockpiling" or substantially increasing the manufacture or importation of noncompliant gas furnaces and boilers between the date publication of the final rule and the effective date. The provision, which is explained more fully in Tab D of the Staff NPR Briefing Package, would prohibit the manufacture or importation of noncompliant products at a rate that is greater than 106 percent of the base period in the first 12 months after promulgation, and 112.50 percent of the base period for the duration of 12 months after promulgation until the effective date. The base period is defined in the proposed rule as the calendar month with the median manufacturing volume, among months with manufacturing volume, during the last 13 months prior to the rule's publication.

We propose a rate of 106 percent for the first 12 months and a rate 112.50 percent in the final 6 months between publication and effective date based on the historical growth of the industry. We propose a higher rate of 112.50 percent for the second year to account for the baseline growth of the industry in the second year.

Individual manufacturers may experience growth rates outside the historical range. Shipment data for gas furnaces and boilers show a steady, yet seasonal, market. Shipments of gas furnaces and boilers begin to rise in March and continuously increase until December, after which they fall off sharply. The Commission seeks public comment on manufacturing, the seasonality of sales, and supply chain of gas furnaces and boilers to further understand these topics.

F. Appendix A to Part 1408 – Findings Under the Consumer Product Safety Act

The findings required by section 9 of the CPSA are discussed throughout this preamble and set forth in Appendix A to the proposed rule.

IX. Preliminary Regulatory Analysis

Pursuant to section 9(c) of the CPSA, publication of a proposed rule must include a preliminary regulatory analysis containing:

- A preliminary description of the potential benefits and potential costs of the proposed rule, including any benefits or costs that cannot be quantified in monetary terms, and an identification of those likely to receive the benefits and bear the costs;
- a discussion of why a relevant voluntary safety standard would not eliminate or adequately reduce the risk of injury addressed by the proposed rule; and
- a description of any reasonable alternatives to the proposed rule, together with a summary description of their potential costs and benefits and why such alternatives should not be published as a proposed rule.

This preamble contains a summary of the preliminary regulatory analysis for the proposed rule. Tab D of the Staff NPR Briefing Package contains a detailed analysis.

A. Market Information

1. The Product

Gas furnaces and boilers are vented gas heating appliances that heat residential dwellings. Section III of the preamble provides a detailed discussion of the nature and operation of gas furnaces and boilers. The average product life for gas furnaces and boilers ranges from approximately 22 to 25 years.

Gas furnaces and boilers include central warm-air furnaces and boilers as well as floor, and wall furnaces.

- Central warm-air furnaces and boilers use a central combustor, or boiler, to heat air using natural gas, and liquid propane. Some of these furnaces move the heated air using a blower or fan through ducts while others rely on the natural flow of warm air going up and cold air down to circulate air. Most boilers supply steam or hot water through conventional radiators or baseboard radiators.
- Floor and wall furnaces are less common than central furnaces and boilers and consist of ductless combustors to heat air. A floor furnace and wall furnace heat the physical parts of the house (*i.e.,* floor or wall) to heat the dwelling. A furnace is typically located in a basement and delivers heated air through a large register in the floor above it.

Consumers purchase gas furnaces and boilers primarily through contract installers, but they may also purchase units at retail stores and online retailers. CPSC staff estimate the average retail price of gas furnaces to be $1,660 and $3,719 for gas boilers.

2. Market Trends for Gas Furnaces and Boilers

Staff identified as many as 70 firms that manufacture or import residential gas furnaces and boilers. When accounting for subsidiaries and multiple brands provided by the same company, staff identified 20 parent firms. In 2016, the largest 10 firms by revenue accounted for 83.3 percent of heating equipment sales. Seven of these firms are based in the U.S.

Department of Energy's (DOE) most recent Residential Energy Consumption Survey (RECS) reports the total number of gas furnaces, gas boilers, and wall furnaces in-use to be 60.94 million in 2020. This is an increase from 57.90 million in 2015. Between 2015 and 2020, therefore, the number of in-scope gas furnaces and boilers grew at an average annual rate of 1.03 percent.

DOE's Government Regulatory Impact Model (GRIM) projects gas furnace sales in 2021 to be 3.58 million units and gas boilers to be 0.30 million units. CPSC staff estimated that residential gas furnaces and boilers sales in 2021 to be $5.94 billion and $1.12 billion, respectively.

CPSC staff estimate that residential gas boiler imports average $117.67 million annually. The Commission requests comment on the value and quantity of gas furnaces and boilers imports that would be subject to a proposed rule.

3. Future Market Size for Gas Furnaces and Boilers

Staff used a 1.03 percent annual growth rate derived from DOE's GRIM to project sales into the future. Using this approach, staff estimates the number of in-use, in-scope gas furnaces and boilers will grow from 64.13 million in 2025 to 90.49 million in 2054.

B. Preliminary Description of Potential Costs and Benefits of the Rule

Staff conducted a cost assessment of the proposed rule. The proposed rule would impose the following costs: increased variable costs of producing furnaces and boilers with CO sensors and shutoff capabilities; one-time conversion costs of redesigning and modifying factory operations for installing CO sensors; increased maintenance costs of gas furnaces and boilers to consumers; and deadweight loss[16] in the market caused by the increasing price due to regulation and the subsequent decline in sales. Staff performed a 30-year prospective cost assessment (2025-2054) on all four cost categories and estimated the total annualized cost from the proposed

[16] Deadweight loss is the value of lost transactions that may occur after major market events such as a new regulation.

rule to be $602.27 million, discounted at three percent.[17] Staff estimated the per-unit cost of a gas furnace or boiler from the proposed rule to be $158.11, discounted at three percent.

Staff also conducted a benefits assessment of the proposed rule. The benefits assessment accounted for the prevention of deaths and injuries from compliant gas furnaces and boilers, which staff monetized using the Value of Statistical Life (VSL) for deaths, and the Injury Cost Model (ICM) for injuries. Over the 30-year study period, staff estimated the proposed rule would prevent 576 deaths (19.20 deaths per year) and 160,699 injuries (5,357 per year). The total annualized benefits from the proposed are $356.52 million, discounted at three percent. Staff estimated the per-unit benefits from the proposed rule to be $93.60, discounted at three percent. Staff calculates net benefits (benefits less costs) to be -$245.74 million on annualized basis, discounted at three percent. The net benefits on per-unit basis are -$64.51, discounted at three percent. Alternatively, this can be described as the proposed rule being a net cost of $64.51 per gas furnace or boiler, which represents approximately three percent of the average price of a gas furnace or boiler, to prevent an estimated 576 deaths and 160,699 injuries over 30 years.

Finally, staff conducted a sensitivity analysis that showed if, by 2035 manufacturers were able to develop compliant gas furnaces and boilers with CO sensors that did not need replacement, and if the analysis took into account that a child's death is considered twice as costly as an adult death[18], the benefit-cost ratio would increase to 0.78.

[17] Staff uses a discount rate to incorporate the time value of money during the 30-year study period. In the analysis, staff presents both costs and benefits in undiscounted dollars, discounted at three percent, and discounted at seven percent.
[18] For more information see CPSC's Draft Guidance for Estimating Value per Statistical Life (88 FR 17826), url: https://www.federalregister.gov/documents/2023/03/24/2023-06081/notice-of-availability-proposed-draft-guidance-for-estimating-value-per-statistical-life

C. Evaluation of Voluntary Standards

Based on staff's evaluation of the relevant ANSI standards discussed in section V of the preamble, the Commission preliminarily determines that current U.S. voluntary standards do not adequately address the hazard of CO exposure from gas furnaces and boilers. Further, the Z21/83 Technical Committee and the subordinate Technical Subcommittees have no clear plan to address these hazards in the relevant voluntary standards. None of the commenters on the ANPR submitted any recommendations for proposed requirements, nor did any commenters submit an existing voluntary standard or a portion of one that would adequately address the CO exposure risk that this proposed rule would address. No standard or portion of a standard was submitted to the Commission under section 9(a)(5) of the CPSA.

D. Alternatives to the Proposed Rule

The Commission considered four alternatives to the proposed rule: (1) continue to work and advocate for change through the voluntary standards process; (2) rely on the use of residential CO alarms; (3) continue to conduct education and information campaigns; and (4) rely on recalls. Each alternative is discussed in detail below.

<u>1. Continue to work and advocate for change through the voluntary standards process</u>

Section V of this preamble highlights CPSC staff's participation in the voluntary standard development process for ANSI Z21.47, Z21.13, and Z21.86. Despite staff encouraging industry to adopt a standard that adequately addresses the hazard, and providing industry with the necessary factual foundation, industry has not adopted such a standard in over 20 years. For this reason, the Commission is not adopting this alternative.

<u>2. Rely on the use of residential CO alarms</u>

CPSC has long promoted CO alarm adoption and states have increasingly required CO alarms in homes over the last two decades. Yet there has not been a significant decline in CO injuries and fatalities, demonstrating that CO alarm adoption alone is insufficient to address the hazard. We also note that residential CO alarms may fail to alert due to battery failure, poor maintenance, manufacturer defect, age, incorrect installation, or defects. Finally, a CO alarm would not shut down a gas furnace or boiler producing a dangerous amount of CO and thus would require the occupant to properly recognize what to do when the alarm is triggered. For these reasons, the Commission is not adopting this alternative.

3. Continue to conduct education and information campaigns

Despite education and information campaigns by CPSC and others regarding CO hazards, CO death and injuries for gas furnaces and boilers remain high. Education and information campaigns alone have not adequately addressed the CO hazard from gas furnaces and boilers in the absence of a performance standard. For these reasons, the Commission is not adopting this alternative.

4. Rely on recalls

Although not all instances of excessive CO concentrations result from a defect in the gas furnace or boiler, the Commission could seek voluntary or mandatory recalls of gas furnaces and boilers that present a substantial product hazard. Recalls only apply to an individual manufacturer and product, and generally do not extend to similar products, and occur only after consumers have purchased and used such products with possible resulting deaths or injuries due to exposure to the hazard. Additionally, recalls can only address products that are already on the market but do not directly prevent unsafe products from entering the market. In the absence of a rule, hazardous gas furnaces and boilers will continue to see sales of several million units annually and the stock of hazardous products will continue to grow. Additionally, while detached gas furnaces and boilers could be easily recalled, installed gas furnace and boiler recalls can be disruptive and costly. For these reasons, the Commission does not choose this alternative.

X. Initial Regulatory Flexibility Analysis

Whenever an agency publishes an NPR, Section 603 of the Regulatory Flexibility Act (RFA), 5 U.S.C. 601–612, requires the agency to prepare an initial regulatory flexibility analysis (IRFA), unless the head of the agency certifies that the rule will not have a significant economic impact on a substantial number of small entities. The IRFA, or a summary of it, must be published in the *Federal Register* with the proposed rule. Under Section 603(b) of the RFA, each IRFA must address:

(1) a description of why action by the agency is being considered;

(2) a succinct statement of the objectives of, and legal basis for, the proposed rule;

(3) a description of and, where feasible, an estimate of the number of small entities to which the proposed rule will apply;

(4) a description of the projected reporting, recordkeeping, and other compliance requirements of the proposed rule, including an estimate of the classes of small entities which will be subject to the requirement and the type of professional skills necessary for preparation of the report or record; and

(5) an identification, to the extent practicable, of all relevant Federal rules which may duplicate, overlap, or conflict with the proposed rule.

The IRFA must also describe any significant alternatives to the proposed rule that would accomplish the stated objectives and that minimize any significant economic impact on small entities.

A. Reason for Agency Action

The intent of this rulemaking is to reduce deaths and injuries resulting from carbon monoxide leaks from gas furnaces and boilers by establishing a mandatory performance standard requiring gas furnaces and boilers to shut off or modulate when CO levels reach specified amounts for a certain duration.

B. Objectives of and Legal Basis for the Rule

The Commission proposes this rule to reduce the risk of death and injury associated with CO leakage from residential gas furnaces and boilers. This standard is promulgated under the authority of the CPSA. To issue a mandatory standard under CPSA section 7, 15 U.S.C. 2056, the Commission must follow the procedural and substantive requirements in section 9 of the CPSA, 15 U.S.C. 2058. *See* 15 U.S.C. 2056(a).

C. Small Entities to Which the Rule Will Apply

The proposed rule would apply to all manufacturers and importers of gas furnaces and gas boilers. CPSC staff is aware of as many as 70 firms manufacturing gas furnaces and boilers for the U.S. market. When accounting for subsidiaries and multiple brands provided by the same company, staff identified 20 parent firms.

Using SBA guidelines, staff identified two small manufacturers of gas furnaces, three small manufactures of residential gas boilers, and one importer of gas furnaces that may fall within the scope the rule. The Commission requests comment on additional manufacturers and importers of gas furnaces and boilers that may meet the SBA definition of a small business.

D. Compliance, Reporting, and Record-Keeping Requirements of Proposed Rule

In accordance with Section 14 of the CPSA, 15 U.S.C. 2063, manufacturers would have to issue a General Certificate of Conformity (GCC) for each of their gas furnace or boiler models, certifying that the model complies with the proposed performance requirement. Each GCC must also be based on a test of each product or a reasonable testing program and provided to all distributors or retailers of the product. The manufacturer would have to comply with 16 CFR part 1110 concerning the content of the GCC, retention of the associated records, and any other applicable requirements.

E. Federal Rules that May Duplicate, Overlap, or Conflict with the Proposed Rule

No federal rules duplicate, overlap, or conflict with the proposed rule.

F. Potential Impact on Small Entities

1. Impact on Small Manufacturers

The preliminary regulatory analysis in Section IX of this preamble discusses costs more fully. Based on that analysis, to achieve compliance with the proposed rule's performance requirements, small domestic manufacturers would incur costs from the increased variable costs of producing furnaces and boilers with CO sensors and shutoff capabilities and testing and certifying such products, as well as the one-time conversion costs of redesigning and modifying factory operations for installing CO sensors.

Installing CO sensors and shutoff capabilities in a gas furnace or boiler is a variable cost that is attached to each unit produced. Staff used a Guidehouse study (Guidehouse 2021) to find that the cost to manufacturers (without any markup included) at an annual production level of 119,572 gas furnace and boiler units yields an average incremental cost of $66.47 per unit.[19] This is an annual total of $7.95 million ($66.47 × 119,572) for each small firm.

Regarding the one-time conversion costs, DOE's findings from its 2015 Rules on Gas Residential Furnaces and Boilers (80 FR 13120 and 80 FR 17222) found an industry cost of

[19] Weighted average between retail price increase from gas furnaces ($65.22) and boilers ($81.10) for the first year impact of the rule.

$413.28 million (inflated to 2021 dollars).[20] This would suggest a maximum conversion cost for small firms of $69.02 million (16.7 percent × $413.28 million) or $13.80 million per firm among the small five manufacturers.

2. Impact on Small Importers

Staff identified one small importer of products that would be within the scope of the standard. Importers may pass on testing responsibility and GCC creation to the foreign manufacturers and then issue the resulting certificate. Changes in production and certification costs incurred by suppliers from the standard could be passed on to the importers, which in turn are likely to be passed onto consumers given the relatively inelastic demand for heating appliances. For this reason, the Commission does not believe that the proposed rule will have a significant impact on small importers.

The Commission seeks public comment on information on importers of gas furnaces and boilers; specifically how many are imported, how many different models each importer sells, and what technologies those models are currently using (atmospheric venting, condensing, non-condensing, premix power burners, etc.). The Commission also seeks public comment on information regarding to what degree supplying firms tend to pass on increases in production and regulatory costs to importers, and to what extent the ability to pass on these costs is limited by the ease with which importers can switch suppliers or substitute to alternative products, such as electrical furnaces and boilers.

G. Alternatives for Reducing the Adverse Impact on Small Businesses

The Commission considered four alternatives to the proposed rule: (1) continue to work and advocate for change through the voluntary standards process; (2) rely on the use of

[20] Conversion costs were calculated in 2013 dollars and reported in 2020 dollars adjusted for 2013-2020 inflation using the Consumer Price Index-Urban.

residential CO alarms; (3) rely on education and information campaigns; and (4) rely on recalls. The Commission is not adopting these alternatives for the reasons in Section IX of the preamble.

The Commission welcomes public comments on this IRFA. Small businesses that believe they would be affected by the proposed rule are encouraged to submit comments. The comments should be specific and describe the potential impact, magnitude, and alternatives that could reduce the impact of the proposed rule on small businesses.

XI. Incorporation by Reference

The Commission proposes to incorporate by reference: ANSI Z21.47-21, Standard: *Gas-fired central furnaces*; ANSI Z21.13-22, Standard: *Gas-fired low-pressure steam and hot water boilers*; and ANSI Z21.86-16, Standard: *Vented Gas-fired space heating appliances*. The Office of the Federal Register (OFR) has regulations regarding incorporation by reference. 1 CFR part 51. Under these regulations, agencies must discuss, in the preamble to a final rule, ways in which the material the agency incorporates by reference is reasonably available to interested parties, and how interested parties can obtain the material. In addition, the preamble to the final rule must summarize the material. 1 CFR § 51.5(b)(3).

In accordance with the OFR regulations, section IV of this preamble summarizes the major provisions of ANSI Z21.47-21, Standard: *Gas-fired central furnaces*; ANSI Z21.13-22, Standard: *Gas-fired low-pressure steam and hot water boilers*; and ANSI Z21.86-16, Standard: *Vented gas-fired space heating appliances* that the Commission incorporates by reference into 16 CFR part 1408. The standard itself is reasonably available to interested parties. Until the final rule takes effect, read-only copies of ANSI Z21.47-21, Standard: *Gas-fired central furnaces*; ANSI Z21.13-22, Standard: *Gas-fired low-pressure steam and hot water boilers,* and ANSI

Z21.86-16, Standard: *Vented gas-fired space heating appliances* are available for viewing, at no cost, at Group: U.S. Incorporated by Reference (IBR) Sta... | CSA Communities (csagroup.org). Once the rule takes effect, a read-only copy of the standards will be available for viewing, at no cost, at Group: U.S. Incorporated by Reference (IBR) Sta... | CSA Communities (csagroup.org). Interested parties can also schedule an appointment to inspect a copy of the standard at CPSC's Office of the Secretary, U.S. Consumer Product Safety Commission, 4330 East West Highway, Bethesda, MD 20814, telephone: (301) 504-7479; e-mail: cpsc-os@cpsc.gov. Interested parties can purchase a copy of the three ANSI standards from the Canadian Standards Association, 8501 East Pleasant Valley Road Independence, OH 44131-5516: 1-800-463-6727; www.csagroup.org/store/.

XII. Environmental Considerations

Generally, the Commission's regulations are considered to have little or no potential for affecting the human environment, and environmental assessments and impact statements are not usually required. *See* 16 CFR § 1021.5(a). The proposed rule is not expected to have an adverse impact on the environment and is considered to fall within the "categorical exclusion" for the purposes of the National Environmental Policy Act. 16 CFR § 1021.5(c).

XIII. Preemption

Executive Order (EO) 12988, Civil Justice Reform (Feb. 5, 1996), directs agencies to specify the preemptive effect of a rule in the regulation. 61 FR 4729 (Feb. 7, 1996). The proposed regulation for gas furnaces and boilers is being promulgated under authority of the CPSA. 15 U.S.C. 2051-2089. Section 26 of the CPSA provides that:

> whenever a consumer product safety standard under this Act is in effect and applies to a risk of injury associated with a consumer product, no State or political subdivision of a State shall have any authority either to establish or to continue in effect any provision of a safety standard or regulation which prescribes any

> requirements as to the performance, composition, contents, design, finish, construction, packaging or labeling of such product which are designed to deal with the same risk of injury associated with such consumer product, unless such requirements are identical to the requirements of the Federal Standard.

15 U.S.C. 2075(a). Thus, the proposed rule would preempt non-identical state or local requirements for gas furnaces and boilers designed to protect against the same risk of injury, *i.e.*, risk of injury and death associated with CO production and leakage from residential gas furnaces and boilers.

States or political subdivisions of a state may apply for an exemption from preemption regarding a consumer product safety standard, and the Commission may issue a rule granting the exemption if it finds that the state or local standard (1) provides a significantly higher degree of protection from the risk of injury or illness than the CPSA standard, and (2) does not unduly burden interstate commerce. 15 U.S.C. 2075(c).

XIV. Effective Date

The Administrative Procedure Act (APA) generally requires that the effective date of a rule be at least 30 days after publication of a final rule. 5 U.S.C. 553(d). Section 9(g)(1) of the CPSA states that a consumer product safety rule shall specify the date such rule is to take effect, and that the effective date must be at least 30 days after promulgation but cannot exceed 180 days from the date a rule is promulgated, unless the Commission finds, for good cause shown, that a later effective date is in the public interest and publishes its reasons for such finding.

The Commission preliminarily proposes an effective date of 18 months after publication of the final rule in the *Federal Register*. The rule would apply to gas furnaces and boilers manufactured after the effective date. The effective date of the proposed rule is based on staff's assessment that, to comply with the final rule, manufacturers would have to:

- Identify and establish contracts with suppliers of CO sensing or combustion control devices;

- redesign the impacted gas furnaces and boilers to integrate CO sensing or combustion control devices;
- work with gas control and control board manufacturers on redesigning gas controls and control boards to properly incorporate power and output signals from CO sensing or combustion control devices;
- conduct qualification testing and analysis of CO sensing or combustion control devices integrated into impacted appliances;
- retool manufacturing lines to allow for CO sensing or combustion control devices to be assembled into impacted appliances;
- incorporate the CO sensing or combustion control devices into existing quality control procedures;
- retrain assembly line staff on the redesigned gas appliances and retooled manufacturing lines;
- incorporate the CO sensing or combustion control devices into the user, maintenance, and installation instruction manuals of impacted appliances;
- develop new guidance for distributors and retail outlets for the impacted appliances; and
- test and certify of the new models to voluntary standards required in many jurisdictions to meet building codes.

A shorter effective date would likely result in manufacturers being unable to produce compliant products or produce enough products to meet their typical demand; resulting in a product shortage in the supply chain, consumers being denied their preferred product with a loss of utility and potentially an additional cost; and quality control issues.

We note the proposed 18-month effective date is consistent with the applicable voluntary standards for gas furnaces, boilers, and wall and floor furnaces (*i.e.,* ANSI Z21.13, ANSI Z21.47, and ANSI Z21.86, as well as all other ANSI Z21 standards), which typically allow for an effective date of 18 months after new standards provisions are approved. While the proposed 18-month effective date is a departure from the 180-day default effective date required by section 9(g)(1) of the CPSA, the Commission preliminarily concludes that there is good cause here to set the effective date at 18 months for manufacturers to ensure compliance with the proposed performance requirements of the rule based on the reasons discussed above. A detailed discussion of the justification for the recommended 18 month effective is available in the Staff NPR Briefing Package. The Commission seeks comments on the effective date with specific information to support any argument that an effective date longer than the 180-day period specified in CPSA section 9(g)(1) is or is not justified by good cause, including for the reasons preliminarily identified above.

XV. Paperwork Reduction Act

This proposed rule contains information collection requirements that are subject to public comment and review by the Office of Management and Budget (OMB) under the Paperwork Reduction Act of 1995 (PRA). 44 U.S.C. 3501–3520. We describe the provisions in this section of the document with an estimate of the annual reporting burden. Our estimate includes the time for gathering certificate data and creating General Certificates of Conformity (GCC), the keeping and maintaining of records associated with the GCCs, and the disclosure of GCCs to distributers and retails.

CPSC particularly invites comments on: (1) whether the collection of information is necessary for the proper performance of the CPSC's functions, including whether the information will have practical utility; (2) the accuracy of the CPSC's estimate of the burden of the proposed collection of information, including the validity of the methodology and assumptions used; (3) ways to enhance the quality, utility, and clarity of the information to be collected; (4) ways to reduce the burden of the collection of information on respondents, including the use of automated collection techniques, when appropriate, and other forms of information technology; and (5) estimated burden hours associated with label modification, including any alternative estimates.

Title: *Safety Standard for Gas Furnaces and Boilers*

Description: The proposed rule would require each gas furnace and boiler to comply with performance requirements under which the appliance shuts off or modulates when CO levels reach specified amounts for a certain time duration.

Description of Respondents: Persons who manufacture or import gas furnaces and boilers.

Staff estimates the burden of this collection of information as follows in Table 2:

Table 2. Estimated Annual Reporting Burden

Burden Type	Number of Respondents	Frequency of Responses	Total Annual Responses	Minutes per Response	Total Burden Hours	Annual Cost
GCC Creation	20	500	10,000	5	833	$63,525
Recordkeeping	20	500	10,000	1.25	208	$7,005
Third Party Disclosure	20	500	10,000	15	2,500	$84,200

Section 14(a)(1) of the CPSA, 15 U.S.C. 2063(a)(1), would require manufacturers to certify that their products conform to the proposed rule and issue a GCC. There are 20 known corporate entities supplying gas furnaces and boilers to the U.S. market. On average, each entity may issue 500 certificates for complying gas furnaces or boilers in the market. Each manufacturer or importer may issue 500 certificates for a total of 10,000 certificates (20 firms times 500 certificates per firm = 10,000 certificates). Staff treats each certificate issued as a new recordkeeping response so there is a total of 10,000 responses for GCC creation. The estimated time required to issue a GCC is estimated at about five minutes (although it often could be less). To comply with the CPSA, gas furnace and boiler manufacturers covered by the rule must subject their products to a reasonable testing program. Quality control and testing is usual and customary for gas furnace and boiler manufacturers, however creation (*i.e.,* recording of test results) may not be. Staff estimates that each firm may spend five minutes per certificate issued recording the results of a reasonable testing program. This would include the time taken to read the test results, create the testing record, and issue a certificate. Therefore, the estimated burden associated with issuance of GCCs is 833 hours (10,000 responses × 5 minutes per response = 50,000 minutes or 833 hours). Staff estimates the hourly compensation for the time required to issue GCCs is $76.26 (U.S. Bureau of Labor Statistics, "Employer Costs for Employee Compensation," March 2023, Table 4, management, business, and financial occupations: Employer Costs for Employee Compensation – March 2023 (bls.gov)). Therefore, the estimated annual cost to industry associated with issuance of a GCC is $63,525 ($76.26 per hour × 833 hours).

We estimate for purposes of this burden analysis that records supporting GCC creation, including testing records, would be maintained for a five-year period. Staff estimates another

10,000 recordkeeping responses, each one of which requires 1.25 minutes per year in routine recordkeeping. This adds up to 12,500 minutes or 208 hours. Staff estimates the hourly compensation for the time required to issue is $33.68 (U.S. Bureau of Labor Statistics, "Employer Costs for Employee Compensation," March 2023, Table 4, office and administrative support occupations: [Employer Costs for Employee Compensation – March 2023 (bls.gov)]). Therefore, the estimated annual cost to industry associated with recordkeeping associated with GCCs is $7,005 ($33.68 per hour × 208 hours).

Section 14(g)(3) of the CPSA also requires that GCCs be disclosed to third party retailers and distributors. Staff estimates another 10,000 third party disclosure responses, each one of which requires 15 minutes per year. This adds up to 150,000 minutes (10,000 responses x 15 minutes per response) or 2,500 hours. Staff uses an hourly compensation for the time required to disclose certificates to third parties of $33.68 (U.S. Bureau of Labor Statistics, "Employer Costs for Employee Compensation," March 2023, Table 4, office and administrative support occupations: [Employer Costs for Employee Compensation – March 2023 (bls.gov)]). Therefore, the estimated annual cost to industry associated with third party disclosure of GCCs is $84,200 ($33.68 per hour × 2,500 hours). There are no operating, maintenance, or capital costs associated with the collection.

Based on this analysis, the proposed standard for gas furnaces and boilers would impose a total paperwork burden to industry of 4,374 hours (833 hours + 833 + 208 hours + 2,500 hours), at an estimated cost of $154,730 annually ($63,525 + $7,005 + $84,200). Existing gas furnace and boiler manufactures would incur these costs in the first year following the proposed rule's effective date. In subsequent years, costs could be less, depending on the number of new GCCs issued for gas furnaces and boilers. As required under the PRA (44 U.S.C. 3507(d)), CPSC has submitted the information collection requirements of this proposed rule to the OMB for review. Interested persons are requested to submit comments regarding information collection by [**insert date 60 days after date of publication in the FEDERAL REGISTER**], to the Office of Information and Regulatory Affairs, OMB as described under the **ADDRESSES** section of this notice.

XVI. Certification

Section 14(a)(1) of the CPSA requires that products subject to a consumer product safety rule under the CPSA, or to a similar rule, ban, standard or regulation under any other act enforced by the Commission, must be certified with a GCC as complying with all applicable CPSC-enforced requirements. 15 U.S.C. 2063(a). A final rule would subject gas furnaces and boilers to this requirement.

XVII. Promulgation of a Final Rule

Section 9(d)(1) of the CPSA requires the Commission to promulgate a final consumer product safety rule within 60 days of publishing a proposed rule. Otherwise, the Commission must withdraw the proposed rule if it determines that the rule is not reasonably necessary to eliminate or reduce an unreasonable risk of injury associated with the product or is not in the public interest. However, the Commission can extend the 60-day period, for good cause shown, if it publishes the reasons for doing so in the *Federal Register*. 15 U.S.C. 2058(d)(1).

The Commission finds that there is good cause to extend the 60-day period for this rulemaking. Under both the APA and the CPSA, the Commission must provide an opportunity for interested parties to submit written comments on a proposed rule. 5 U.S.C. 553; 15 U.S.C. 2058(d)(2). The Commission is providing 60 days for interested parties to submit written comments. A shorter comment period may limit the quality and utility of information CPSC receives, particularly for areas where it seeks data and other detailed information that may take time for commenters to compile. Additionally, the CPSA requires the Commission to provide interested parties with an opportunity to make oral presentations of data, views, or arguments. 15 U.S.C. 2058. This may require time for the Commission to arrange a public meeting for this purpose and provide notice to interested parties in advance of that meeting. After receiving written and oral comments, CPSC staff must have time to review and evaluate those comments.

These factors make it impractical for the Commission to issue a final rule within 60 days of this proposed rule. Accordingly, the Commission finds that there is good cause to extend the 60-day period for promulgating the final rule after publication of the proposed rule.

XVIII. Request for Comments

We invite all interested persons to submit comments on all aspects of the proposed rule. The Commission particularly seeks comment on the following items:

- the CO concentration and associated time thresholds in the proposed performance requirements;
- the proposed fail safe provisions in the performance requirement;
- the efficacy of the proposed fail safe provisions and whether there is a more appropriate approach to address fail safe;
- should the proposed performance requirement include an audible alarm notification requirement that indicates when a gas furnace or boiler exceeds the proposed CO limits or when a CO sensor is no longer working properly;
- effort required to obtain sensors and information on sensors including the lifespan;
- effort required to redesign control systems;
- effort required to test prototypes;

- effort required to bring re-engineered appliances to production;
- costs associated with an effective date six months after publication of the rule;
- costs associated with an effective date 30 days after publication of the rule;
- costs associated with shipping and inventory of gas furnaces and boilers;
- costs associated with manufacturing gas furnaces and boilers, along with a description of the process including the timing and whether any firms have seasonal production;
- under the proposed stockpiling provision should zero-production months be averaged in to maintain a roughly constant level of supply for a seasonally produced product to avoid dramatic stockpiling if the manufacturer converted to constant production;
- effort required to incorporate sensors and/or combustion control systems in production;
- data or information on research and development and modifications to the production process the proposed rule would impose on manufacturers;
- data or information on price elasticity for gas furnaces or boilers;
- additional manufacturers and importers of gas furnaces and boilers that may meet the Small Business Administration (SBA) definition of a small business;
- information on importers of gas furnaces and gas boilers, specifically:
  - how many are imported;
  - how many different models each importer sells; and
  - what technologies those models are currently using (atmospheric venting, condensing, non-condensing, premix power burners, etc.); and
- information regarding the degree to which supplying firms are able to pass on increases in production and regulatory costs to importers.

XIX. Notice of Opportunity for Oral Presentation

Section 9 of the CPSA requires the Commission to provide interested parties "an opportunity for the oral presentation of data, views, or arguments." 15 U.S.C. 2058(d)(2). The Commission must keep a transcript of such oral presentations. *Id.* Any person interested in making an oral presentation must contact the Commission, as described under the **DATES** and **ADDRESSES** section of this notice.

List of Subjects

16 CFR Part 1408

Administrative practice and procedure, Consumer protection, Incorporation by reference, Gas furnaces and boilers.

For the reasons discussed in the preamble, the Commission amends Title 16 of the Code of Federal Regulations by adding a new part to read as follows:

PART 1408—SAFETY STANDARD FOR RESIDENTAL GAS FURNACES AND BOILERS

Sec.

1408.1 Scope, purpose, and effective date.

1408.2 Definitions.

1408.3 Performance requirements for residential gas furnaces and boilers.

1408.4 Incorporation by reference.

1408.5 Prohibited stockpiling.

Appendix A – Preliminary Findings Under the Consumer Product Safety Act

Authority: 15 U.S.C. 2056, 15 U.S.C 2058, and 5 U.S.C. 553

§ 1408.1 Scope, purpose, and effective date.

This part establishes performance requirements for residential gas furnaces, boilers, and wall and floor furnaces (gas furnaces and boilers) that are consumer products used to heat dwellings, including but not limited to, single family homes, townhomes, condominiums, and multifamily dwellings, as well as multi-family buildings such as apartments and condominiums. The purpose of these requirements is to reduce the occurrence of carbon monoxide-related deaths, injuries, and exposures associated with gas furnaces and boilers. All residential gas furnaces and boilers manufactured after [INSERT 18 MONTHS AFTER PUBLICATION IN THE *FEDERAL REGISTER*] must meet the requirements of this part.

§ 1408.2 Definitions.

Gas Central Furnace means a gas-burning appliance that heats air by the transfer of heat of combustion through a heat exchanger and supplies heated air through ducts to spaces remote from or adjacent to the appliance location.

Gas Floor Furnace means a furnace suspended between the floor joists of the space being heated. A floor furnace provides direct heating of the room in which it is located and to adjacent rooms.

Gas Steam and Hot Water Boiler means a gas burning appliance that heats steam at a pressure not exceeding 15 psi (100 kPa), or hot water at a pressure not exceeding 160 psi (1100 kPa) and at a temperature not exceeding 250 °F (121 °C). The heated steam or water is pumped to spaces remote from or adjacent to the appliance location through piping to radiators, where the heat of combustion is transferred to heat the air around the radiator.

Gas Wall Furnace means a gas appliance installed within a wall that provides heated air directly to the room in which it is installed and to adjacent rooms through grilles.

§ 1408.3 Performance requirements for gas furnaces and boilers.

(a) General. All residential vented gas furnaces, boilers, wall furnaces, and floor furnaces must have a means to either directly or indirectly monitor the concentration of carbon monoxide (CO) produced during the combustion process (*i.e.*, "CO emissions"), and shut down or modulate combustion to reduce average CO concentrations to below the CO levels for the durations of time specified in paragraph (b) of this section. If the average CO emissions reach or exceed the CO limits and time durations specified in paragraph (b), then the gas furnace or boiler must either shut down or modulate combustion to reduce average CO emissions to below 150 ppm. If average CO levels range between 200 and 299 ppm for 50 minutes, then the gas furnace or boiler must either shut down or modulate combustion to reduce average CO emissions to below 150 ppm. If average CO levels range between 300 and 399 ppm for 40 minutes, then the gas furnace or boiler must either shut down or modulate combustion to reduce average CO emissions to below 150 ppm. If average CO levels range between 400 and 499 ppm for 30 minutes, then the gas furnace or boiler must either shut down or modulate combustion to reduce average CO emissions to below 150 ppm. If average CO levels range from 500 ppm or higher for 15 minutes, then the gas furnace or boiler must either shut down or modulate combustion to reduce average CO emissions to below 150 ppm. Indirect monitoring and control of CO emissions can be accomplished by monitoring and controlling other combustion parameter(s) that accurately correlate to the production of CO. Examples of parameters that can serve as a proxy for CO production include carbon dioxide (CO_2), oxygen (O_2), the Gas/Air Ratio, and the flame ionization current produced by the burner flame.

(b) *Performance requirements for gas furnaces and boilers.* A gas furnace, boiler, wall furnace, or floor furnace must be equipped with a means to continuously monitor CO emission and must meet the requirements using one of the methods described in either subparagraph (b)(1)(i) or subparagraph (b)(2)(i) for the multipoint method or subparagraph (b)(1)(ii) or (b)(2)(ii) for the single point method of this section when tested using the test method described in paragraph (d) of this section.

(1) Direct means to monitor CO emissions. (i) Multipoint method. A gas furnace, boiler, wall furnace, or floor furnace equipped with a means to directly monitor CO emissions, must either cause shut down of the gas furnace or boiler or cause modulation of the gas furnace or boiler combustion, in response to the following conditions within the gas furnace or boiler:

(A) average CO concentration is 500 ppm or higher for 15 minutes;

(B) average CO concentration between 400 ppm and 499 ppm for 30 minutes;

(C) average CO concentration between 300 ppm and 399 ppm for 40 minutes;

(D) average CO concentration between 200 ppm and 299 ppm for 50 minutes;

(E) average CO concentration between 150 and 199 ppm for 60 minutes.

(ii) Single point method. A manufacturer may use the single point method instead of the multipoint method described in subparagraph (b)(1)(i) for a gas furnace, boiler, wall furnace, or floor furnace equipped with a means to directly monitor CO emissions; which must either cause shut down of the gas furnace or boiler or cause modulation of the gas furnace or boiler combustion, in response to the following conditions within the gas furnace or boiler:

(A) Average CO concentration of 150 ppm or higher for 15 minutes. Shutdown or modulation of the gas furnace or boiler must begin immediately after any of the conditions described in subparagraphs (b)(1) (i) (A) through (E) are reached or the alternative condition described in subparagraph (b)(1)(ii)(A) is reached. After modulation begins, the CO concentration within the gas furnace or boiler must be reduced to below 150 ppm within 15 minutes.

(B) [Reserved]

(2) Indirect means to monitor CO emissions. (i) Multipoint method. A gas furnace, boiler, wall furnace, or floor furnace equipped with an indirect means to monitor CO emissions, must either cause shut down of the gas furnace or boiler or cause modulation of combustion of the gas furnace or boiler, each in response to the combustion conditions that correlate to the following conditions within the gas furnace or boiler:

(A) average CO concentration is 500 ppm or higher for 15 minutes;

(B) average CO concentration between 400 ppm and 499 ppm for 30 minutes;

(C) average CO concentration between 300 ppm and 399 ppm for 40 minutes;

(D) average CO concentration between 200 ppm and 299 ppm for 50 minutes;

(E) average CO concentration between 150 and 199 ppm for 60 minutes.

(ii) Single Point method. A manufacturer may use the single point method instead of the multipoint method described in subparagraph (b)(2)(i) for a gas furnace, boiler, wall furnace, or floor furnace equipped with a means to indirectly monitor CO emissions, which must either cause shut down of the gas furnace or boiler or cause modulation of combustion within the gas furnace or boiler, in response to the following condition within the gas furnace or boiler:

(A) Average CO concentration of 150 ppm or higher for 15 minutes. Shutdown or modulation of the gas furnace or boiler must begin immediately after any of the conditions described in subparagraphs (b)(2)(i)(A) through (E) are reached or the alternative condition described in subparagraph (b)(2)(ii)(A) is reached. After modulation begins, the CO concentration within the gas furnace or boiler must be reduced to below 150 ppm within 15 minutes.

(B) [Reserved]

(3) Fail Safe. During the life of the gas furnace or boiler, if a CO sensor, combustion sensor, combustion control system, or other device designed to meet these requirements fails to operate properly or at all, then the gas furnace or boiler must shutdown and restart after 15 minutes and repeat this cycle until the failed component is replaced. Consumers and service technicians must be notified of device failure by either a flashing light or other appropriate code on the gas furnace or boiler control board that corresponds to the device failure.

(c) *Test Configuration.* Gas furnace or boilers must be configured in the following manner for testing. Gas Furnaces, boilers, wall furnaces, and floor furnaces must each be set up with the burner and primary air adjusted in accordance with the provisions of the Combustion sections of the respective voluntary standards (section 5.8.1 of ANSI Z21.47-2021 for gas furnaces; section 5.5.1 of ANSI Z21.13-2022 for gas boilers; and sections 9.3.1, 11.2.1, and 13.3.1, of ANSI Z21.86-2016 for gas wall and floor furnaces). These tests must be conducted in an atmosphere having normal oxygen supply of approximately 20.94 percent. Burner and primary air adjustments must be made for furnaces, boilers, wall furnaces, and floor furnaces in accordance with the provisions of each respective standard (section 5.5.4 of ANSI Z21.47-2021 for gas furnaces; section 5.3.1 of ANSI Z21.13-2022 for gas boilers; and section 2.3.4 of ANSI Z21.86-16 for gas wall and floor furnaces). After adjustment, and with all parts of the furnace, boiler, wall furnace, or floor furnace at room temperature, the pilot(s), if provided, must be placed in operation and allowed to operate for a period of five minutes. The main burner(s) must then be placed in operation and the gas furnace or boiler operated for three minutes at normal inlet test pressure at which time a sample of the flue gases must be secured. Immediately upon securing the sample at normal inlet test pressure, the reduced inlet test pressure (section 5.5.1 of

ANSI Z21.47:2021; section 5.3.1 of ANSI Z21.13-2022; and section 2.3.1 of ANSI Z21.86-16) must be applied and, following a purge period of at least two minutes, another sample of the flue gases must be secured. For atmospheric burner units, samples must be secured at a point preceding the inlet to the unit's draft hood or flue outlet where uniform samples can be obtained. The flue gas sample must be analyzed for carbon dioxide and carbon monoxide. The average concentration of carbon monoxide for the flue gas samples must not exceed 150 ppm in a sample of flue gases after 15 minutes.

(d)(1) Test Procedure. To test a furnace, boiler, wall furnace, or floor furnace to the performance requirements specified in paragraph (b) of this section, induce the production of CO or related combustion parameters, one or a combination of the following methods must be used:

(i) Progressively increase the gas control valve's outlet pressure until the unit produces a CO concentration of approximately 150 ppm ±10 ppm CO. For natural gas units, use a propane conversion kit to achieve the desired CO concentration if this was not accomplished by increasing the gas valve's outlet pressure. For propane units, use either option in subparagraph (b)(2)(i)(B) or (C). If neither option results in a CO concentration of approximately 150 ppm, then use both options in subparagraphs (b)(3)(i) (B) and (C). Once a CO concentration of at least 150 ppm is achieved, that condition must be maintained for 15 minutes.

(ii) Progressively block the exhaust vent or flue outlet until the unit produces approximately 150 ppm ±10 ppm CO. Disable the unit's blocked vent shutoff switch (BVSS) if necessary, in order to achieve the desired CO concentration. Once a CO concentration of approximately 150 ppm is achieved, that condition must be maintained for 15 minutes.

(iii) Reduce the fan speed of the inducer motor or premix power burner (for induced draft or premix power burner units only) by reducing the supply voltage to 85 percent of the gas furnace or boiler rating plate voltage until the unit produces a CO concentration of approximately 150 ppm ±10 ppm CO. An additional combustion sample must be secured with the gas furnace or boiler operating at normal inlet test pressure and with the supply voltage reduced to 85 percent of the gas furnace or boiler rating plate voltage. This sample must be secured 15 minutes after the furnace has operated at the reduced voltage. The input rating may vary from normal as a result of the voltage reduction. Once a CO concentration of approximately 150 ppm is achieved, that condition must be maintained for 15 minutes.

For gas furnaces and boilers that employ modulation (e.g., using a Gas/Air Ratio Controller, an automatic step-rate control, or automatic modulating controls, etc.) the unit must immediately begin modulation to reduce the CO concentration to below 150 ppm. For gas furnaces and boilers that do not employ modulation, the unit must shut down.

(2) Time for shutoff using multipoint method or modulation. The time for the gas to the main burner(s) to be shut off or begin modulation by the device used to directly or indirectly monitor CO emissions must be:

(i) After 15 minutes at an average CO concentration of 500 ppm or more.

(ii) After 30 minutes at an average CO concentration of 400 ppm-499.

(iii) After 40 minutes at an average CO concentration of 300-399 ppm.

(iv) After 50 minutes at an average CO concentration of 200-299 ppm.

(v) After 60 minutes at an average CO concentration of 150-199 ppm.

(3) Time for shutoff using single point method or modulation. A manufacturer, instead of using the multipoint method describe in subparagraph (d)(2) may use the following single point conditions and time to shut off the gas furnace or boiler or begin modulation in response to the following condition within the gas furnace or boiler:

(i) Average CO concentration of 150 ppm or higher for 15 minutes. Shutdown or modulation of the appliance shall begin immediately after any of the conditions described in subparagraph (d)(2) is reached. After modulation begins, the CO concentration within the appliance shall be reduced to below 150 ppm within 15 minutes.

(ii) [Reserved]

§ 1408.4 Incorporation by reference.

Certain material is incorporated by reference into this part with the approval of the Director of the Federal Register in accordance with 5 U.S.C. 552(a) and 1 CFR part 51. All approved incorporation by reference (IBR) material is available for inspection at the Consumer Product Safety Commission and at the National Archives and Records Administration (NARA). Contact the U.S. Consumer Product Safety Commission at: Office of the Secretary, U.S. Consumer Product Safety Commission, 4330 East-West Highway, Bethesda, MD 20814; telephone (301) 504-7479, e-mail cpsc-os@cpsc.gov. For information on the availability of this material at NARA, visit *www.archives.gov/federal-register/CFR/IBR-locations.html* or email *fr.inspection@nara.gov*. The following material may be obtained from the Canadian Standards Association, 8501 East Pleasant Valley Road
Independence, OH 44131-5516: 1-800-463-6727; www.csagroup.org/store/:

(a) ANSI Z21.47-2021, Standard: *Gas-fired central furnaces,* published May 2021.

(b) ANSI Z21.13-2022, Standard: *Gas-fired low-pressure steam and hot water boilers,* published August 2022.

(c) ANSI Z21.86-2016, Standard: *Vented gas-fired space heating appliances,* published January 2017.

§ 1408.5 Prohibited stockpiling.

(a) *Prohibited acts.* Manufacturers and importers of gas furnaces, boilers, wall furnaces, and floor furnaces shall not manufacture or import products that do not comply with the requirements of this part between [DATE OF PUBLICATION OF FINAL RULE] and [EFFECTIVE DATE OF FINAL RULE] at a rate greater than 106 percent of the base period in the first 12 months after promulgation of the rule, and 112.50 percent of the base period for the remaining six months until the effective date for the rule.

(b) *Base period.* The base period for gas furnaces, boilers, wall furnaces, and floor furnaces is the calendar month with the median manufacturing or import volume within the last 13 months immediately preceding the month of promulgation of the final rule.

Appendix A to Part 1408 — Preliminary Findings Under the Consumer Product Safety Act

The Consumer Product Safety Act requires that the Commission, in order to issue a standard, make the following findings and include them in the rule. 15 U.S.C. 2058(f)(3).

A. Degree and Nature of the Risk of Injury.

The Commission proposes this rule to reduce the risk of death and injury associated with CO production and leakage from residential gas furnaces, boilers, wall furnaces, and floor furnaces. Between 2017 to 2019 (the most recent period for which data are complete), there were annually an estimated 21 CO deaths associated with residential gas furnaces and boilers. For the 20-year period 2000 through 2019, these products were associated with a total of 539 CO deaths. Between the years 2014 and 2018, 236 nonfatal injuries were reported through the National Electronic Injury Surveillance System (NEISS) related to CO leakages from gas furnaces and boilers. Staff used NEISS incidents and the Injury Cost Model to extrapolate and generate national estimates for injuries from CO leakages from gas furnaces and boilers with 30,587 nonfatal injuries from CO leakages from 2014 to 2018.

B. Number of Consumer Products Subject to the Rule.

An estimated 70 firms manufacturers residential gas furnaces and boilers. When accounting for subsidiaries and multiple brands provided by the same company, 20 parent manufacturers have been identified. In 2020, there was an estimated of 60.94 million total number of residential gas furnaces and boilers in use. In 2021 residential gas furnace sales were estimated to be 3.58 million units, and 0.30 million units for gas boilers.

C. Need of the Public for the Products and Probable Effect on Utility, Cost, and Availability of the Product.

(1) Residential gas furnaces and boilers are fueled by natural gas or propane (gas) and are used to heat all categories of residential dwellings, including single family homes, townhomes, condominiums, and multifamily dwellings, as well as small-to medium-sized commercial dwellings. Because the rule is a performance standard that allows for the sale of compliant gas furnaces and boilers, it is not expected to have an impact on the utility of the product.

(2) The cost of compliance to address CO hazards include increased variable costs of producing furnaces and boilers with CO sensors and shutoff capabilities; one-time conversion costs of redesigning and modifying factory operations for installing CO sensors; increased maintenance costs of gas furnaces and boilers to consumers, and deadweight loss in the market caused by the increasing price due to regulation and the subsequent decline in sales. Staff performed a 30-year prospective cost assessment (2025-2054) on all four cost categories and estimated the total annualized cost from the proposed rule to be $602.27 million, discounted at three percent. Staff estimated the per-unit (of a gas furnace or boiler) costs from the proposed rule to be $158.11, discounted at three percent.

Dead weight loss refers to the lost producer and consumer surplus from reduced quantities of gas furnaces and boilers sold and used due to the rule-induced increases in manufacturer cost and retail price. Producer surplus represents the difference between the amount a producer is willing to sell a good or service for and the price they actually receive. Consumer surplus represents the benefit that consumers receive from purchasing a good or service at a price that is lower than their willingness to pay. For those units no longer produced due to the rule, suppliers lose out on the producer surplus associated with those units, and consumers lose out on the consumer surplus associated with those units.

In the first year, producer manufacturing costs are expected to increase by $22.08 per gas furnace causing a $70.44 per unit in higher retail costs to the consumer in the form of higher retail prices. Gas boiler manufacturing costs are expected to increase by $26.54 per unit causing an $87.59 in higher retail costs to the consumer. The resultant decrease in the number of gas furnaces and boilers sold and used is expected to generate a dead weight loss of about $1 million per year nationwide.

(3) Staff does not expect that the availability of gas furnaces and boilers will be substantially impacted by the rule. Staff estimates baseline (status quo) sales of 3.96 million units of gas furnaces and boilers in 2025 which in the absence of the rule, would grow to 4.72 million by 2054. With the promulgation of the rule staff expects gas furnace and boiler sales of 3.92 million units in 2025 would grow to 4.69 million units by 2054.

D. Any Means to Achieve the Objective of the Rule, While Minimizing Adverse Effects on Competition and Manufacturing.

(1) The rule reduces CO hazards associated with residential gas furnaces and boilers while minimizing the effect on competition and manufacturing. Manufacturers can transfer

some, or all, of the increased production cost to consumers through price increases. At the margins, some producers may exit the market because their increased marginal costs now exceed the increase in market price. Likewise, a very small fraction of consumers may be excluded from the market if the increased market price exceeds their personal price threshold for purchasing a gas furnace or boiler. However, the Commission did not find any information or assessment that would suggest significant changes to market competition or composition.

(2) The Commission considered alternatives to the rule to minimize impacts on competition and manufacturing including: (1) continuing to work and advocate for change through the voluntary standards process; (2) relying on the use of residential CO alarms; (3) continuing to conduct education and information campaigns; and (4) relying on recalls. The Commission determines that none of these alternatives would adequately reduce the risk of deaths and injuries associated with the CO hazards presented by residential gas furnaces and boilers.

E. The rule (including its effective date) is reasonably necessary to eliminate or reduce an unreasonable risk of injury. Between 2000 and December 2019, incident data show 539 fatal incidents related to CO hazards associated with gas furnaces and boilers. The incident data show that these incidents continue to occur and are likely to increase because the existing ANSI voluntary standards do not have requirements that would adequately reduce the CO hazard presented by gas furnaces and boilers and the market for gas furnaces and boilers is forecast to grow. The rule establishes performance requirements to address the risk of CO poisoning associated with residential gas furnaces and boilers. The effective date provides a reasonable amount of time for manufacturers to comply with the rule and produce products that prevent the CO hazard. Given the deaths and injuries associated with CO leakage from gas furnaces and boilers, the Commission finds that the rule and its effective date are necessary to address the unreasonable risk of injury associated with gas furnaces and boilers.

F. Public Interest. The rule addresses an unreasonable risk of death and injuries presented from CO hazards associated with gas furnaces and boilers. Adherence to the requirements of the rule would reduce deaths and injuries from CO poisoning associated with gas furnaces and boilers; thus, the rule is in the public interest.

G. Voluntary Standards. If a voluntary standard addressing the risk of injury has been adopted and implemented, then the Commission must find that the voluntary standard is not likely to eliminate or adequately reduce the risk of injury or substantial compliance with the voluntary standard is unlikely. The Commission determines that the relevant U.S. voluntary standards (ANSI Z21.13-2022, ANSI Z21.47-2021, and ANSI Z21.86-2016) do not contain performance requirements to protect against the known failure modes or conditions identified that have been associated with the production and leakage of CO into living spaces of U.S. residences resulting in numerous deaths and injuries, and thus do not adequately address the hazard of CO exposure from residential gas furnaces and boilers.

H. Reasonable Relationship of Benefits to Costs.

The Commission determines the benefits expected from the rule bear a reasonable relationship to its costs. The rule significantly reduces the CO hazard associated with residential gas furnaces and boilers, and thereby reduces the societal costs of the resulting injuries and deaths. When costs are compared to benefits, the estimated costs of the rule are greater than the estimated benefits. Staff calculates net benefits (benefits less costs) to be -$245.74 million on annualized basis, discounted at three percent. The net benefits on per-unit basis are -$64.51, discounted at three percent. Alternatively, this can be described as the proposed rule being a net cost of $64.51 per gas furnace or boiler, which represents approximately three percent of the average price of a gas furnace or boiler. Overall, the proposed rule has a benefit-cost ratio of 0.59; in other words, for every $1 in cost of the proposed rule, there is a return of $0.59 in benefits from mitigated deaths and injuries. However, the rule is estimated to address 90-100 percent of deaths caused by the CO hazard associated with gas furnaces and boilers, resulting in potential total societal annualized benefits from the rule of $356.52 million, discounted at three percent. Staff conducted a sensitivity analysis that showed if by 2035 manufacturers were able to develop compliant gas furnaces and boilers with CO sensors that did not need replacement, and if the analysis took into account that a child's death is considered twice as costly as an adult death, the benefit-cost ratio would increase to 0.78.

I. Least-Burdensome Requirement that Would Adequately Reduce the Risk of Injury. The Commission considered four alternatives to the proposed rule: (1) continue to work and advocate for change through the voluntary standards process; (2) rely on the use of residential CO alarms; (3) continue to conduct education and information campaigns; and (4) rely on recalls. Although these alternatives may be less burdensome alternatives to the rule, the Commission determines that none of the alternatives would adequately reduce the risk of deaths and injuries associated with gas furnaces and boilers that is addressed by the rule.

____

Alberta E. Mills, Secretary

Consumer Product Safety Commission

United States
Consumer Product Safety Commission

Staff Briefing Package

Notice of Proposed Rulemaking: Performance Requirements to Address Carbon Monoxide Deaths and Injuries Caused by Residential Gas Furnaces and Boilers

September 20, 2023

Executive Summary

This notice of proposed rulemaking (NPR) briefing package addresses carbon monoxide (CO) hazards associated with gas-fired central furnaces, boilers, wall furnaces, and floor furnaces (referred to as "gas furnaces and boilers" in this memorandum). These gas appliances provide comfort and life-sustaining heat to a dwelling through the combustion of either natural gas or propane gas. Central furnaces are the most commonly used of these gas appliances in the United States and natural gas is the most commonly used fuel source for furnaces and boilers. These products all utilize a vent system which must function properly without leaks or blockage to safely remove the exhaust products from the dwelling.

U.S. Consumer Product Safety Commission (CPSC) staff estimates that gas furnaces and boilers were associated with 21 deaths per year, on average from 2017-2019, and an estimated total of 539 CO deaths from 2000 to 2019. Staff estimates that approximately 30,587 CO poisoning injuries associated with these products occurred between 2014 and 2018. The primary hazard pattern involves products that do not limit the production of dangerous concentrations of CO in the exhaust vent system of the product, and leakage of that CO into the living space due to compromised venting.

In 2000 and 2015, CPSC staff requested that the American National Standards Institute (ANSI) Z21/83 Technical Committee add performance requirements to the ANSI Z21, Gas Appliance Standards (ANSI Z21.47, Gas-fired Central Furnaces; ANSI Z21.13, Gas-fired low pressure steam and hot water appliances; and ANSI Z21.86, Vented Gas-fired Space Heating Appliances) to address the known hazard patterns associated with CO poisoning from gas appliances. None of these gas appliance standards include performance requirements that adequately reduce the risk of CO poisoning, and so injuries and deaths have continued to occur.

On August 9, 2019, CPSC published an advance notice of proposed rulemaking (ANPR) concerning the gas appliance CO poisoning hazards and failure of the relevant voluntary standards to adequately address them. CPSC staff has developed proposed mandatory requirements to address the multiple failure conditions that staff identified in the hazard patterns associated with these products. The proposed requirements in this NPR address the hazard patterns by requiring gas furnaces and boilers to either shut down in response to dangerous levels of CO within the heat exchanger or flue passageways of the appliance or adjust its combustion to reduce CO to safe levels. The proposed requirements are based on staff's review and analysis of incident data, comments received in response to the ANPR, results from staff testing of gas appliances and CO/combustion sensors, European and Japanese standards for gas appliances, the existence of European and Japanese gas appliances equipped with CO/combustion sensors and controls, as well as results from contractor studies and tests and analysis.

CPSC staff estimate that, over a 30-year period, the draft proposed rule would prevent

576 deaths (19.20 deaths per year) and 160,699 injuries (5,357 per year). Staff conducted economic analyses to assess the costs and benefits of implementing the proposed rule to prevent those injuries and deaths. Annualized costs over a 30-year period are estimated to be $602.27 million, using a discount rate of 3 percent. Staff estimate the per-unit (of a gas furnace or boiler) costs from the draft proposed rule to be $158.11, when discounted at 3 percent. Staff also conducted a benefits assessment of the draft proposed rule. The annualized benefits, including the value of lives saved and injuries prevented, would be $356.52 million, discounted at 3 percent. Staff estimate the per-unit benefits from the draft proposed rule to be $93.60, discounted at 3 percent.

Therefore, staff calculates net costs of $64.51 per gas furnace or boiler. For every $1 in cost of the draft proposed rule, there is a return of $0.59 in benefits from mitigated deaths and injuries. Staff conducted a sensitivity analysis that showed under certain assumptions (see section 5.1 in TAB D) benefits could reach $0.78 from reduced deaths and injuries for every $1 in costs.

CPSC staff's research and analysis demonstrate that staff's recommended requirements will reduce CO deaths and injuries by limiting dangerous levels of CO production in the combustion process in gas furnaces and boilers. CPSC staff concludes the recommended requirements are technologically feasible and also are necessary because 1) the voluntary standards do not have adequate requirements to address the hazard, and 2) preventable CO poisoning deaths and injuries continue to occur. For these reasons, CPSC staff recommends that the Commission publish the draft NPR for Gas Furnaces and Boilers submitted with this briefing package.

Briefing Memorandum

Contents

United States
Consumer Product Safety Commission

Memorandum

TO: The Commission
Alberta E. Mills, Secretary

DATE: September 20, 2023

THROUGH: Austin C. Schlick, General Counsel
Jason K. Levine, Acting Executive Director
DeWane Ray, Deputy Executive Director

FROM: Duane Boniface, Assistant Executive Director
Office of Hazard Identification and Reduction
Ronald Jordan, Project Manager
Division of Mechanical and Combustion Engineering
Directorate for Engineering Sciences

SUBJECT: Notice of Proposed Rulemaking: Performance Requirements to Address Carbon Monoxide Deaths and Injuries Caused by Residential Gas Furnaces and Boilers

Introduction

On August 9, 2019, the Commission voted to publish an advance notice of proposed rulemaking (ANPR) to develop a rule to address the risk of injury and death associated with carbon monoxide (CO) production and leakage from residential gas furnaces, boilers, wall furnaces and floor furnaces (referred to as "furnaces and boilers"). The ANPR was published on August 19, 2019 (84 FR 42847) with a 60-day comment period. In response to a request for additional time to submit comments from the Air-Conditioning, Heating, & Refrigeration Institute (AHRI), the Commission reopened the comment period on November 7, 2019, for an additional 60 days (84 FR 60010).

This briefing package presents the following from U.S. Consumer Product Safety Commission (CPSC) staff:

- Recommendations for a proposed rule;
- Staff's responses to public comments on the ANPR;
- A preliminary regulatory analysis that discusses the potential benefits and costs of the draft proposed rule, along with an initial regulatory flexibility analysis that discusses the potential impact of the draft proposed rule on small businesses; and
- Other supporting documents.

Staff recommends that the Commission publish a notice of proposed rulemaking (NPR) to address CO hazards associated with residential gas furnaces and boilers.

Carbon Monoxide Poisoning (Tab F)

CO is an odorless, colorless, and tasteless gas at room temperature and atmospheric pressure. CO poisoning is often called a silent killer due to its imperceptible nature. People with severe CO poisoning can become critically ill and eventually die. Low-level, chronic exposure can also lead to neurological and cognitive deficits that do not resolve after removal from the CO source. Exposure to 400 parts per million (ppm) of CO for healthy adults results in headaches within 1-2 hours and is life threatening after 3 hours. For reference, UL listed CO alarms must alarm within 15 minutes in a 400 ppm environment.

Background

1. Products

Residential, gas-fired central furnaces, boilers, wall furnaces, and floor furnaces ("gas furnaces and boilers") are fueled by natural gas or propane ("gas") and are used to heat all categories of consumer dwellings, including single family homes, townhomes, condominiums, and multifamily dwellings, as well as small-to medium-sized commercial dwellings. These products provide heat to a dwelling by burning a mixture of gas and air within the combustion chamber of a heat exchanger. As the mixture of fuel and air is burned, heat is released and transferred through the wall of the heat exchanger to the medium surrounding the heat exchanger and circulated through air ducts (for central furnaces), water pipes throughout the dwelling (for boilers), or directly into the ambient air to provide heat (for wall furnaces and floor furnaces). Figure 1 provides a diagram of exhaust gas flow through a vent system and heated air through a duct system.

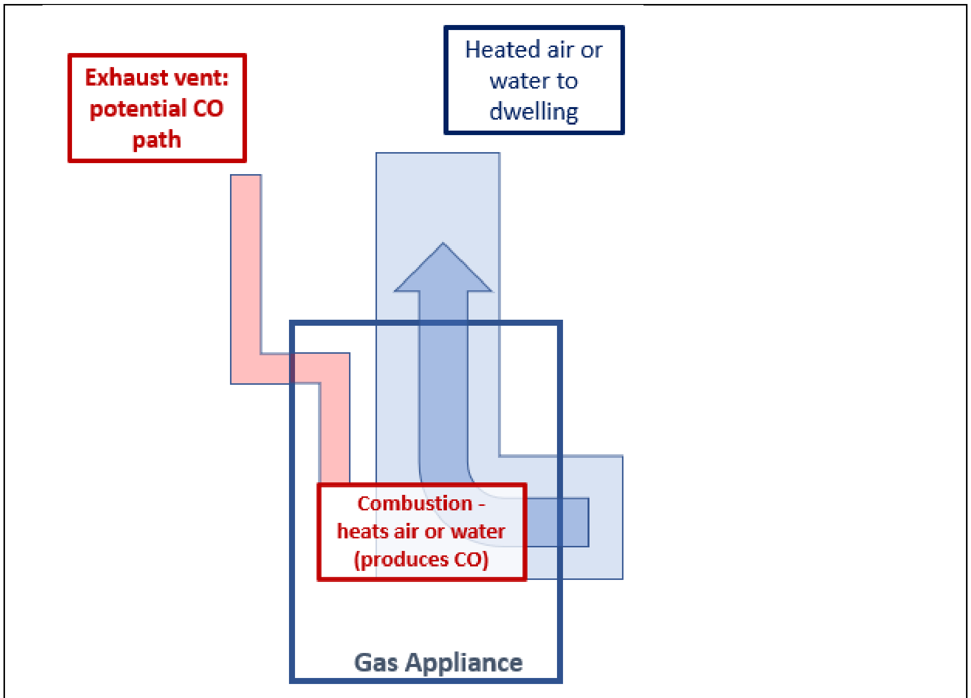


Figure 1. Diagram of a vent system and supply duct system.

Burning the mixture of fuel and air results in the formation of combustion products that are typically composed of oxygen, carbon dioxide, water vapor, and CO. When the mixture of fuel and air is burned completely, the concentration of CO produced should remain relatively low. The combustion products are exhausted to the outdoors through a vent system, either vertically through the roof, or horizontally through a side wall through the vent pipe. However, when issues with the combustion process arise (e.g., when fuel mixtures vary from optimal levels), dangerous levels of CO can be produced. Problems can arise in this scenario as well, resulting in leakage of combustion products into living spaces. The combination of production of dangerous levels of CO during the combustion process and leakage of that CO through the vent system into the living space is a hazard pattern identified by CPSC staff.

In a gas-fired central furnace (Figure 2), air is the medium that surrounds and is heated by the heat exchanger. A large fan is used to force-circulate the heated air across the exterior surfaces of the heat exchanger, through a duct system, and then the heated air exits the duct system through warm air registers typically within the dwelling. The red arrow in Figure 2
depicts the vent pipe.

In a gas boiler (Figure 3), water or steam is the medium that surrounds and is heated by the heat exchanger. The heated water or steam is circulated, using a pump to force the fluid through a piping system to radiators typically in each room in the dwelling. Heat is transferred through radiative and conductive heat transfer from the heated water or steam supplied to the radiators to the room. Gas-fired central furnaces and boilers are considered central heating appliances because they provide heat to each room of a dwelling. The red arrow in Figure 3 points to the boiler’s vent pipe.

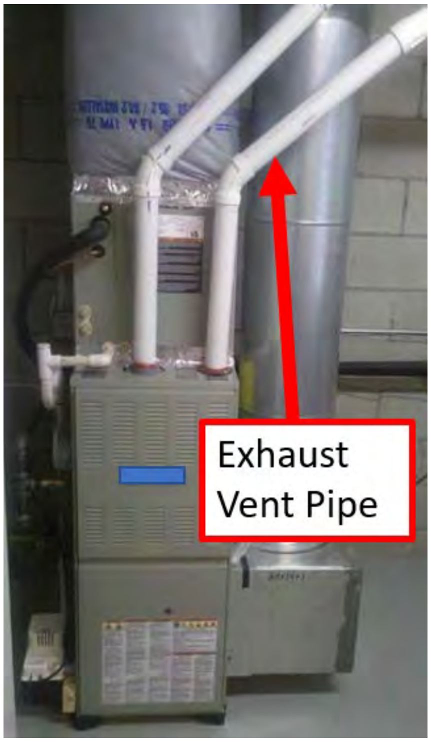


Figure 2. Gas-fired central furnace

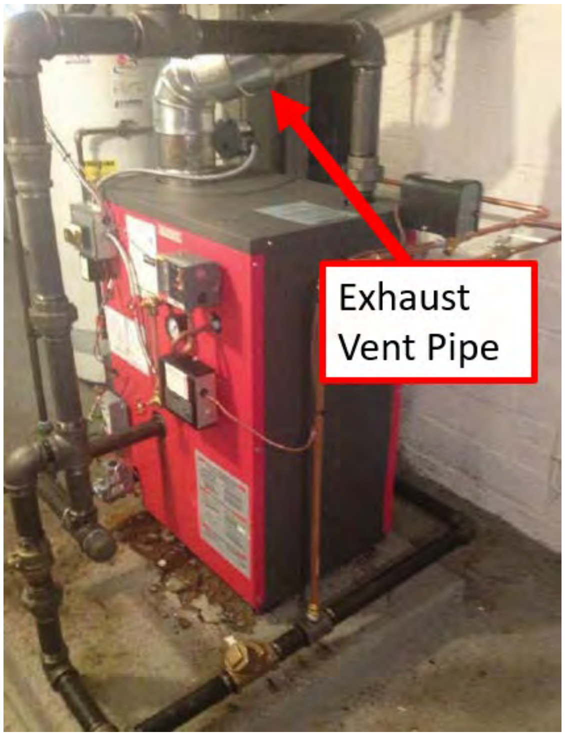


Figure 3. Gas boiler

In addition to central gas-fired furnaces and boilers, the proposed scope of the NPR also includes gas wall furnaces (Figure 4) and gas floor furnaces (Figure 5). As their names indicate, gas wall furnaces are installed in wall spaces, typically between the wall stud framing members; and floor furnaces are installed in the floor, typically between the floor joist framing members. Wall furnaces and floor furnaces both provide localized heating directly to the room in which they are located, and indirectly to adjoining rooms within the dwelling. The combustion products of wall furnaces are vented to the outdoors, either vertically through the roof, or horizontally through a side wall with the vent pipe running along the length of the wall studs between which the unit is installed. The combustion products of a floor furnace are typically vented horizontally through a side wall, with the vent pipe running along the length of the floor joists between which the unit is installed and through an exterior wall.

Figure 4. Gas wall furnace

Figure 5 Gas floor furnace

2. Gas Furnace, Boiler, Wall Furnace, and Floor Furnace Market

Staff identified as many as 70 firms that supply residential gas furnaces and boilers (Freedonia 2017). When accounting for subsidiaries, staff identified 20 parent firms.[1] In 2016, the largest 10 firms by revenue accounted for 83.3 percent of heating equipment sales. Seven of these firms are based in the U.S.

Staff used the U.S. Department of Energy's (DOE) Government Regulatory Impact Model (GRIM) to estimate sales for gas furnaces and boilers. GRIM projected gas furnace sales in 2021 to be 3.58 million units[2] and gas boilers to be 0.30 million units. Staff estimates that residential gas furnace and boiler sales in 2021 were $5.50 billion and $1.02 billion, respectively. The U.S. Energy Information Administration (EIA) conducts the Residential Consumption Survey (RECS) at irregular intervals. EIA published most recent RECS in 2021, which reports the total number of gas furnaces, gas boilers, and wall furnaces in use to be 60.94 million[3] in 2020. This is an increase from 57.90 million in 2015 – the most recent EIA survey before 2020. Therefore, between 2015 and 2020, the number of in-scope gas furnaces and boilers grew at an average annual rate of 1.03 percent. Of the four gas appliance types within the scope of the draft NPR, gas central furnaces are the most common in U.S. households.

Incident Data and Hazard Patterns

- *Fatalities (Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products 2019 Annual Estimates, TAB A)*

From 2017 to 2019 (the most recent period for which data are complete), there were annually an estimated 21 CO deaths associated with gas furnaces, boilers, wall furnaces, and floor furnaces (liquefied petroleum, natural gas, and unspecified gas).[4] For the 20-year period, 2000 through 2019, these products were associated with a total of 539 CO deaths.

- *Injury estimates (Residential Gas Furnaces and Boilers Preliminary Regulatory Analysis, TAB E, page 84)*

To estimate the annual number of injuries associated with CO exposure from natural gas and propane furnaces and boilers, an interdisciplinary team of CPSC staff evaluated injuries reported through the National Electronic Injury Surveillance System (NEISS). Staff queried NEISS for data between the years 2014 and 2018, focusing on product codes for gas furnaces and boilers (*i.e.*, codes 308, 310, 322,

[1] Dun and Bradstreet.
[2] GRIM's shipment estimate for 2021 was 3.41 million, which did not include wall or floor furnaces. Staff imputed wall and floor furnaces using the 4.68% estimate of built-ins of total furnace population by DOE's 2020 RECS microdata. This likely overestimates the in-scope population for this rule as built-ins include more types of furnaces than wall or floor furnaces.
[3] Staff used the microdata provided by RECS for its 2020 survey to aggregate units for gas appliances of equipment that are either "central furnace" or "Steam or hot water system with radiators or pipes".
[4] *Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products 2019 Annual Estimates*. J. Topping. CPSC Directorate for Epidemiology. September 2022.

392, and 393), and for carbon monoxide poisoning-related diagnosis codes (*i.e.*, codes 65 and 68). Staff identified 236 nonfatal injuries related to CO leakages from gas furnaces and boilers that occurred during this period. Of the 236 nonfatal injuries, 18 resulted in hospital admissions via the emergency department (ED), and 218 were treated in the ED and released.[5] Staff used NEISS incidents and the Injury Cost Model (ICM) to extrapolate and generate national estimates for injuries from CO leakages from gas furnaces and boilers treated in ED and other settings. Staff, using the ICM, calculated that the aggregate number of nonfatal injuries from CO leakages from gas furnaces and boilers from 2014 to 2018 was 30,587. Staff estimated that of the 30,587 injuries, 22,817 were treated in an outpatient setting (*e.g.*, doctor's office, or clinic), 7,358 resulted in ED treatment, 333 resulted in hospital admissions via the ED, and 79 resulted in direct hospital admissions.

- *Hazard Patterns*

In the ANPR briefing package published July 31, 2019, staff's memorandum in TAB C, *Updated Review of In-Depth Investigations Associated with Carbon Monoxide Poisoning and "Modern" Gas Furnaces and Boilers,* established that the hazard pattern for carbon monoxide poisoning associated with gas appliances involves: [6]

- hazardous levels of CO from incomplete combustion of the source fuel/gas, and
- exhaust leakage of that CO into the living space through a leak in the exhaust vent system.

Staff established the hazard patterns from a review of 83 incidents that conclusively involved a "modern" gas furnace or boiler that was manufactured after 1989 (and therefore was equipped with safety components in accordance with the latest safety requirements in the voluntary standards for those products). Staff's review of the 83 incidents, in conjunction with findings from earlier IDI reviews, also identified the following factors related to the incomplete combustion and exhaust leakage hazard patterns. Staff's ongoing review of IDIs confirms that these hazard patterns have not changed.

<u>Production of Dangerous Levels of CO from Incomplete Combustion</u>

Complete combustion of hydrocarbon fuels, such as natural gas or liquefied petroleum gas (LP-gas or propane), requires a proper mixture of air (*i.e.*,

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[5] Physicians have noted difficulty in correctly diagnosing these injuries (*e.g.,* Aniol, 1992). Carbon monoxide poisoning may mimic many conditions, including alcohol or drug intoxication, psychiatric disorders, flulike illnesses, and others conditions that can lead to misdiagnoses (ibid). Measurement of HbCO levels in the blood can also be confounded, based on the time elapsed and any breathing treatment administered that can lower counts before measurement. M.J. Aniol, Carbon Monoxide Toxicity: The Difficulty in Diagnosing This Leading Cause of Poisoning. *Can Fam Physician*. 1992 2123-2134, 2174.

[6] Draft Advance Notice of Proposed Rulemaking: Performance Requirements for Residential Gas Furnaces and Boilers. Retrieved at: https://cpsc.gov/s3fs-public/Draft%20ANPR%20-%20Performance%20Requirements%20for%20Residential%20Gas%20Furnaces%20and%20Boilers.pdf

combustion air) and fuel, as well as an adequate amount of heat to ignite the combustion air-fuel mixture. Incomplete combustion of the fuel supplied to gas appliances can lead to production of hazardous levels of CO.

Incomplete combustion can occur when the following conditions exist:

- *There is inadequate combustion air*: Inadequate air for combustion supplied to an appliance occurs when:
    1. air openings to the appliance combustion chamber or burner assembly are blocked;
    2. combustion air inlet piping (in the case of direct vent appliances) to the appliance is blocked;
    3. the exhaust outlet from the appliance is blocked;
    4. the appliance is installed in a room that does not have a large enough volume to provide the proper amount of air for combustion; or
    5. the appliance is installed in a smaller room or closet that does not have adequately sized combustion and ventilation air openings to support proper combustion.

- *Too much fuel is supplied to the appliance burner (i.e., over-firing)*: "Over-firing" can occur when the appliance gas manifold pressure is too high, causing the quantity of fuel delivered to the burner to be too high for complete combustion of the fuel/air mixture. This causes incomplete combustion of the fuel/air mixture and production of CO. This scenario can occur as a result of improper adjustment by a service technician, or a product defect or component failure/malfunction associated with the gas valve or the burner orifice.

- *The burner flame temperature falls below the ignition temperature of the combustion air-fuel mixture (i.e., flame quenching)*: Inadequate or reduced flame temperature can occur when the appliance burner is misaligned, causing the burner flame to contact a metal surface within the combustion chamber. Because the metal surface is much cooler than the burner flame, direct contact will cause a greater rate of heat transfer from the flame to the metal, resulting in a reduction in the flame temperature (*i.e*., flame quenching).

- Depending on the severity and duration, all these conditions can result in incomplete combustion of the fuel, which, in turn, can result in the gas appliance producing dangerous levels of CO.

<u>Exhaust leakage</u>

Combustion products from a gas furnace or boiler are normally vented to remove them from the home through a properly functioning vent system. A potential CO hazard in a home can arise if the furnace or boiler's combustion is malfunctioning, producing hazardous levels of CO, and a faulty exhaust system allows the CO to leak into the occupied space of the home. Typical exhaust failure leakage paths include: (1) a totally or partially blocked vent, chimney, or heat exchanger; or (2) a disconnected vent pipe, or a hole in the vent pipe. Another potential leakage mechanism occurs when an exhaust fan or fireplace is installed in the same room, or in a room adjacent to a gas appliance. The actions of the exhaust fan or a warm chimney created by a fireplace can have the effect of pulling air out of the room in which the gas appliance is installed. This action can depressurize the room, resulting in reverse flow of the combustion products through the appliance vent system or flue passageways. Instead of being vented safely to the outdoors, depressurization can cause combustion products, including CO, to spill into the living space. Other mechanisms that can lead to spillage include venting that is undersized for the gas appliance(s) connected to it. This can be caused by total or partial vent blockage, installation of a vent pipe that is too small for the appliance, or the connection of too many appliances to the vent so that the vent is rendered too small.

Recalls

Over the preceding 10-year period (2013 – 2022) there have a total of nine (9) CO hazard-related recalls associated with gas boilers. These recalls involved over 122,000 gas boilers, 23 incidents, 2 nonfatal injuries, and 1 death. (Tab G)

Staff Assessment of Existing Voluntary Standards

In the ANPR briefing package published July 31, 2019, staff analyzed existing voluntary standards in a memorandum in TAB D, *Existing Voluntary Standards and Voluntary Standards Development with Carbon Monoxide Hazards Associated with Gas Furnaces and Boilers*, described the current ANSI Z21 standards for gas furnaces and boilers (ANSI Z21.47 Gas-fired Central Furnaces, ANSI Z21.13 Gas-fired low pressure steam and hot water appliances, and ANSI Z21.86 Vented Gas-fired Space Heating Appliances) . Staff concluded that the standards do not include requirements to protect against the failure modes or conditions associated with production and leakage of CO into living spaces of U.S. households.

1. <u>U.S. Voluntary Standards</u>

The four types of gas appliances within the scope of the draft NPR are governed by the following U.S. voluntary standards:

1. ANSI Z21.13, Standard for Gas-Fired Low Pressure Steam and Hot Water Boilers
2. ANSI Z21.47, Standard for Gas-fired central furnaces
3. ANSI Z21.86, Standard for Vented Gas-Fired Space Heating Appliances

These standards all require the appliances to do the following:

- not produce CO in excess of 400 ppm (under prescribed laboratory test conditions)
- shut off when vent or flue is fully blocked
- shut off when blower door is not sealed properly (gas-fired central furnaces only)
- shut off if flames issue outside of jacket.

However, these requirements do not protect against many of the known failure modes or conditions that have been associated with production and leakage of CO into living spaces of U.S. households which the proposed rule is intended to address, which include:

- disconnected or breached flues, vents, and chimneys
- partially blocked heat exchangers, flues, vents, and chimneys
- over-fired appliances, and
- inadequate combustion air to appliances.

Based on the hazard patterns identified in staff's review of fatal CO poisoning incidents involving gas appliances, CPSC staff concludes requirements that address CO risk at the source of production, before potentially deadly levels of CO can enter the living space, will reduce the occurrence of CO-related deaths, injuries, and exposures associated with gas furnaces and boilers. Staff concludes that the incidents demonstrate that, in certain real scenarios as described above, situations do arise where hazardous levels of CO are produced by the appliances and can sometimes leak into homes leading to the deaths and injuries reported in this briefing package. This occurs even if a product complies with all applicable voluntary standards.

In 2015, CPSC staff requested that the ANSI Z21/83 Technical Committee add performance requirements for CO Shutoff/Reponses to the respective voluntary standards for gas-fired central furnaces, boilers, wall furnaces, and floor furnaces. The proposed voluntary standard performance requirements would have required the appliance to limit the production of CO below a threshold level, or for the appliance to shut off when CO emissions in the combustion chamber, flue passageways, or vent pipe exceed a hazardous level. This proposal was supported by proof-of-concept testing conducted by CPSC staff as well as by current standards for gas appliances in Europe and Japan that include similar requirements to use combustion sensors to regulate CO production and shut down the appliance or modulate its performance if CO production exceeds a specified safe level.

The Z21/83 Technical Committee studied staff's request and asserted that the technology required to meet the performance requirements was not feasible. Staff finds that international usage and testing done for CPSC under contract indicate that it is feasible to address these hazards through performance standards, but to date, none of the U.S. gas appliance standards include performance requirements that address the CO poisoning hazard at the source of CO production or leakage paths in the exhaust. Therefore, staff assesses that the U.S. voluntary standards do not adequately reduce the risk of CO poisoning from gas appliances and to-date, there are no indications that the Z21/83 Technical Committee or the subordinate Technical Subcommittees plan to address these risks. None of the commenters on the ANPR submitted any recommendations for proposed requirements nor did any commenters submit an existing voluntary standard or a portion of one that would adequately address the CO exposure risk.

2. International Standards

Japanese and European gas appliance voluntary standards exist that include CO shutoff or combustion control[7] requirements, as well as gas sensing technologies that are being used to implement those standards' requirements.

Japan

The primary gas heating appliances used in Japan are gas water heaters, gas boilers, and gas space heaters. Based on our review of the Japanese gas appliance market, instantaneous tankless gas water heaters[8] (Figure 6) are more common than traditional gas water heaters with storage tanks.

Figure 6. Japanese tankless gas water heater

Figure 7. European gas boiler

The governing voluntary performance and safety standards for these appliances in Japan are:[9]

- JIS-S-2109 - Gas burning water heaters for domestic use
- JIS S 2112 - Gas hydronic[10] heating appliances for domestic use
- JIS S 2122 - Gas burning space heaters for domestic use.

[7] Combustion control refers to a means to control the combustion of a gas/air mixture to ensure complete combustion of the gas/air mixture and to limit the production of carbon monoxide.
[8] Instantaneous tankless gas water heaters provide heated water on demand and therefore, do not require the use of a large storage tank, whereas traditional gas storage water heaters include a large storage tank used to store heated water.
[9] JIS-S-2112 and JIS-S-2122 were not available in English. To confirm the existence of incomplete combustion preventive device requirements with these standards, the table of contents and sections of the standards pertaining to incomplete combustion, carbon monoxide, and CO were translated from Japanese to English using: https://www.bing.com/search?q=translate+from+japanese+to+english&form=IENTHT&mkt=en-us&httpsmsn=1&refig=ffc0d5a3070d45d3c5187baeb690b6dd&sp=1&ghc=1&qs=AS&pq=translate+from+japanese+to+en glish&sc=8-34&cvid=ffc0d5a3070d45d3c5187baeb690b6dd. Staff's partial translation and review of these standards confirmed that they both included requirements for devices to prevent incomplete combustion to protect against CO poisoning and that were consistent with the requirements in JIS-S-2109.
[10] "Hydronic" denotes a cooling or heating system in which heat is transported using circulating water. A boiler is a type of appliance that provides this capability.

These Japanese Industrial Standards (JIS) have explicit performance requirements for vented gas water heaters, gas boilers, and gas space heaters that require shutoff of the appliance in response to CO levels above a certain threshold (*i.e.*, 300 ppm CO) (TAB E). The CO detection strategies used by Japanese manufacturers include detection of CO within the combustion chamber of the appliance and shutoff or combustion control in response to detection of hazardous levels of CO.

Europe

Gas boilers (Figure 7) are a common space heating appliance used throughout Europe in residential settings and are similar in design and function to power vented residential gas boilers certified to ANSI Z21.13 and sold in the United States. The relevant Committee for European Standardization (CEN) standards for residential gas boilers are:

- EN 15502 -1, Gas-fired heating boilers, Part 1: General requirements and tests
- EN 15502-2-1, Gas-fired central heating boilers, Part 2-1: Specific standard for type C appliances and type B2, B3 and B5 appliances of a nominal heat input not exceeding 1 000 kW
- EN 15502-2-2, Gas-fired central heating boilers, Part 2-2: Specific standard for type B1 appliances.

These CEN standards include explicit performance requirements for gas boilers to either shut down before the CO concentration inside the flue exceeds 2,000 ppm or not start if the CO concentration exceeds 1,000 ppm.

3. Technological Considerations

In the ANPR briefing package published July 31, 2019, staff's memorandum in TAB E *Technological Considerations for a Standard on Carbon Monoxide Shutoff/Response Requirements for Residential Gas Furnaces and Boilers*, summarized the technology that staff considered in recommending an advance notice of proposed rulemaking. A lack of feasible technology can be a barrier to implementing a new or proposed performance standard. Over the years, CPSC staff has identified CO/combustion sensing technologies capable of implementing the CO shutoff/response proposals staff made to voluntary standards groups in 2000 and 2015, which demonstrates the feasibility of these technologies.

In addition, staff has researched international standards that required the same or similar performance requirements as staff's 2000 and 2015 proposals. Staff identified several gas-sensing technologies that were either being used for CO shutoff or combustion control of residential gas appliances in Japan and Europe to correspond with the respective standards. The CO-detection strategies used by Japanese manufacturers include detection of CO within the combustion chamber of the appliance and shutoff or combustion control in response.

In Europe, residential gas boilers are required to meet certain European combustion-efficiency requirements, as well as CO safety requirements. The combustion-control strategies used by European gas boiler manufacturers to comply with the standards are often accomplished by monitoring the gas/air mixture, the combustion flame, or the concentration of CO, oxygen, or carbon dioxide within the combustion products. The combustion-control strategies are also used to detect CO, but rather than causing shut-down of the appliance, CO production is either prevented or limited by modulating the appliance's operation. The Japanese and European standards do not specify a minimum lifespan for sensing devices used to implement their respective CO safety and combustion efficiency requirements.

4. Contract Work

The findings of contractor research and testing conducted on behalf of CPSC staff to support staff's proposed mandatory performance requirements to mitigate carbon monoxide (CO) exposure hazards associated with gas furnaces, boilers, wall furnaces and floor furnaces (collectively referred to as "furnaces and boilers") are provided at Tab D. The purpose of this research and testing was to: (1) gain a better understanding of the impact of CO/combustion sensor use in gas appliances in Europe and Japan; and (2) estimate the life span of CO/combustion sensors if used in gas appliances in the U.S.

Staff's accelerated life test contractor work demonstrated that CO/combustion sensors are currently commercially available for use in gas appliances; the CO/combustion sensors that were tested have expected lifespans ranging from 6.4 to 10-years operating under conditions that replicate the main stress conditions expected within a gas appliance; and appliances with design platforms based on premix power burners are better suited to incorporate combustion control for CO risk mitigation because they typically have a single burner which allows them to maintain the ideal air-fuel ratio using a single flame ionization sensor. Maintaining the ideal air-fuel ratio is necessary to ensure complete combustion, and complete combustion of the air-fuel mixture is necessary to prevent production of excessive concentrations of CO. Gas appliances with induced draft or atmospheric vent design platforms would be better suited to use CO/combustion sensors for appliance shut-down to mitigate the CO risk because they typically have multiple in-shot burners (the number of which depends on overall capacity), with each burner corresponding to an individual heat exchanger pathway (*i.e.,* cell) that combustion gases flow through. Given the multiple burner and heat exchanger design of most U.S. gas furnaces, wall furnaces, and floor furnaces, as well as some boilers, the combustion control approach would be more costly and therefore, less desirable, as this would require a flame ionization sensor for each burner.

5. Conclusion

Staff reviewed the existing voluntary standards that are applicable to gas furnaces and boilers in the United States, Europe, and Japan; considered the technologies required to detect CO production and trigger shut down or modulation of the appliance; and researched the efficacy of CO sensors in gas appliance environments. Based on staff's analysis of the hazard patterns associated with CO poisoning, staff concludes that the current U.S. voluntary standards do not adequately reduce the risk of CO poisoning from gas appliances because the standards: 1) lack requirements that protect against known conditions that cause or contribute to CO exposure and 2) lack requirements for the appliance to monitor and manage CO production to prevent the introduction of hazardous levels of CO in the appliance's exhaust vent system. To date, there are no indications that the Z21/83 Technical Committee or the subordinate Technical Subcommittees intend to address these risks. None of the commenters on the ANPR submitted recommendations for proposed requirements nor did any commenters submit an existing voluntary standard or a portion of one that would address the CO exposure risk.

Recommended Performance Requirements

Proposed Performance Requirements (TAB B)

The governing voluntary standards for gas-fired central furnaces, boilers, wall and floor furnaces are, respectively, ANSI Z21.47, *Standard for Gas-fired central furnaces*; ANSI Z21.13, *Standard for Gas-fired low-pressure steam and hot water boilers;* and ANSI Z21.86, *Standard for Vented Gas-Fired Space Heating Appliances*. As discussed in the Voluntary Standards section of this briefing package, the proposed mandatory performance requirements are necessary for the following reasons:

1. The existing voluntary standards do not include provisions that would protect consumers from a number of conditions (described above under "Hazard Patterns") known to cause or contribute to the production of dangerous concentrations of CO or the leakage of CO into the living space of a dwelling;
2. The gas appliances under consideration here are the second leading cause of nonfire related CO deaths amongst all consumer products, resulting in an estimated 21 deaths per year, on average from 2017-2019, and an estimated total of 539 CO deaths associated with gas furnaces and boilers from 2000 to 2019;
3. In the 22 years that CPSC staff has studied and worked on this issue by submitting proposals to voluntary standards organizations, with accompanying support for those proposals with incident data, technology demonstrations, and similar international standards, the ANSI Z21 Technical Committee and its subordinate Technical Subcommittees for gas boilers (*ANSI Z21.13*), furnaces (*ANSI Z21.47*), and wall and floor furnaces (*ANSI Z21.86*) have not developed performance requirements to address the risk of CO raised by CPSC staff; and

CPSC staff's proposed performance requirements include provisions requiring continuous supervision (*i.e.*, monitoring) of CO emissions or other combustion parameters related to CO production. In addition, the proposed requirements also consider the different types of design platforms (*i.e.*, premix power burner, induced draft, or atmospheric venting) of the appliances within scope of this rule. As outlined in the CPSC contractor report titled "Review of Combustion Control and Carbon Monoxide Sensors in Europe and Japan" (TAB C, Attachment 1), the type of design platform an appliance is built upon would determine which CO mitigation approach, shut-down or modulation, could be most readily incorporated into the appliance. Shut-down of an appliance refers to the flow of gas to the appliance being stopped, effectively stopping the operation of the appliance. Modulation refers to either the gas pressure to the appliance burner being increased or decreased, or the fan speed to the appliance inducer or premix power burner fan motors being increased or decreased, or a combination of both occurring to maintain proper combustion. Modulation occurs without shutting the appliance off. The proposal also allows the option of direct or indirect monitoring of and response to CO emissions as follows.

<u>Proposed Performance Requirements</u> (Tab B)
A gas furnace, boiler, wall furnace or floor furnace shall be equipped with a means to continuously monitor CO emission and must meet requirements below when tested to the test method described in paragraph (c) by either directly monitoring CO emissions or indirectly monitoring CO by monitoring conditions that correlate to the specified CO emissions levels.

<u>Direct means to monitor CO emissions</u>
A gas furnace, boiler, wall furnace, or floor furnace equipped with a means to directly monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of appliance combustion, each in response to the following conditions[11] within the appliance:

a) Average CO concentration is 500 ppm or higher for 15-minutes;
b) Average CO concentration between 400 ppm and 499 ppm for 30-minutes;
c) Average CO concentration between 300 ppm and 399 ppm for 40-minutes;
d) Average CO concentration between 200 ppm and 299 ppm for 50-minutes;
e) Average CO concentration between 150 and 199 ppm for 60-minutes.

Alternatively, a gas furnace, boiler, wall furnace, or floor furnace equipped with a means to directly monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of appliance combustion, in response to the following conditions within the appliance:

f) Average CO concentration of 150 ppm or higher for 15-minutes.

Shutdown or modulation of the appliance shall begin immediately after any of the

[11] These CO ranges are based on Curve G of the CO Concentration vs. Time graph (Figure 41.1 excerpted from UL 2034), which indicates what an individual's carboxyhemoglobin (COHb) levels would be if exposed to various CO concentrations and the time of exposure needed to reach that COHb level. Curve G represents a 20 percent COHb level and the onset of health effects in individuals (i.e., headaches).

conditions described in a) through e) are reached or the alternative condition described in f) is reached. After modulation begins, the CO concentration within the appliance shall be reduced to below 150 ppm within 15 minutes.

<u>Indirect means to monitor CO emissions</u>
A gas furnace, boiler, wall furnace, or floor furnace equipped with an indirect means to monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of combustion of the appliance, each in response to the combustion conditions that correlate to the following conditions within the appliance:

a) Average CO concentration is 500 ppm or higher for 15-minutes;
b) Average CO concentration between 400 ppm and 499 ppm for 30-minutes;
c) Average CO concentration between 300 ppm and 399 ppm for 40-minutes;
d) Average CO concentration between 200 ppm and 299 ppm for 50-minutes;
e) Average CO concentration between 150 and 199 ppm for 60-minutes.

Alternatively, a gas furnace, boiler, wall furnace, or floor furnace equipped with a means to indirectly monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of combustion within the appliance, each in response to the combustion conditions that correlate to the following condition within the appliance:

f) <u>Average CO concentration of 150 ppm or higher for 15-minutes.</u>

Shutdown or modulation of the appliance shall begin immediately after any of the conditions described in a) through e) are reached or the alternative condition described in f) is reached. After modulation begins, the CO concentration within the appliance shall be reduced to below 150 ppm within 15 minutes.

Fail Safe
During the life of the appliance, if a CO sensor, combustion sensor, combustion control system, or other device designed to meet these requirements, fails to operate properly or at all, then the appliance shall shutdown and restart after 15 minutes and repeat this cycle until the failed component is replaced. Consumers and service technicians shall be notified of device failure by either a flashing light, or other appropriate code on the appliance control board, that corresponds to the device failure.

Appliance design platforms that utilize premix power burners could more readily incorporate modulation of gas flow and/or air flow reduction because they typically have a single burner which allows them to maintain the ideal air-fuel ratio using a single flame ionization sensor. Maintaining the ideal air-fuel ratio is necessary to ensure complete combustion, and complete combustion of the air-fuel mixture is necessary to prevent production of excessive concentrations of CO. Shut-down of a gas furnace, wall furnace, floor furnace as well as some boilers in response to elevated levels of CO is more suitable for appliance design platforms that are either of the induced draft or atmospheric vent type, because these appliances typically have multiple burners and corresponding heat exchanger cells. Because most U.S. gas furnaces, wall furnaces, and floor furnaces, as well as some boilers, have multiple burner and heat exchanger cell designs, the combustion control approach would require a flame ionization sensor for each burner and therefore be more costly and less desirable.

Staff assesses that the proposed rule would be 90-100 percent effective in eliminating CO exposure deaths and injuries associated with gas furnaces and boilers (TAB B, page 61) for the following reasons:

1. Detection of CO at the source of production.
2. Prevents or limits production of harmful levels of CO.
3. Selecting CO response concentrations that fall on the 20 Percent COHb curve.[12]
4. Addresses all of the known hazard patterns.
5. Conforms to the Z21/83 Technical Committee's Two-Failure Philosophy.[13]

Economic Analysis for the Proposed Rule on Gas Furnaces and Boilers

Preliminary Regulatory Analysis (TAB D) and Initial Regulatory Flexibility Analysis (TAB E)

CPSC staff from the Directorate for Economic Analysis (EC) prepared a Preliminary Regulatory Analysis (TAB D) and an Initial Regulatory Flexibility Analysis (TAB E). This section summarizes the information in the Preliminary Regulatory Analysis and Initial Regulatory Flexibility Analysis included in this NPR.

Costs Analysis

The draft proposed rule would impose the following costs: increased costs of producing furnaces and boilers with CO sensors and shutoff capabilities; one-time conversion costs of redesigning and modifying factory operations for installing CO sensors; increased maintenance costs to consumers to replace old or failed CO sensors, and deadweight loss[14] in the market caused by the increasing price due to regulation and the subsequent decline in demand. Staff performed a 30-year prospective cost assessment (2025-2054) on all four cost categories and estimated the total annualized cost from the draft proposed rule to be $602.27 million,

[12] Carbon Monoxide concentration (ppm CO) versus time curve, Figure 41.1, UL 2034, Standard for Safety, Single and Multiple Station Carbon Monoxide Alarms. The 20% Carboxyhemoglobin (COHb) Curve represents the COHb levels that a person would begin to experience a headache when exposed to any CO concentration that falls on the curve for the listed durations. CPSC staff selected this curve as response setpoints since it was believed that these levels provided the greatest level of protection without creating a risk of false alarms caused by setpoint CO levels that were too low.

[13] The "Two Failure Philosophy" is the position taken by gas appliance industry groups, such as the Z21/83 Technical Committee, that the following two failures must occur before a vented gas appliance poses a CO hazard: 1) production of excessive CO levels; and 2) creation or existence of a leakage path for CO to migrate from inside the appliance into the living space.

[14] Deadweight loss is the value of lost transactions that may occur after major market events such as a new regulation.

discounted at 3 percent.[15] Staff estimated the per-unit (of a gas furnace or boiler) costs from the draft proposed rule to be $158.11, discounted at 3 percent.

Benefit Analysis

Staff also conducted a benefits analysis of the draft proposed rule. The benefits analysis accounted for the prevention of deaths and injuries from compliant gas furnaces and boilers, which staff monetized using the value of statistical life (VSL) for deaths, and the Injury Cost Model (ICM) for injuries. Staff from CPSC's Engineering Sciences Directorate estimate a 90 to 100 percent range effective rate for the draft proposed rule's risk mitigation of death and injuries from CO poisoning. Staff from CPSC's Economic Analysis Directorate used the midpoint effective rate, 95 percent, for the benefits assessment of the draft proposed rule. Over the 30-year study period, staff estimated the draft proposed rule would prevent 576 deaths (19.20 deaths per year) and 160,699 injuries (5,357 per year). The total annualized benefits from the draft proposed are $356.52 million, discounted at 3 percent. Staff estimated the per-unit benefits from the draft proposed rule to be $93.60, discounted at 3 percent.

Comparison of Potential Costs and Benefits of the Draft Proposed Rule for Gas Furnaces and Boilers

Staff compared estimated benefits and costs to assess the relation between benefits and costs of the draft proposed rule. Staff found that the costs of the proposed rule outweighed the benefits by approximately $246 million on an annualized basis or approximately $65 on a per unit basis. In other words, for every $1 in cost, the draft proposed rule generates $0.59 in benefits (by preventing an average of approximately 19 deaths and 5,357 injuries annually over 30 years).

Annualized net benefits

	Benefits Compared to Costs		
Annualized Net Benefits ($M)	**Undiscounted**	**3% Discount**	**7% Discount**
Benefits	$411.61	$356.52	$290.60
Costs	$661.24	$602.27	$535.75
Net Benefits (Benefits – Costs)	($249.62)	($245.74)	($245.15)
B/C Ratio	0.62	0.59	0.54

Per-unit net benefits

	Benefits Compared to Costs		
Per Unit Net Benefits ($)	**Undiscounted**	**3% Discount**	**7% Discount**
Benefits	$165.39	$93.60	$48.30
Costs	$265.69	$158.11	$89.04
Net Benefits (Benefits – Costs)	($100.30)	($64.51)	($40.74)
B/C Ratio	0.62	0.59	0.54

[15] Staff uses a discount rate to incorporate the time value of money during the 30-year study period. In the analysis, staff presents both costs and benefits in undiscounted dollars, discounted at 3 percent, and discounted at 7 percent.

Alternatives to the Draft Proposed Rule

Staff considered the following four alternatives to the draft proposed rule:

- **Voluntary standard.** The Commission could continue to have staff work on the existing voluntary standards, ANSI Z21.13, ANSI Z21.47, and ANSI Z21.86, and continue to work with the Canadian Standards Association Group (CSA Group) to develop more effective requirements to address the identified hazards, instead of issuing a mandatory rule.

- **CO alarms.** The Commission could continue to advocate for the use of residential CO alarms and for regional and national building codes provisions that require their use.

- **Information and education.** The Commission could continue to issue annual and semi-annual news releases warning consumers about the dangers of CO and promoting the importance of consumers getting annual safety inspections of their fuel burning heating systems, instead of issuing a mandatory rule.

- **Reliance on recalls.** The Commission has obtained recalls from gas furnace and boiler manufacturers related to CO leakage hazards. The Commission could continue to rely on recalls, both voluntary and mandatory, instead of promulgating a mandatory rule.

The Commission could pursue one or more of these alternatives to reduce the identified hazards associated with production and leakage of CO from gas furnaces and boilers. Staff recommends against these, as they do not address the hazard pattern identified and would result in continuing preventable injuries and deaths.

Response to ANPR Comments

The Commission published an advance notice of proposed rulemaking for residential gas furnaces and boilers in the *Federal Register* on August 19, 2019, with a 60-day comment period, which was subsequently extended for an additional 60 days. The public comment period ended on January 6, 2020. CPSC received 15 comments, which are available at regulations.gov under docket number CPSC-2019-0020. The following commenters submitted comments:

1. John J. Gibbons, Carrier
2. Dr. Edward W. Johann, U.S. Boiler Company, Inc.
3. John R. Busse, U.S. Boiler Company, Inc.
4. Ashley A. Armstrong, A.O. Smith Corporation
5. Paul Sohler, Crown Boiler
6. Karen Meyers, Rheem
7. Shannon M. Corcoran, Air Conditioning, Heating, and Refrigeration Institute

(AHRI)
8. James A. Ranfone, American Gas Association (AGA)
9. Sarah J. Reboli, National Propane Gas Association (NPGA)
10. Frank Stanonik, Stanonik Consulting LLC
11. Mark Strauch
12. Dave Schryver, American Public Gas Association (APGA)
13. Centrotherm Eco Systems
14. Joint comments submitted by: Dr. Frank Hammer, Lamtec; Steve Craig, Hays Cleveland; and Werner Born, Federal Association of Companies in the Gas and Water Industry e.V. (FIGAWA)
15. Joint comments submitted by William J. Hansen, McDermott Attorneys, LLC; and Mark Passamaneck, Entropy Engineering Corp.

Of the 15 commenters, two commenters were in support of the CPSC staff proposal while 13 commenters opposed the proposal. The commenters who supported the proposal indicated that they support the use of CO sensor technology in gas appliances. The 13 commenters who opposed proposed rulemaking were comprised primarily of U.S. gas appliance stakeholders, including seven gas appliance manufacturers' representatives, four gas appliance industry trade association representatives, one gas appliance industry consultant, and one individual who didn't identify a particular organizational or business affiliation. In general, the comments in opposition to the proposal included the following topic areas: recommending residential CO alarms; making assertions of no-heat or unsafe alternative heat hazards; recommending information and education; making assertions that existing standards and designs are adequate; making assertions about the inadequacy of existing CO/combustion technology, the proposed standard and the effectiveness of the overall approach; recommending maintaining the status quo; and making assertions that the incident reports do not support the rule.

Below is summary of the comments and CPSC staff's responses by topic area.

<u>Alternatives to Performance Requirements</u>

Comment: Nine commenters (A.O Smith, Carrier, Crown, Rheem, USB EJ, USG JB, AHRI, M. Strauch, and Stanonik) stated that rulemaking is not necessary because residential CO alarms will prevent CO poisoning from gas appliances. One commenter (Stanonik) further claimed that information from CPSC's in-depth-investigation (IDI) reports show that CO alarms are effective in protecting participants from exposure to hazardous levels of CO and that a survey conducted by CPSC should be completed before rulemaking occurs. Four commenters (Crown, USB EJ, USB JB, and AHRI) supported changing the ANSI gas appliance standards and/or building codes to require CO alarm installation.

Response: Although CPSC staff advocates for the use of residential CO alarms, not all homes are equipped with functioning and maintained alarms, and fewer still have them in all occupied spaces into which CO leakage may occur. Staff notes that despite campaigns to increase the use of CO alarms, injuries and fatalities that occur annually are evidence that this hazard continues to kill and injure consumers. Therefore, staff concludes that developing effective performance requirements for gas appliances is critical to consumer safety. Staff's research and analysis determined that stopping CO at the source of production, before it leaks into the living space, is the most effective way of addressing the CO risks associated with gas furnaces and boilers. This approach was used with vented and unvented gas space heaters through the use of vent safety shutoff systems (VSSS) and oxygen depletion safety (ODS) systems and has been extremely effective for those products. Voluntary standards organizations in Japan and Europe have successfully developed standards similar to those in the proposed rule, demonstrating that the technology is feasible.

Comment: One commenter (USB JB) stated a CO monitor in the equipment room or living space would provide a better solution than a carbon monoxide monitor on the appliance.

Response: CPSC staff disagrees with the commenter's assertion because a monitoring system located within the equipment room or living space would not detect CO at numerous points of potential leakage along the length of the vent system. CPSC staff finds that detecting excessive CO at the point of production would protect consumers from CO exposure, regardless of the point or mechanism of leakage or the cause of elevated CO production. CPSC staff finds that direct measurement of conditions that cause or contribute to the production of dangerous levels of CO is more accurate and would provide a response directly linked to those conditions and appliance performance.

Comment: One commenter (USB JB) stated the CPSC should sponsor and provide funding for multi-functional task force to develop solutions to reduce and eliminate carbon monoxide poisoning caused by residential gas furnaces. The commenter mentioned federal assistance resources (by the CPSC), participation or leading sponsored research, and support from manufacturers in providing samples and engineering support.

Response: In the ANPR briefing package published July 31, 2019, staff's memorandum in TAB D, *Existing Voluntary Standards and Voluntary Standards Development with Carbon Monoxide Hazards Associated with Gas Furnaces and Boilers*, summarizes CPSC staff's efforts from 2000 to 2019 to work with the ANSI Z21/T83 Technical Committee to address carbon monoxide poisoning that were continuing to occur despite the latest revisions to the gas appliance standards. CPSC staff provided leadership by sharing incident reports with the Committee members, conducting preliminary research and sharing the results, and submitting two proposals to the Technical Committee (in 2000 and 2015) requesting that the relevant voluntary standards add requirements to address the production of hazardous levels of CO and the risk of that CO entering the living space of the dwelling.[6] In 2019 the working group working on the effort was disbanded by the Technical Committee. Despite staff's efforts over two decades, as well as the developments of voluntary standard requirements in Japan and Europe, the voluntary standards community in the United States has not adopted any new performance requirements to address CO risk at the source of production in gas appliances.

Comment: One commenter (USB JB) stated that gas appliances and boilers will eventually be replaced with electric heating appliances because current and future efforts to reduce carbon emissions will eliminate or restrict the availability of natural gas for residential appliances.

Response: The commenter did not provide evidence to support this claim. Gas appliances and boilers continue to be sold and used for residential heating. Without adopting the proposed revisions to the governing standards, these products will continue to present a potential CO hazard. Therefore, staff concludes that performance requirements to address CO production by gas appliances are needed to reduce deaths and injuries from CO exposure that otherwise will continue to occur.

Comment: One commenter (USB JB) referred to periodic inspection and service of the gas appliance and queried if CPSC's data provided evidence that "formalized inspection and service requirements would reduce carbon monoxide poisoning." Two other commenters (Crown and AHRI) also state a formal program to check installation, service, and maintenance will reduce carbon monoxide incidents.

Response: CPSC staff is not aware of data analysis that supports the commenters' theory. Manufacturers already recommend routine maintenance of furnaces and boilers, yet injuries and deaths continue to occur for the reasons described above. Further, CPSC lacks jurisdiction over homeowners' spending on maintenance services.

Comment: Two commenters (Crown and USB JB) state CPSC should rely on the existing recall program to prevent/reduce CO incidents involving boilers and furnaces.

Response: When a product is involved in a CPSC recall, the product may have been involved in an incident, in this case a CO exposure incident that may have caused serious injury or death. In those cases, to wait for a product to become involved in a CPSC recall can potentially place consumers at risk of CO exposure resulting in injury or death, from failure modes and conditions Including blockages and vent leaks. Between 2013 and 2022, CPSC has been involved in nine CO-related recalls of gas boilers (Tab G). The gas boilers involved in these recalls were also involved in 23 CO exposure incidents, with 2 nonfatal injuries. By contrast, CPSC estimated that gas furnaces and boilers were associated with an estimated 24 CO deaths (Tab A) in 2019 and 236 average annual non-fatal injuries (Tab E) between 2014 and 2018. This further demonstrates that relying solely on CPSC recalls would needlessly place more consumers at risk of CO exposure. The CPSC will continue to utilize the CPSA section 15 recall process, independent of the outcome of this rulemaking process, but staff finds that the draft proposed rule will reduce deaths and injuries and recommends that the Commission proceed with rulemaking.

Rely on Consumer or Installer Education

Comment: Five commenters (Carrier, Crown, Rheem, USB EJ, and USB JB) stated that information and education programs for consumers, installers, and maintenance personnel will adequately address CO poisoning hazards.

Response: Staff of CPSC's Directorate for Engineering Sciences, Division of Human Factors (ESHF) agrees that warnings, instructions, and educational campaigns or programs related to the topics identified above are important and useful, but finds they are not sufficient on their own without a performance standard to directly address the hazard. Instead, staff finds that information and education programs exist already, and the deaths and injuries noted in this briefing package demonstrate that these programs do not adequately address the hazard. Consumers should be encouraged to install and maintain residential CO alarms, which are effective in alerting consumers to hazardous CO levels and in limiting CO exposure. Moreover, consumers should have gas furnaces and boilers maintained and regularly inspected, and HVAC service and inspection professionals should be properly educated on the safe installation, maintenance, and inspection of gas furnaces and boilers. Staff supports revisions to voluntary standard requirements for user manuals and service instructions to include warnings and recommendations related to these topics. Nevertheless, staff finds that such approaches have not been effective to adequately reduce CO poisonings, and that injuries and deaths will continue to occur unless the Commission requires the performance requirements in this draft proposed rule that would directly address the CO poisoning hazard associated with gas furnaces and boilers.

Safety literature consistently identifies a classic hierarchy of approaches for controlling hazards. Providing warnings and instructions about hazards is viewed universally as less effective at eliminating or reducing exposure to hazards than either designing the hazard out of a product or guarding the consumer from the hazard.[16] Warnings are less effective because they rely on educating consumers about the hazard and persuading consumers to alter their behavior in some way to avoid the hazard. To be effective, warnings also depend on consumers noticing or otherwise receiving the message, attending to the message, remembering the recommended behaviors when needed, and behaving consistently, regardless of situational or contextual factors that influence precautionary behavior, such as fatigue, stress, or social influences. Thus, one should view reliance on warnings and other hazard communications as a "last resort" that supplements, rather than replace, redesign or guarding efforts, unless these latter, higher-level hazard-control efforts are not feasible.

[16] Smith, T. P. (2016) Human Factors Staff Responses to Labeling-Related Public Comments on 2006 ANPR for Portable Generators and 2012 CPSC Staff Report, Technology Demonstration of a Prototype Low Carbon Monoxide Emission Portable Generator. In J. Buyer. (2016) *Briefing Package for Notice of Proposed Rulemaking for Safety Standard for Carbon Monoxide Hazard for Portable Generators* (Tab F). Staff Briefing Package, U.S. Consumer Product Safety Commission, Washington, DC. Available: https://www.cpsc.gov/s3fs-public/Proposed-Rule-Safety-Standard-for-Portable-Generators-October-5-2016.pdf.

One public comment (U.S. Boiler Company) recommends updating voluntary standard requirements for user manuals to recommend installing CO alarms in the room containing the gas appliance, but this does not appear to be universally recommended by the industry. In fact, CPSC and other sources recommend installing CO alarms on each level of a dwelling outside of sleeping areas,[17] not near gas appliances. Consumers very well might question the validity of recommendations that seemingly contradict other recommendations or requirements, or simply might become confused about the appropriate course of action in light of these contradictions, leading them to reject the message altogether. Performance requirements that limit consumer's exposure to CO emissions from gas furnaces and boilers are feasible and avoid these problems.

CPSC staff supports information and education (I&E) for consumers, service and maintenance personnel. However, the lengthy history of CO exposure incidents demonstrates that these efforts by themselves have not and will not resolve the problem. Staff concludes that in order to adequately reduce the risk, the Commission should establish performance standards addressing the known hazard conditions. Staff also notes that the current ANSI Z21 standards for gas furnaces (ANSI Z21.47), boilers (ANSI Z21.13), and wall and floor furnaces (ANSI Z21.86) do not protect consumers from these hazard conditions.

Rely on Voluntary Standards

Comment: Commenters (A.O. Smith, Rheem, and NPGA) state the CPSC should work with the voluntary standards process to address the hazard.

Response: In the ANPR briefing package published July 31, 2019, staff's memorandum in TAB D, *Existing Voluntary Standards and Voluntary Standards Development with Carbon Monoxide Hazards Associated with Gas Furnaces and Boilers*, summarizes CPSC staff's efforts from 2000 to 2019 to work with the ANSI Z21/T83 Technical Committee to address carbon monoxide poisoning incidents that were continuing to occur despite past revisions to the gas appliance standards. CPSC staff shared incident reports with the Committee members, conducted preliminary research and shared the results, and submitted two proposals to the Technical Working Group (in 2000[18] and 2015[19,20,21]) requesting that the relevant voluntary standards add requirements to address the production of hazardous levels of CO and the risk of that CO entering the living space of the dwelling. In 2019, the Technical Committee disbanded the working group working on this effort. Despite staff's efforts over two decades, as well as the

[17] Carbon Monoxide Fact Sheet | CPSC.gov
[18] CO shutoff/response proposal letter Canadian Standards Association International, CPSC. Jordan, R., November 2000.
[19] CO shutoff/response proposal letter to CSA Group and the ANSI Z21 Boiler Technical Subcommittee. CPSC. Jordan, R., September 30, 2000.
[20] CO shutoff/response proposal letter to CSA Group and the ANSI Z21 Furnace Technical Subcommittee. CPSC. Jordan, R., September 30, 2015.
[21] CO shutoff/response proposal letter to CSA Group and the ANSI Z21 Vented Heaters Technical Subcommittee. CPSC. Jordan, R., September 30, 2015.

developments of voluntary standard requirements in Japan and Europe, the voluntary standards community in the United States has not adopted any new performance requirements to address CO risk at the source of production in gas appliances.

Comment: Two commenters (Carrier and AHRI) stated that current appliance designs certified to applicable ANSI/CSA Z21 safety standards already incorporate several safety features that reduce the risk of carbon monoxide production including: (a) blocked vent/intake switches, (b) draft hood spill switches, and (c) flame roll-out switches. Another commenter (USB JB) stated that the ANSI standard for direct and non-direct vent boilers includes a test method to limit CO levels when the flue outlet is blocked or partially blocked which addresses the impact of snow blocking the vent. Another commenter (Stanonik) stated that two-pipe or direct vent systems have fewer CO risks and some atmospherically vented appliances are not susceptible to depressurizing and back drafting that lead to CO exposure in the living space.

Response: CPSC staff notes the safety features (i.e., blocked vent/intake pressure switches, draft hood spill switches, and flame rollout switches) are all requirements that were added to and became effective in the standards between 1987 and 1993. It has been and continues to be CPSC staff's position that despite these changes to the standards, these safety devices do not protect against other conditions identified by staff to have caused or contributed to CO incidents involving gas furnaces and boilers. These incidents include death and injuries, and over the years the incident reports have been summarized and shared with the ANSI Z21/83 TC and technical subcommittees for gas furnaces and boilers. These injuries and deaths have continued to occur despite the existence of these voluntary standards provisions and the fact that there is substantial compliance to the standards.

In reference to the blocked vent provisions in the ANSI Z21 standards (i.e., ANSI Z21.13, ANSI Z21.47, and ANSI Z21.86) for direct vent and non-direct vent gas furnaces and boilers, CPSC staff is aware of an incident in 2005 in which the blocked vent shutoff system (BVSS) was activated by snow blockage, but then conditions including snow melt and gaps in the vent system allowed CO into the living space which resulted in the fatality of a pregnant victim and her daughter. The circumstances of this incident demonstrated how the current provisions in the ANSI Z21 standards are not able to protect against some vent blockage scenarios and how the proposed performance requirements to limit CO production to safe levels at the source would be more effective than the "leakage path" approach currently employed within the ANSI Z21 standards for gas furnaces and boilers.

In reference to two-pipe or direct vent systems and atmospherically vented appliances, incidents involving all these systems have been and continue to be involved in CO poisoning incidents that result in deaths and injuries.

Furthermore, the commenter's last statement that "These features combined with the proper installation, service and maintenance of the appliances eliminates the risk of carbon monoxide generation within the appliances" is not accurate. This statement is not supported by the technical capabilities in any of the current standards because none of the devices cited protect against a disconnected vent. In addition, this statement is contradicted by the CO incident data over the past 40 years that demonstrate CO incidents continue to occur in gas furnaces and boilers that meet the ANSI Z21 gas appliance standards.

Adverse/Unintended consequences of shut-off triggered by CO sensor

Comment: Six commenters (Carrier, Crown, USB EJ, USG JB, AHRI, and M. Strauch) stated that improper shut-down of a gas appliance by a CO sensor will cause a no-heat hazard.

Response: The commenter is alleging a cold weather hazard posed by a gas appliance that was shut down by an integral CO sensor; however, the commenter did not provide any evidence to substantiate this allegation. CPSC staff is not aware of any epidemiological data that quantifies or otherwise characterizes this alleged hazard. Furthermore, a CO shutoff device, when activated, would create the same effect (i.e., shutoff of the appliance), and create no more of a risk (i.e., no heat due to appliance shut-down) than other currently used safety "shutoff" devices integral to gas furnaces and boilers (e.g., BVSS, flame rollout switches, etc.). In consideration of these comments and other staff analyses, however, the NPR would require a Fail Safe provision such that during the life of the appliance, if a CO sensor, combustion sensor, combustion control system, or other device designed to meet these requirements, fails to operate properly or at all, then the appliance shall shutdown and restart after 15 minutes and repeat this cycle until the failed component is replaced. Consumers and service technicians shall be notified of device failure by either a flashing light, or other appropriate code on the appliance control board, that corresponds to the device failure.

Comment: One commenter (Crown) stated that a shut-down central heating appliance may encourage the use of less safe heating alternatives.

Response: CPSC does not have the evidence required to substantiate this claim, nor did the commenter provide such evidence. Rather than speculate about unsubstantiated risks from appliance shut-down, staff finds that shutting off or correcting the performance of an appliance due to production of excessive CO would prevent CO exposure, death, and injury associated with gas furnaces and boilers. There are other shut-off devices on gas furnaces and boilers (e.g., BVSS, flame rollout switches, and over temperature limit switches) that have been required by the ANSI Z21 standards for 25 to 30 years. However, staff is not aware of any trends of consumers using less safe heating alternatives as the result of safety shut-down of these products. Nevertheless, in consideration of these comments and other staff analyses, the NPR proposes the Fail Safe provision described above, which provides warning to consumers without complete loss of functionality.

Carbon monoxide sensor – Sensitivity and Durability

Comment: Two commenters (AGA and USB JB) focused on the carbon monoxide sensors, stating that measuring “air-free” carbon monoxide (CO) concentrations benchmarked to the ANSI-recognized “safe” concentration of 400 ppm would be complex because a carbon monoxide monitor measures “raw” CO concentrations which includes the “air-free” carbon monoxide concentration multiplied by the ratio of air that was not used in combustion. Consequently, the air-free CO will always be lower than the measured CO.

Response: CPSC staff agrees that an air-free measurement calculation would be more complex since it would require the measurement of carbon dioxide or oxygen as well, and the proposed rule does not require this calculation.

Comment: One commenter (USB JB) stated the performance of existing CO sensors has not been established at the 400 ppm level and lower.

Response: Staff disagrees with this comment. Staff’s experience has been that sensor manufacturers specify the maximum and minimum concentration range that a sensor can detect, as well as whether the sensor provides a linear output voltage in response to the gas (i.e., CO) it’s designed to detect. For example, if a manufacturer specifies that their sensor has a linear response range of 0 to 10,000 ppm of CO, then the sensor can detect between 0 and 10,000 ppm CO, including 400 ppm CO or lower.

Comment: Commenters submitted comments on the development of CO sensors and asserted that research does not show that CO sensors are durable enough to last for 15 to 20 years (M. Strauch) or that tolerances on sensors have not been addressed (USB JB).

Response: CPSC staff disagrees with the premise that CO sensors must have a 15 to 20 year lifespan. CPSC staff’s understanding of gas appliances indicate that there are many parts which may fail during the lifetime of a furnace, typically resulting in the need for a service call to fix or replace the part. CO sensors would be expected to be treated in this same manner. The costs of such service are included in the preliminary regulatory analysis in Tab D. Regarding the comment about tolerance, the commenter was describing an external condition (i.e., 40 mph wind) as an example of a condition that CPSC staff’s proposed performance requirements do not address. CPSC staff also disagrees with the use of the phrase “device tolerance,” in this context, by the commenter to characterize attributes of a CO sensor, or any other device, component, or part within the context of the comment. Device tolerance refers to the total allowable error or deviation from a specified measurement level and is typically expressed as “+/-.” CPSC staff’s proposed performance requirements were designed to address CO exposure risks at the source of production, internally within the appliance, and to provide protection to consumers, regardless of whether an internal or external condition is the cause of excessive CO production. Also, in consideration of these comments and other staff analyses the NPR proposes the Fail

Safe provision described above, which provides warning to consumers without complete loss of functionality.

Requirements in International Standards

Comment: Two commenters (Crown and USB JB) stated that there is no widespread use of CO sensors in gas appliances in Europe and Japan. One commenter (AHRI) asserted that, “contrary to CPSC staff assertions, the EN standards (EN 15502-1, EN 15502-2-1 and EN 15502-2-2) do not require manufacturers to incorporate a CO-sensor shut-off device within the appliance.” In addition, that commenter states none of the U.S. or international standards, including JIS S 2019, specifically require a carbon monoxide sensor within the appliance.

Response: Concerning the Japanese standard, JIS S 2019, and the European standards, EN 15502-2-1 and EN 15502-2-2, each standard includes performance requirements for in-situ CO and combustion sensors if the appliance manufacturer opts to use that particular strategy to meet the standard. There are some European and Japanese gas boilers on the market that are certified to those standards and are equipped with CO sensor shutoff capability. The importance of these standards provisions and the existence of gas appliances with CO shutoff sensors is that they provide direct evidence addressing the concern raised by the ANSZ21/83 Technical Committee about the availability of sensors for in-situ gas appliance usage. The existence and use of CO/combustion sensors in gas appliances in Europe and Japan demonstrate the current availability of sensors for this application. The existence of performance standards with provisions for these devices demonstrate that other industrialized regions and countries have dealt with and overcome any technical hurdles necessary to develop a consensus standard. There are gas heating appliances sold in Europe and Japan that incorporate these devices for the purpose of CO safety and energy efficiency.

Comment: Five commenters (A.O. Smith, Carrier, Crown, USB EJ, and AHRI) stated that the Japanese standard referenced by CPSC staff at the voluntary standards meetings has requirements that do not correlate to 400 ppm CO concentration levels in the combustion exhaust. In particular, one commenter (AHRI) states the JIS-S-2109 standard referenced by CPSC staff is based on a maximum room concentration of 300 ppm, which does not correlate to the expectation that the equipment does not produce CO levels greater than 400 ppm.

Response: The primary reason that CPSC staff referenced international standards, such as JIS-S-2109, as well as EN 15502-2-1, and EN 15502-2-2, was to demonstrate the existence, in other industrialized regions of the world, of standards that address the performance of sensing devices within the harsh environments of a gas appliance combustion chambers, flue passageways, or vents. The existence of international standards for, and gas appliances with, integral CO sensors shows that sensors for this type of application are available and feasible. The value of the international standards to this process is that they demonstrate: 1) that CO/combustion devices can be operated within the harsh environment of a gas furnace or boiler; and 2) how the performance of CO/combustion sensors can be tested.

In response to whether the JIS-S-2109 standard requirement for maximum room CO concentration of 300 ppm correlates to a maximum appliance production of 400 ppm, CPSC staff does not assert an equivalence between the Japanese standard and the CPSC proposal, but rather that the Japanese standard, as well as the European standard, each demonstrate the existence of gas appliance standards for in-flue CO detection and shut-down or response to elevated CO.

Comment: One commenter (AHRI) stated that the most commonly used CO sensor by Nemoto Sensor Engineering, Ltd. is designed to work when carbon monoxide levels exceed 1000 ppm.

Response: The published Nemoto literature indicates that the CO sensors in question have a linear response range of zero to 10,000 ppm CO,[22] thus the sensors in question are represented to have the capability to provide an output voltage response to all of the CO levels within that range, including 400 ppm CO and lower.

Feasibility of performance requirements with existing CO/Combustion technology

Comment: Many commenters focused on how long it would take to develop voluntary standards requirements, revise voluntary standards, and saturate the market with new products. Two commenters (Carrier and AHRI) stated that “a minimum of 20 years is needed to replace existing residential gas appliances with a carbon monoxide sensor-equipped appliances” based on the anticipated lifespan of an appliance. Another commenter (USB JB) stated that it would take a minimum of 2 to 3 years to develop and validate performance requirements and then revise the standards through the consensus process.

Response: Staff agrees that it will take time for existing gas furnaces and boilers to be replaced by this proposed rule requiring additional safety features for future furnaces, since it does not require replacement of existing installed furnaces. This is reflected in staff’s economic analysis. Approximately 2 million gas furnaces and 800,000 gas boilers without risk-reducing/eliminating CO sensors are sold each year, thus prolonging the time it would take to replace old stock. As a result, each year of further delay in instituting recommended safety features will result in millions of units without these features being installed and remaining in homes for multiple decades, risking additional preventable deaths and injuries.

Comment: Two commenters (Carrier and AHRI) stated CO sensors will not detect leakage from the venting system.

Response: CPSC staff agrees with this statement that a CO sensor will not detect

[22] NAP-78SU --Nemoto Sensor Engineering for Gas Sensors

leakage from a venting system. However, CO detection at the source of production would provide protection to consumers regardless of the location of downstream leakage. Currently ANSI Z21.13 voluntary standard does not have requirements to address disconnected vents[23] . A CO sensor onboard an appliance would not be designed to detect CO leaking from a vent; rather, it would be designed to detect elevated CO at the source of production, so that it would protect consumers from high levels of CO exposure, regardless of where the leak occurred. Staff focused on the source rather than at leakage points throughout the exhaust path given the extent and variability of the exhaust path in homes. CPSC staff disagrees with AHRI's assertion that a CO sensor-equipped appliance would be ineffective against a compromised vent.

Comment: One commenter (A.O. Smith) stated CO sensors in a gas appliance cannot be easily replaced in the field.

Response: The commenter did not provide technical evidence to support this claim. CPSC staff is aware of and has possession of gas appliances that utilize CO sensors, air/fuel ratio sensors, and other combustion control devices within the combustion chamber of flue passageways to provide CO safety and/or energy efficiency. These devices have no greater complexity or difficulty in gaining access for maintenance or replacement than other safety devices, such as pressure switches, flame sensors, and flame rollout switches, currently required by the ANSI standards for gas appliances. Sensors are comprised of a sensing element covered by shielding and a mounting flange. Typically, the shielded, sensing element is inserted through an access hole through the bulkhead of a combustion chamber, plenum, or flue passageway. The sensor is typically mounted to the bulkhead with two screws with a heat-resistant gasket between the mounting flange and the bulkhead. CPSC staff concludes that CO sensors in a gas appliance could be replaced in consumer homes in a manner similar to other furnace or boiler components that are currently serviced and replaced in consumer homes.

Comment: One commenter (USB JB) queried if the Commission has data on the effectiveness of oxygen depletion sensor (ODS) technology to prevent deaths and injuries from CO exposure.

Response: Unvented space heaters are often equipped with an ODS device to prevent CO exposure. Staff is not aware of incidents with an ODS-equipped unvented gas space heater, and commenters do not identify such incidents.

Comment: One commenter (Rheem) stated that more work is needed to fully evaluate the CO shutoff proposal and other alternatives.

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[23] The standards for gas boilers and furnaces had provisions added to protect against combustion product leakage caused by disconnected vents (circa 1987 and 1989 for gas boilers and furnaces, respectively). However, the disconnected vent coverage was removed from ANSI Z21.13 in 1991 due to an interaction with vent dampers that reportedly caused false positives. In approximately 1993, the disconnected vent coverage was removed from the furnace standard for the same concern.

Response: CPSC staff has worked through the voluntary standards process since 2002 in attempts to accomplish what the commenter recommends, including two different working groups that were formed to evaluate CO shutoff. Unfortunately, these were disbanded in 2005 and again in 2019. Furthermore, the ANPR provided commenters with the opportunity to evaluate and comment on CO shutoff proposals and other alternatives, and the public again is invited to submit comments in response to the proposed rule. There were an estimated 24 CO deaths associated with gas furnaces and boilers in 2019.

Comment: One commenter (Rheem) stated that some of the referenced/observed failure modes cannot be addressed through appliance design alone.

Response: CPSC staff does not agree with the assertion that the issues cannot be addressed through appliance design alone. The levels of CO will be greatest at the source. By ensuring that harmful levels of CO are not produced, the proposed regulation removes the need to provide protection throughout the entire exhaust vent system.

Comment: One commenter (M. Strauch) stated that there are no separate Japanese performance standards for incomplete combustion preventive devices.

Response: Performance requirements for incomplete combustion preventive devices (ICPD) are included in JIS-S-2109 under Section 7.8, Duty-cycle operation test, Subsection 7.8.2, Incomplete combustion preventive device. CPSC staff also notes the following European performance standards for gas sensors and gas/air ratio controls:

1. EN 12067-2 (Gas/air ratio controls for gas burners and gas burning appliances — Part 2: Electronic types);
2. EN 13611 (Safety and control devices for burners and appliances burning gaseous and/or liquid fuels — General requirements); and
3. EN 16340 (Safety and control devices for burners and appliances burning gaseous or liquid fuels— Combustion product sensing devices).

CPSC staff cited these European standards, as possible benchmarks to use to develop a U.S. CO shutoff/response standard, to the Z21/83 Technical Committee and the furnace and boiler Technical Subcommittees in 2015 and the ANSI Z21 CO sensor working group in 2016.

CPSC staff considered aspects of the European and Japanese standards that could be applied to requirements for U.S. gas appliances. These standards demonstrated that the technologies required to meet the proposed requirements are feasible.

Comment: One commenter (Stanonik) stated that CPSC held a forum on CO and combustion sensors in June 2014 and published a report of findings, “Findings from CPSC’s 2014 Carbon Monoxide/Combustion Sensor Forum and Request for Information.” The commenter states that a specific sensor technology that appeared to address durability and longevity concerns was very expensive and reflected the "significant process" involved in going from "proof of concept" to the development of durable and reliable products.

Response: CPSC staff agrees that the cost the commenter referenced would be high. However, the cost of the sensing technology in question was an evaluation unit not a full scale production unit and came with electronic controls necessary to operate and evaluate the sensor, resulting in elevated costs for that particular sensing technology. Staff would not expect a full scale production to bare the same costs. In the past, after receiving permission from other sensor manufacturers, CPSC staff has shared estimated sensor costs with the Z21/83 Technical Committee as the Z21/83 sensor working group. Based on volume purchases, costs ranged from approximately $5 to $15 per unit. The preliminary regulatory analysis in Tab D provides further analysis of potential costs and benefits.

Stockpiling (Tab D)

The proposed rule includes an anti-stockpiling provision[24] that would prohibit firms from manufacturing or importing gas furnaces or boilers that are noncompliant with the draft proposed rule between the promulgation of the final rule and the effective date, at a rate greater than 106 percent of the base period in the first 12 months after promulgation, and 112.50 percent of the base period for the duration of 12 months after promulgation until the effective date. The base period is defined in the draft proposed rule as the calendar month with the median manufacturing volume, among months with manufacturing volume, during the last 13 months prior to rule publication. For example, if CPSC promulgates the rule in July 2024, then base period would be the median monthly production from June 2023 and June 2024, for the months that manufacturer had production. If the median monthly production was 1,000 units, then the manufacturer would be able to manufacture 1,060 units a month from July 2024 until June 2025, and 1,125 units from July 2025 until December 2025 (18 months after promulgation).

Staff recommends a rate of 106 percent for the first 12 months and a rate 112.50 percent in the final 6 months between promulgation and the staff-recommended effective date based on historical growth of the industry. Historical data on shipments going back to 2013 show year-over-year growth between 4.5 percent and 7.1 percent.[25] The midpoint of this range is 5.8 percent, which staff rounds up to 6 percent growth and applies it to the anti-stockpiling provision. Staff recommends a higher rate of 112.50 percent for the next six months to account for the secular growth of the industry in the

[24] According to Section 9 paragraph (g)(2) of the CPSA, CPSC is required to consider whether to prohibit stockpiling from the date of promulgation of the rule to the effective date of the rule. Stockpiling is defined as manufacturing or importing a non-complying product which is significantly greater than the rate at which such products were produced or imported during a base period. The base period is defined as the 13 months preceding promulgation of the rule.

[25] Monthly gas furnace shipments data come from American Heating/Cooling Research Institute) (AHRI). Note that these data include both residential and commercial gas furnaces but does not include gas boilers. Staff assumes that any annual and seasonal variation in demand for residential and commercial furnaces are similar and that these annual and seasonal patterns can also be applied to gas boilers.

second year. Without higher rate in the second year, the stockpiling amendment would constrain manufacturers to zero percent growth in the second year.

The historical shipment data is of the entire industry. Individual manufacturers may experience growth rates outside the historical range. Shipment data for gas furnaces and boilers show a steady, yet seasonal, market. Shipments of gas furnaces and boilers begin to rise in March and continuously increase until December, after which they fall off sharply. Staff recommends that the Commission seek public comment on manufacturing, the seasonality of sales, and supply chain of gas furnaces and boilers to further understand these topics.

Effective Date

Our assessment is guided by section 9 of the CPSA. Section 9(f)(3) provides "that the rule (including its effective date)" must be "reasonably necessary to eliminate or reduce an unreasonable risk injury associated with such product." Consistent with the judicial review provision of CPSA section 11(c), the determination of reasonable necessity should be supported by substantial evidence. Section 9(g)(1) addresses effective dates in greater detail and requires that the effective date shall not exceed 180 days from the date the rule is promulgated, "unless the Commission finds, for good cause shown, that a later effective date is in the public interest and publishes its reasons for such finding." Similarly, the effective date must not be less than 30 days after promulgation "unless the Commission for good cause shown determines that an earlier effective date is in the public interest."

The CPSC Commissioners determine what effective date is in the public interest, utilizing information and recommendations provided by staff along with other record evidence and policy considerations. These factors will be documented in the Commission's final decision. Given the explicit statutory preference for an effective date in the 30-day to 180-day range, the Economics Staff has examined whether there is specific, detailed, and credible evidence that the public interest supports setting an earlier or later effective date. This economic analysis uses the best available evidence (including data collected by CPSC, inputs from received from the public during the notice and comment process, and the professional judgment of CPSC's technical staff) to characterize the impacts to the American economy, including the statutorily required analysis of impacts to small entities. The analysis includes review of various effective date options. Given the statutory direction in the CPSA, staff's economic analysis will recommend an effective date within the 30-day to 180-day range unless (i) there is clear evidence that a shorter or longer period is required to prevent unreasonable burdens, or (ii) a shorter or longer period would ensure a reasonable relationship between expected benefits and costs. This information is intended to assist the Commission's ultimate determination of the appropriate effective date. *See, e.g.*, CPSA § 9(f)(3)(E), (F).

Based on the reasons described below, staff preliminarily believes there is good cause for an effective date later than 180 days, and recommends an 18 month effective date from the date of publication of the final rule in the *Federal Register* to allow manufacturers adequate time to meet the requirements of the rule.

The applicable voluntary standards for gas furnaces, boilers, wall and floor furnaces (i.e., ANSI Z21.13, ANSI Z21.47, and ANSI Z21.86, as well as all other ANSI Z21 standards) typically allow for an effective date of 18 months after new standards provisions are approved. The effective date of the proposed rule needs to be based on such factors as interdependencies associated with the availability and ordering of CO sensing or combustion control devices; gas control and control board manufacturers and performance standards; retooling of the manufacturing line and retraining of manufacturing staff; and qualification testing of new, integrated devices, as well as testing and certification of the new models to voluntary standards required in many jurisdictions to meet building codes. If the proposed mandatory requirements are approved by the Commission as a CPSC mandatory standard, staff tentatively recommends an effective date of 18 months after the date of publication of the final rule in the *Federal Register*. Subject to public comment, staff believes an 18-month effective date will allow gas appliance manufacturers adequate time to do the following necessary actions in preparation for compliance with the new rule:

1. Identify and establish contracts with OEM suppliers of CO sensing or combustion control devices.
2. Redesign the impacted appliances to integrate CO sensing or combustion control devices.
3. Work with gas control and control board manufacturers on redesigning gas controls and control boards to properly incorporate power and output signals from CO sensing or combustion control devices.
4. Conduct qualification testing and analysis of CO sensing or combustion control devices integrated into impacted appliances.
5. Retool manufacturing lines to allow for CO sensing or combustion control devices to be assembled into impacted appliances.
6. Incorporate the CO sensing or combustion control devices into existing quality control procedures.
7. Retrain assembly line staff on the redesigned gas appliances and retooled manufacturing lines.
8. Incorporate the CO sensing or combustion control devices into the User, Maintenance, and Installation Instruction manuals of impacted appliances.
9. Develop new guidance for distributors and retail outlets for the impacted appliances.

A shorter time for manufacturers to comply with the draft proposed rule could result in potentially significant costs such as:

1. <u>Shortage Cost to the Supply Chain.</u>

   Manufacturers that are unable to produce a compliant product or are not yet able to produce enough products to meet their typical demand would likely result in a shortage of product. The inability to produce enough compliant gas furnaces and boilers would generate revenue loss in all levels of the supply chain – suppliers, producers, intermediaries, transporters, wholesalers, and retailers. There could also be additional cost such as penalties from broken or unfulfilled contracts due to the shortage. These costs could be significant. Some or most of this revenue may be an economic transfer because some consumers would purchase substitute products, but not all, and that fraction could still be a significant cost. Additionally, the individual firms and brands affected would still feel the full impact of the revenue loss which could trigger costly business decisions by management (e.g., layoffs).

2. Shortage Cost to the Consumers.

A shortage of product would deny consumers availability their preferred product. The cost to consumers is a loss of utility and potentially a financial loss from buying a more expensive substitute. Consumers who prefer gas furnaces or boilers but cannot buy them in the short-term due to a shortage would either purchase a substitute product, wait until gas furnaces and boilers become available again, or forego the purchase altogether. Staff assesses that most consumers would likely purchase a substitute because of the perceived necessity of the product. Consumers could purchase an electric furnace which would also provide safety benefits of having no risk of a CO leak but would be more expensive than a gas furnace or boiler.[26] Additionally, there would be a loss of utility as these consumers prefer gas furnaces and boilers over electric furnaces, and the intrinsic value they place on gas furnaces or boilers is lost. Those consumers who wait until a gas furnace or boiler becomes available again would have their utility for the product reduced because of the delay. Consumers who drop out of the market have an incremental loss of utility because they would use the money which would have purchased the gas furnace or boiler for another product or activity that is their second choice.

3. Loss of benefits.

While not a cost compared to the status quo, a shortage would reduce the expected benefits during the 30-year study from the draft proposed rule. Each gas furnace or boiler that is not available because manufacturers were unable to be produce compliant products by the effective date means there are fewer potential benefits from the draft proposed rule, especially if consumers choose to drop out of the market and continue to operate noncompliant products that have a risk of CO leaks. While these losses are likely small compared to the overall benefits of the rule, it is potentially another cost from shortages and supply chain disruptions added to the costs previously described.

4. Unforeseen quality control issues.

[26] As of this document, electric heating was more expensive than natural gas and heating oil, but less expensive than propane, according to EIA's Winter Fuels Outlook, October 2022. https://www.eia.gov/outlooks/steo/report/winterfuels.php

A condensed production and testing timeline could increase the risk of latent operational issues with the compliant gas furnaces and boilers such as nuisance shut-downs. These issues would potentially cost consumers by inconveniencing them with operational issues, and potentially cost manufacturers if a recall is needed, including harm in brand reputation.

The proposed effective date would help ensure that manufacturers have adequate time to properly transition to the new rule and design and test new products before they are placed into commerce. Staff seeks comments on the effective date with specific information to support any argument that an effective date longer than the 180-day period specified in CPSA section 9(g)(1) is or is not justified by good cause, including for the reasons preliminarily identified above.

Request for Comments to NPR

Staff recommends that the Commission request comments on all aspects of the proposed rule, but especially on the proposed performance requirements and the following items:

1. Effort required to obtain sensors and information on sensors including the lifespan
2. Effort required to redesign control systems
3. Effort required to test prototypes
4. Effort required to bring re-engineered appliances to production
5. Costs associated if effective date were to be 6 months after publication of the rule
6. Costs associated if effective date were to be 30 days after publication of the rule
7. Costs associated with shipping and inventory of gas furnaces and boilers
8. Costs associated with manufacturing gas furnaces and boilers, along with a description of the process including the timing and whether any firms have seasonal production
9. Effort required to incorporate sensors and/or combustion control systems in production
10. Data or information on R&D and modifications to the production process the draft proposed rule would impose on manufacturers
11. Data or information on price elasticity for gas furnaces or boilers
12. Additional manufacturers and importers of gas furnaces and boilers that may meet the SBA definition of a small business
13. Information on importers of gas furnaces and gas boilers, specifically
    a. how many are imported,
    b. how many different models each importer sells, and
    c. what technologies those models are currently using (atmospheric venting, condensing, non-condensing, premix power burners, etc.)
14. Information regarding to what degree supplying firms pass on increases in production and regulatory costs to importers
15. To what extent is the ability to pass on these costs limited by the ease with which importers can switch suppliers or substitute to alternative products

16. The effectiveness of the draft proposed rule to address CO poisoning fatalities and injuries, given the maximum flue gas levels and the diffusion of those levels throughout a home
17. The effectiveness and feasibility of multiple limits for flue-gas CO concentrations to address deaths and injuries.
18. CPSC staff's proposed performance requirements: A gas furnace, boiler, wall furnace or floor furnace shall be equipped with a means to continuously monitor CO emission (directly or indirectly) shall either: 1) cause shut-down of the appliance, or 2) cause modulation of appliance combustion, each in response to the following conditions within the appliance:

    a) Average CO concentration is 500 ppm or higher for 15-minutes;
    b) Average CO concentration between 400 ppm and 499 ppm for 30-minutes;
    c) Average CO concentration between 300 ppm and 399 ppm for 40-minutes;
    d) Average CO concentration between 200 ppm and 299 ppm for 50-minutes;
    e) Average CO concentration between 150 and 199 ppm for 60-minutes.

Alternatively, a gas furnace, boiler, wall furnace, or floor furnace equipped with a means to directly monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of appliance combustion, in response to the following conditions within the appliance:

f) Average CO concentration of 150 ppm or higher for 15-minutes.

Shutdown or modulation of the appliance shall begin immediately after any of the conditions described in a) through e) are reached or the alternative condition described in f) is reached. After modulation begins, the CO concentration within the appliance shall be reduced to below 150 ppm within 15 minutes.

19. CPSC staff's proposed performance requirements include the following Fail Safe provisions:

    Fail Safe
    During the life of the appliance, if a CO sensor, combustion sensor, combustion control system, or other device designed to meet these requirements, fails to operate properly or at all, then the appliance shall shutdown and restart after 15 minutes and repeat this cycle until the failed component is replaced. Consumers and service technicians shall be notified of device failure by either a flashing light, or other appropriate code on the appliance control board, that corresponds to the device failure.

    CPSC staff requests comments on the efficacy of these fail safe provisions and whether there is a more appropriate approach to address fail safe.

Staff Conclusions and Recommendations

Staff estimates 21 deaths per year, on average from 2016-2018, and a total of 539 deaths occurred from 2000 to 2019 as a result of CO poisoning associated with gas furnaces and boilers. The hazard pattern for carbon monoxide (CO) poisoning associated with gas appliances involves the combination of:

- hazardous levels of CO from incomplete combustion of the source fuel/gas, and
- exhaust leakage of that CO into the living space through a leak in the exhaust vent system.

Staff's analysis of these incidents determined that existing U.S. voluntary standards do not adequately address this hazard scenario. Staff's research demonstrates that it is technologically feasible to develop a performance requirement to monitor CO production at the gas appliance level and address the condition before dangerous levels of CO can be introduced in a defective or leaking vent system and thus into the living space. This is further confirmed by European and Japanese industry compliance to voluntary standards addressing the CO hazard.

To reduce deaths and injuries associated with CO poisoning from gas appliances, staff recommends performance requirements that require a gas furnace, boiler, wall furnace, or floor furnace, depending on whether it adopts direct or indirect monitoring of CO emission, to have the ability to perform either:

<u>Direct monitoring of CO emissions</u>
A gas furnace, boiler, wall furnace, or floor furnace equipped with a means to directly monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of appliance combustion, each in response to the following conditions within the appliance:

a) Average CO concentration is 500 ppm or higher for 15-minutes;
b) Average CO concentration between 400 ppm and 499 ppm for 30-minutes;
c) Average CO concentration between 300 ppm and 399 ppm for 40-minutes;
d) Average CO concentration between 200 ppm and 299 ppm for 50-minutes;
e) Average CO concentration between 150 and 199 ppm for 60-minutes.

Alternatively, a gas furnace, boiler, wall furnace, or floor furnace equipped with a means to directly monitor CO emissions, shall either: 1) cause shut-down of the appliances, or 2) cause modulation of appliance combustion, in response to the following conditions within the appliance:

f) Average CO concentration of 150 ppm or higher for 15-minutes.

Shutdown or modulation of the appliance shall begin immediately after any of the conditions described in a) through e) are reached or the alternative condition described in f) is reached. After modulation begins, the CO concentration within the appliance shall be reduced to below 150 ppm within 15 minutes.

<u>Indirect monitoring of CO emissions</u>
A gas furnace, boiler, wall furnace, or floor furnace equipped with an indirect means to monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of combustion of the appliance, each in response to the combustion conditions that correlate to the following conditions within the appliance:

a) Average CO concentration is 500 ppm or higher for 15-minutes;
b) Average CO concentration between 400 ppm and 499 ppm for 30-minutes;
c) Average CO concentration between 300 ppm and 399 ppm for 40-minutes;
d) Average CO concentration between 200 ppm and 299 ppm for 50-minutes;
e) Average CO concentration between 150 and 199 ppm for 60-minutes.

Alternatively, a gas furnace, boiler, wall furnace, or floor furnace equipped with a means to directly monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of combustion within the appliance, in response to the following condition within the appliance:

f) Average CO concentration of 150 ppm or higher for 15-minutes.

Shutdown or modulation of the appliance shall begin immediately after any of the conditions described in a) through e) are reached or the alternative condition described in f) is reached. After modulation begins, the CO concentration within the appliance shall be reduced to below 150 ppm within 15 minutes.

<u>Fail Safe</u>
During the life of the appliance, if a CO sensor, combustion sensor, combustion control system, or other device designed to meet these requirements, fails to operate properly or at all, then the appliance shall shutdown and restart after 15 minutes and repeat this cycle until the failed component is replaced. Consumers and service technicians shall be notified of device failure by either a flashing light, or other appropriate code on the appliance control board, that corresponds to the device failure.

Staff's accelerated life test contractor work (Attachment 3, TAB C) demonstrated that CO/combustion sensors are currently commercially available for use in gas appliances; the CO/combustion sensors that were tested have expected lifespans ranging from 6.4 to 10 years operating under conditions that replicate the main stress conditions expected within a gas appliance; appliances with design platforms based on premix power burners are better suited to incorporate combustion control for CO risk mitigation, while gas appliances with induced draft or atmospheric vent design platforms would be better suited to use CO/combustion sensors for appliance shut-down to mitigate the risk.

Staff recommends that the Commission propose an effective date of 18 months after publication of the final rule for manufacturers to comply with the rule.

TAB A: Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products 2019 Annual Estimates

https://ecpsc.cpsc.gov/apps/6b-Temp/Section%206b%20Tracking/Non-Fire%20Carbon%20Monoxide%20Deaths%20Associated%20with%20the%20Use%20of%20Consumer%20Products%202019%20Annual%20Estimates.docx

United States
Consumer Product Safety Commission

Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products 2019 Annual Estimates

March 2023

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*This report was prepared by the CPSC staff.
It has not been reviewed or approved by,
and may not necessarily reflect the views of,
the Commission.*

Table of Contents

Executive Summary

This report provides information about the estimated number of unintentional non-fire deaths attributed to carbon monoxide (CO) poisoning that were associated with the use of consumer products in 2019, along with companion statistics since 2009. Because the U.S. Consumer Product Safety Commission (CPSC) has not received reports of deaths from every state for 2018 and 2019, the estimates for those years may change in subsequent reports.

Some of the key findings[1] in this report are:

For 2019:

- CPSC has records from 168 incidents resulting in an estimated 250 unintentional non-fire CO poisoning deaths associated with the use of consumer products under the CPSC's jurisdiction.
- Fourteen percent of the 168 incidents involved multiple deaths, including two incidents where four people died, and another two incidents where three people died.
- Engine-Driven Tools (EDTs) were associated with the largest percentage of non-fire CO poisoning deaths, more than any other category. This category includes generators, the single product under CPSC's jurisdiction that is associated with the most CO deaths. Just under half (118 or 47%) of the estimated 250 deaths associated with consumer products involved an EDT. One hundred of the 118 estimated EDT-associated deaths involved generators,
- Heating Systems were associated with the second largest percentage of non-fire CO poisoning deaths. An estimated 69 deaths (28%) were associated with some type of heating appliance. Seventy-five percent of the estimated 250 CO deaths in 2019 resulted from CO exposure in a home location. Within incidents coded as home locations, a few deaths resulted from CO exposure in an external structure at a residence (*e.g.,* detached garage), a non-fixed location domicile used as a home (*e.g.*, camper trailers), a structure not designed for habitation but used as a home (*e.g.*, metal shed), as well as tents, or temporary shelters.
- In 2019, males constituted 77 percent of CO poisoning victims.

For 2017-2019:

- The estimated annual average from 2017 to 2019 was 216 deaths.
- Most CO deaths occurred in the colder months of the year, with more than half of the deaths occurring during the four cold months of November, December, January, and February.
- Adults 45 years and older comprised an annual average of more than 66 percent of all non-fire, consumer product-related CO deaths, which was disproportionately higher for this age group than their representation in the U.S. population. Conversely, children younger than 15 years of age accounted for a disproportionately lower annual average of less than 4 percent of the yearly CO poisoning deaths.

[1] Note that the estimates for individual categories may not sum to that of the broader category due to rounding effects.

- In the period 2017-2019, some statistical evidence demonstrates that the proportion of deaths by race/ethnicity differs from the proportions of race/ethnicity in the U.S. population. The proportion of Hispanic victims (irrespective of race) is significantly lower than the proportion of Hispanic Americans in the U.S. population; in contrast, the proportion of White victims was significantly greater than their percentage in the U.S. population.

For 2009-2019:

- Staff found evidence of a statistically significant upward trend in non-fire CO deaths for the 11-year period from 2009 to 2019. The estimated number of consumer product-related CO deaths in 2019 is greater than any other year in this report; in fact, the estimate in this category is greater than any estimate since the changeover from ICD-9 to ICD-10 in 1999. The estimate has increased now for the seventh straight year.
- Since 2009, portable generators alone have been associated with an estimated 765 non-fire CO poisoning deaths, accounting for 40 percent of all CO deaths related to consumer products under CPSC's jurisdiction.

Introduction

Carbon monoxide (CO) is a colorless, odorless, and poisonous gas that results from the incomplete combustion of fuels, such as natural or liquefied petroleum (LP) gas, gasoline, oil, wood, coal, and other fuels. The health effects related to CO depend upon its concentration in blood, which, in turn, depends upon its concentration in air, an individual's duration of exposure, and an individual's general health. Carbon monoxide combines with the body's hemoglobin (Hb) with an affinity about 250 times that of oxygen, forming carboxyhemoglobin (COHb) and interfering with oxygen uptake, delivery, and use by the cells. Generally, no perceptible health effects or symptoms in healthy individuals occur at COHb levels below 10 percent. Symptoms associated with blood levels at or above 10 percent COHb include headache, fatigue, nausea, and cognitive impairment. Loss of consciousness, coma, and death can occur at COHb levels greater than 20 percent; but for healthy adults, CO deaths typically require levels above 50 percent COHb.[2] Staff notes that during exposure to rapidly rising, high CO levels (as can result with exposure to exhaust from gasoline-powered, engine-driven tools), sudden extreme hypoxia can result in rapid incapacitation and loss of consciousness, which prevent exposed individuals from leaving the CO environment.

Some symptoms of CO poisoning may mimic common illnesses, such as influenza or colds. Thus, a possibility of initial misdiagnosis by physicians and victims exists (Long and Saltzman, 1995). Frequently, patients are unaware of exposures, and health care providers may not always consider CO poisoning as a cause of such nonspecific symptoms. COHb formation is reversible, as are some clinical symptoms of CO poisoning. However, some delayed neurological effects that develop after severe poisonings, especially those involving prolonged unconsciousness, may not be reversible. Prompt medical attention is important to reduce the risk of permanent damage.

Any fuel-burning appliance can be a potential source of fatal or hazardous CO levels. Fuels, such as natural and LP gas, kerosene, oil, coal, and wood, can produce large amounts of CO when insufficient oxygen is available for combustion. Consumer products that burn kerosene, oil, coal, or wood (such as wood stoves, oil boilers, and kerosene heaters) often produce an irritating smoke that can sometimes alert the victim to a potentially hazardous situation. EDTs powered by gasoline engines produce large amounts of CO, even in locations where sufficient oxygen is available for combustion. However, EDTs may not emit an irritating exhaust smoke. Other fuels, such as charcoal briquettes and pressed wood-chip logs produce relatively smokeless fires, even at times of inefficient combustion. In these cases, victims receive no obvious sensory warning that can alert victims to a potentially hazardous situation. Another hazard scenario is present when gas appliances are not vented properly or are malfunctioning. Natural and LP gas burn more efficiently and cleanly, compared to other forms of fuel. However, in circumstances of poor maintenance, inadequate ventilation, or faulty exhaust pathways, natural and LP gas appliances may emit potentially lethal amounts of CO without any irritating fumes. Again, many victims may be unaware of a potential problem.

National Estimates of Non-Fire CO Poisoning Deaths Associated with Consumer Products

The national estimates presented in this report are based on death certificate records obtained from all 50 states, the District of Columbia, New York City, and some U.S. territories, directly augmented by information collected in CPSC's In-Depth Investigations (IDIs), and to a lesser extent, news articles, and medical examiners' reports contained in the CPSC Injury or Potential Injury Incident (IPII) database. Death certificate data from some states can lag for months, or even years, and may not be available in time for use in this report.

The estimates of consumer product-related CO poisoning deaths presented in this report are based on reporting up to September 1, 2022. The National Center for Health Statistics (NCHS) has records of every death certificate filed in the United States and its territories. Before 2017, there was evidence that CPSC records contained a large portion of the records reported to NCHS. For the years 2008 through 2015, CPSC records contain approximately 82 percent of all the fatal CO poisoning deaths that occurred in the United States as reported to NCHS. However, in 2016, and to a slightly lesser extent in 2017, there appears to have been an anomaly with the method used by Texas in assigning ICD-10 codes used in this analysis, in particular, the Y17 code (see Appendix A for details on the methodology used to determine estimates). The estimates presented here are based on the number of deaths for which CPSC has records, scaled to the NCHS totals, to adjust for missing records. Appendix A of this report describes the detailed process used to generate the national estimates presented in this report.

It also should be noted that, due to extended reporting delays from a small proportion of U.S. states, a potentially significant portion of death certificates are missing from the 2018 and 2019 data. Although most states apparently completed reporting through 2019, there seems to be not even a single death certificate captured in CPSC databases from the state of Washington for the year 2018 or 2019. This seems to reflect delays considerably beyond most other states that have not reported additional 2018 or prior deaths since July 2021, when data were already consolidated for last year's version of this report. Consequently, estimates for years 2018 and earlier remain unchanged since last year. There also appear to be anomalies with reporting from Wisconsin and Texas, highly suggestive of incomplete capture of relevant death certificates from those states for 2018 and 2019. Some adjustments were made using historical patterns to account for anomalies in previous years 2016 and 2017 for the state of Texas, when there was no comparable anomaly for the state of Wisconsin. For the years 2018 and 2019, there are not yet sufficient data to support special adjustments for any of these three states, and therefore, the estimates should be considered incomplete for those most recent 2 years. See additional discussion on this topic in Appendix A.

During 2019, an estimated 250 non-fire CO poisoning deaths were associated with the use of a consumer product under the jurisdiction of the CPSC. This report does not include CO poisoning deaths involving products outside CPSC's jurisdiction, such as incidents where the CO gas resulted from a fire, or solely from a motor vehicle, or directly work related; and the report also does not include deaths that were suicides or otherwise intentional in nature. Over the prior 10 years, the annual average was 166 estimated non-fire CO deaths from consumer products. Please note that the estimates and findings for the 11 years covered in this report, include three incidents (one each in 2013, 2015, and 2016), where the exhaust from a motor vehicle engine may have contributed to the victim's CO poisoning death, in addition to a consumer product. Additionally, in another included 2016 incident, a farm tractor may have contributed to a CO fatality, along with an unspecified lawn mower that was running in a residential storage shed. Utility vehicles and ATVs are considered consumer products (not motor vehicles); and therefore, CO from their exhaust is considered relevant, regardless. For example, in 2019, four such CO deaths due to exhaust (3 from utility vehicles and 1 from an ATV) are classified as Off-Highway Vehicles (OHVs), as a subcategory under Engine-Driven-Tools.

Although multiple factors may contribute to a CO poisoning fatality, the source of CO is virtually always a fuel-burning product. The following factors can cause or contribute to a fuel-burning product producing dangerous levels of CO: poor product design, product failure or malfunction; improper service or maintenance; improper venting of exhaust products; consumer misuse; inadequate ventilation of the room in which the product is located. CPSC staff produces the CO estimates associated with consumer products, to identify and monitor product groups involved in these fatal CO scenarios. Within the individual product-specific CPSC projects, additional analysis assesses whether improvements are warranted in the areas of product design, ventilation safeguards, or user information and education.

The annual CO estimates for the years 2009 through 2019, are presented in two formats: by product category (Table 1), and by product within fuel type (Table 2). The data are presented as an average of the most recent 3-year period (2017 through 2019), followed by yearly estimates for each of the 11 years covered by this report. As noted, collection of death certificates from some states is incomplete for 2018 and 2019. Accordingly, although reporting for those years is complete from most states through 2019, estimates for those years may change, if additional data become available, in particular, from non-reporting states. Therefore, data for 2018 and 2019 are reported using italic font in the tables, to signify reporting is incomplete.

Because the numbers presented in this document represent national estimates of unintentional, non-fire deaths attributed to CO poisoning associated with the use of consumer products, the generator and other EDT death estimates would not be expected to match the observed fatality counts presented in this report or in the CPSC report, "Fatal and Nonfatal Incidents Associated with Non-Fire Carbon Monoxide from Engine-Driven Generators and Other Engine-Driven Tools, 2011–2021," published in August 2022.

By Product Category

Table 1 shows the estimated average annual number of CO poisoning deaths associated with various consumer products for 2017 to 2019, as well as the annual estimated CO deaths for the individual years from 2009 through 2019. The annual average for 2017 through 2019 is estimated to be 216 (with a standard error of approximately 9.8). Appendix B contains a graph and the data point values for the annual estimates of CO poisoning deaths associated with a consumer product under CPSC's jurisdiction for 1980 through 2019.

The estimate for Heating Systems, which historically account for a large percentage of the deaths, is further broken down into heating system subcategories within various fuel types. Fatality estimates for the Engine-Driven Tools category were distributed between generators and other engine-driven tools. The consumer product-related estimate and estimate-by-product distribution were derived using the methodology described in Appendix A.

In 2019, products in the Heating Systems category were associated with an estimated 69 deaths (28% of the total 250 CO poisoning deaths from consumer products). Of the 69, the majority (86% or 59 deaths) were known to have involved gas heating systems or devices. Natural gas heating was associated with an estimated 17 deaths (25% of all heating system-related deaths). LP gas heating was associated with an estimated 40 deaths (58% of heating system-related deaths); and unspecified gas heating was associated with an estimated two deaths (3% of heating system-related deaths).

Staff notes that several other fuel-burning devices, not specifically designed for heating purposes, were known or suspected of having been used for heating an enclosed space where a victim died of CO poisoning. Such devices included charcoal/charcoal grills (an estimated 14 deaths) and gas ranges (3 deaths).

Of the estimated 17 deaths associated with natural gas (NG) heating, the majority (76% or 13 deaths) involved installed freestanding furnaces. The remaining four involved an NG wall furnace. At least half of the estimated 40 deaths in 2019 that were associated with LP gas heating systems involved unvented portable propane heaters, not including an additional 10 (25%) that involved an unidentified LP heating device. The unvented, portable propane heaters were fueled by a propane tank and were not a component of an installed heating system. The portable LP heaters are intended as camping heaters or heaters for other temporary spaces and use disposable, refillable, or exchangeable propane tanks.

There were also an estimated two deaths associated with coal-burning heating devices: one from a coal furnace, and one from a coal-burning stove.

Additionally, in 2019:

- An estimated four deaths were associated with some type of heating system where the fuel was unknown, one product was known to be a furnace, and three products simply were identified as heating systems.
- An estimated 14 CO deaths (6% of the 250 total estimated deaths) were associated with charcoal or charcoal grills. As noted, most of these were either known to have been used, or were suspected of being used for heating purposes, often in temporary spaces, like inside a vehicle.
- An estimated 18 deaths (7%) were associated with residential water heaters, where an estimated 10 were propane-fueled, three were natural gas water heaters, and five were fueled by an unspecified gas.
- An estimated 16 deaths were associated with multiple appliances (6% of the total estimated deaths). The multiple-products category includes all incidents where multiple fuel-burning products were used simultaneously, such that a single source of the CO could not be determined.

In recent years, the Engine-Driven Tools category, which includes generators, lawn mowers, leaf blowers, tillers, power washers, and snow blowers, among other EDTs, has been associated with more CO deaths than any other category. Nearly half of the estimated average number of CO deaths in the three most recent years (2017 through 2019) were associated with engine-driven tools (107 of 216, not including multiple-product incidents). Over the 11 years covered in this report, the total number of estimated CO deaths associated with engine-driven tools (893) exceeds the estimates for heating systems (562). Estimated generator-related CO deaths alone exceed those for heating systems over these 11 years (765 generator-related deaths, versus 562 heating system-related deaths). When a single CO-producing product is involved, generator-related deaths comprise most engine-driven, tools-related CO deaths, accounting for 86 percent of all engine-driven tools-related deaths over the entire 11 years covered by this report.

The availability of detailed information regarding the condition of products associated with CO deaths varies widely. Information collected often describes conditions indicative of compromised vent systems, flue passageways, and chimneys for furnaces, boilers, and other heating systems. Vent systems include the portion of piping that either connects the flue outlet of the appliance and exhausts air to the outside through a ceiling or sidewall or connects to a chimney. According to the information available, some products had vents that became detached or were installed/maintained improperly. Vents were also sometimes blocked by soot caused by inefficient combustion, which, in turn, may have been caused by several factors, such as leaky or clogged burners, an over-firing condition, or inadequate combustion air.

Other reported furnace-related conditions included compromised heat exchangers or filter doors/covers that were removed or not sealed. Some products were old and apparently not well maintained. Other incidents mentioned a backdraft condition, large amounts of debris in the chimney, and the use of a product that was later prohibited by the utility company and designated not to be turned on until repaired.

Table 1: Estimated Non-Fire Carbon Monoxide Poisoning Deaths by Associated Fuel-Burning Consumer Product, 2009–2019

Consumer Product	2017–2019+		Annual Estimates										
	Average Estimate	Average Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018+	2019+
Total	***216***	***100%***	**148**	**159**	**163**	**137**	**146**	**164**	**172**	**178**	**188**	***210***	***250***
Heating Systems	***58***	***27%***	**41**	**58**	**49**	**46**	**43**	**64**	**37**	**50**	**41**	***64***	***69***
Furnaces (incl. Boilers)	***22***	***10%***	**16**	**30**	**22**	**27**	**21**	**24**	**20**	**34**	**17**	***27***	***22***
Coal	*1*	*1%*	*	*	1	*	*	*	*	*	2	*1*	*1*
Liquid Petroleum (LP) Gas	*2*	*1%*	1	7	*	4	1	11	3	3	*	*	*5*
Natural Gas	*13*	*6%*	10	15	6	15	5	6	6	15	6	*21*	*13*
Oil	*1*	*<1%*	3	1	2	*	5	1	3	2	1	*1*	*
Unspecified Gas	*2*	*1%*	1	4	10	4	10	6	8	11	4	*	*1*
Unspecified Fuel	*3*	*1%*	1	2	2	5	*	*	1	2	4	*4*	*1*
Portable Heaters	***22***	***10%***	**8**	**19**	**13**	**11**	**12**	**18**	**11**	**11**	**19**	***26***	***21***
Kerosene	*1*	*<1%*	*	1	2	1	*	2	1	4	2	*	*1*
Liquid Petroleum (LP) Gas	*21*	*10%*	8	18	11	10	12	14	10	6	16	*26*	*20*
Natural Gas	*	*	*	*	*	*	*	1	*	*	*	*	*
Unspecified Gas	*	*	*	*	*	*	*	*	*	1	*	*	*
Unspecified Fuel	*<1*	*<1%*	*	*	*	*	*	*	*	*	1	*	*
Wall/Floor Furnaces	***3***	***1%***	**6**	**5**	**1**	*****	*****	**5**	**1**	**1**	**2**	***1***	***5***
Liquid Petroleum (LP) Gas	*<1*	*<1%*	5	1	*	*	*	*	*	1	*	*	*1*
Natural Gas	*2*	*1%*	1	2	*	*	*	2	1	*	*	*1*	*4*
Unspecified Gas	*<1*	*<1%*	*	*	*	*	*	2	*	*	1	*	*
Unspecified Fuel	*<1*	*<1%*	*	1	1	*	*	*	*	*	1	*	*
Room/Space Heaters	***6***	***3%***	**9**	**1**	**5**	**5**	**9**	**8**	**1**	**1**	**1**	***6***	***10***
Coal	*1*	*<1%*	*	*	2	*	1	1	*	*	*	*1*	*1*
Liquid Petroleum (LP) Gas	*2*	*1%*	5	1	1	4	3	7	*	*	*	*	*7*
Natural Gas	*	*	2	*	*	*	2	*	*	*	*	*	*
Wood	*2*	*1%*	2	*	1	*	2	*	*	*	1	*4*	*1*
Unspecified Gas	*<1*	*<1%*	*	*	1	*	*	*	*	1	*	*1*	*
Unspecified Fuel	*<1*	*<1%*	*	*	*	1	*	*	1	*	*	*	*1*
Unspecified Heater/System	***5***	***2%***	**2**	**4**	**8**	**2**	**1**	**9**	**3**	**3**	**1**	***4***	***10***
Liquid Petroleum (LP) Gas	*3*	*1%*	*	1	3	1	*	8	1	*	*	*2*	*7*
Natural Gas	*	*	*	*	1	*	*	*	*	*	*	*	*
Unspecified Gas	*<1*	*<1%*	1	1	1	1	*	*	*	*	*	*	*1*
Unspecified Fuel	*2*	*1%*	1	1	2	*	1	1	1	3	1	*2*	*3*
Charcoal Grills, Charcoal	***11***	***5%***	**7**	**17**	**10**	**6**	**11**	**7**	**11**	**7**	**10**	***10***	***14***

Table 1: Estimated Non-Fire Carbon Monoxide Poisoning Deaths by Associated Fuel-Burning Consumer Product, 2009–2019 (continued)

	2017–2019+		Annual Estimates										
Consumer Product	Average Estimate	Average Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018+	2019+
Engine-Driven Tools	***107***	***50%***	**76**	**56**	**73**	**64**	**68**	**62**	**92**	**80**	**104**	***100***	***118***
Generators – Gasoline	*78*	*36%*	64	40	64	57	55	53	84	61	89	*72*	*74*
Generators – LP	*	*	*	2	*	*	*	*	*	7	*	*	*
Generators – Unspecified Fuel	*14*	*7%*	*	*	*	*	1	1	*	*	6	*11*	*26*
Other Engine-Driven Tools	*15*	*7%*	12	14	10	6	13	8	8	12	10	*16*	*18*
Ranges or Ovens	***8***	***4%***	**4**	**5**	**8**	**4**	**10**	*****	**5**	**7**	**12**	***9***	***3***
Liquid Petroleum (LP) Gas	*1*	*<1%*	*	1	1	1	1	*	3	*	1	*1*	*
Natural Gas	*2*	*1%*	2	2	3	*	2	*	3	6	*	*2*	*3*
Unspecified Gas	*5*	*2%*	2	1	3	2	2	*	*	*	11	*5*	*
Unspecified Fuel	*	*	*	*	*	*	5	*	*	1	*	*	*
Water Heaters	***9***	***4%***	**5**	**2**	**8**	**5**	**2**	**5**	**9**	**6**	**4**	***5***	***18***
Liquid Petroleum (LP) Gas	*4*	*2%*	2	*	1	*	1	1	*	*	*	*2*	*10*
Natural Gas	*3*	*1%*	1	2	4	*	*	*	*	1	4	*1*	*7*
Oil	*	*	*	*	*	*	*	*	*	*	*	*	*
Unspecified Gas	*2*	*1%*	1	*	1	2	*	2	8	4	*	*1*	*1*
Unspecified Fuel	*	*	1	*	1	2	1	1	1	*	*	*	*
Pool Heaters	***1***	***<1%***	*****	**1**	**1**	*****	**3**	**2**	*****	**2**	**4**	*****	*****
Liquid Petroleum (LP) Gas	*	*	*	1	*	*	*	*	*	*	*	*	*
Natural Gas	*1*	*<1%*	*	*	*	*	3	1	*	*	4	*	*
Unspecified Gas	*	*	*	*	1	*	*	*	*	2	*	*	*
Unspecified Fuel	*	*	*	*	*	*	*	1	*	*	*	*	*
Lanterns	*	*	1	*	2	2	*	5	5	1	*	*	*
Liquid Petroleum (LP) Gas	*	*	1	*	1	2	*	4	5	1	*	*	*
Kerosene	*	*	*	*	*	*	*	1	*	*	*	*	*
Unspecified Fuel	*	*	*	*	1	*	*	*	*	*	*	*	*
Grills, Camp Stoves	*5*	*2%*	*	*	2	*	1	6	4	3	6	*4*	*4*
Liquid Petroleum (LP) Gas	*3*	*1%*	*	*	2	*	*	2	4	3	6	*1*	*1*
Coal	*<1*	*<1%*	*	*	*	*	*	*	*	*	*	*1*	*
Wood	*1*	*<1%*	*	*	*	*	*	1	*	*	*	*	*3*
Unspecified Fuel	*<1*	*<1%*	*	*	*	*	1	2	*	*	*	*1*	*

Note: Use of a natural gas water heater not as the product was intended with Liquid Petroleum (LP) gas (instead of natural gas) is associated with an estimated 4 deaths in 2019. Those deaths are classified based on *product type* under "Water Heaters -- *natural gas*", even though LP gas was used.

Table 1: Estimated Non-Fire Carbon Monoxide Poisoning Deaths by Associated Fuel-Burning Consumer Product, 2009–2019 (continued)

	2017–2019+		Annual Estimates										
Consumer Product	**Average Estimate**	**Average Percent**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018+**	**2019+**
Other Products	***5***	***2%***	**2**	**5**	**3**	**2**	**2**	**7**	**1**	**2**	**1**	***7***	***8***
Chimney – Unspecified Fuel	*1*	*<1%*	*	*	*	1	1	*	*	*	*	*	*3*
Fire Pit – Wood	*	*	*	*	*	*	*	*	*	1	*	*	*
Fireplace – Coal	*	*	*	1	*	*	*	*	*	*	*	*	*
Other Products – LP Gas	*2*	*1%*	1	1	2	*	1	4	1	*	1	*4*	*
Other Products – Natural Gas	*	*	1	*	*	*	*	*	*	*	*	*	*
Other Products – Unspecified Fuel	*	*	*	*	*	*	*	1	*	*	*	*	*
Unidentified Product	*2*	*1%*	*	2	1	1	*	1	*	*	*	*1*	*5*
Unidentified Product – LP Gas	*1*	*<1%*	*	*	*	*	*	1	*	1	*	*2*	*
Multiple Products	***11***	***5%***	**11**	**15**	**8**	**5**	**5**	**7**	**9**	**19**	**6**	***12***	***16***

+ Data collection for 2018 and 2019 is only partially complete, and data are shown in italics. Italicized estimates may change in the future if more reports of deaths are received.
* No reports received by CPSC staff.
Source: U.S. Consumer Product Safety Commission/EPHA.
CPSC Death Certificate File, CPSC Injury or Potential Injury Incident File, CPSC In-Depth Investigation File, National Center for Health Statistics Mortality File, 2009–2019.
Note: Reported annual estimates and estimated averages and percentages may not add to subtotals or totals due to rounding.

By Fuel Type

Table 2 (beginning on page 18) organizes the estimates, by product, within fuel type. The three major fuel types include: *Gas-Fueled Products* (natural gas and liquid petroleum—LP including propane and butane—gas); *Solid-Fueled Products* (charcoal, coal, and wood); and *Liquid-Fueled Products* (gasoline, kerosene, and oil). Of these fuel types, *Gas-Fueled Products* were associated with 89 of the 250 (36%) estimated CO deaths in 2019. *Liquid-Fueled Products* were associated with an estimated 97 (39%) deaths; and *Solid-Fueled Products* were associated with an estimated 21(8%) deaths in the same period. There were also 40 fatalities (16%), where the fuel type of the device could not be identified.

In the *Gas-Fueled Products* category in 2019, an estimated 68 of the 89 gas-fueled appliance deaths (76%) were associated with heating systems or heaters, including furnaces, portable heaters, and room or space heaters. Additionally, all eight of the *Multiple Gas-Fueled Products* fatalities were associated with a heating-related product and another product.

All but four of the estimated 97 liquid-fueled, appliance-related deaths in 2019, were associated with engine-driven tools (*e.g.*, generators, lawn mowers/garden tractors). An estimated 74 deaths were associated with gasoline-fueled generators.

In 2019, an estimated 21 deaths fit within the *Solid-Fueled Products* category. Fourteen of these were associated with charcoal or charcoal grills.

Table 2: Estimated Non-Fire Carbon Monoxide Poisoning Deaths Associated with Consumer Products Organized by Fuel Type, 2009–2019

Consumer Product	2017–2019+ Average Estimate	2017–2019+ Average Percent	Annual Estimates 2009	2010	2011	2012	2013	2014	2015	2016	2017	2018+	2019+
Total	216	100%	148	159	163	137	146	164	172	178	188	210	250
Gas-Fueled Products	76	35%	53	70	58	51	45	78	53	69	60	78	89
Natural Gas	21	10%	17	23	15	15	13	11	10	21	13	23	26
Furnace (incl. Boilers)*	12	6%	10	15	6	15	5	6	6	15	6	18	13
Pool Heater	1	1%	*	*	*	*	3	1	*	*	4	*	*
Portable Heater	*	*	*	*	*	*	*	1	*	*	*	*	*
Range/Oven	2	1%	2	2	3	*	2	*	3	6	*	2	3
Room/Space Heater	*	*	2	*	*	*	2	*	*	*	*	*	*
Wall/Floor Furnace	2	1%	1	2	*	*	*	2	1	*	*	1	4
Water Heater	4	2%	1	2	4	*	*	*	*	1	4	1	7
Unspecified Heater	*	*	*	*	1	*	*	*	*	*	*	*	*
Other Appliance	*	*	1	*	*	*	*	*	*	*	*	*	*
Liquid Petroleum (LP) Gas	39	18%	23	35	23	22	20	52	27	22	24	41	51
Furnace (incl. Boilers)	2	1%	1	7	*	4	1	11	3	3	*	2	5
Generator	<1	<1%	*	2	*	*	*	*	*	7	*	1	*
Grill/Camp Stove	3	1%	*	*	2	*	*	2	4	3	6	1	1
Lantern	*	*	1	*	1	2	*	4	5	1	*	*	*
Other Products/Unknown	1	1%	1	*	*	*	*	2	1	1	*	4	*
Pool Heater	*	*	*	1	*	*	*	*	*	*	*	*	*
Portable Heater	20	9%	8	18	11	10	12	14	10	6	16	24	20
Range/Oven	1	0%	*	1	1	1	1	*	3	*	1	1	*
Refrigerator	1	0%	*	1	2	*	1	2	*	*	1	2	*
Room/Space Heater	2	1%	5	1	1	4	3	7	*	*	*	*	7
Unspecified Heater/System	3	1%	*	1	3	1	*	8	1	*	*	2	7
Wall/Floor Furnace	<1	<1%	5	1	*	*	*	*	*	1	*	*	1
Water Heater	4	2%	2	*	1	*	1	1	*	*	*	2	10
Unspecified Gas	9	4%	5	6	17	10	13	11	15	20	16	7	4
Furnace (incl. Boilers)	2	1%	1	4	10	4	10	6	8	11	4	*	1
Pool Heater	*	*	*	*	1	*	*	*	*	2	*	*	*
Portable Heater	*	*	*	*	*	*	*	*	*	1	*	*	*
Range/Oven	5	2%	2	1	3	2	2	*	*	*	11	5	*
Room/Space Heater	<1	<1%	*	*	1	*	*	*	*	1	*	1	*
Fireplace	*	*	*	*	*	*	*	*	*	*	*	*	*
Wall/Floor Furnace	<1	<1%	*	*	*	*	*	2	*	*	1	*	*
Water Heater	1	0%	1	*	1	2	*	2	8	4	*	1	1
Unspecified Heater	<1	<1%	1	1	1	1	*	*	*	*	*	*	1

Table 2: Estimated Non-Fire Carbon Monoxide Poisoning Deaths Associated with Consumer Products Organized by Fuel Type, 2009–2019 (continued)

	2017–*2019*+		Annual Estimates										
Consumer Product	Average Estimate	Average Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	*2018*+	*2019*+
Multiple Gas-Fueled Products	*7*	*3%*	8	6	3	4	*	5	1	6	6	*6*	*8*
Liquid-Fueled Products	*96*	*44%*	81	60	79	65	73	67	96	83	102	*89*	*97*
Gasoline-Fueled	*92*	*42%*	77	53	73	64	67	61	92	73	98	*86*	*91*
Generator	*78*	*36%*	64	40	64	57	55	53	84	61	88	*72*	*74*
Other Engine-Driven Tools	*14*	*6%*	12	14	10	6	13	8	8	12	10	*15*	*17*
Kerosene-Fueled	*1*	*<1%*	*	1	2	1	*	4	1	4	2	*	*1*
Portable Heater	*1*	*<1%*	*	1	2	1	*	2	1	4	2	*	*1*
Lantern	*	*	*	*	*	*	*	1	*	*	*	*	*
Oil-Fueled	*1*	*<1%*	3	1	2	*	5	1	3	2	1	*1*	*
Furnace (incl. Boilers)	*1*	*<1%*	3	1	2	*	5	1	3	2	1	*1*	*
Water Heater	*	*	*	*	*	*	*	*	*	*	*	*	*
Diesel-Fueled	*	*	*	*	*	*	*	*	*	*	*	*	*
Water Heater	*	*	*	*	*	*	*	*	*	*	*	*	*
Multiple Liquid-Fueled Products	*2*	*1%*	1	5	1	*	1	1	*	3	*	*1*	*5*
Solid-Fueled Products	*17*	*8%*	9	18	14	5	14	9	11	8	13	*17*	*21*
Charcoal-Fueled	*11*	*5%*	7	17	10	5	11	7	11	7	10	*10*	*14*
Charcoal/Charcoal Grills	*11*	*5%*	7	17	10	5	11	7	11	7	10	*10*	*14*
Coal-Fueled	*3*	*1%*	*	1	3	*	1	1	*	*	2	*4*	*3*
Furnace (incl. Boilers)	*1*	*<1%*	*	*	1	*	*	*	*	*	2	*1*	*1*
Room/Space Heater	*1*	*<1%*	*	*	2	*	1	1	*	*	*	*1*	*1*
Coal Grill/Coal	*<1*	*<1%*	*	*	*	*	*	*	*	*	*	*1*	*
Chimney/Fireplace	*	*	*	1	*	*	*	*	*	*	*	*	*
Wood-Fueled	*3*	*1%*	2	*	1	*	2	1	*	1	1	*4*	*4*
Fire Pit	*	*	*	*	*	*	*	*	*	1	*	*	*
Grill/Stove	*1*	*<1%*	*	*	*	*	*	1	*	*	*	*	*3*
Room/Space Heater	*2*	*1%*	2	*	1	*	2	*	*	*	1	*4*	*1*

Table 2: Estimated Non-Fire Carbon Monoxide Poisoning Deaths Associated with Consumer Products Organized by Fuel Type, 2009–2019 (continued)

	2017–2019+		Annual Estimates										
Consumer Product	**Average Estimate**	**Average Percent**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018+**	**2019+**
Unspecified Fuel Products	***25***	***11%***	**3**	**7**	**9**	**11**	**10**	**8**	**5**	**7**	**13**	***21***	***40***
Chimney	*1*	*<1%*	*	*	*	1	1	*	*	*	*	*	*3*
Furnace (incl. Boilers)	*3*	*1%*	1	2	2	5	*	*	1	2	4	*4*	*1*
Generator	*14*	*7%*	*	*	*	*	1	1	*	*	6	*11*	*26*
Grill/Camp Stove	*<1*	*<1%*	*	*	*	*	1	2	*	*	*	*1*	*
Lantern	*	*	*	*	1	*	*	*	*	*	*	*	*
Pool Heater	*	*	*	*	*	*	*	1	*	*	*	*	*
Portable Heater	*<1*	*<1%*	*	*	*	*	*	*	*	*	1	*	*
Range/Oven	*	*	*	*	*	*	5	*	*	1	*	*	*
Room/Space Heater	*<1*	*<1%*	*	*	*	1	*	*	1	*	*	*	*1*
Unspecified Heater	*2*	*1%*	1	1	2	*	1	1	1	3	1	*2*	*2*
Wall/Floor Furnace	*<1*	*<1%*	*	1	1	*	*	*	*	*	1	*	*
Unidentified Product	*2*	*1%*	*	2	1	1	*	1	*	*	*	*1*	*4*
OEDT	*<1*	*<1%*	*	*	*	*	*	*	*	*	*	*1*	*1*
Water Heater	*	*	1	*	1	2	1	1	1	*	*	*	*
Multiple Product - Different Fuels	***2***	***1%***	**2**	**4**	**3**	**4**	**3**	**1**	**8**	**10**	*	***5***	***2***
Gas & Liquid	*2*	*1%*	1	1	2	2	3	1	6	8	*	*5*	*2*
Gas & Solid	*	*	1	*	*	1	*	*	*	1	*	*	*
Liquid & Solid	*	*	*	2	1	*	*	*	*	*	*	*	*
Liquid & Unspecified	*	*	*	*	*	*	*	*	1	1	*	*	*

+ Data collection for 2018 and 2019 is only partially complete. Italicized estimates may change in the future if more reports of deaths are received.
* No reports received by CPSC staff.
Source: U.S. Consumer Product Safety Commission/EPHA.
CPSC Death Certificate File, CPSC Injury or Potential Injury Incident File, CPSC In-Depth Investigation File, National Center for Health Statistics Mortality File, 2009–2019.

Note: Use of a natural gas water heater not as the product was intended with Liquid Petroleum (instead of natural gas) is associated with an estimated 4 deaths in 2019. Those deaths are classified based on product type under “natural gas” [water heater], even though LP gas was used.

Engine-Driven Tools

Table 3 shows a breakdown of the fatality estimates for the 11-year period from 2009 through 2019, in the *Engine-Driven Tools* category. During 2019, engine-driven tools were associated with an estimated 123 carbon monoxide poisoning deaths (49% of the 250 total consumer product-related CO death estimate). In the 3 most recent years, EDTs comprised 51 percent of all consumer-product-related CO fatalities (estimated annual average of 111 out of 216 – when including several multiple product deaths associated with a generator and/or EDT). Of these EDT fatalities, generators dominated, with an estimated annual average of 93 out of 111.

Lawnmowers were associated with slightly less than half of the deaths listed in the *Other Engine-Driven Tools* category for the 11-year period (58 of 127 total fatalities). There were six other deaths associated with a lawnmower and another product in this period. There was an estimated average of six lawnmower-related CO deaths per year from 2017 to 2019 (18 deaths, excluding multiproduct deaths). There were multiple fatalities for six other sub-categories over the 2017 to 2019 period: power washers (an estimated 6 fatalities), OHV (6), leaf blowers (2), snow blowers (2), and unspecified EDTs (2).

Table 3: Estimated Non-Fire Carbon Monoxide Poisoning Deaths Associated with Engine-Driven Tools, 2009–2019

Engine-Driven Tools	2017-2019+		Annual Estimate										
	Average Estimate	Average Percentage	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018+	2019+
Total	*111*	*100%*	**78**	**61**	**78**	**66**	**73**	**64**	**97**	**92**	**104**	***106***	***123***
Generators	*93*	*84%*	**64**	**42**	**64**	**57**	**56**	**54**	**84**	**67**	**95**	***84***	***100***
Gasoline-fueled	*78*	*70%*	64	40	64	57	55	53	84	61	88	*72*	*74*
LP-fueled	*<1*	*<1%*	*	**2**	*	*	*	*	*	7	*	***1***	*
Unspecified Fuel	*14*	*13%*	*	*	*	*	1	1	*	*	6	*11*	*26*
Other Engine-Driven Tools (OEDTs)	*15*	*14%*	**12**	**14**	**10**	**6**	**13**	**8**	**8**	**12**	**10**	***16***	***18***
Lawn Mowers	*6*	*5%*	**6**	**7**	**3**	**4**	**7**	**2**	**4**	**7**	**5**	***9***	***4***
Riding Mowers	*3*	*3%*	6	5	3	2	6	1	3	7	4	*5*	*
Unspecified Mowers	*3*	*3%*	*	2	*	1	1	1	1	*	1	*4*	*4*
Paint Sprayer	*	*	*	*	1	*	*	*	*	*	*	*	*
Power Washer	*2*	*2%*	1	*	2	*	*	2	*	1	1	*1*	*4*
Snow Blower/Thrower	*1*	*1%*	3	1	1	*	2	1	1	1	*	*1*	*1*
OHV (*e.g.*, ATV or UTV)	*2*	*2%*	*	4	2	1	1	1	*	*	1	*	*5*
Water Pump	*<1*	*<1%*	*	1	*	*	1	*	*	*	*	*	*1*
Welder	*	*	*	*	*	*	*	*	3	1	*	*	*
Tiller	*<1*	*<1%*	1	*	*	*	*	*	*	*	*	*1*	*
Leaf Blower	*1*	*1%*	*	*	*	*	*	*	*	1	*	*2*	*
Go-Cart	*	*	1	*	*	*	*	*	*	*	*	*	*
Antique Tractor	*<1*	*<1%*	*	*	*	*	*	*	*	*	1	*	*
Small Engine	*	*	*	*	*	*	*	*	*	1	*	*	*
Snowmobile	*<1*	*<1%*	*	*	*	*	*	*	*	*	*	*	*1*
Stump Grinder	*<1*	*<1%*	*	*	*	*	1	*	*	*	1	*	*
Wood Splitter	*	*	*	*	*	1	*	1	*	*	*	*	*
Unspecified EDT	*1*	*1%*	*	*	*	*	*	*	*	*	*	*1*	*1*
Multiple Product: Engine-Driven Tools Involved	*4*	*4%*	**2**	**6**	**4**	**2**	**5**	**2**	**5**	**12**	*	***6***	***5***
Generator + OEDT	*<1*	*<1%*	*	*	*	*	*	*	*	1	*	*	*1*
Generator + other Product	*3*	*3%*	2	6	3	2	3	2	4	10	*	*6*	*4*
Multiple OEDT	*	*	*	*	1	*	*	*	*	1	*	*	*
OEDT + other product	*	*	*	*	*	*	1	*	1	*	*	*	*

\+ Data collection for 2018 and 2019 is only partially complete, and data are shown in italics. Italicized estimates may change in the future if more reports of deaths are received.

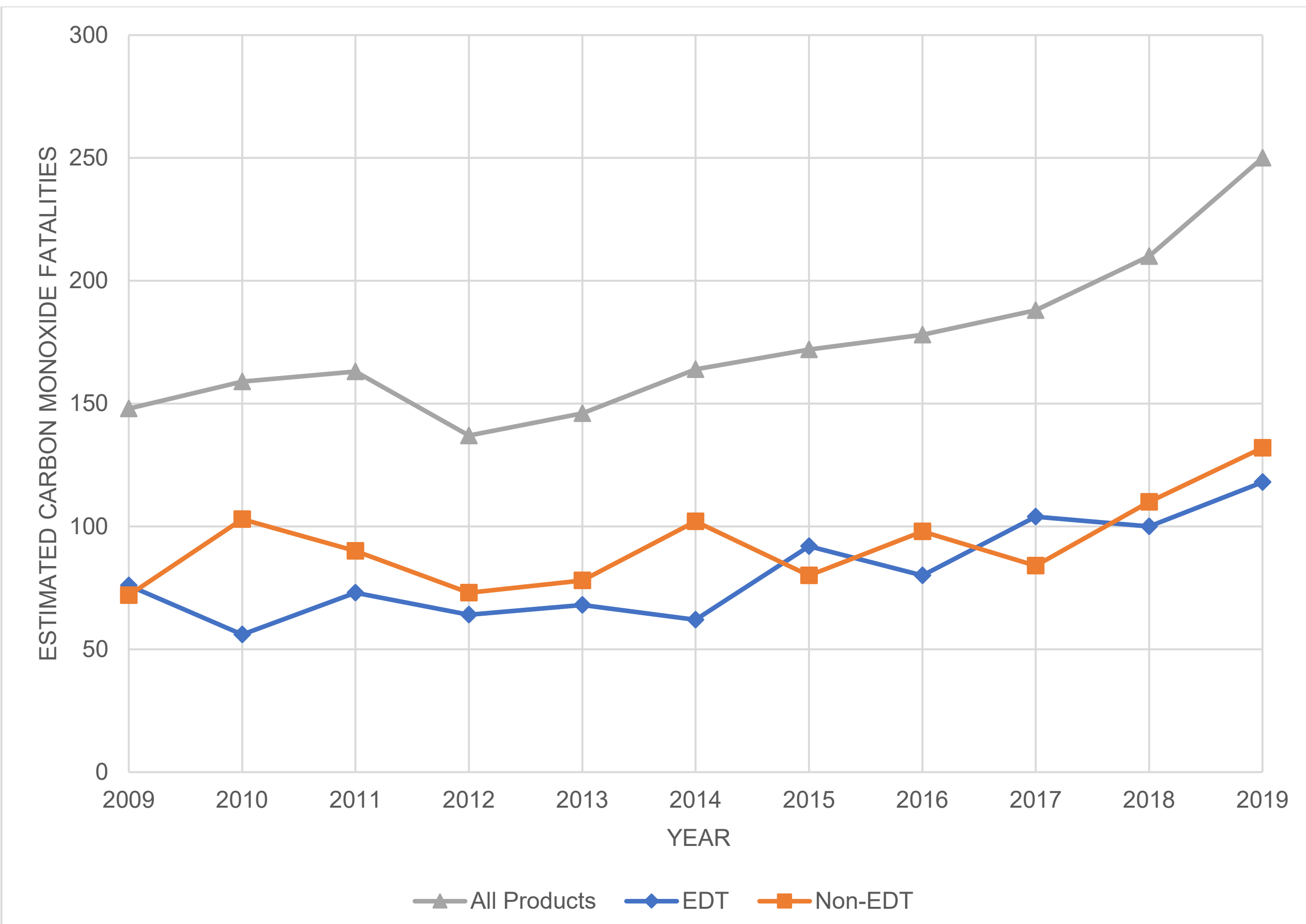
* No reports received by CPSC staff.

Source: U.S. Consumer Product Safety Commission/EPHA.
CPSC Death Certificate File, CPSC Injury or Potential Injury Incident File, CPSC In-Depth Investigation File, National Center for Health Statistics Mortality File, 2009–2019.
Note: Reported annual estimates and estimated averages and percentages may not add to subtotals or totals due to rounding.

Comparison of Trends

Figure 1 provides a graphic representation of the CO fatality trends related to: (1) all consumer products; (2) engine-driven tools; and (3) non-engine-driven tool products. A regression analysis of the estimated number of all non-fire, consumer product-related CO poisoning deaths from 2009 to 2019, indicates evidence of a statistically significant trend (p-value = 0.0015). The estimated CO fatalities from consumer products has now risen for the seventh straight year. In 2018, the estimated number of CO fatalities had risen above 200 deaths for the first time since before the changeover from ICD-9 to ICD-10 in 1999, and the estimate increased to 250 in the year 2019. Part of this is likely due to an uptick in CO fatalities associated with engine-driven tools.

Figure 1: Comparison of Trends in Consumer Product-Related Carbon Monoxide Deaths, 2009 to 2019



Source: U.S. Consumer Product Safety Commission/EPHA.
CPSC Death Certificate File, CPSC Injury or Potential Injury Incident File, CPSC In-Depth Investigation File, 2009–2019.

Number of Deaths per Incident Reported to CPSC

Table 4 presents a summary of the incident data broken down by the number of deaths per incident. Staff notes that this table does **not** provide estimates; the numbers presented are counts observed in the CPSC databases. Therefore, the counts presented in Table 4 should not be expected to add up to the estimated deaths in other tables. Table 4 shows that in 2019, 145 of the 168 fatal CO incidents (85% of fatal CO incidents reported to the CPSC) involved a single death. Table 4 accounts for only the fatally injured victims in each CO poisoning incident. It is not uncommon for CO incidents involving one or more deaths to also result in one or more nonfatal CO poisoning injuries. However, the breakdown of these injuries was not quantified for analysis in this death-focused report.

Occasionally, even though CPSC records indicate that there was more than one fatality in a specific incident, not all the deaths are used in the estimation process. Deaths for which CPSC does not have a death certificate are not used in the analyses, because the scaling estimation process accounts for missing records. Also, if an additional fatality is recorded as work related, that fatality is not counted in the estimation process, because work-related deaths are out of scope for this report. However, both scenarios are included in Table 4 to highlight the danger of multiple deaths in CO poisoning cases.

Death certificates do not include information about other deaths for the same incident. The number of deaths for a particular incident is based primarily on CPSC In-Depth Investigation (IDI) records. Some additional multiple-fatality incidents were identified by matching the incident date of death and location of death to the death certificate, while others were identified from news articles contained in the CPSC Injury or Potential Injury Incident (IPII) database. Over the 11-year period covered by this report, CPSC records indicate that 18 percent of the incidents resulted in multiple deaths. Nineteen incidents resulted in four or more CO deaths, including an incident in 2015, where eight people died, and another incident in 2016, in which six people died.

Table 4: Number of Carbon Monoxide Poisoning Incidents Reported to CPSC by Number of Deaths per Incident, 2009–2019

Number of Deaths Reported in Incident	2017−*2019*+		Annual Incidents										
	Annual Average	Average Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	*2018*+	*2019*+
All Incidents	***148***	***100%***	**117**	**116**	**120**	**90**	**106**	**110**	**104**	**130**	**131**	***145***	***168***
1	*125*	*85%*	93	100	95	74	84	86	83	110	112	*119*	*145*
2	*19*	*13%*	19	14	22	14	21	21	15	16	15	*23*	*19*
3	*2*	*2%*	4	1	1	1	*	1	2	1	3	*2*	*2*
4	*1*	*1%*	1	1	1	*	1	1	3	2	1	*1*	*2*
5	*	*	*	*	1	1	*	1	*	*	*	*	*
6	*	*	*	*	*	*	*	*	*	1	*	*	*
7	*	*	*	*	*	*	*	*	*	*	*	*	*
8	*	*	*	*	*	*	*	*	1	*	*	*	*

\+ Data collection for 2018 and 2019 is only partially complete, and data are shown in italics. Italicized counts may change in the future if more reports of deaths are received.
Note: Percentages do not add to 100% due to rounding.

Numbers presented here are counts based on records available to CPSC staff. These do not represent national estimates and should not be expected to match estimates presented elsewhere in this document.

Source: U.S. Consumer Product Safety Commission/EPHA
CPSC Death Certificate File, CPSC Injury or Potential Injury Incident File, CPSC In-Depth Investigation File.

By Location of Exposure

Table 5 shows that in 2019, an estimated 187 CO poisoning deaths resulted from exposure to CO in home locations, including an estimated 15 deaths from CO in detached structures at residential locations (*i.e.*, sheds, detached garages); and another 18 from CO in structures not intended originally as a permanent residence (*i.e.*, camper trailers, sea-land shipping containers). From 2017 to 2019, an estimated annual average of 164 deaths (76% of the annual average estimate for all CO deaths) resulted from exposure to CO in home locations. In 2019, an estimated 21 deaths resulted from CO in temporary shelters, such as campers, cabins, and trailers used for shelter. For 2017 to 2019, an annual average of 22 deaths (10%) resulted from CO in temporary shelters. Deaths due to CO exposures in temporary shelters were most associated with heating sources or generators.

A small percentage of the CO poisoning deaths resulted from CO in vehicles (such as passenger vans, trucks, automobiles, or boats), where a consumer product was the CO-producing product in use. In 2019, there were an estimated 19 CO deaths in this category. For the 3-year period 2017 to 2019, an annual average of 17 deaths (8%) resulted from CO in vehicles. Vehicle location incidents in this 3-year period usually involved a generator, LP heater, grill, or the burning of charcoal inside the vehicle.

Table 5: Estimated Non-Fire Carbon Monoxide Poisoning Deaths by Location of Exposure, 2009−2019

Location of Exposure	2017−*2019*⁺ Average Estimate	2017−*2019*⁺ Average Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	*2018*⁺	*2019*⁺
Total	***216***	***100%***	**148**	**159**	**163**	**137**	**146**	**164**	**172**	**178**	**188**	***210***	***250***
Home[1]	*135*	*62%*	109	125	122	107	104	100	113	135	142	*108*	*154*
Home – External Structure[2]	*12*	*6%*	7	5	10	5	13	15	14	11	5	*17*	*15*
Home – But Not House[3]	*17*	*8%*	1	5	5	1	3	12	4	3	11	*23*	*18*
Temporary Shelter	*22*	*10%*	18	17	15	21	16	21	24	19	13	*33*	*21*
Vehicles (including boats)	*17*	*8%*	12	6	9	*	7	6	12	4	10	*22*	*19*
Outdoors	*6*	*3%*	*	*	*	*	*	*	*	1	*	*1*	*11*
Other	*9*	*4%*	*	1	1	*	2	8	5	1	7	*4*	*17*
Unknown	*3*	*1%*	*	*	1	2	*	1	*	1	*	*2*	*4*

\+ Data collection for 2018 and 2019 is only partially complete, and data are shown in italics. Italicized estimates may change in the future if more reports of deaths are received.

* No reports received by CPSC staff.

Note: Percentages do not add to 100% due to rounding.

1 Traditional home (*e.g.,* detached house, townhouse, apartment, mobile home)

2 External structure at residential locations (*e.g.,* detached garage, shed)

3 Non-fixed structure or structure not originally designed for permanent occupation (*e.g.,* camper trailer, van, converted sea-land shipping container).

Source: U.S. Consumer Product Safety Commission/EPHA.
CPSC Death Certificate File, CPSC In-Depth Investigation File, CPSC Injury or Potential Injury Incident File,
National Center for Health Statistics Mortality File, 2009–2019.

By Time of Year

CPSC data indicate that there were more CO deaths attributable to incidents that occurred in the cold months than in the warm months. This is most likely because of the use of furnaces and portable heaters in the cold months. Additionally, generators are often used in the cold months because of power outages due to snow and ice storms. Table 6 shows the annual estimated CO deaths categorized by month of death. In 2019, an estimated 137 of the 250 estimated CO deaths (55%) were attributable to deaths that occurred during the four cold months of November, December, January, and February. Over the 11 years covered by this report, the average percentage of deaths occurring in the four colder months is 55 percent. In 2019, an estimated 73 deaths (29%) are attributable to incidents that occurred during the transition months of March, April, September, and October. This is only slightly lower than the 11-year average of 30 percent for the same four months. And in the warmer months of May, June, July, and August, an estimated 40 CO deaths (16%) occurred.

Table 6: Estimated Non-Fire Carbon Monoxide Poisoning Deaths by Month and Year of the Fatality, 2009–2019

Month of Death	2017−*2019*⁺		Annual Estimate										
	Average Estimate	Average Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	*2018*⁺	*2019*⁺
Total	***216***	***100%***	**148**	**159**	**163**	**137**	**146**	**164**	**172**	**178**	**188**	***210***	***250***
Cold Months	***112***	***52%***	**85**	**109**	**85**	**75**	**82**	**83**	**82**	**109**	**80**	***120***	***137***
November	*24*	*11%*	12	18	34	26	16	20	10	32	17	*27*	*27*
December	*25*	*11%*	20	38	20	25	28	20	23	19	21	*29*	*24*
January	*35*	*16%*	29	38	24	10	22	26	24	28	27	*38*	*40*
February	*29*	*14%*	24	15	8	14	16	17	24	29	16	*26*	*46*
Transition Months	***65***	***30%***	**41**	**33**	**55**	**46**	**43**	**44**	**62**	**49**	**65**	***56***	***73***
March	*16*	*7%*	12	22	9	6	12	10	19	12	13	*12*	*22*
April	*16*	*7%*	8	6	11	14	6	14	28	13	14	*15*	*18*
September	*16*	*7%*	4	2	13	6	5	6	11	7	23	*20*	*5*
October	*17*	*8%*	17	2	23	20	21	14	4	17	14	*10*	*27*
Warm Months	***39***	***18%***	**21**	**17**	**23**	**16**	**21**	**37**	**29**	**20**	**42**	***34***	***40***
May	*10*	*5%*	5	8	9	2	4	17	4	5	9	*11*	*10*
June	*14*	*6%*	10	5	2	5	6	4	9	3	16	*14*	*12*
July	*7*	*3%*	4	2	4	7	7	13	11	6	10	*1*	*10*
August	*8*	*4%*	2	1	8	1	5	4	5	6	9	*7*	*8*

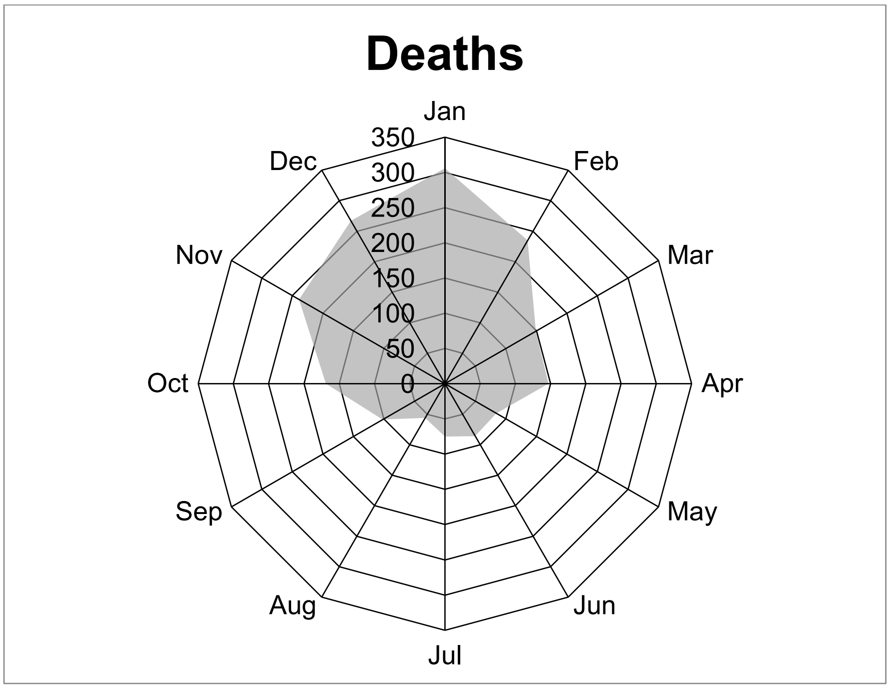
\+ Data collection for 2018 and 2019 is only partially complete. Italicized estimates may change in the future if more reports of deaths are received.

Source: U.S. Consumer Product Safety Commission / EPHA.
CPSC Death Certificate File, CPSC In-Depth Investigation File, CPSC Injury or Potential Injury Incident File,
National Center for Health Statistics Mortality File, 2009–2019

Note: Reported annual estimates and estimated averages and percentages may not add to subtotals or totals due to rounding.

Figure 2 graphically illustrates the relationship between the time of year and the estimated number of CO poisoning deaths from 2009 through 2019. The total estimated number of CO poisoning deaths is presented on the radar graph by month of death. The shaded area represents the estimated total number of deaths for the 11-year period, distributed by each month of a year. Notably, more CO deaths occur in the cold months, particularly November, December, January, and February, than in warm months. Fatalities increase as the winter months continue, until a slight drop off in February before the spring months come. Conversely, as time gets deeper into the warmer months, the number of deaths decreases, with the lowest number of fatalities occurring in July and August.

Figure 2: Estimated Number of Consumer Product-Related Carbon Monoxide Deaths by Month of Death, 2009–2019



Source: U.S. Consumer Product Safety Commission/EPHA.
CPSC Death Certificate File, CPSC In-Depth Investigation File, CPSC Injury or Potential Injury Incident File, National Center for Health Statistics Mortality File, 2009–2019.

Victim Demographics from Non-Fire Carbon Monoxide Poisoning Deaths Associated with the Use of Consumer Products

Age of Victim

Table 7 shows the estimated number of CO poisoning deaths categorized by victim age for the 11 most recent years of data (2009–2019). From the data, it appears that consumer product-related CO deaths are skewed toward older individuals. For the 3 most recent years (2017–2019), children younger than 15 years of age accounted for an annual average of 4 percent (an estimated 9 deaths out of 216) of the yearly CO poisoning deaths, while this age group represents an average of about 19 percent of the U.S. population. For the same time frame, deaths among adults 45 years and older accounted for more than 66 percent (143 of 216), while this age group represented about 42 percent of the U.S. population. Statistical tests confirm (see Appendix C for p-values) the significance in the age-related differences in CO poisoning deaths. Percentages of children below the age of 15, as well as individuals 15 to 24 years old were each identified as statistically significantly below population estimates. Conversely, percentage of CO deaths among individuals 45 to 65, and those over age 65, were identified as statistically greater than their population representation.

Table 7: Estimated Non-Fire Carbon Monoxide Poisoning Deaths by Age of Victim, 2009–2019

Age	2017–*2019*+		Estimated Percentage of U.S. Population@	Annual Estimate										
	Average Estimate	Average Percent		2009	2010	2011	2012	2013	2014	2015	2016	2017	*2018*+	*2019*+
Total	***216***	***100%***	**100%**	**148**	**159**	**163**	**137**	**146**	**164**	**172**	**178**	**188**	***210***	***250***
Under 5	*3*	*2%*	6%	3	1	*	1	*	2	*	1	2	*4*	*4*
5 - 14	*6*	*3%*	13%	2	1	4	4	5	7	17	6	9	*1*	*7*
15 - 24	*13*	*6%*	13%	14	12	9	6	11	8	15	6	17	*7*	*14*
25 - 44	*51*	*24%*	27%	43	39	36	37	34	35	45	54	55	*55*	*43*
45 - 64	*89*	*41%*	26%	59	69	63	56	62	67	65	83	55	*89*	*124*
65 and over	*54*	*25%*	16%	27	36	52	32	36	44	31	29	51	*54*	*58*

+ Data collection for 2018 and 2019 is only partially complete. Italicized estimates may change in the future if more reports of deaths are received.

* No reports received by CPSC staff.

@ Based on estimated U.S. population statistics for the 3- year average (2017-2019). U.S. Census Bureau.

Source: U.S. Consumer Product Safety Commission/EPHA.
CPSC Death Certificate File, CPSC In-Depth Investigation File, CPSC Injury or Potential Injury Incident File,
National Center for Health Statistics Mortality File, 2009-2019.
U.S. Census Bureau, Population Division. Annual Estimates of the Resident Population by Sex, Age, Race, and Hispanic Origin for the United States and States: April 1, 2010 to July 1, 2019. June 2020.

Note: Reported annual estimates and estimated averages and percentages may not add to subtotals or totals due to rounding.

Gender of Victim

Table 8 presents the distribution of estimated CO deaths categorized by gender. In 2019, 77 percent of CO poisoning victims were males, and 23 percent were females. These percentages varied slightly from year to year over the 11 years of this report. However, every year there were many more male CO deaths than female. For 2017 through 2019, the average percentage of male CO victims was 76 percent, and the average percentage of female victims was 24 percent. By contrast, about 49 percent of the U.S. population is male, and 51 percent of the U.S. population is female.[3] The gender-related differences in CO poisoning deaths were confirmed to be statistically significant (p-value < 0.0001).

Table 8: Estimated Non-Fire Carbon Monoxide Poisoning Deaths by Gender of Victim, 2009-2019

Gender	2017−*2019*+		Estimated Percentage of U.S. Population*	Annual Estimate										
	Average Estimate	Average Percent		2009	2010	2011	2012	2013	2014	2015	2016	2017	*2018*+	*2019*+
Total	***216***	***100%***	**100%**	**148**	**159**	**163**	**137**	**146**	**164**	**172**	**178**	**188**	***210***	***250***
Male	***165***	***76%***	49%	109	121	111	92	124	127	125	140	138	*164*	*192*
Female	***51***	***24%***	51%	39	38	52	45	22	37	48	38	50	*46*	*57*

\+ Data collection for 2018 and 2019 is only partially complete. Italicized estimates may change in the future if more reports of deaths are received.

* Based on estimated U.S. population statistics for the 3-year average (2017-2019).

Source: U.S. Consumer Product Safety Commission/EPHA.
CPSC Death Certificate File, CPSC In-Depth Investigation File, CPSC Injury or Potential Injury Incident File, National Center for Health Statistics Mortality File, 2009–2019.
U.S. Census Bureau, Population Division. Annual Estimates of the Resident Population by Sex, Age, Race, and Hispanic Origin for the United States and States: April 1, 2010 to July 1, 2019. June 2020

Note: Reported annual estimates and estimated averages and percentages may not add to subtotals or totals due to rounding.

[3] Three-year average, 2017 to 2019, from June 2020 U.S. Census estimates of the U.S. population.

Victim Race/Ethnicity

Table 9 provides a summary of CO fatality victims characterized by race/ethnicity for the years 2009 through 2019. Because of the growing proportion of people of Hispanic descent, Hispanic victims were categorized separately, irrespective of their race. Estimates of the percentage of the U.S. population categorized into the various race/ethnicity groupings were based on single-race characterizations, as represented in the U.S. Census Bureau reports. Non-Hispanic individuals reported as multiracial are included in the *Unknown/Other/Mixed* category.

The estimated percentages of the 2017 through 2019 annual average CO deaths demonstrated some race/ethnicity-based differences in CO poisoning deaths that were statistically significant (p-value = 0.0400). When looked at as one race/ethnicity versus the rest, there was a statistically significant difference between the number of White victims of CO poisoning (approximately 69 percent of all CO poisoning deaths) and the resident White population (about 60 percent of the U.S. population), the p-value of this comparison was 0.0489. CO fatalities among Black and African American represented 11 percent of all CO fatalities, while their representation in the U.S. population is 13 percent. The difference is not determined to be statistically significant. However, in prior years of this report, the proportion of Black or African American victims has been determined to be statistically significantly greater than the resident population. It is unclear whether this is an anomaly in the recent data or an actual change.

Additionally, as has been seen before, the proportion of the CO poisoning fatality victims who were of Hispanic ethnicity (approximately 11%) was below the percentage of Hispanics in the U.S. population (about 18%), where the p-value was 0.0094. Among other races/ethnicities, no statistically significant differences were observed.

Table 9: Estimated Non-Fire Carbon Monoxide Poisoning Deaths by Race/Ethnicity, 2009–2019

Race/ Ethnicity	2017–*2019*+		Estimated Percentage of U.S. Population@	Annual Estimate										
	Average Estimate	Average Percent		2009	2010	2011	2012	2013	2014	2015	2016	2017	*2018*+	*2019*+
Total	*216*	*100%*	100%	148	159	163	137	146	164	172	178	188	*210*	*250*
White[4]	*149*	*69%*	60%	93	82	106	82	86	108	109	118	121	*153*	*173*
Black or African American[4]	*23*	*11%*	13%	20	43	38	31	35	26	47	32	24	*18*	*26*
Hispanic (All races)	*25*	*11%*	18%	11	18	9	11	13	18	14	13	19	*26*	*29*
Asian/Pacific[1]	*5*	*2%*	6%	3	4	3	5	7	6	*	7	7	*4*	*5*
American Indian[2]	*5*	*2%*	1%	1	5	1	*	1	1	*	1	7	*4*	*5*
Unknown/Other /Mixed[3]	*9*	*4%*	2%	19	8	6	7	5	5	3	6	9	*6*	*11*

\+ Data collection for 2018 and 2019 is only partially complete. Italicized estimates may change in the future if more reports of deaths are received.
* No reports received by CPSC staff.

@ Based on estimated U.S. population statistics for the 3- year average (2017-2019). U.S. Census Bureau.
1 Includes Asian, Pacific Islander, and Native Hawaiian
2 Includes American Indian, Native American, and Native Alaskan
3 Includes non-Hispanic Unknown races, Other races, and Multiple races
4 Only includes non-Hispanic ethnicities.

Source: U.S. Consumer Product Safety Commission/EPHA.
CPSC Death Certificate File, CPSC In-Depth Investigation File, CPSC Injury or Potential Injury Incident File,
National Center for Health Statistics Mortality File, 2009-2019.
U.S. Census Bureau, Population Division. Annual Estimates of the Resident Population by Sex, Age, Race, and Hispanic Origin for the United States and States: April 1, 2010 to July 1, 2019. June 2020.
Note: Reported annual estimates and estimated averages and percentages may not add to subtotals or totals due to rounding.

Population Density of Place of Death

Table 10 provides a breakdown of the CO poisoning deaths characterized by population density of the incident location. The table is presented as three sections: (1) incidents occurring at all locations; (2) incidents occurring in locations identified as a permanent home (*e.g.*, house, apartment, mobile home); and (3) incidents occurring only in non-home locations (*e.g.*, camper trailer, tent, motel room). Please note that "Home Locations" and "Non-Home Locations" sum to "All Locations."

All fatal incidents were designated as occurring in one of four rural/urban categories, based on the Rural-Urban Commuting Area (RUCA) codes developed by the Economic Research Service (ERS) of the U.S. Department of Agriculture (USDA) in conjunction with the Center for Rural Health, School of Medicine and Health Sciences, University of North Dakota. The categories are based on theoretical concepts used by the U.S. Office of Management and Budget (OMB) to define county-level metropolitan and micropolitan areas.[4] This 21-category classification system is based on measures of population density, urbanization, and daily commuting. The OMB methodology is based on a county-level delineation. ERS refined the methodology by applying it to smaller census tracts. ERS further delineated the characterization by cross-referencing each zip code in the United States to its RUCA code classification.[5] The update of the RUCAs to version 3.1 was developed by Center for Rural Health, School of Medicine and Health Sciences, University of North Dakota and ERS and is funded by the U.S. Department of Health and Human Services, Health Resources and Services Administration, Office of Rural Health Policy, and the USDA Economic Research Service. The zip code cross-reference was used to characterize each of the CO deaths into one of four broad categories: Urban Core, Sub-Urban, Large Rural Town, and Small Town/Rural Isolated. The RUCA codes are updated approximately once every 10 years. The most recent update applicable to years addressed in this report was for the year 2010. It is unlikely that there would be a substantial change in the urban-rural population distribution between 2010 and the more recent 3-year period average of 2017 through 2019.

Table 10 also includes the estimated percentage of the U.S. population, per population density designation category. As can be seen in the *All Locations* section, the estimated average percentage of CO deaths during the 3-year period 2017 through 2019, in urban locations (50%), is smaller than the percentage of the U.S. population living in urban core locations (73%). The difference is offset by the larger percentages in the other three categories: sub-urban locations (24% versus 15% of the U.S. population), large rural town locations (9% versus 6%), and small town/rural isolated locations (15% versus 5%). CO deaths that occurred in small town/rural isolated locations were nearly three times the percentage of the U.S. population living in these isolated locations. Additionally, due to lack of detail in some of the death certificates that CPSC receives, the exact location of some incidents (6%) could not be ascertained. The 2017 through 2019 data do not show a distinct difference between Home Locations and Non-Home Locations.

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[4] OMB BULLETIN NO. 13-01: Revised Delineations of Metropolitan Statistical Areas, Micropolitan Statistical Areas, and Combined Statistical Areas, and Guidance on Uses of the Delineations of these Areas. February 28, 2013.

[5] Version 3.10 of the ZIP code Rural-Urban Commuting Areas (RUCAs) geographic taxonomy, August 4, 2014. Center for Rural Health, University of North Dakota School of Medicine and Health Sciences. Comparable data presently available from [USDA ERS - Rural-Urban Commuting Area Codes.]

Table 10: Estimated Non-Fire Carbon Monoxide Poisoning Deaths by Population Density of Place of Death, 2009–2019

RUCA Population Density Designation	2017–2019+		Estimated Percentage of US Population@	Annual Estimates										
	Average Estimate	Average Percent		2009	2010	2011	2012	2013	2014	2015	2016	2017	2018+	2019+
All Locations	216	100%	100%	148	159	163	137	146	164	172	178	188	210	250
Urban Core	108	50%	73%	78	94	95	79	84	73	77	108	103	107	114
Sub-Urban	52	24%	15%	42	33	33	25	27	34	41	25	39	51	65
Large Rural Town	19	9%	6%	10	25	14	9	12	19	14	20	13	24	21
Small Town/Rural Isolated	32	15%	5%	18	7	18	19	23	32	39	22	33	27	37
Unknown Location	4	2%	-	*	*	2	6	1	6	1	2	*	*	13
Home Locations	162	75%	100%	117	135	137	113	121	127	131	150	150	148	188
Urban Core	83	38%	73%	66	88	78	71	73	63	62	92	83	76	89
Sub-Urban	39	18%	15%	30	24	28	20	24	29	39	21	33	32	51
Large Rural Town	15	7%	6%	10	19	14	6	7	14	11	18	9	18	17
Small Town/Rural Isolated	25	12%	5%	11	4	15	11	15	21	18	18	27	22	27
Unknown Location	1	1%	-	*	*	2	5	1	*	*	*	*	*	4
Non-Home Locations	53	25%	100%	30	24	26	24	26	37	41	28	38	62	62
Urban Core	26	12%	73%	11	6	18	7	11	11	14	16	21	32	26
Sub-Urban	13	6%	15%	12	8	5	5	2	5	1	3	6	20	14
Large Rural Town	5	2%	6%	*	6	*	2	5	5	3	2	5	6	4
Small Town/Rural Isolated	7	3%	5%	7	4	3	7	8	11	22	4	6	5	9
Unknown Location	3	1%	-	*	*	*	1	*	6	1	2	*	*	9

\+ Data collection for 2018 and 2019 is only partially complete* No reports received by CPSC staff.

@ Estimated 2010 U.S. population categorized by Rural Urban Commuting Area (RUCA 3.1) designation. U.S. population estimates by RUCA classification were determined by cross-referencing the Center for Rural Health, School of Medicine and Health Sciences, University of North Dakota/Economic Research Service, Department of Agriculture RUCA3.1 zip code table with the 2010 U.S. Census population estimates by zip code area.019 is only partially complete. Italicized estimates may change in the future if more reports of deaths are received.

Source: U.S. Consumer Product Safety Commission / EPHA.
CPSC Death Certificate File, CPSC In-Depth Investigation File, CPSC Injury or Potential Injury Incident File,
National Center for Health Statistics Mortality File, 2009– 2019
Center for Rural Health, University of North Dakota School of Medicine and Health Sciences, ZIP code RUCA Version 3.10

Note: Reported annual estimates and estimated averages and percentages may not add to subtotals or totals due to rounding.

Geographical Region of Incident

Table 11 provides a breakout of the CO poisoning deaths characterized by geographic region where the incident occurred. As the table reflects, for the 3 most recent years (2017 to 2019), CO deaths in some of the regions appear to be different from what would be expected based on the percentage of the U.S. population living in these regions. This may indicate that geographic location influences the likelihood of fatal CO poisoning incidents; however, these results may be influenced due to incompleteness of the estimates for a few states. The regional estimates and proportions for recent years, therefore, are not assessed for statistical significance.

The states that comprise each of the regions are set forth in Appendix D.

Table 11: Estimated Non-Fire Carbon Monoxide Poisoning Deaths by Geographical Region of Incident, 2009–2019

Region‡	2017–*2019*+		Estimated Percentage of US Population@	Annual Estimates										
	Average Estimate	Average Percent		2009	2010	2011	2012	*2013*	2014	2015	2016	2017	*2018+*	*2019+*
Total	**216**	**100%**	**100%**	**148**	**159**	**163**	**137**	**146**	**164**	**172**	**178**	**188**	***210***	***250***
Northeast	**27**	**13%**	**17%**	**14**	**23**	**43**	**25**	**34**	**37**	**30**	**21**	**11**	***30***	**41**
New England	9	4%	5%	5	5	16	1	14	8	13	8	4	*12*	10
Middle Atlantic	19	9%	13%	9	18	27	24	20	29	17	13	7	*18*	31
South	**70**	**32%**	**38%**	**55**	**55**	**55**	**55**	**43**	**42**	**62**	**55**	**67**	***74***	**69**
East South Central	14	6%	6%	19	12	13	7	3	9	11	10	10	*20*	13
South Atlantic	39	18%	20%	13	26	23	31	20	21	29	27	36	*43*	38
West South Central	17	8%	12%	23	17	19	17	20	12	22	18	21	*11*	18
Midwest	**58**	**27%**	**21%**	**48**	**49**	**33**	**31**	**48**	**40**	**44**	**69**	**61**	***53***	**59**
East North Central	36	17%	14%	28	40	27	26	27	22	27	44	40	*26*	43
West North Central	21	10%	7%	20	10	6	5	21	18	17	25	21	*27*	16
West	**62**	**29%**	**24%**	**31**	**31**	**32**	**25**	**22**	**44**	**37**	**33**	**50**	***54***	**81**
Mountain	27	13%	7%	16	11	9	13	8	26	14	18	12	*36*	33
Pacific	35	16%	16%	14	20	23	12	14	18	23	15	38	*18*	48

‡ Region designation is based on U.S. Census Bureau reporting practices. See Appendix D for identification of specific regional designation of state of occurrence.

\+ Data collection for 2018 and 2019 may be only partially complete due to apparently incomplete reporting from some states. Italicized estimates may change in the future if more reports of deaths are received.

@ Based on estimated U.S. population statistics for the 3-year average (2017-2019).

Source: U.S. Consumer Product Safety Commission/EPHA.

Appendix A: Methodology

This appendix describes the data sources and methodology used to compute the national estimate of non-fire carbon monoxide (CO) poisoning deaths associated with the use of consumer products and the estimates by product, victim age, and incident location.

All death certificates filed in the United States are compiled by the National Center for Health Statistics (NCHS) into a multiple cause-of-mortality data file. The NCHS Mortality File contains demographic and geographic information, as well as the International Statistical Classification of Diseases and Related Health Problems codes for the underlying cause of death. Data are compiled in accordance with the World Health Organization instructions, which request that member nations classify causes of death by the current Manual of the International Statistical Classification of Diseases and Related Health Problems. The International Classification of Diseases, Tenth Revision (ICD-10) was implemented in 1999. Although the NCHS data contain cause-of-death codes that are helpful in identifying deaths due to CO poisoning, the records do not contain any narrative information that might indicate the involvement of a consumer product.

CPSC staff purchases death certificates from the 50 states, New York City, the District of Columbia, and some U.S. territories. Specifically, CPSC staff purchases death certificates with certain cause-of-death codes for which a high probability exists that consumer products are involved. In addition to the cause-of-death codes and demographic and geographic information, the death certificate contains information about the incident location and a brief narrative describing the incident. Any references to consumer products are usually found in these narratives. As resources allow, CPSC staff conducts follow-up In-Depth Investigations (IDIs) on selected deaths to confirm and expand upon the involvement of consumer products. These data from CPSC complement the NCHS mortality data.

ICD-10 classifies deaths associated with CO poisoning with the codes listed below. The focus of this report is accidental CO poisoning deaths, and the report concentrates on deaths coded as X47 and Y17. Deaths coded under Code X67, intentional CO poisonings, are excluded from this analysis.

ICD-10 Code	Definitions
X47	**Accidental–** Poisoning by and exposure to other gases and vapors. Includes: carbon monoxide, lacrimogenic gas, motor (vehicle) exhaust gas, nitrogen oxides, sulfur dioxide, utility gas.
X67	**Intentional–** Poisoning by and exposure to other gases and vapors. Includes: carbon monoxide, lacrimogenic gas, motor (vehicle) exhaust gas, nitrogen oxides, sulfur dioxide, utility gas.
Y17	**Undetermined intent–** Poisoning by and exposure to other gases and vapors. Includes: carbon monoxide, lacrimogenic gas, motor (vehicle) exhaust gas, nitrogen oxides, sulfur dioxide, utility gas.

The first step in compiling the annual estimates is computing the total estimates of CO poisoning deaths associated with consumer products. The CPSC's Death Certificate (DTHS) File and the CPSC's Abbreviated Death Certificate (ABDT) File were searched for cases associated with ICD-10 codes X47 and Y17.

Each case in the CPSC's DTHS File that was coded as X47 or Y17 was reviewed by an analyst and categorized as in-scope, out-of-scope, or source of CO unknown or questionable. In-scope cases are unintentional, non-fire CO poisoning deaths associated with a consumer product under the jurisdiction of the CPSC. Out-of-scope cases are cases that involve CO sources that are not under the jurisdiction of the CPSC, fire- or smoke-related exposures, or intentional CO poisonings. Examples of out-of-scope cases include poisonings due to gases other than CO (*i.e.*, natural gas, ammonia, butane); motor vehicle exhaust- or boat exhaust-related poisonings; and work-related exposures. The source of CO was classified as unknown or questionable in cases where a consumer product was possibly associated with the incident, but the exact source of CO was unknown.

The CPSC's ABDT File contains death certificates for CO poisonings (X47 and Y17) that involve motor vehicle exhaust, cases where the source of the CO is unknown, or where the death certificate does not mention a consumer product. Other examples of cases that may appear in the abbreviated file are cases associated with farm accidents, smoke inhalation from a structural fire, or other gas poisonings. Occasionally, newer information from CPSC IDIs may be matched with ABDT cases that were originally classified as having no known source or did not mention a consumer product. If information from IDIs indicated that an ABDT case should be considered in scope, then it was included with the DTHS database files. For 2008, 2009, 2010, and 2011, no ABDT records were reclassified as in scope. From 2012 through 2017, nine cases were reclassified: three cases for 2012; one case for 2013; four cases for 2014; two cases in 2015; one case in 2016; two cases in 2017. No cases were reclassified in 2018. In 2019, only one ABDT record was reclassified as in scope.

In 2016, and to a slightly lesser extent in 2017, the way the state of Texas designated death certificates with the Y17 code seems to have changed. Before 2016, the maximum number of

Y17-coded death certificates from any individual state was 21 (coincidentally, Texas in 2013). In 2016, CPSC received 56 Y17-coded death certificates from Texas, and 129 from the entire country. In 2016, Michigan, the second highest number of Y17, had 13. In 2017, death certificates from Texas with the Y17 code dropped to 34 but were still much higher than any state for any year. In 2017, the second highest number of Y17-coded death certificates was only six by Oklahoma and Oregon. NCHS records indicate 94 Y17s in 2016, and 85 in 2017. For these two years, CPSC has 90 Y17-coded death certificates from Texas, more than the rest of the country combined. Clearly, in 2016 and 2017, some discrepancy exists with the way Texas codes Y17 death certificates compared to the rest of the states in the country. As noted in the prior year's report, it appeared as though there were many 2018 death certificates missing from the CPSC database as of the search date for that year's report. That report anticipated additional collection (from particular states), but the expected missing reports have gone unreported without any change from July 2021 through September 2022. CPSC data for 2019 also appears to be incomplete from all states, even if most are complete. With reporting for 2018 and 2019 still incomplete, no comparable adjustments are made for 2019, or changes to the prior calculations for previous years, in the absence of the anticipated additional death certificate reporting from some states for those prior years.

Thus far, Texas, Washington, and Wisconsin have reported considerably fewer relevant deaths for the years 2018 and 2019 than typical of previous years. Therefore, the death certificate data available to CPSC for 2018 and 2019, likely underrepresents the distribution of deaths among those three states (*i.e.*, Texas, Washington, and Wisconsin). Estimation methodologies in this report generally assume randomized non-reporting, which does not appear to represent an accurate assumption of distribution at the individual state level for 2018 and 2019. To a lesser degree, incomplete estimates *by region* may also merit some skepticism for the incomplete years 2018 and 2019. Despite these caveats, the incomplete estimates for 2018 and 2019 nevertheless, may provide valuable information, in assessing the U.S. as a whole.

To compensate for the apparent anomalies in 2016 and 2017 only, this report maintains the most recent report's substitution of the average yearly number of Y17 reports from the prior 10 years for Texas, in place of the 2016 and 2017 count of Texas Y17s in the scaling calculations. The average number of Y17-coded death certificates from the previous 10 years is 7.6. However, no similar compensation appears appropriate yet for 2018 and 2019.

Table A.1: Initial Categorization for 2019 Data

ICD-10 Code	NCHS Total	CPSC DTHS File & ABDT File				Number of Cases to be Imputed
		In-Scope	Unknown Scope	Out-of-Scope	Total	
X47	994	189	51	572	812	233
Y17	112	3	9	108	120	1
Total	**1,106**	**192**	**60**	**680**	**932**	**234**

[1] "NCHS Total" cases, minus "Total in CPSC Database," plus "Unknown Scope" from DTHS.
Source: U.S. Consumer Product Safety Commission/EPHA.
CPSC Death Certificate File, CPSC In-Depth Investigation File, Abbreviated Death Certificate File, National Center for Health Statistics Mortality File, 2019.

The proportion of death certificates found in the CPSC database associated with non-fire, unintentional X47 or Y17 deaths and associated with consumer products was applied to the NCHS totals to calculate the total estimated number of non-fire CO poisoning deaths associated with consumer products. In theory, the NCHS totals comprise all death certificates in the United States, and the same proportion of in-scope cases should exist in the death certificates that are missing from the combined CPSC Death Certificate and Abbreviated Death Certificate files or are from an unknown source. Applying the proportion of in-scope cases to the NCHS database totals, therefore, should provide an estimate of in-scope cases nationwide. This was done in the following way for ICD-10 codes X47 and Y17, separately:

1. The number of in-scope deaths in the CPSC's two death certificate files coded under the specific ICD10 code that were associated with an accidental non-fire CO poisoning and a consumer product were identified (n_1).

2. The total number of deaths in the CPSC's Death Certificate File and the Abbreviated Death Certificate File coded under the specific ICD10 code were summed separately, excluding cases with an unknown or highly questionable source (n_2).

3. The total number of deaths in the NCHS data associated coded under the specific ICD10 code was counted (n_3).

4. The estimate of the number of non-fire CO poisoning deaths associated with consumer products under the specific ICD-10 code was calculated, using the formula:

$$N = (n_1 / n_2) * n_3$$

The proportion (n_1 / n_2) represents the number of in-scope cases found in the CPSC's files, divided by the total of in-scope and out-of-scope cases.

5. The estimates of the number of non-fire CO poisoning deaths associated with consumer products under the specific ICD10 codes were summed to calculate the total estimate of non-fire CO poisoning deaths.

$$\text{Total Estimate} = N_{X47} + N_{Y17}$$

The ratio (n_3 / n_2) represents the weighting factor used to calculate the annual estimates. The CPSC's Death Certificate File does not contain death certificates for all deaths listed in the NCHS file; therefore, a weighting factor was calculated to account for death certificates that are missing. The weighting factor allows the computation of national estimates of CO deaths by consumer products and by other characteristics collected by CPSC about each death.

Table A.2 contains the values for the variables used in the calculation, as well as the final computed 2019 estimates of CO poisoning deaths.

Table A.2: Calculation Detail of the Final Computed 2019 Estimate of Non-Fire CO Poisoning Deaths Associated with Consumer Products

Variable	ICD-10 Code	
	X47	Y17
n_1	189	3
n_2	812 – 51 = 761	120 - 9 = 111
n_3	994	112
Weighting Factor (n_3 / n_2)	1.3062	1.0090
N	246.8673	3.027
Total Estimate	{246.8673 + 3.027 = 249.8943 ~ 250}	

Source: U.S. Consumer Product Safety Commission/EPHA. CPSC Death Certificate File, CPSC In-Depth Investigation File, Abbreviated Death Certificate File, National Center for Health Statistics Mortality File 2019.

Death certificates received by NCHS are routinely checked for accuracy of state personnel-identified ICD-10 coding. On occasion, NCHS staff will correct codes before entering the data into their databases. CPSC staff has no way of correcting CPSC records to mesh with NCHS records. CPSC receives death certificate facsimiles or electronic death certificates directly from the states before any possible corrections are deemed necessary per NCHS procedures. Consequently, there may be slight discrepancies between final NCHS counts and CPSC records. For this report, CPSC staff has assumed that, over time, the number of death certificates with ICD-10 codes changed by NCHS staff to the codes of interest (X47 and Y17), would equal approximately those changed to codes other than X47 or Y17, thereby having little long-term effect on the estimates.

Table A.3 shows the weighting factors used to calculate the estimates for the years 2009–2019, based on the information available to CPSC staff.

Table A.3: CO Fatality Cases and Weighting Factors Used to Calculate the Estimates for the Years 2009–2019

Year	NCHS Total	Total in CPSC Databases*	In-Scope Cases	Weighting Factor
2009				
X47	734	769	145	1.0000
Y17	72	52	2	1.3846
2010				
X47	675	567	125	1.1905
Y17	98	68	7	1.4412
2011				
X47	786	730	143	1.0767
Y17	89	76	8	1.1711
2012				
X47	736	591	109	1.2453
Y17	114	84	1	1.3571
2013				
X47	704	608	123	1.1579
Y17	76	60	3	1.2667
2014				
X47	803	679	137	1.1826
Y17	106	61	1	1.7377
2015				
X47	847	665	134	1.2737
Y17	91	53	1	1.7170
2016				
X47	921	822	154	1.1204
Y17	94	72.6	4	1.2948
2017				
X47	936	770	150	1.2156
Y17	85	75.6	5	1.1243
2018				
X47	896	730	164	1.2274
Y17	106	97	8	1.0928
2019				
X47	994	761	189	1.3062
Y17	112	111	3	1.0090

* This is the total number of deaths in the Death Certificate File and Abbreviated Death Certificate File, excluding deaths associated with an unknown or questionable source of CO.

Source: U.S. Consumer Product Safety Commission/EPHA. CPSC Death Certificate File, CPSC In-Depth Investigation File, Abbreviated Death Certificate File, National Center for Health Statistics Mortality File, 2009–2019.

Incidents with unknown or highly questionable CO sources were excluded from the denominator (the number of deaths in the CPSC databases) of the weighting factor. The group of cases with unknown or highly questionable sources was assumed to contain the same proportion of cases associated with a consumer product as the group of cases within the CPSC database with known CO sources (this is the same assumption that is made for cases where the death certificate is missing). To include these cases within the denominator assumes that these cases can be classified as in-scope or out-of-scope cases when their scope status is unknown.

Therefore, for weighting purposes, cases with unknown or questionable sources were treated in the same way as missing cases.

In-scope cases were examined further to determine which product was associated with the incident. Additional information on the CO deaths was obtained from review of the CPSC's IDI File.

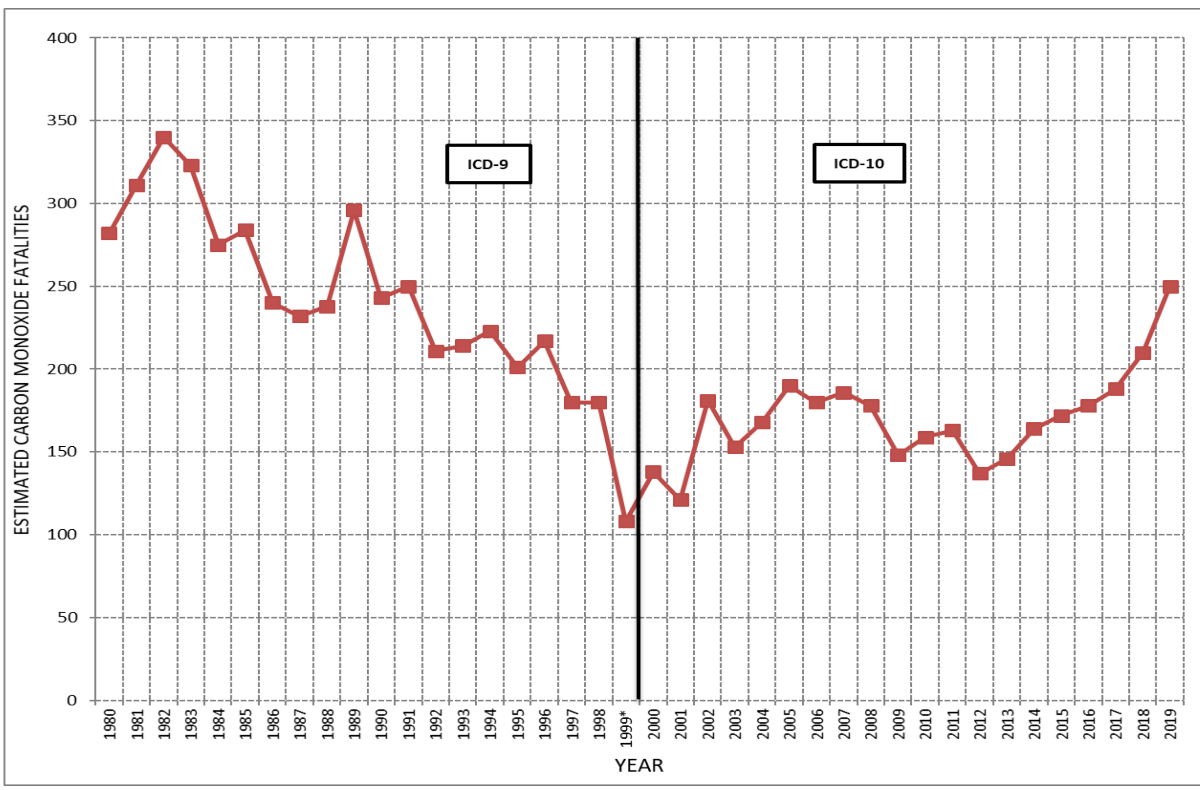
Reports of non-fire CO poisoning deaths were retrieved from the DTHS and ABDT files, based on the following criteria: date of death between 1/1/2009 and 12/31/2019, and ICD-10 code of X47 or Y17. Death certificates entered in the CPSC's database before September 1, 2022, were included in this analysis. Whenever possible, each CO death was reviewed and coded by the author, according to the consumer product and type of fuel involved, incident location, and whether multiple deaths were associated with the same incident.

In Table 1 of this report, the *Heating Systems* category includes CO poisoning deaths from subcategories for furnaces and boilers (combined under the heading of *Furnaces*), vented floor and wall heaters, unvented room/space heaters, unvented portable heaters, and other miscellaneous heating systems. Each subcategory is further delineated by fuel type used. Deaths associated with charcoal burned alone and in the absence of an appliance (*e.g.*, in a pail or in the sink) were presented with *Charcoal/Charcoal Grills*, even though this practice typically is done for heating purposes. Examples of products historically included in the *Other Products* category include LP gas refrigerators and gas pool heaters. LP gas grill, LP fish cooker, and other LP gas portable cooking appliance incidents are classified in the *Grills, Camp Stoves* category. Deaths where multiple fuel-burning products were used simultaneously, such that a single source of the fatal CO could not be determined, were classified under *Multiple Products*. *Engine-Driven Tools* included generators and power gardening equipment, such as power lawn mowers, garden tractors, concrete cutters, gasoline-powered water pumps, and snow blowers. Generators that were original equipment installed on a recreational vehicle (RV), trailer, camper, or boat were considered out of scope because they are likely outside the jurisdiction of the CPSC.

Appendix B: National Estimates and Mortality Rates of Consumer Product-Related CO Poisoning Deaths, 1980 to 2018

Figure B.1 below graphically suggests a trend of the estimated CO deaths from 1980 to 2019. Before the implementation of the ICD-10 coding in 1999, the estimated number of non-fire, consumer product-related CO poisoning deaths decreased from the early 1980s to the late 1990s, from a high of 340 in 1982, to a low of 180 in both 1997 and 1998. In 1999, there were an estimated 108 consumer product-related CO deaths, well below the estimated 180 deaths in each of the two previous years. The difference may be due, in part, to the change from ICD-9 coding to ICD-10 coding, where product identification could be assessed more accurately. As can be seen in the graph below, 2018 was the first year since ICD-10 was implemented in 1999 to exceed 200 CO fatalities before increasing to an estimated 250 such fatalities in 2019. However, some part of this increase is due to population growth. According to the U.S. Census, the U.S. population grew by more than 17 percent between 1999 and 2019.

Figure B.1: Estimated Non-Fire CO Poisoning Deaths Associated with Consumer Products: 1980–2019



* **Implementation of ICD-10.**

Source: U.S. Consumer Product Safety Commission/EPHA. CPSC Death Certificate File, CPSC Injury or Potential Injury Incident File, CPSC In-Depth Investigation File, 2009–2019.

Estimated 3-Year CO Mortality Trends

Table B.1 presents the annual estimates from 1980 to 2019, and the 3-year average mortality rates associated with each year, where 3 years of data were available. The 3-year average mortality rate is presented in the table for the mid-point year. The estimated 3-year average mortality rate decreased from the 1982 high of 14.02 per 10 million population, to a 3-year average rate of 4.34 per 10 million in 2000, a reduction of 69 percent. Subsequently, the 3-year average rate increased annually through 2006, to a rate of 6.21. Since 2006, the rate slowly dropped to the 2013 estimate of 4.71, before reversing the trend and rising in the 2018 estimate to a rate of 6.61. This 2018 rate estimate exceeds the 2006 estimate of 6.21, which still included the effects of the devastation of Hurricane Katrina and other 2005 hurricanes.

Table B.1: Estimated Non-Fire Carbon Monoxide Poisoning Death Rates Associated with Consumer Products, 1980−2019

Year	Estimate	U.S. Population Estimates (thousands)	3-Year Average Mortality Rate per 10 Million Population
1980	282	227,225	
1981	311	229,466	13.55
1982	340	231,664	14.02
1983	323	233,792	13.38
1984	275	235,825	12.47
1985	284	237,924	11.19
1986	240	240,133	10.49
1987	232	242,289	9.77
1988	238	244,499	10.44
1989	296	246,819	10.49
1990	243	249,623	10.53
1991	250	252,981	9.27
1992	211	256,514	8.77
1993	214	259,919	8.31
1994	223	263,126	8.08
1995	201	266,278	8.02
1996	217	269,394	7.40
1997	180	272,647	7.05
1998	180	275,854	5.66
1999*	108	279,040	5.09
2000	138	282,172	4.34
2001	121	285,082	5.15
2002	181	287,804	5.27
2003	153	290,326	5.76

2004	168	293,046	5.81
2005	190	295,753	6.06
2006	180	298,593	6.21
2007	186	301,580	6.01
2008	178	304,375	5.61
2009	148	307,007	5.27
2010	159	309,338	5.06
2011	163	311,644	4.91
2012	137	313,993	4.74
2013	146	316,235	4.71
2014	164	318,857	5.05
2015	172	321,419	5.34
2016	178	323,128	5.55
2017	188	325,719	5.90
2018	210	326,838	6.61
2019	250	328,240	

Note: The 3-year average mortality rate is reported at the mid-point year.
* The Tenth Revision of the International Statistical Classification of Diseases and Related Health Problems (ICD-10) was implemented.
Source: U.S. Consumer Product Safety Commission/EPHA.
U.S. Census Bureau, Population Division. Annual Estimates of the Resident Population by Sex, Age, Race, and Hispanic Origin for the United States and States: April 1, 2010 to July 1, 2019. June 2020.

Before implementation of ICD-10 in 1999, generating estimates for an important category of products—generators and other engine-driven tools—was not possible.[6] With the advent of ICD-10 coding, generating estimates of deaths associated with generators and other engine-driven tools is now possible. Table B.2 presents a summary of the mortality rates associated with generators, which steadily increased from 1999 through 2006, but retracted until 2011, from the previous 2006 high point. However, the rate generally increased after 2013, with the most recent 3-year average for 2016 to 2018, as the highest level (2.85) so far, exceeding the previously highest 2.69 rate in 2006, which included the Hurricane Katrina impact of 2005. This most recent 3-year average mortality rate range for generators alone is more than five times greater than the 3-year average rate in 2000.

[6] See Appendix B of Mah (2001) for details.

Table B.2: Estimated Non-Fire Carbon Monoxide Poisoning Death Rates Associated with Generators, 1999−2018*

Year	Estimate+	U.S. Population (thousands)	3-Year Average Mortality Rate per 10 Million Population
1999	7	279,040	
2000	19	282,172	0.54
2001	20	285,082	0.95
2002	42	287,804	1.29
2003	49	290,326	1.52
2004	41	293,046	2.02
2005	88	295,753	2.41
2006	85	298,593	2.69
2007	68	301,580	2.53
2008	76	304,375	2.28
2009	64	307,007	1.98
2010	42	309,338	1.83
2011	64	311,644	1.74
2012	57	313,993	1.88
2013	56	316,235	1.76
2014	54	318,857	2.03
2015	84	321,419	2.12
2016	66	323,128	2.54
2017	95	325,719	2.52
2018	84	326,838	2.85
2019	100	328,240	

* Estimates are based on single source product incidents as multiple source incidents could be included in multiple categories.

\+ Estimates in this table do not include multiple product-related deaths because a generator was not the sole product associated with the fatality.

Note 1: The 3-year average mortality rate is reported using the mid-year population estimates.

Note 2: Mortality rate changes from last year's report are due to changes in CPSC CO death estimates and changes in U.S. Census population estimates.

Table B.3 shows the CO poisoning mortality rates associated with all consumer products, excluding generators. The data indicate that, when generators are excluded, there does not appear to be a trend in the mortality rate for consumer product-related CO deaths. The 2000, 3-year annual average mortality rate was 3.60. The 2018, 3-year average mortality rate was 3.42, and the rate has risen each year since the 2016 low of 2.66.

Table B.3: Estimated Non-Fire Carbon Monoxide Poisoning Death Rates Associated with Consumer Products (Excluding Generator-Related Deaths),* 1999-2018

Year	Estimate+	U.S. Population (thousands)	3-Year Average Mortality Rate per 10 Million Population
1999	95	279,040	
2000	117	282,172	3.60
2001	93	285,082	3.93
2002	126	287,804	3.65
2003	96	290,326	3.93
2004	120	293,046	3.48
2005	90	295,753	3.35
2006	87	298,593	3.07
2007	98	301,580	3.04
2008	90	304,375	2.86
2009	73	307,007	2.88
2010	102	309,338	2.87
2011	91	311,644	2.87
2012	75	313,993	2.66
2013	85	316,235	2.77
2014	103	318,857	2.79
2015	79	321,419	2.85
2016	92	323,128	2.66
2017	87	325,719	3.01
2018	114	326,838	3.42
2019	134	328,240	

* Estimates are based on single source product incidents as multiple source incidents could be included in multiple categories.

\+ Excludes estimates of deaths associated with a generator only.

Note 1: The 3-year average mortality rate is reported at the mid-year population estimates.

Note 2: Mortality rate changes from last year's report are due to changes in CPSC CO death estimates and changes in U.S. Census population estimates.

Table B.4 shows the 3-year average mortality rates of all engine-driven tools, including generators, through 2018. Although the average mortality rates for 2007 through 2011 have dropped slightly since the 2006 high (3.18), in 2018, the rate (3.28) increased to the highest rate since the 2007 rate of 2.93. The table shows that the 3-year average mortality rate has more than quadrupled from the rate in 2000 (0.71), to 2018 (3.28).

Table B.4: Estimated Non-Fire Carbon Monoxide Poisoning Death Rates Associated with Generators and Other Engine-Driven Tools, 1999–2018*

Year	Estimate+	U.S. Population (thousands)	3-Year Average Mortality Rate per 10 Million Population
1999	13	279,040	
2000	26	282,172	0.71
2001	21	285,082	1.16
2002	52	287,804	1.49
2003	56	290,326	1.88
2004	56	293,046	2.43
2005	102	295,753	2.95
2006	104	298,593	3.18
2007	79	301,580	2.93
2008	82	304,375	2.60
2009	76	307,007	2.32
2010	56	309,338	2.21
2011	73	311,644	2.06
2012	64	313,993	2.18
2013	68	316,235	2.06
2014	62	318,857	2.32
2015	92	321,419	2.43
2016	80	323,128	2.84
2017	104	325,719	2.91
2018	100	326,838	3.28
2019	118	328,240	

* Estimates are based on single source product incidents as multiple source incidents could be included in multiple categories.

\+ Estimates in this table do not include multiple product-related deaths because an EDT was not the sole product associated with the fatality. The one exception to this is the 2001 estimate that includes one estimated death associated with a generator and another EDT.

Note 1: The 3-year average mortality rate is reported at the mid-year population estimates.

Note 2: Mortality rate changes from last year's report are due to changes in CPSC CO death estimates and changes in U.S. Census population estimates.

Table B.5 shows the CO mortality rates associated with all consumer products, excluding generators and other engine-driven tools. The data indicate that the annual average, 3-year mortality rate decreased by about 13 percent for non-engine-driven tool consumer products (*i.e.*, excluding generators and other engine-driven tools), from the 2000 rate of 3.44, to the 2018 rate of 2.98. However, in the 14 years between 2005 and the current estimate for 2018, the non-EDT CO fatality rates has been relatively consistent, fluctuating in a narrow band between 2.37 and 2.98 per 10 million population.

Table B.5: Estimated Non-Fire Carbon Monoxide Poisoning Death Rates Associated with Consumer Products (Excluding Generator- and Other Engine-Driven Tool-Related Deaths)*, 1999−2019

Year	Estimate+	U.S. Population (thousands)	3-Year Average Mortality Rate per 10 Million Population
1999	89	279,040	
2000	110	282,172	3.44
2001	92	285,082	3.72
2002	116	287,804	3.44
2003	89	290,326	3.56
2004	105	293,046	3.07
2005	76	295,753	2.81
2006	68	298,593	2.58
2007	87	301,580	2.64
2008	84	304,375	2.54
2009	61	307,007	2.53
2010	88	309,338	2.49
2011	82	311,644	2.55
2012	68	313,993	2.37
2013	73	316,235	2.49
2014	95	318,857	2.50
2015	71	321,419	2.55
2016	79	323,128	2.35
2017	78	325,719	2.62
2018	98	326,838	2.98
2019	116	328,240	

* Estimates are based on single source product incidents as multiple source incidents could be included in multiple categories.

\+ Excludes estimates of deaths associated with EDTs only. Multiproduct-associated incidents are included here because an EDT could not be identified as the only product involved. The one exception to this is the 2001 estimate, which excludes one estimated death associated with a generator and another EDT.

Note 1: The 3-year average mortality rate is reported at the mid-year population estimates.

Note 2: Mortality rate changes from last year’s report are due to changes in CPSC CO death estimates and changes to U.S. Census estimates.

Summary of Tables B.1 – B.5

When all consumer products are considered, there has been a 36 percent increase in the CO mortality rate from a 3-year average mortality rate of 4.34 in 2000, to 6.61 in 2018, as shown in Table B.1. Engine-driven tools and generators have had a substantial impact on the increase in the CO poisoning mortality rate involving consumer products. But, in recent years, non-generator-related CO fatalities have also been on the rise.

Appendix C: Chi-Squared Test Results

Age Group Test Result

Table 7 shows the estimated number of CO poisoning deaths categorized by victim age for the 11 most recent years of data (2009–2019). For the Chi-Square statistical analysis, the two younger groups ("Under 5" and "5−14") were combined, due to their small, estimated averages. Chi-Square goodness-of-fit test results indicate a statistically significant difference between the proportion of CO victims in each age group from the general U.S. population. Each age group was analyzed separately, versus the expected proportion of the respective age group, based on U.S. population figures (assuming there was no age group effect on the CO poisoning fatality rate), to determine which age group proportions were significantly different from expectation. Binomial tests indicate that four of the five individual groups were found to be significantly different from what would be expected if there was no population group effect:

1. The "Under 15" group[7] was significantly lower (< 0.0001).
2. The "15–24" group was significantly lower (0.0020).
3. The "45–64" group was significantly higher (< 0.0001).
4. The "65 and over" group was also significantly higher (< 0.0001).

Gender Group Test Result

Table 8 presents the distribution of estimated CO deaths categorized by gender. For 2017–2019, the average percentage of male CO victims was also 76 percent, and the average percentage of female victims was 24 percent. By contrast, about 49 percent of the U.S. population is male, and 51 percent of the U.S. population is female.[8] The gender-related differences in CO Poisoning deaths were confirmed to be statistically significant (p-value < 0.0001).

Ethnicity/Race Group Test Result

Table 9 provides a summary of CO fatality victims characterized by race/ethnicity for the years 2008 through 2018. Estimates of the percentage of the U.S. population categorized into the various race/ethnicity groupings were based on single-race characterizations, as represented in the U.S. Census Bureau reports. Individuals reported as multi-race are included in the *Unknown/Other/Mixed* category.

Chi-square goodness-of-fit test results indicate a significant statistical difference (p-value = 0.0322) between the proportion of CO victims categorized by race/ethnicity from that of the general U.S. population. Each race/ethnicity group was analyzed separately, versus the expected proportion of the respective race/ethnicity group based on U.S. population figures,

[7] "Under 5" and "5–14" groups were combined due to small sample sizes.
[8] Three-year average, 2016 to 2018, from July 2020 U.S. Census estimates of the U.S. population.

assuming there was no race/ethnicity group effect on the CO poisoning fatality rate. A Chi-Square statistical analysis was performed to determine which race/ethnicity group proportions were significantly greater than or less than the expectation. For the Chi-Square analysis, the three smaller groups (“Asian/Pacific,” “American Indian,” and “Unknown/Other/Mixed”) were combined, due to their relatively small proportion of the U.S. population. Binomial tests indicate that two race/ethnicity groups were statistically significantly different from the expected proportion based on the U.S. population. The observed proportion of Hispanic CO deaths was significantly lower (p-value of 0.0140) than the proportion of Hispanics in the U.S. population. Additionally, the observed proportion of White CO deaths was significantly higher (p-value = 0.0071) than the proportion of White Americans in the U.S. population. In previous years of this report, Black or African Americans demonstrated a significantly higher proportion of CO deaths than their proportion in the U.S. population and White Americans did not. This finding was similarly observed in the most recent previous (which included estimates up until 2018). Although this finding continues to be observed for the second year in a row, it is unclear if this is an anomaly or a pattern change.

Appendix D: Regional Definitions

1) Northeast comprises New England and Middle Atlantic states.
  - **a)** New England: Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, and Connecticut.
  - **b)** Middle Atlantic: New York, New Jersey, and Pennsylvania.

2) Midwest comprises East North Central and West North Central states.
  - **a)** East North Central: Ohio, Indiana, Illinois, Michigan, and Wisconsin.
  - **b)** West North Central: Minnesota, Iowa, Missouri, North Dakota, South Dakota, Nebraska, and Kansas.

3) South comprises South Atlantic, East South Central and West South-Central states.
  - **a)** South Atlantic: Delaware, Maryland, District of Columbia, Virginia, West Virginia, North Carolina, South Carolina, Georgia, and Florida.
  - **b)** East South Central: Kentucky, Tennessee, Alabama, and Mississippi.
  - **c)** West South Central: Arkansas, Louisiana, Oklahoma, and Texas.

4) West comprises Mountain and Pacific states.
  - **a)** Mountain: Montana, Idaho, Wyoming, Colorado, New Mexico, Arizona, Utah, and Nevada.
  - **b)** Pacific: Washington, Oregon, California, Alaska, and Hawaii

Source: U.S. Census Bureau 2012 Statistical Abstract http://www.census.gov/compendia/statab/cats/population.html

References

Hnatov, Matthew V., Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products 2018 Annual Estimates. Washington, D.C.: U.S. Consumer Product Safety Commission. 2021.

Hnatov, Matthew V., *Fatal and Nonfatal Incidents Associated with Non-Fire Carbon Monoxide from Engine-Driven Generators and Other Engine-Driven Tools, 2011–2021*. Washington, D.C.: U.S. Consumer Product Safety Commission. 2022.

Inkster S.E. *Health Hazard Assessment of CO Poisoning Associated with Emissions from a Portable, 5.5 Kilowatt, Gasoline-Powered Generator*. Washington, D.C.: U.S. Consumer Product Safety Commission, 2004.

Long, K., Saltzman, L. (1995). Non-fire Carbon Monoxide Incidents: Morbidity and Mortality Related to the Use of Household Appliances. Washington, D.C.: U.S. Consumer Product Safety Commission.

Mah, J., Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products 1998 Annual Estimates. Washington, D.C.: U.S. Consumer Product Safety Commission. 2001.

U.S. Census Bureau, Population Division*. Annual Estimates of the Resident Population by Sex, Age, Race, and Hispanic Origin for the United States and States: April 1, 2010 to July 1, 2019. June 2020* <https://www2.census.gov/programs-surveys/popest/tables/2010-2019/national/asrh/nc-est2019-sr11h.xlsx>

U.S. Census Bureau, Population Division*. Annual Estimates of the Resident Population for the United States, Regions, States, and Puerto Rico: April 1, 2010 to July 1, 2019 (NST-EST2019-01) <https://www2.census.gov/programs-surveys/popest/tables/2010-2019/state/totals/nst-est2019-01.xlsx>*

U.S. Department of Agriculture, Economic Research Service. *2010 Rural-Urban Commuting Area Codes* <http://www.ers.usda.gov/data-products/rural-urban-commuting-area-codes.aspx>

Center for Rural Health, University of North Dakota School of Medicine and Health Sciences. ***Temporary Zip Ruca 3.10 File Access Page***

U.S. Office of Budget and Management. *OMB BULLETIN NO. 13-01: Revised Delineations of Metropolitan Statistical Areas, Micropolitan Statistical Areas, and Combined Statistical Areas, and Guidance on Uses of the Delineations of These Areas*. February 28, 2013

TAB B: Memorandum from the Directorate for Engineering Sciences, Division of Mechanical Engineering and Combustion

United States
Consumer Product Safety Commission

Memorandum

TO: To file **DATE:** September 20, 2023

FROM: Ronald Jordan, Project Manager
Directorate for Engineering Sciences

SUBJECT: Proposed Performance Requirement to Mitigate Carbon Monoxide Exposure Hazards Associated with Gas Furnaces, Boilers, Wall Furnaces, and Floor Furnaces

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Introduction

On July 31, 2019, U.S. Consumer Product Safety Commission (CPSC) staff submitted to the Commission an advance notice of proposed rulemaking (ANPR) briefing package for a rule to address the risk of injury and death associated with carbon monoxide (CO) production and leakage from residential gas furnaces and boilers.[27] On August 19, 2019, the Commission published an ANPR to develop such a rule. CPSC staff now recommends a proposed rule to reduce CO deaths associated with gas furnaces, boilers, wall furnaces, and floor furnaces (collectively referred to as "furnaces and boilers").

In this memorandum, staff provides the following information:

1. Summary of tests and evaluation conducted by CPSC contractors
2. Staff recommendation for performance requirements for a draft proposed rule

Testing and Evaluation Conducted by Contractors

Tab C contains the findings of contractor research and testing conducted on behalf of CPSC staff to support staff's proposed mandatory performance requirements to mitigate CO exposure hazards associated with gas furnaces, boilers, wall furnaces and floor furnaces. The purpose of this research and testing was to: (1) gain a better understanding of the impact of CO/combustion sensor use in gas appliances in Europe and Japan; and (2) estimate the life span of CO/combustion sensors if used in gas appliances in the U.S.

A CPSC contract for a study on the impact of CO/combustion sensors used in residential gas boilers and water heaters in Europe and Japan was awarded to Guidehouse (formerly Navigant, Inc.) on September 25, 2019, under CPSC contract number 61320619F0133. The purpose of this contract was to gain a better understanding of the use of CO sensors in gas appliances in other parts of the world and their impact in mitigating CO risks associated with gas appliances. This work was commissioned given industry concerns about the feasibility of using sensors in the exhaust flue of gas furnaces and boilers. Work on this contract concluded in 2021 and the findings are documented in a contractor report titled, "Review of Combustion Control and Carbon

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[27] Performance Requirements Residential Gas Furnaces and Boilers. Retrieved at: https://cpsc.gov/s3fs-public/Draft%20ANPR%20-%20Performance%20Requirements%20for%20Residential%20Gas%20Furnaces%20and%20Boilers.pdf

Monoxide Sensors in Europe and Japan," dated June 28, 2021. The contractor report is included as Attachment 3 to this memorandum. This contractor report examined:

- regulations and standards governing CO production by gas space heating and water heating appliances in the European Union (EU) and Japan;
- technologies used in the European and Japanese markets to meet these regulations and standards;
- the effectiveness of these regulations in reducing injuries and deaths from CO poisoning caused by gas space heating and water heating appliances; and
- how the EU and Japanese space heating and water heating markets compare to the United States (US) market.

Two CPSC contracts to estimate expected lifespans of CO/combustion sensors while operating in a furnace or boiler application The first contract was awarded to ANSYS (formerly DfR Solutions, Inc.) on September 21, 2016, under Department of Health and Human Services contract number HHSP233201650108A. Work on this contract concluded in 2019 and the findings documented in a contractor report titled "Performance and Accelerated Life Testing of Carbon Monoxide and Combustion Sensors," dated May 28, 2019. This report is included in Attachment 1, Tab C of this memorandum. The second contract was awarded to ANSYS on September 26, 2018, under CPSC contract number 61320618P0050-1. Work on this contract concluded in early 2022 and the findings were documented in the contractor report titled, "Performance and Accelerated Life Testing of Redesigned Carbon Monoxide and Combustion Gas Sensors," dated February 25, 2022. The ANSYS report is included as Attachment 2 of this memorandum. The accelerated life test contractor work demonstrated that CO/combustion sensors are currently commercially available for use in gas appliances; the CO/combustion sensors that were tested have expected lifespans ranging from 6.4 to 10 years operating under conditions that replicate the main stress conditions expected within a gas appliance. Appliances with design platforms based on premix power burners are better suited to incorporate combustion control because they typically have a single burner, a single heat exchanger cell, and a single flame ionization sensor to monitor the burner flame.

Staff Proposed Performance Requirements

This memorandum provides staff's proposed mandatory performance requirements to mitigate CO exposure risks associated with gas central furnaces, boilers, wall furnaces, and floor furnaces. Staff determined the draft proposed performance requirements are reasonably necessary and feasible for the following reasons:

1. The gas appliances under consideration are associated with an estimated 21 deaths per year, on average (2017-2019) and an estimated total of 539 CO deaths from 2000 to 2019;[28]
2. The existing voluntary standards do not include provisions that would protect consumers from a number of conditions[29] known to cause or contribute to the production of dangerous concentrations of CO or the leakage of CO into the living space of a dwelling;
3. There is no indication that the Z21/83 Technical Committee or any of the technical Subcommittees for gas furnaces, boilers, wall and floor furnaces intend to address this hazard;

[28] "*Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products 2019 Annual Estimates,"* CPSC. J. Topping, January 2023.

[29] Described earlier within Tab C and within this briefing memorandum under Hazard Patterns

4. From a technological standpoint, any potential solution that sought to limit CO production through modulation or appliance shutoff, would likely need to involve continuous monitoring of either the combustion process or the concentration of carbon monoxide within the combustion gases which could be accomplished using commercially available CO/combustion sensing or combustion control technology.

Staff recommends the proposed performance requirements described in this section to reduce the occurrence of CO-related deaths, injuries, and exposures associated with gas furnaces and boilers. Specifically, these appliances would be required to continuously monitor CO emissions and shut down or modulate its combustion if any of the average CO ranges specified in Table 1[30] are detected in the appliance flue gases for the durations listed.

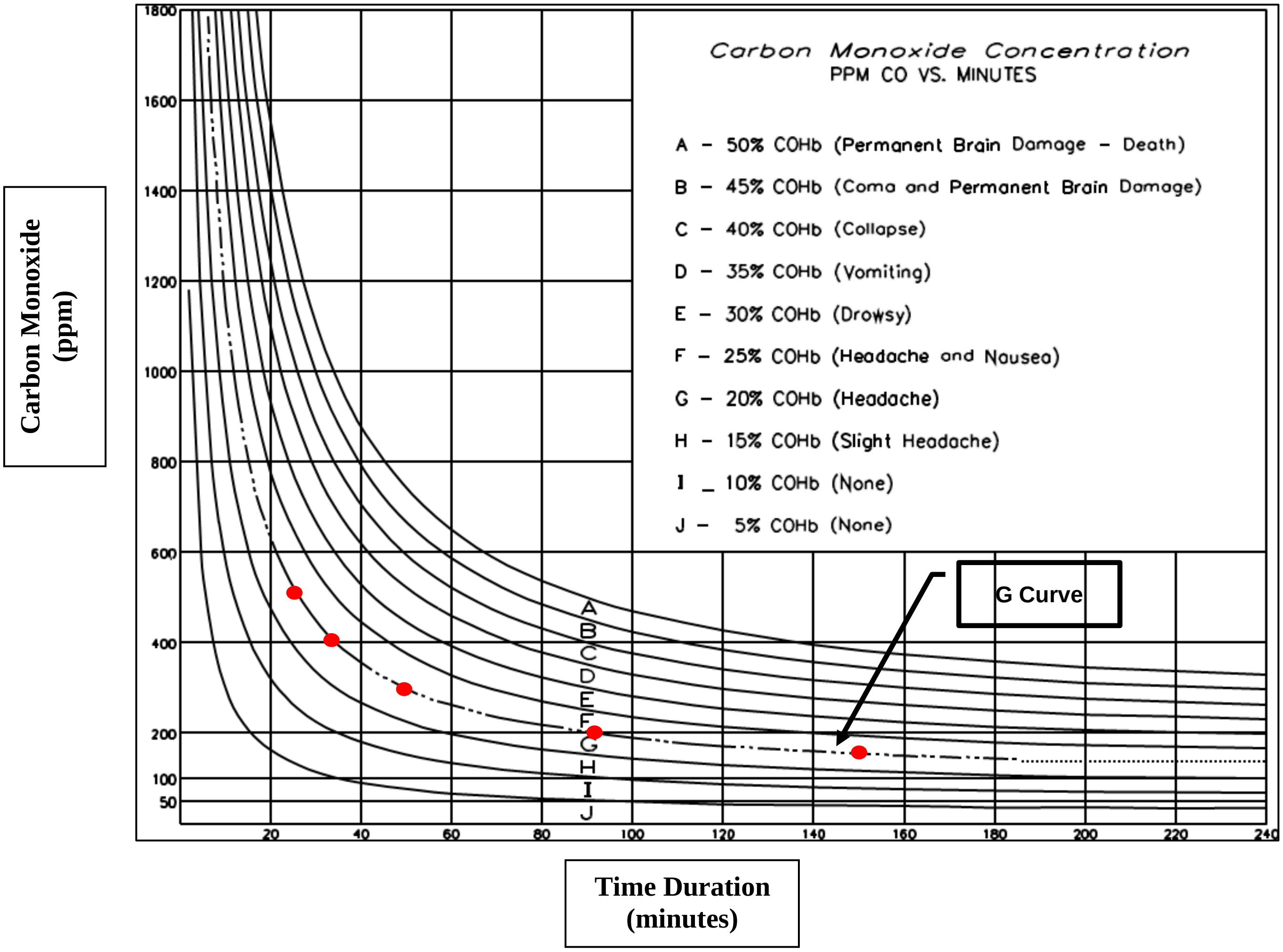
Table 1. CO ranges and durations for shut-down or modulation

Average CO (ppm)	Duration (minutes)
500 or above	15
400-499	30
300-399	40
200-299	50
150-199	60

The average CO ranges in Table 1 are the proposed setpoints and durations at which a gas furnace or boiler shall either shut-down or begin modulation. These CO ranges are based on Curve G of the CO Concentration vs. Time graph (Figure 41.1 excerpted from UL 2034) below which indicates what an individual's carboxyhemoglobin (COHb) levels would be if exposed to various CO concentrations and the time of exposure needed to reach that COHb level. Curve G represents a 20 percent COHb level and the onset of health effects in individuals (i.e., headaches). The values on the y-axis represent CO exposure levels in parts per million (ppm) from zero ppm CO to 1800 ppm CO. The values on the x-axis represents the time durations (in minutes) of exposure to the CO concentrations presented on the y-axis. The curves on the graph, A through J represent the various carboxyhemoglobin levels an individual can reach when exposed to CO (y-axis) over a period of time (x-axis).

[30] The proposed CO range setpoints and durations reflected in Table XX are derived from UL 2034, Standard for Safety Single and Multiple Station Carbon Monoxide Alarms, 4th Edition, (2017), the voluntary standard for in-home carbon monoxide alarms. UL 2034 provides requirements for electrically operated single and multistation CO alarms intended for protection in ordinary indoor locations of dwelling units. Section 41.1 of UL 2034 provides the levels at which a carbon monoxide alarm must trigger. Section 1.2 of UL 2034 covers carbon monoxide alarms intended to respond to the presence of carbon monoxide from various sources, including the abnormal operation of fuel-fired appliances.

Figure 1 (Based on Figure 41.1 in UL 2034)
Carbon monoxide concentration versus time



To interpret the graph in Figure 1, begin at a given CO concentration on the y-axis, extend a horizontal line to the right until the line intersects a COHb curve. At the point of intersection, extend a vertical line downwards until it crosses the x-axis. The time value at this point of intersection represents the amount of time, at the selected CO concentration, at which an individual would reach a certain COHb level. For example, at a 400 ppm CO concentration, it would take approximately 35-minutes for an individual to reach a COHb of 20% since a 400 ppm CO level intersects the 20% COHb curve (i.e., Curve G) at @35-minutes on the x-axis. At a CO concentration of 300 ppm, it would take approximately 50-minutes to reach a COHb of 20% since a 300 ppm CO level intersects the 20% COHb curve (i.e., Curve G) at @50-minutes. At a CO concentration of 200 ppm, it would take approximately 90-minutes to reach a COHb of 20% since a 200 ppm CO level intersects the 20% COHb curve (i.e., Curve G) at @90-minutes. At a CO concentration of 150 ppm, it would take approximately 160-minutes to reach a COHb of 20% since a 50 ppm CO level intersects the 20% COHb curve (i.e., Curve G) at @160-minutes. The red dots on the graph in Figure 41.1 illustrate that the entire proposed CO response range (i.e., 150 - 400 and above) all fall on Curve G. A performance requirement that requires shut-down or modulation of a gas furnace or boiler at this range of CO levels provides protection to consumers from the onset of the more serious CO-related health effects, such as vomiting, coma, and death.

The proposed performance requirement for the range and time period for CO exposure is consistent with the existing UL 2034 standard for consumer carbon monoxide alarms which use similar requirements to protect consumers from CO exposure in the home.

An alternative option would be to either shut down or begin modulation of the gas furnace or boiler if the average CO level reaches 150 ppm over a 15-minute duration. This alternative simplifies the performance requirement to a single CO setpoint rather than multiple setpoints as described above. It provides the same level of protection as the multiple setpoint approach described above because the furnace will shut down or modulate at the lowest threshold of CO production (150 ppm) that can result in low-level health effects (i.e., headache per the 20% COHb curve). The short time duration (15-minutes) is protective at higher CO concentrations of 200 ppm or more that can begin to cause the onset of health effects (i.e., headache per the 20% COHb curve).

These proposed performance requirements are also based, in part on, on the definitions and performance requirements in ANSI Z21.47, *Standard for Gas-fire central furnaces*; ANSI Z21.13, *Standard for Gas-fired low pressure steam and hot water boilers*; and ANSI Z21.86, *Standard for Vented Gas-Fired Space Heating Appliances*, as well as performance requirements from the Committee for European Standardization (CEN)[31,32] standards for domestic gas boilers, and CEN standards for safety and control devices for gas appliances[33,34] and gas/air ratio controls for gas appliances,[35] and Japanese Industrial Standards (JIS) standard for domestic gas water heaters, boilers and space heaters.[36,37,38] The CEN and JIS standards were selected as the basis for staff's proposed performance requirements for the following reasons:

1. **European and Japanese standards for gas boilers already exist that have performance requirements similar to the staff's proposed performance requirements**. The CEN and JIS standards for gas boilers include provisions that give European and Japanese manufacturers the option of appliance shutoff or combustion control to prevent or limit the production of CO to acceptable levels. The provisions in these standards are: (1) very similar to staff's proposed performance requirements for gas furnaces and boilers in this NPR, as well as staff's past CO shutoff/response proposals submitted to the ANSI Z21 standards for gas furnaces and boilers; and (2) can be applied to U.S. gas furnaces and boilers.
2. **European standards for CO/combustion sensors and combustion controls used in gas boilers already exist**. The CEN standards for safety and control devices include performance provisions for combustion product sensing devices (including CO/combustion sensors) and combustion control devices for gas appliances (e.g., gas/air ratio controls) that can be applied to U.S. gas furnaces and boilers.
3. **The operating environments of European and Japanese gas boilers are similar to**

[31] EN 15502-2-1, *Gas-fired central heating boilers, Part 2-1: Specific standard for type C appliances and Type B2, B3 and B5 appliances of a nominal heat input not exceeding 1 000 kW.*
[32] EN 15502-2-2, *Gas-fired central heating boilers Part 2-2: Specific standard for type B 1 appliances.*
[33] BS EN 13611, Safety and control devices for burners and appliances burning gaseous and/or liquid fuels — General requirements.
[34] BS EN 16340, Safety and control devices for burners and appliances burning gaseous or liquid fuels — Combustion product sensing devices.
[35] Gas/air ratio controls for gas burners and gas burning appliances — Part 2: Electronic types
[36] JIS-S-2109, *Gas burning water heaters for domestic use*.
[37] JIS-S-2112. *Gas hydronic heating appliances for domestic use.*
[38] JIS-S-2122, *Gas burning space heaters for domestic use*.

operating environment in U.S. gas furnaces and boilers. Although there are significant differences between the design platforms of European and Japanese gas boilers (i.e., predominantly premix power burner designs) and U.S. gas furnaces, boilers, wall furnaces and floor furnaces (i.e., predominantly induced draft and some atmospheric vent designs), the basic operating environment parameters (e.g., temperature, humidity, and combustion gases) within the heat exchangers and flues of European and Japanese gas boilers and U.S. gas furnaces and boilers are similar. This demonstrates the commercial availability of CO/combustion sensors and combustion controls that (1) provide CO/combustion sensor-based shutoff or reduced CO through combustion control; (2) are durable enough to survive in heat exchangers or flues of gas appliances, despite concerns, raised by the ANSI Z21 Technical Committee and Technical Subcommittees for gas furnaces and boilers, that such devices were not available; and (3) can be applied to U.S. gas furnaces and boilers.

Staff proposes specific test methods to introduce a simulated 400 ppm, 300 ppm, 200 ppm and 150 ppm CO emission level into the exhaust gas to determine if the safety system passes or fails the proposed performance requirements. The following section describes staff's recommended regulatory text for the draft proposed rule to establish a safety standard for Gas Central Furnaces (i.e., furnaces), Gas Steam and Hot Water Boilers ("boilers"), and Gas Wall Furnaces and Floor Furnaces. This regulatory text includes general provisions, such as scope and definitions, as well as the recommended performance requirements for these products.

Staff assesses that the proposed rule would be 90 to 100 percent effective in preventing CO deaths and injuries associated with gas furnaces and boilers because CO production at the appliance would be limited to levels that produce a headache in exposed consumers. Staff's assessment is based on the following key metrics used to assess the capability of the performance requirement in protecting consumers from these CO exposure risks:

1. Detecting CO at the source of production. This provides a greater level of protection to consumers (than residential CO alarms) because it detects CO at the source of production within the gas appliance, before it leaks into a dwelling, and allows for an earlier response time to protect consumers.
2. Prevents or limits production of harmful levels of CO. Shutoff or modulation of the appliance provides a greater level of protection since this directly addresses harmful CO production by requiring the appliance to provide a direct shutoff or modulation response.
3. Selecting CO response concentrations that fall on the 20 Percent COHb curve. Selecting multiple CO response concentrations or a single, threshold CO concentration (150 ppm or higher) that would limit the severity of any potential health effects to a headache (i.e., the 20 percent COHb curve).
4. Addresses all of the known hazard patterns. Although the performance requirements do not prevent combustion product (including CO) leakage, it protects against any harm that leakage of combustion products would cause by limiting/preventing CO production. The performance requirement would address all of the known hazard patterns.
5. Conforms to the Z21/83 Technical Committee's Two-Failure Philosophy. The ANSI Z21/83 Technical Committee has stated that the following two failures must exist in order for a vented gas appliance to pose a CO hazard: 1) production of excessive CO; and 2) leakage

of excessive CO into the living space.[39,40] The proposed rule addresses the excessive CO failure directly by either preventing excessive CO production through shutoff or by limiting CO production through modulation. The proposed rule addresses leakage of CO indirectly, through shutoff or modulation.

Staff Proposed Regulatory Text

16 C.F.R part xxxx: Safety Standard for Gas Furnaces and Boilers

§ xxxx.1 Scope, Purpose, Effective Date

(a) Scope and purpose. This part establishes performance requirements for residential gas furnaces, boilers, and wall and floor furnaces that are consumer products used to heat dwellings, including single family homes, townhomes, condominiums, and multifamily dwellings, as well as multi-family buildings such as apartments and condominiums. The purpose of this requirement is to reduce the occurrence of carbon monoxide-related deaths, injuries, and exposures associated with gas furnaces, boilers, and wall and floor furnaces.

(b) Effective Date. All residential gas furnaces/boilers that are manufactured after [INSERT 18 MONTHS AFTER PUBLICATION IN THE FEDERAL REGISTER] are subject to the requirements of this part.

§ xxxx.2 Definitions

Gas Central Furnace means a gas-burning appliance that heats air by the transfer of heat of combustion through a metal heat exchanger to the air and designed to supply heated air through ducts to spaces remote from or adjacent to the appliance location.

Gas Floor Furnace means a furnace suspended between the floor joists of the space being heated. A floor furnace provides direct heating of the room it is located in and to adjacent rooms.

Gas Steam and Hot Water Boiler means a gas burning appliance that heats steam at a pressure not exceeding 15 psi (100 kPa), or hot water at a pressure not exceeding 160 psi (1100 kPa) and at a temperature not exceeding 250 °F (121 °C). The heated steam or water is then pumped to spaces remote from or adjacent to the appliance location through piping to radiators at each of these spaces where the heat of combustion is transferred through the metal radiator to heat the air around the radiator within the space it is located in.

Gas Wall Furnace means a gas appliance installed within a wall between wood construction members and that provides heated air directly to the room it is installed in and to adjacent rooms through grilles.

§ xxxx.3 Performance **Requirement for Gas Furnaces and Boilers**

(a) *General.* All residential vented gas furnaces, boilers, wall furnaces, and floor furnaces shall have a means to either directly or indirectly monitor the concentration of carbon monoxide (CO)

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[39] Letter from the Gas Appliance Manufacturer's Association (GAMA) to R. Jordan, CPSC. August 7, 1998.
[40] Letter from the Z21/83 Accredited Standards Committee to R. Jordan, CPSC. July 16, 1998.

produced during the combustion process (*i.e.*, “CO emissions”) and shut down or modulate combustion to reduce average CO concentrations to below the CO levels for the durations of time specified in Table 1 and paragraph (b) of this section. If CO emissions reach or exceed the limits and time durations specified in Table 1 and paragraph (b), then the gas furnace or boiler shall either shut down or modulate combustion to reduce CO emissions to below 150 ppm. If average CO levels range between 200 and 299 ppm for 50 minutes, then the gas furnace or boiler shall either shut down or modulate combustion to reduce emissions to below 150 ppm. Indirect monitoring and controlling of CO emissions can be accomplished by monitoring and controlling other combustion parameter(s) that accurately correlate to the production of CO. Examples of parameters that can serve as a proxy for CO production include carbon dioxide (CO_2), oxygen (O_2), the Gas/Air Ratio, and the flame ionization current produced by the burner flame.

(b) *Performance Requirement for Gas Furnace, Boiler.* A gas furnace, boiler, wall furnace or floor furnace shall be equipped with a means to continuously monitor CO emission and must meet requirements below when tested to the test method described in paragraph (c) .

(1) Direct means to monitor CO emissions

Multipoint method
A gas furnace, boiler, wall furnace, or floor furnace equipped with a means to directly monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of appliance combustion, each in response to the following conditions within the appliance:

a) Average CO concentration is 500 ppm or higher for 15-minutes;
b) Average CO concentration between 400 ppm and 499 ppm for 30-minutes;
c) Average CO concentration between 300 ppm and 399 ppm for 40-minutes;
d) Average CO concentration between 200 ppm and 299 ppm for 50-minutes;
e) Average CO concentration between 150 and 199 ppm for 60-minutes.

Single Point method
Alternatively, a gas furnace, boiler, wall furnace, or floor furnace equipped with a means to directly monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of appliance combustion, in response to the following conditions within the appliance:

f) Average CO concentration of 150 ppm or higher for 15-minutes.

Shutdown or modulation of the appliance shall begin immediately after any of the conditions described in a) through e) are reached or the alternative condition described in f) is reached. After modulation begins, the CO concentration within the appliance shall be reduced to below 150 ppm within 15 minutes.

(2) Indirect means to monitor CO emissions

Multipoint method
A gas furnace, boiler, wall furnace, or floor furnace equipped with an indirect means to monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of combustion of the appliance, each in response to the combustion conditions that correlate to the following conditions within the appliance:

a) Average CO concentration is 500 ppm or higher for 15-minutes;
b) Average CO concentration between 400 ppm and 499 ppm for 30-minutes;
c) Average CO concentration between 300 ppm and 399 ppm for 40-minutes;
d) Average CO concentration between 200 ppm and 299 ppm for 50-minutes;
e) Average CO concentration between 150 and 199 ppm for 60-minutes.

Single Point method
Alternatively, a gas furnace, boiler, wall furnace, or floor furnace equipped with a means to indirectly monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of combustion within the appliance, in response to the following condition within the appliance:

f) Average CO concentration of 150 ppm or higher for 15-minutes.

Shutdown or modulation of the appliance shall begin immediately after any of the conditions described in a) through e) are reached or the alternative condition described in f) is reached. After modulation begins, the CO concentration within the appliance shall be reduced to below 150 ppm within 15 minutes.

(3) Fail Safe
During the life of the appliance, if a CO sensor, combustion sensor, combustion control system, or other device designed to meet these requirements, fails to operate properly or at all, then the appliance shall shutdown and restart after 15 minutes and repeat this cycle until the failed component is replaced. Consumers and service technicians shall be notified of device failure by either a flashing light, or other appropriate code on the appliance control board, that corresponds to the device failure.

(c) *Test Configuration.* The furnace or boilers shall be configured in the following manner:

Gas Furnaces, boilers, wall furnaces, and floor furnaces shall each be set up with the burner and primary air adjusted in accordance with the provisions of the Combustion sections of the respective voluntary standards (section 5.8.1 of CSA/ANSI Z21.47:2016 for gas furnaces; section 5.5.1 of CSA/ANSI Z21.13:22 for gas boilers; and sections 9.3.1, 11.2.1, and 13.3.1, of ANSI Z21.86-2016 for gas wall and floor furnaces). These tests shall be conducted in an atmosphere having normal oxygen supply of approximately 20.94 percent.

Burner and primary air adjustments shall be made for furnaces, boilers, wall furnaces, and floor furnaces in accordance with the provisions of each respective standard (section 5.5.4 of CSA/ANSI Z21.47:2016 for gas furnaces; section 5.3.1 of ANSI Z21.13 for gas boilers; and section 5.3.4 of ANSI Z21.86 for gas wall and floor furnaces).

After adjustment, and with all parts of the furnace, boiler, wall furnace, or floor furnace at room temperature, the pilot(s), if provided, shall be placed in operation and allowed to operate for a period of 5 minutes. The main burner(s) shall then be placed in operation and the appliance operated for 3 minutes at normal inlet test pressure at which time a sample of the flue gases shall be secured. Immediately upon securing the sample at normal inlet test pressure, the reduced inlet test pressure (section 5.5.1 of CSA/ANSI Z21.47:2016; section 5.3.1 and 5.3.3 of ANSI Z21.13;

and section 5.3.1 of ANSI Z21.86) shall be applied and, following a purge period of at least 2 minutes, another sample of the flue gases shall be secured. For atmospheric burner units, samples shall be secured at a point preceding the inlet to the unit's draft hood or flue outlet where uniform samples can be obtained. The flue gas sample shall be analyzed for carbon dioxide and carbon monoxide. The concentration of carbon monoxide for the flue gas samples shall not exceed 150 ppm in a sample of flue gases after 15 minutes.

(d) *Test Procedure*. To test a furnace, boiler, wall furnace, or floor furnace to the performance requirements specified in (b) of this section, induce the production of carbon monoxide (CO) or related combustion parameters, using one or a combination of the following methods shall be used:

1. Progressively increase the gas control valve's outlet pressure until the unit produces a CO concentration of approximately 150 ppm ±10 ppm CO. For natural gas units, use a propane conversion kit to achieve the desired CO concentration if this was not accomplished by increasing the gas valve's outlet pressure. For propane units, use either option (2) or (3) below. If neither option results in a CO concentration of approximately 150 ppm, then use both options (2) and (3) below. Once a CO concentration of at least 150 ppm is achieved, that condition shall be maintained for 15 minutes.

2. Progressively block the exhaust vent or flue outlet until the unit produces approximately 150 ppm ±10 ppm CO. Disable the unit's blocked vent shutoff switch (BVSS) if necessary, in order to achieve the desired CO concentration. Once a CO concentration of approximately 150 ppm is achieved, that condition shall be maintained for 15 minutes.

3. Reduce the fan speed of the inducer motor or premix power burner (for induced draft or premix power burner units only) by reducing the supply voltage to 85 percent of the appliance rating plate voltage until the unit produces a CO concentration of approximately 150 ppm ±10 ppm CO. An additional combustion sample shall be secured with the appliance operating at normal inlet test pressure and with the supply voltage reduced to 85 percent of the appliance rating plate voltage. This sample shall be secured 15 minutes after the furnace has operated at the reduced voltage. The input rating may vary from normal as a result of the voltage reduction. Once a CO concentration of approximately 150 ppm is achieved, that condition shall be maintained for 15-minutes.

For appliances that employ modulation (e.g., using a Gas/Air Ratio Controller, an automatic step-rate control, or automatic modulating controls, etc.) the unit shall immediately begin modulation to reduce the CO concentration to below 150 ppm. For appliances that do not employ modulation, the unit shall shut down. The time for the gas to the main burner(s) to be shut off by the device used to directly or indirectly monitor CO emissions shall be as follows:

1. After 15-minutes at an average CO concentration of 500 ppm or more.
2. After 30-minutes at an average CO concentration of 400 ppm-499.
3. After 40-minutes at an average CO concentration of 300-399 ppm.
4. After 50-minutes at an average CO concentration of 200-299 ppm.
5. After 60-minutes at an average CO concentration of 150-199 ppm.

Alternatively, a gas furnace, boiler, wall furnace, or floor furnace equipped with a means to directly monitor CO emissions, shall either: 1) cause shut-down of the appliance, or 2) cause modulation of combustion within the appliance, in response to the following single, condition within the appliance:

1. Average CO concentration of 150 ppm or higher for 15-minutes.

Shutdown or modulation of the appliance shall begin immediately after any of the conditions described in a) through e) are reached or the alternative condition described in f) is reached. After modulation begins, the CO concentration within the appliance shall be reduced to below 150 ppm within 15 minutes.

TAB C: Contractor Reports with cover memos

ATTACHMENT 1

Review of Combustion Control and Carbon Monoxide Sensors in Europe and Japan

Final Report

Prepared for:

United States Consumer Product Safety Commission

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ANPR	Advanced Notice of Proposed Rulemaking
ANSI	American National Standards Institute
BOP	Balance-of-plant
CCPC	Competition and Consumer Protection Commission
CEN	European Committee for Standardization
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPSC	United States Consumer Product Safety Commission
CPDSD	Combustion Product Safety Discharge Device
CPSD	Combustion Product Sensing Device
C_xH_y	Hydrocarbons
DOE	United States Department of Energy
EEC	European Economic Community
EEPROM	Electrically erasable programmable read-only memory
EN	European Standards (European Norms)
EU	European Union
GARC	Gas Air Ratio Control
H_2	Hydrogen
H_2O	Water
HSE	Health and Safety Executive
HVAC	Heating, Ventilation, and Air-conditioning
ICPD	Incomplete Combustion Prevention Device
JIS	Japanese Industrial Standards
JSA	Japanese Standards Association
kW	kilowatts
LNG	Liquified natural gas
LPG	Liquified petroleum gas
METI	Ministry of Economy, Trade, and Industry
NITE	Japanese National Institute of Technology and Evaluation
NO_X	Nitrogen Oxides
O_2	Oxygen
OEM	Original Equipment Manufacturer
PCB	Printed circuit board
R&D	Research and development
RH	Relative humidity
SO_2	Sulfur Dioxide
UK	United Kingdom
US	United States
WHO	World Health Organization

DISCLAIMER

EXECUTIVE SUMMARY

This report examines the following topics: regulations and standards governing carbon monoxide (CO) production by gas space heating and water heating appliances in the European Union (EU) and Japan; various technologies being used in the European and Japanese markets to meet these regulations; and the effectiveness of these regulations in reducing injuries and deaths from CO poisoning caused by gas space heating and water heating appliances. This report also explores how the EU and Japanese space heating and water heating markets compare to the United States (US) market.

Guidehouse, Inc. (Guidehouse) initially identified and reviewed the regulations and standards that govern the allowable CO production in gas-fired combustion space heating and water heating appliances in Europe and Japan. We then conducted market research and obtained boilers and water heaters from Europe and Japan for physical examination to gain an understanding of the technologies being used in the European and Japanese markets to reduce CO production of gas-fired combustion space heating and water heating appliances. Finally, we interviewed and/or surveyed European and Japanese manufacturers and regulators to gain a better understanding of the applicable regulations and the technologies used to meet the requirements.

In Europe, gas appliance safety is governed by Regulation (EU) 2016/426 on appliances burning gaseous fuels, and compliance with the applicable standard published by the European Committee for Standardization (CEN) is generally considered as a way to demonstrate compliance with the law. In Japan, the Gas Business Act and the Act on the Securing of Safety and the Optimization of Transaction of Liquefied Petroleum Gas require that a manufacturer or importer ensure that the gas-fired equipment conforms to the technical standards established by an Ordinance of the Ministry of Economy, Trade and Industry. Multiple agencies in Japan develop standards, including Japanese Standards Association (JSA), which publishes Japanese Industrial Standards (JIS), and the Japan Gas Appliances Inspection Association (JIA). The governing standards in both the EU and Japan provide general requirements for construction and performance of gas-fired space heating and water heating appliances, as well as specific requirements for the allowable CO production under certain specified conditions.

In the EU, in general, the amount of CO produced by boilers under normal operation must not exceed 1,000 parts per million (ppm) (or 0.10%) in the flue gases. There are also requirements for the amount of CO produced during certain "limit conditions" and "special conditions," with limitations on the amount of CO that can be produced under certain circumstances (usually 1,000 ppm or 2,000 ppm). In all cases, units must either adjust the combustion to reduce the amount of CO produced or shut off when these conditions are present. In Japan, various requirements exist, depending on the type of water heater. For certain water heaters, the amount of CO in the room and adjacent room must remain below 300 ppm (or 0.03%) during testing. For these water heaters, the Japanese standards require inclusion of an incomplete combustion prevention device (ICPD) to close the gas passage to the burner before CO concentration in the atmosphere of the laboratory reaches 300 ppm. For other types of water

heaters, an ICPD is not required, but the CO produced during combustion must be below 1,400 ppm (0.14%) during windless conditions or 2,800 ppm (0.28%) for windy conditions.

Through market research, reverse engineering (i.e., "teardown") analysis of European and Japanese products, and discussions with manufacturers, Guidehouse identified multiple ways that manufacturers ensure compliance with the CO limitations in the applicable standards:

- In Europe, premix combustion systems with power burners and controls that indirectly limit CO production by ensuring proper air-fuel ratios are common. Systems with minimal excess air may need CO sensors in the flue gas as flame ionization sensors alone may not be sufficient to detect the conditions that lead to and prevent CO production.
- In Japan, Guidehouse identified similar technologies and approaches. Some manufacturers also indicated that for certain types of water heaters in Japan, the CO limitations can be met with an oxygen depletion sensor (ODS).[1]

Guidehouse evaluated each of these technologies to assess their impact on the design of the appliance, and associated effects on cost, operation, maintenance, and lifetime. For products in the European and Japanese markets, we found limited evidence of increased maintenance or reduced lifetime, as most manufacturers of those products indicated the devices are designed to last from 10 years to the lifetime of the equipment and/or are easily replaceable if failure occurs.

The cost of adding CO control measures to an appliance depends on multiple factors, such as the combustion technology the appliance is using, the sophistication of the extant control system, the availability of line power, and the stringency of the targeted CO limits. Table ES-1 shows a summary of the costs for various implementations of these technologies, as observed in Japanese and European units that were reverse-engineered for this report, and they are discussed in detail in section 3 of this report. These costs represent the ongoing increased costs from additional materials, labor, and overhead, but do not include one-time expenditures associated with product redesign, updates to product literature, certification costs, etc.

Table ES-1: Summary of Estimated Manufacturer Costs to Implement Technologies Used in Europe and Japan to Limit CO Production during Combustion

Technology	Est. Manufacturing Cost*
Integrated Flue CO Sensor Package	$12-$29
Integrated Flame Ionization	$5-$18

* The estimated costs include all components such as the sensor, wiring, fasteners, and additional printed circuit board (PCB) components, etc., as applicable, including the material, labor, and overhead costs associated with each component. The ranges reflect differences in purchasing volumes with the low end reflecting purchase volumes of 1,000,000 and the high end reflecting purchasing volumes of 10,000.

[1] An ODS is designed to shut off the burner when the oxygen level in the room falls below a safe threshold. In the US, they are commonly used in vent-free gas log sets / room heaters, for example.

Unlike the power burners generally used in EU and Japanese appliances whose CO-controls the team reversed-engineered, residential US appliances generally use inducer-based or atmospheric (i.e., no exhaust blower) venting systems. In Japan and Europe, increasing energy efficiency has driven the market away from atmospherically-vented products. In the US, atmospherically-vented residential gas boilers, wall furnaces, and floor furnaces are still prevalent in lower efficiency equipment. Nearly all residential gas central furnaces use an inducer-based combustion system, and most high efficiency water heaters and boilers similarly use fan-assisted combustion (i.e., induced or forced draft). Although products with power burners are available on the US market, the appliance categories in which power burners are common in the US typically consist of imported products or appliances that were assembled domestically from imported components (e.g., tankless water heaters, condensing boilers).

Some atmospherically vented appliances in the US rely on just a pilot light and a mechanical thermostat to control the gas valve. Depending on the level of CO control desired, devices without access to line power would likely be the most difficult and expensive to retrofit with CO controls. Further, we did not identify any CO sensors or combustion control strategies on the market that have been demonstrated in atmospherically-vented systems, as the systems identified in Japan and Europe that utilize a CO sensor also incorporate a power burner. Even if the technical challenges with implementing a CO sensor in an atmospheric appliance (e.g., withstanding the harsh combustion environment, maintaining accuracy in presence of certain combustion gases) can be overcome, the costs associated with upgrading and certifying low-volume appliances in terms of required research and development, capital costs to change production and assembly processes, and updating safety certification could be prohibitive. This is especially relevant in industries with declining sales like floor furnaces or direct heating equipment, where justifying additional investments is difficult, if not impossible.

For inducer-based systems, a flame-ionization system meant to monitor the air-fuel ratio may also have implementation challenges and may only be cost-effective in appliances with just one or two burners, if it can even be proven to work like it has in power burner systems. Appliances with multiple burners would likely need one flame sensor rod per burner, which our research suggests quickly becomes cost prohibitive compared to other approaches and makes an approach involving combustion control via a CO sensor more likely. Although a CO sensor may be a viable approach for these products, we note that sensors observed in Europe and Japan were installed in high efficiency appliances with low NO_x emissions and their performance has not been demonstrated in the comparably low-efficiency, high NO_x appliances that are still widely available in the US.

Systems with power burners and sophisticated control systems like the ones found in the models the team reverse-engineered would likely have little or no implementation costs other than the regulatory/testing hurdles, assuming the flame sensor approach can meet the lower limits proposed by the CPSC. Higher CO limits might be in order to accommodate operating principles of each sensor technology.

Some concerns with implementing sensors or combustion control strategies for limiting CO in the US that are similar to those used in Japan and Europe include: 1) limited suppliers of commercially available CO sensors capable of meeting the needs of the target application (we identified only one supplier of a commercially-available CO sensor currently on the market and in use in residential gas appliances in Europe or Japan, although we note that other suppliers have or have had similar CO sensors on the market even though they are not currently found in residential gas space and water heating appliances; in addition, there is one manufacturer with its own in-house design which suggests manufacturers could decide to develop a CO sensor); 2) reliability concerns for US appliances due to differences in installation and maintenance practices in the US as compared to Japan and Europe; 3) the aforementioned technical challenges with applying these technologies to atmospherically-vented appliances; and 4) increased product costs. In section 3.6 of this report, these issues are explored in greater detail.

Guidehouse researched trends in CO deaths and injuries from gas-fired space heating and water heating appliances in the EU and Japan. For the EU, we were unable to obtain comprehensive annualized statistics of CO-related incidents caused by gas-fired space heating and water heating appliances over time that would be necessary to analyze the trends and evaluate the effectiveness of the standards and regulations for the entire EU. However, we found numerous data sources for the United Kingdom (UK) and evaluated those sources as a proxy for the broader EU. In addition, we sought feedback from manufacturers regarding their experiences and knowledge of CO-related injuries and deaths in the EU. The anecdotal impressions conveyed by manufacturers is that injuries and deaths from CO poisoning caused by gas-fired space heating and water heating appliances have generally been decreasing over time. This feedback aligns with the UK data, which generally showed decreases in the number of CO injuries and deaths caused by gas-fired appliances from the mid-1990s to the present.

For Japan, the National Institute of Technology Evaluation (NITE) supplied us with CO incident data dating back to 1996, which classified incidents by severity and cause. Gas-fired appliances were responsible for the majority of CO incidents and deaths over the time period. However, after the introduction of the requirement to include an ICPD for certain water heaters, the number of CO incidents and deaths from gas appliances has decreased along with the proportion of the total CO incidents and deaths that are caused by gas-fired appliances.

While data from the EU (in particular the UK) and Japan show that the number of injuries and deaths from CO poisoning incidents caused by gas space heating and water heating appliances have decreased over time, it is not clear how much of the decrease is attributable to regulations as compared to other factors. For Europe, manufacturers noted that the increase in market share of direct vent sealed systems, improved combustion controls, better maintenance practices, and increasing trends to change from gas-fired space heating and water heating appliances to electric products could be contributing factors to a decline in CO poisoning incidents.

In summary, the EU and Japan have regulations requiring that gas space heating and water heating appliances operate safely, and the technical standards used to demonstrate safe operation include requirements on the production of CO in gas space heating and water heating appliances. There are a variety of strategies for complying with the regulations and standards, including both direct monitoring of the CO level in flue gases and indirectly limiting production of CO by ensuring complete combustion occurs based on other characteristics of combustion (e.g., flame characteristics). Since the implementation of regulations and the widespread adoption of improved combustion control and sensor technologies that meet the requirements of the standards in the EU and Japan, both the EU and Japan have seen a reduction in the number of deaths and injuries that are caused by CO poisoning due to a gas-fired space and/or water heating appliance. However, given the confluence of other factors that could also contribute to a decline in CO poisonings, it is difficult to attribute the decline in CO incidents solely to the regulations and technologies used to comply with them.

1. BACKGROUND

Guidehouse developed this report for the United States Consumer Product Safety Commission (CPSC). The goal of this report is to explore the standards and regulations in the EU and Japan that are intended to limit carbon monoxide[2] production in residential gas-fired space heating and water heating appliances (*e.g.*, boilers, tankless water heaters), understand how those regulations are met by manufacturers, and assess the effectiveness of such measures in reducing CO-related injuries and fatalities in the EU and Japan.

In combustion appliances, CO can form if incomplete combustion occurs, usually as a result of an incorrect air-fuel ratio. During complete combustion, carbon and hydrogen from a fuel combine with oxygen (O_2) in air to produce carbon dioxide (CO_2) and water (H_2O). During incomplete combustion, some of the carbon atoms are not completely oxidized leading to the production of CO. CO is dangerous to building occupants when inhaled, and depending on the concentration of CO in the building and the length of exposure, can cause exposed building occupants to experience symptoms ranging from headache, dizziness, fatigue, nausea, and shortness of breath to loss of consciousness, brain damage, and death. In both the EU and Japan, regulations and standards exist to limit the production of CO by gas-fired space heating and water heating appliances.

Guidehouse examined several European and Japanese standards initially identified in CPSC's August 19, 2019 Advanced Notice of Proposed Rulemaking (ANPR)[3] to gain an initial understanding of the requirements related to CO production of gas-fired space and water heating appliances in Europe and Japan. We also reviewed manufacturer literature including marketing material, specification sheets, and installation and operation manuals, as well as various research reports to identify technologies for monitoring and/or limiting CO production from gas-fired space and water heating appliances. To supplement our understanding of the requirements and technologies used to meet them, we surveyed and/or interviewed 11 stakeholders including 5 manufacturers of gas-fired boilers and water heaters in Europe and Japan, CO sensor original equipment manufacturers (OEMs), NITE (a Japanese regulatory agency), the Competition and Consumer Protection Commission (CCPC, an Irish regulatory agency), and a European notified body.[4] Several of the interviews and surveys with manufacturers were conducted under confidentiality agreements, and therefore, manufacturer responses are only presented in aggregate in this report. The surveys that Guidehouse provided to European manufacturers, Japanese manufacturers, and regulatory agencies are provided in Appendices, A, B, and C, respectively.

[2] Carbon monoxide is a by-product of incomplete combustion caused by an incorrect air-fuel ratio. At elevated levels and over time, carbon monoxide exposure is hazardous to human health.

[3] "Performance Requirements for Residential Gas Furnaces and Boilers; Advance Notice of Proposed Rulemaking" (84 FR 42847, August 19, 2019) For more information see: https://www.federalregister.gov/documents/2019/08/19/2019-17512/performance-requirements-for-residential-gas-furnaces-and-boilers-advance-notice-of-proposed

[4] In the EU, a notified body is an organization that has been designated by a member state to assess the conformity of certain products with the applicable technical requirements before they are placed on the EU market.

In addition, we obtained two boiler samples directly from the European market, and were provided an additional three boilers by the CPSC which represent designs available in the Japanese market. For each sample, we conducted a physical examination and teardown analysis of the combustion control system, and when present, CO sensor. We also obtained a commercially available CO-sensor for physical examination and teardown directly from the sensor OEM. Teardowns reviewed visible printed circuit board (PCB) real estate, traces, and mounted components to build a required resource list to conduct flame ionization monitoring, CO measurement, etc. Since this reverse-engineering effort was conducted without the assistance of the OEMs, we relied on our experience to identify and isolate associated components.

Every component associated with flame ionization and CO-sensing was identified individually and costed out at representative manufacturing volumes. For example, most PCBs suggested that respective OEMs had designed them but that their manufacture and component assembly was outsourced. Similarly, all non-PCB components needed to sense the flame or combustion gases were also costed out in detail. Excluded from this cost analysis were shared PCB components with multiple on-board uses such as the microcontroller, power supplies, etc., as those components are required regardless of whether the CO sensor or flame ionization circuit are present.

To consider the issue of effectiveness of regulations on the CO produced by gas space heating and water heating appliances, we first researched data on the numbers of accidental CO deaths and injuries in Europe and Japan that were caused by gas space heating and water heating appliances. For the EU, we reviewed reports published by the World Health Organization (WHO),[5] the Gas Safety Trust,[6] the Carbon Monoxide and Gas Safety Society,[7] and the United Kingdom Health and Safety Executive (HSE).[8] For Japan, NITE provided comprehensive CO incident data for the Japanese market dating to 1996, which classified incidents by severity and cause. For both the EU and Japan, we also discussed trends in accidental CO poisonings from gas space heating and water heating appliances with European and Japanese manufacturers of these products during the aforementioned interviews and/or through surveys. We then reviewed the data to identify trends in CO-related injuries and deaths and compared changes over the years to the implementation dates of various requirements to examine whether any changes in the trends would likely be due to new or updated regulations or standards. We also considered other possible causes of any changes in trends in accidental CO poisoning incidents caused by gas space heating and/or water heating appliances.

[5] "Mortality associated with exposure to carbon monoxide in WHO European Member States" M. Braubach, A. Algoet, M. Beaton, S. Laurious, M. -E. Heroux, m. Kryzanowski. WHO Regional Office for Europe. 2012.

[6] According to its website, The Gas Safety Trust was established in 2005 as a registered charitable body, and is the UK's leading gas safety research charity with the key objectives of further improving gas/fossil fuel safety for the public and industry throughout the UK and reducing the incidents of death and serious injury from CO exposure. For more information see: http://gassafetytrust.org/about-us/.

[7] According to its website, the Carbon Monoxide and Gas Safety Society is an independent registered charity which works to try to reduce accidents from Carbon Monoxide (CO) poisoning and other gas dangers. For more information, see: https://www.co-gassafety.co.uk/.

[8] For more information see: https://www.hse.gov.uk/.

The subsequent sections provide additional detail on the materials reviewed and the analysis conducted for this report. Initially, this report discusses the technical standards pertaining to the safe construction and operation of gas space heating and/or water heating appliances in the EU and Japan, along with several associated standards in Europe relevant to combustion controls. It then identifies and describes the various combustion control systems and technologies used in European and Japanese gas space and/or water heating appliance markets that limit the formation of CO during the combustion process, and discusses the estimated costs of implementing these technologies, as well as how the technologies compare to those in the US market. Finally, this report evaluates data on CO injuries and deaths to assess the impact of the aforementioned standards and technologies on reducing CO-related injuries and deaths.

2. EUROPEAN AND JAPANESE STANDARDS REVIEW

As an initial step in understanding the regulatory requirements pertaining to the CO produced by gas heating appliances, Guidehouse identified and reviewed the standards governing the construction and operation of gas heating appliances in Europe and Japan. In Europe, standards are developed by the European Committee for Standardization (CEN) and in Japan, the Japanese Standards Association (JSA) publishes Japanese Industrial Standards (JIS). In Europe, gas appliance safety is mandated by Regulation (EU) 2016/426 on appliances burning gaseous fuels,[9] and compliance with the applicable standard published by CEN is generally considered as one way to be compliant with the law. As a result, most appliances sold within Europe are certified to one of the applicable industry standards. Similarly, in Japan, industry association requirements and consumer and market expectations result in most gas appliances in Japan being certified to the applicable standard and bearing either JIS or JIA certification. In addition these appliances are regulated by the Gas Business Act and the Act on the Securing of Safety and the Optimization of Transaction of Liquefied Petroleum Gas, which requires that a manufacturer or importer ensure that the gas equipment conforms to the technical standards established by an Ordinance of the Ministry of Economy, Trade and Industry.[10] Since many gas appliances sold in the European and Japanese markets are certified to the standards discussed in the following sections, it is important to understand their requirements pertaining to combustion and production of carbon monoxide.

2.1 European Union Standards

The series of standards that govern the operation and safety of gas fired boilers in Europe are developed by CEN. These standards are:

- EN 15502-1: *Gas-fired heating boilers – Part 1: General requirements and tests*
- EN 15502-2-1: *Gas-fired central heating boilers, Part 2-1: Specific standard for type C appliances and type B2, B3 and B5 appliances of a nominal heat input not exceeding 1000 kW*
- EN 15502-2-2: *Gas-fired central heating boilers, Part 2-2: Specific standard for type B1 appliances*

In addition, CEN has established several standards that specify the requirements for control devices for gas burning appliances:

- EN 13611: *Safety and control devices for burners and appliances burning gaseous and/or liquid fuels—General requirements*
- EN 16340: *Safety and control devices for burners and appliances burning gaseous or liquid fuels—Combustion product sensing devices*

[9] For more information see: https://ec.europa.eu/growth/sectors/pressure-gas/gas-appliances/regulation_en.

[10] For more information see: http://www.japaneselawtranslation.go.jp/law/detail/?vm=04&id=39&re=02, https://elaws.e-gov.go.jp/search/elawsSearch/elaws_search/lsg0500/detail?lawId=342AC0000000149#I

- EN 12067-2: *Gas/air ratio controls for gas burners and gas burning appliances—Part 2: Electronic types*

Table 2-1 summarizes the relevant provisions of these standards and additional discussion is contained immediately below the table.

Table 2-1: European Union Standards for Safety and Control Devices and Gas-fired Central Heating Boilers

Standard	Summary of Relevant Provisions
EN 13611: Safety and control devices for burners and appliances burning gaseous and/or liquid fuels—General requirements	• Includes general requirements for all safety control devices for gas and or liquid fuel burning appliances • Includes test criteria for such devices • This code is meant to be used in conjunction with the other codes of interest
EN 16340: Safety and control devices for burners and appliances burning gaseous or liquid fuels—Combustion product sensing devices	• Provides specific information regarding the performance of combustion product sensing devices (CPSD) • Includes test procedures and allowable tolerances for CPSDs
EN 12067-2: Gas/air ratio controls for gas burners and gas burning appliances—Part 2: Electronic types	• Includes the performance standards for electronic GARCs in gas burners and gas burning appliances • Defines electronic GARC as: closed loop modulating system consisting of the electronic control, actuating elements for the gas flow and air flow as a minimum, and allocated feedback signal(s) • Requires that GARCs have the ability to initiate safety shutdowns
EN 15502-1: Gas -fired heating boilers – Part 1: General requirements and tests	• Requires boilers with fans to check supply of combustion air; one of the ways listed is the use of a GARC • CO levels are required to not exceed 1,000 ppm during normal operation and “limit conditions” During “special conditions” which includes incomplete combustion, varied fan supply voltage between 85%-110%, and flame lift CO levels are not to exceed 2,000 ppm

EN 15502-2-1: Gas-fired central heating boilers, Part 2-1: Specific standard for type C appliances and type B2, B3 and B5 appliances of a nominal heat input not exceeding 1000 kW	• Includes instructions for monitoring of CO and other combustion products during testing • Includes separate provisions for CO testing for gas appliances with and without GARCs • CO levels are required to not exceed 1,000 ppm during “limit conditions” and 2,000 ppm during “special conditions” (incomplete combustion and flame lift). Requires that CO not reach 1,000 ppm under test conditions including blocked air inlets, blocked vents, and internal recirculation • Includes alternative supervision strategies for air proving including continuous supervision (shutting down if CO reaches 2000 ppm) and start-up supervision (the unit must not start if CO reaches 1000 ppm).
EN 15502-2-2: Gas-fired central heating boilers, Part 2-2: Specific standard for type B1 appliances	• Defines a combustion products discharge safety device (CPDSD) as: a device that at least causes safety shutdown of the main burner when there is an unacceptable spillage of combustion products at the draft diverter. • Requires combustion product discharge safety devices CPDSDs to be designed such that they can withstand the thermal stress resulting from spillage of combustion products. • Requires continuous supervision of combustion air rate or combustions product rate for type B_{12} and B_{13} boilers • CO levels are required to not exceed 1,000 ppm during “limit conditions” and 2,000 ppm during “special conditions” (incomplete combustion and flame lift). Requires that CO not reach 1,000 ppm under test conditions including blocked air inlets, blocked vents, and internal recirculation • Includes alternative supervision strategies for air proving including continuous supervision (shutting down if CO reaches 2000 ppm) and start-up supervision (the unit must not start if CO reaches 1000 ppm).

EN-15502-1 contains general requirements applicable to the majority of the boiler product types on the European market, while EN 15502-2-1 and EN 15502-2-2 contain additional requirements specific to certain types of boilers. Specifically, EN 15502-2-1 addresses type C appliances and type B_2, B_3 and B_5 appliances with a nominal heat input not exceeding 1000 kW, while EN 15502-2-2 addresses type B_1 appliances.[11]

EN 15502-1 includes test provisions and requirements for the maximum CO gas-fired boilers may produce during normal operation and under “limit conditions” and “special conditions.” During normal operation, the CO concentration in dry-air combustion gases cannot exceed 1,000 ppm (0.10%) in a sample of the flue gases taken once the boiler reaches thermal equilibrium at the nominal input rate. The “limit conditions” test requires that CO concentration in a sample of the flue gases taken once the unit reaches thermal equilibrium not exceed 1,000 ppm (0.10%) during testing carried out under the following conditions: (1) at the maximum test pressure for boilers without a regulator or with gas/air ratio controls, (2) at 1.07 times the nominal heat input for boilers with a regulator using a first family gas, (3) at 1.05 times the nominal heat input for boilers with a regulator using second and third family gas.[12] The limit conditions test also requires additional testing for low temperature or condensing boilers. If the boiler is equipped with a condensate discharge then the boiler must either (1) shutoff the gas supply to the boiler before CO concentration exceeds 2,000 ppm (0.20%) when the condensate discharge is blocked, or (2) prevent restart from cold when the condensate discharge is blocked causing a restriction in the flow of combustion products or air for combustion, resulting in a CO concentration equal to or greater than 1,000 ppm (0.10%) at equilibrium.

Finally, EN 15502-1 requires “special conditions” tests consisting of testing for incomplete combustion, a supplementary test for fan assisted boilers, and for flame lift. During the incomplete combustion test, the boiler input rate is adjusted depending on its characteristics: boilers without any form of input gas regulator are adjusted to 1.075 times the nominal rate, boilers with gas/air ratio controls are adjusted to the nominal heat input, and boilers with regulators or those meant to be installed solely on a gas installation with a governed meter are set to 1.05 times the nominal rate.[13] After the boiler is adjusted to the applicable input rate the reference gas[14] is replaced by an “incomplete combustion gas” and the exhaust gas composition is examined for CO. The CO concentration must not exceed 2,000 ppm (0.20%) during the

[11] Type C boilers are boilers in which the combustion circuit (air supply, combustion chamber, heat exchanger and evacuation of the products of combustion) is sealed with respect to the room in which the appliance is installed. Type B boilers are intended to be connected to a flue that evacuates the products of combustion to the outside of the room containing the appliance. The combustion air is drawn directly from the room. A type B_2 boiler is a type B boiler without a draft diverter. A type B_3 boiler is a type B boiler without a draft diverter, which is designed for connection to a common flue duct system. This common duct system consists of a single natural draft flue. All pressurized parts of the appliance containing products of combustion are completely enclosed by parts of the appliance supplying combustion air. Combustion air is drawn into the appliance from the room by means of a concentric duct, which encloses the flue. The air enters through defined orifices situated in the surface of the duct. A type B_5 boiler is a type B boiler without a draft diverter, that is designed for connection via its flue duct to its flue terminal. A type B_1 boiler is a Type B boiler incorporating a draft diverter.

[12] First family gases include manufactured gases, while second and third family gases include natural gas and liquefied petroleum gas.

[13] For boilers with heat inputs > 300 kW, EN 15502-1 provides alternative adjustments that can be applied. However, this report is focused on residential products, which are generally well below that threshold.

[14] EN 437, “Test Gases – Test Pressures – Appliance Categories” specifies the characteristics of the reference gas for testing. EN 437 defines reference gases as test gases with which appliances operate under nominal conditions when they are supplied at the corresponding normal pressure.

incomplete combustion test. The special conditions test for fan assisted boilers consists of varying the supply voltage to the fan from 85% to 110% of the nominal voltage stated by the manufacturer while the boiler is supplied with a reference gas. The exhaust gas composition is examined for CO and the concentration must not exceed 2,000 ppm (0.20%). Lastly, the special condition test for flame lift requires boilers without pressure regulators set to the minimum inlet gas pressure, boilers with gas/air ratio controls adjusted to the minimum heat input, and boilers with pressure regulators to be adjusted to a heat input equal to 0.95 times the minimum heat input. The reference gas is replaced with a "flame lift gas" and the exhaust composition is examined for CO. As with the previous two special conditions, the CO concentration must not exceed 2,000 ppm (0.20%).

EN 15502-1 also requires boilers with fans to check supply of combustion air (also referred to as air proving). When a gas burning appliance has an improper air-fuel ratio, it can result in elevated CO levels in the exhaust. For this reason, having means to verify the combustion air supply may serve as a supplement to CO regulations, as it ensures adequate supply of combustion air is provided and a proper air-fuel ratio can be maintained. EN 15502-1 provides that air proving can be performed using one of the following four possible options:

1. supervision of the combustion air pressure or the combustion products pressure;
2. supervision of the combustion air rate or the combustion products rate;
3. automatic gas/air ratio control (GARC)[15]; or
4. indirect supervision (*e.g.*, fan speed supervision) when there is an air proving device which proves the air rate at least once at each start up and provided that there is a shutdown at least every 24 hours.

EN 15502-2-1 is used in conjunction with EN 15502-1 and provides additional requirements specifically for type C, B_2, B_3, or B_5 boilers with less than 1000 kW of nominal heat input. EN 15502-2-1 contains requirements for the acceptable CO levels in the flue gas during normal operation, "limit conditions" and "special conditions" that are similar to those in EN 15502-1 and described above.

For normal operation, the requirements reference EN 15502-2-1 and are identical to the requirements in EN 15502-1 described previously.

The limit conditions requirements in EN 15502-2-1 are identical to those contained in EN 15502-1 for units without GARCs, except that EN 15502-2-1 also includes specific instructions for the flue of Type B_5 boilers, for boilers intended to operate with pressurized flue ducts, and for

[15] A GARC is defined as a closed loop modulating system consisting of the electronic control, actuating elements for the gas flow and air flow as a minimum, and allocated feedback signal(s). GARCs are defined to either be pneumatic (in which case they must comply with EN 88-1) or electronic (in which case they must comply with EN 12067-2).

boilers with a gas rate adjuster or governor that are put out of operation for one or more gas families.

For boilers with GARCs, EN 15502-2-1 requires the boiler be subjected to the following limit tests, with CO and CO_2 concentrations being measured:

1. The GARC is adjusted in accordance with the technical instructions (or if not adjustable, left at the factory settings) and the boiler operated at maximum and minimum heat input allowed by the controls;

2. To simulate reasonable maladjustment of any adjustable "throttle" setting the CO_2 value at the maximum rate is adjusted to be 0.5% higher than the maximum value to which the GARC should be set and the boiler operated at the maximum and minimum heat input allowed by the controls; and

3. To simulate maladjustment of any adjustable "offset" setting the offset screw is adjusted to increase differential pressure in the GARC by 5 Pa and the boiler is operated at both minimum and maximum heat input rates allowed by the controls. This test is repeated with the pressure offset screw adjusted to decrease differential pressure by 5 Pa from the standard pressure as well.

During each of these test conditions, the limit of 1,000 ppm (0.10%) maximum allowable CO concentration in the flue gases must be met.

The special conditions tests in EN 15502-2-1 are largely the same as those in EN 15502-1 described above, with a few exceptions. The special conditions section of EN 15502-2-1 references the testing in EN 15502-1 for the incomplete combustion test, the supplementary test for fan assisted boilers, and the flame lift test. These tests are identical to those described in EN 15502-1 above and the CO concentration must not exceed 2,000 ppm (0.20%). In addition, EN 15502-2-1 requires that the CO concentration not exceed 2,000 ppm (0.20%) during the sooting test. The sooting test consists of adjusting the boiler as per the incomplete combustion test, but substituting the "sooting gas" during testing, rather than the "incomplete combustion" gas. The boiler is then operated for either 1 hour (boilers with heat input ≤ 70 kW) or 15 minutes (boilers with heat inputs > 70 kW) to check whether the requirements are met.

In addition, EN 15502-2-1 contains additional special flue condition requirements for certain Type C and Type B boilers, which are not included in EN 15502-1. This testing consists of a series of tests with different combinations of wind speed/angle of incidence, suctions, and downdrafts applied. During each of these tests (and during the other special conditions tests as described above), EN 15502-2-1 requires that the CO concentration not exceed 2,000 ppm (0.20%).

In addition, the acceptable methods for air proving differ slightly between EN 15502-1 and EN 15502-2-1. Specifically, the air proving methods specified in EN 15502-2-1 are as follows:

1. gas/air ratio controls;
2. continuous supervision of the combustion air rate or combustion products rate; or
3. startup supervision of the combustion air rate or combustion products rate, provided that the combustion product circuit is completely surrounded by the air supply circuit, or that certain leakage rate requirements are met, there is a shutdown at least every 24 hours, and that there is an indirect method for air proving (*e.g.*, fan speed supervision) during operation.

EN 15502-2-1 also places requirements on the CO concentration in the flue gas depending on the air proving method. The boiler is fitted with the longest combustion air supply and combustion air evacuation ducts specified by the installation manual and tested under the following three conditions:

1. Progressive blockage of the air inlet;
2. Progressive blockage of the combustion products evacuation ducts; and
3. Progressive reduction of the fan speed, for example by reduction of fan voltage.

The tests are performed when the boiler is at thermal equilibrium, at the nominal heat input, or for modulating boilers, at the maximum and the minimum heat input and at the heat input corresponding to the arithmetic mean of these two inputs. When several rates are provided, supplementary tests are performed at each of these rates. The CO and CO_2 concentrations are measured continuously.

Boilers that use continuous supervision of the combustion air rate or combustion products rate for air proving must shut down if the CO levels exceed 2,000 ppm (0.20%) over the range of modulation, or when the measured CO times the ratio of the instantaneous input rate to the minimum input rate reaches 2,000 ppm (0.20%). Boilers that use start up supervision of the combustion air rate or combustion products rate must not start if the CO concentration exceeds 1,000 ppm (0.10%). Boilers that use GARCs must meet the same requirements and, when the CO_2 is adjustable, are subject to additional tests with the CO_2 at maximum heat input adjusted to the maximum CO_2 value and at the minimum heat input to the minimum CO_2 value, and the CO_2 at maximum heat input adjusted to the minimum CO_2 value and at the minimum heat input allowed by the controls to the maximum CO_2 value. The boiler must meet the CO requirements at all of the required CO_2 settings.

EN 15502-2-2, like EN 15502-2-1, is used in conjunction with EN 15502-1. The required tests (normal operation, limit tests, and special conditions tests) and allowable CO levels are the same as those in 15502-1, with additional requirements for boilers using natural draft. Under EN 15502-2-2 a boiler with a natural draft may not have combustion products with CO levels exceeding 1,000 ppm (0.10%) under the following test conditions (which are performed with the boiler at the nominal heat input and with any combustion safety devices out of operation):

1. When the flue is blocked; and
2. At continuous down-draft of speeds at the top of the flue of 1 meter per second (m/s), 1.5 m/s, 2 m/s, 2.5 m/s, and 3 m/s.

EN 15502-2-2 also substitutes its own air proving options for type B_{12}, and B_{13} boilers. Similar to the test provisions in 15502-2-1, EN 15502-2-2 provides requirements for the allowable CO concentration in the flue gas for type B_{12} and B_{13} boilers during the following three conditions:

1. Progressive blockage of the air inlet;
2. Progressive blockage of the combustion products evacuation ducts; and
3. Progressive reduction of the fan speed, for example by the reduction of the fan voltage.

As with EN 15502-2-1, the tests are performed when the boiler is at thermal equilibrium, at the nominal heat input, or for modulating boilers, at the maximum and the minimum heat input and at the heat input corresponding to the arithmetic mean of these two inputs. When several rates are provided, supplementary tests are performed at each of these rates. The CO and CO_2 concentrations are measured continuously.

There are two supervision strategies allowed for air proving, and EN15502-2-2 provides two different allowable CO levels depending on which air proving method is used. The first method is the use of continuous supervision in which the unit must shutdown if the CO levels exceed 2,000 ppm (0.20%) over the range of modulation specified in the installation manual. The second method is start up supervision. Using this method, the unit must not be able to start up if the CO concentration exceeds 1,000 ppm (0.10%).

Additionally, EN 15502-2-2 includes a definition for combustion product discharge safety devices (CPDSDs). EN 15502-2-2 defines a combustion products discharge safety device as: a device that at least causes safety shutdown of the main burner when there is an unacceptable spillage of combustion products at the draft diverter. This standard requires that B_{11}, B_{12}, and B_{13} boilers shall be constructed such that there is no release of combustion products in a dangerous quantity into the room concerned states that this can be achieved with a CPDSD.[16] Products equipped with these devices are then designated as B_{11BS}, B_{12BS}, B_{13BS} boilers. EN 15502-2-2 provides exceptions for boilers installed either in open air or in a room separated from living rooms and with appropriate ventilation directly outside, but requires

[16] Type B_1 boilers consist of B_{11}, B_{12}, B_{13}, and B_{14} boilers. Of relevance to this discussion, a B_{11} boiler is a type B boiler with a natural draft; a B_{12} boiler is a type B boiler designed for a natural draft flue incorporating a fan downstream of the combustion chamber/heat exchanger and upstream of the draft diverter; and a B_{13} boiler is a type B boiler designed for a natural draft flue incorporating a fan upstream of the combustion chamber/heat exchanger.

packaging and instructions to be clearly labeled to indicate the limit on the use of the boiler. Thus, CPDSDs are one way to reduce risk of CO poisoning by requiring the unit to shut down if spillage is detected, but their use is not explicitly required in all instances. During CO testing for natural draft units, the CPDSD must be out of operation and the unit must not produce CO in excess 1,000 ppm (0.10%).

Specific test requirements are provided in 15502-2-2 for boilers equipped with CPDSDs to ensure that the device does not cause nuisance shutdowns and to set maximum shutdown times for blocked vents. For the nuisance shutdown test, the boiler is operated at its maximum temperature for 30 minutes during which time it is confirmed that the device does not cause shutdown. The device also must not send a signal to initiate shutdown of the boiler due any additional temperature rise after the burner is turned off at the end of the 30-minute period. For the maximum shutdown times test, the maximum allowable shutdown time varies based on the degree of blockage (either complete or partial blockage) and input rate.

The next set of European standards we examined provide requirements specific to the safety and control devices that are used in certain gas-fired appliances. The standards are as follows:

- EN 13611: *Safety and control devices for burners and appliances burning gaseous and/or liquid fuels—General requirements*
- EN 16340: *Safety and control devices for burners and appliances burning gaseous or liquid fuels—Combustion product sensing devices*
- EN 12067-2: *Gas/air ratio controls for gas burners and gas burning appliances—Part 2: Electronic types*

EN 13611 specifies the performance, electrical, fault mode, safety integrity level and various other general requirements for all safety control devices for appliances burning gas or liquid fuel. This standard is used in conjunction with other specific control standards (e.g., EN 16340 and EN 12067-2), which provide more specific requirements.

EN 16340 specifies the performance requirements and test procedures for combustion product sensing devices (CPSDs). (which are referenced in EN 15502-2-2, as discussed previously). The devices covered by this standard must be able to measure the flue gas concentration of oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), hydrocarbons (C_xH_y), nitrogen oxides (NO_x), sulfur dioxide (SO_2), or any combination of these gases. This standard in conjunction with EN 13611 includes error tolerances and test procedures to ensure proper performance of the CPSDs. The test conditions used in EN 16340 most relevant to CPSDs include exposure to flue gas temperatures, humidity, and operation above and below recommended voltage input.

EN 12067-2 provides the construction and functional requirements for electronic GARCs (which are referenced in both EN 15502-1 and EN 15502-2-1, as discussed previously). GARCs provide a means to supervise and control the combustion process in order to help ensure the desired air-fuel ratio is maintained. EN 12067-2 requires that the GARC be interfaced and interlocked with the burner control interface. EN12067-2 also requires GARCs to be tested for accuracy, endurance, and repeatability under standard ambient temperatures (20 ºC +/- 5 ºC), humidity (40%-80%), and supply voltage/frequency unless otherwise stated in the specifications of the unit.

2.2 Japanese Standards

As previously noted, in Japan, most appliances are certified to either JIS or JIA standards to ensure safe construction and operation. Given the prevalence of models certified to JIS standards, and the availability of these standards in the US, we focused on JIS standards for this review. The JSA publishes certain JIS standards pertaining to the construction and performance of gas appliances, including water heaters, boilers, and space heaters. These standards are:

- JIS-S-2109—*Gas burning water heaters for domestic use*
- JIS-S-2112—*Gas hydronic heating appliances for domestic use*
- JIS-S-2122—*Gas burning space heaters for domestic use*

Of the three standards, only JIS-S-2109 was available in English as of the time of this report, and thus, the discussion that follows primarily focuses on JIS-S-2109. However, based on information from stakeholder interviews, Guidehouse understands that the CO requirements in the three standards are essentially the same. Table 2-2 summarizes the relevant provisions of the standard and additional discussion is contained immediately below the table.

Table 2-2: Summary of CO Requirements in JIS-S-2019

Standard	Summary of Relevant Provisions
JIS S 2109: Gas burning water heaters for domestic use	• Specifies Maximum allowable CO levels for various operational conditions and types of water heaters. Depending on the type of water heater, can include requirements for CO produced and/or CO concentrations in the room and adjacent room. • When CO reaches the maximum allowable level, requires activation of the incomplete combustion preventative device (ICPD) for certain types of water heaters. • Test conditions vary by water heater type, but for example can include incomplete ventilation, incomplete combustion, windy conditions in exhaust pipe, and exhaust air shut off.

JIS-S-2109 specifies the maximum allowable CO requirements for various types of water heaters during a variety of test conditions. The standard also requires use of an ICPD for unvented water heaters, and for “CF” and “FE” water heaters,[17] and specifies requirements for the ICPD construction and operation. For these water heaters, during each test if the CO concentration reaches a specified level, the ICPD must close the gas passage to the main burner and not allow it to automatically open again. The specific tests included in JIS-S-2109 are discussed in the paragraphs immediately below.

For unvented systems, the insufficient ventilation test involves installing the unit in a test room with incomplete ventilation. The oxygen in the room is gradually reduced until either the unit closes the gas passage or the CO concentration in dry combustion gas reaches 300 ppm (0.03%). The ICPD must close the gas passage to the burner before the CO concentration reaches the limit and shouldn’t automatically reopen again. In addition, for unvented systems there is a heat exchanger shut-off test, that consists of partially shutting off the heat exchanger to the point that the CO concentration in dry combustion gas reaches 300 ppm (0.03%) and the gas passage is required to close automatically within 30 seconds.

For “CF” water heaters, there is a safety under windy conditions test, which requires operating the water heater with drop wind velocities of 0.5 m/s, 1 m/s, 2 m/s and 3 m/s in the secondary exhaust pipe[18] after 15 minutes from the ignition of burner. At each of these test conditions, the ICPD must close the gas passage to the burner before the CO concentration in the test room reaches 300 ppm (0.03%). There is also a safety under exhaust air-shutoff test for CF type water heaters, which involves blocking the vent with a plate 1 meter from the connection of the secondary exhaust pipe. As with the previous conditions, the ICPD must close the gas passage to the burner before the CO concentration in the test room reaches 300 ppm (0.03%).

For “FE” water heaters, there is a test for contamination of the same room, under which the unit is installed and operated in the test room and the ICPD must close the gas passage to the burner before the CO concentration in the test room reaches 300 ppm (0.03%). JIS 2109 provides that the test room concentration of CO may be calculated using the following formula:

$$K= (1 – e^{-t*(Q+M)/V})*(M*p)/(Q+M)$$

Where, K is the CO concentration in the test chamber after t hours (%)
e is the base natural algorithm
t is the period from re-ignition until gas passage closure

[17] JIS-S-2109 and JIS-S-2093 (which is referenced by JIS-S-2109) refer to water heaters as follows:
CF = natural exhaust
FE = forced exhaust
FF-W = forced air supply / exhaust outer wall type
FF-C = forced air supply / exhaust chamber type
FF-D = forced air supply / exhaust duct type
BF-W = balanced exterior wall
BF-C = balanced chamber
BF-D = balanced duct type
RF = outdoor

[18] From Figure 16 of JIS-S-2109, the “secondary exhaust pipe” refers to the section of the vent following the draft hood.

Q is the ventilation quantity (m^3/h). Q=0.5*V-M, but Q=0, when Q<0
M is the combustion gas generated quantity (m^3/h), wet condition
V is the volume of the test chamber (m^3), V=16.8 m^3
p is the CO concentration in average dry combustion gas during t hours (%)

Thus, in order to use the above method to calculate the test room concentration (K) of CO, the concentration of CO in the combustion gas (p) must be determined.

There is also a test for contamination of "other" room (i.e., an adjacent room) that requires use of a "pressure control box" in the test room into which the appliance is vented. The standard states that the damper of the pressure control box be gradually closed until the ICPD is activated to shut off the gas passage to the burner, and the damper set at that point. Then the test room air is substituted with fresh air, the appliance re-ignited, and tested to examine whether it closes that gas passage to the burner before the CO concentration in the test room reaches 300 ppm (0.03%). Lastly, there is a partial combustion test, which entails operating the water heater such that part of the burner is set to cause incomplete combustion, or if there is a filter installed at the air supply, closing the air supply opening. The ICPD again must close the gas passage to the burner before the CO concentration in the room reaches 300 ppm (0.03%).

Two additional tests are required by JIS-S-2109 to further ensure the proper operation of the ICPDs: the activation indication test and the interlocking function test. The activation indication test is a visual examination to verify the presence of an active indication once the ICPD is activated during the previously described tests. The interlocking function requires an examination of whether the unit continues to allow normal operation within a set number of safety shut offs (3 for unvented or 5 for other types) by the ICPD.

In addition to the testing for proper functionality of the ICPD with respect to shutting of the burner at the required CO level, the standard includes requirements for testing the duty-cycle of the ICPD. For the duty-cycle test, unvented appliances are subjected to 1,000 cycles of operations, with one cycle of which consisting of igniting the burner, burning it for 5 minutes, extinguishing and standing for 10 min. Then the ICPD is tested to determine whether it functions normally. For CF and FE appliances, the standard also requires the appliance to be activated 1,000 times[19] after which the ICPD functionality is tested to determine whether it is operating normally. The standard also specifies that the ICPD be installed in a position where it will not easily shift nor be accessible under normal use conditions, that if the sensor is damaged the gas passage to the burner must close automatically, and that the connection between the ICPD and the control board requires a special tool or exclusive terminal for connection, or is protected by a special enclosure that requires a special tool to access.

[19] For CF and FE appliances, an alternate procedure is also specified where CO can be blown into the combustion gas sensor for 5 minutes and then stopped for 1 minute to reduce CO concentration by blowing nitrogen gas. This cycle is repeated 1,000 times, then the sensor is installed on the appliance and the burner ignited at specified test conditions. After burning for 5 minutes the burner is extinguished, then left for 5 minutes, which counts as 1 cycle, and must be repeated 1,000 times.

The standard also contains limitations on CO production for "FF" and "BF" water heaters. For "FF-D" and "BF-D" water heaters, the CO concentration in theoretical dry combustion gas must be 1,400 ppm (0.14%) or less during windless conditions and 2,800 ppm (0.28%) or less during the low oxygen atmosphere condition. For "BW-W," "BF-C," "FF-W" and "FF-C," the standard requires that the CO concentration be 2,800 ppm (0.28%) or less during the windy condition test. These tests are specified by reference to JIS S 2093, "Test Methods of gas burning appliances for domestic use."

2.3 Comparison of European and Japanese Standards Requirements to Previous CPSC Proposals

In the August 2019 ANPR, CPSC stated that it is considering developing a rule to address the risk of injury and death associated with CO production and leakage from residential gas furnaces and boilers (including residential, gas-fired central furnaces, boilers, wall furnaces, and floor furnaces). Because the August 2019 ANPR addressed similar topics to those considered in this report and provides valuable context, Guidehouse reviewed the CPSC proposal for comparison with the international standards. CPSC noted in the August 2019 ANPR that voluntary standards published by the American National Standards Institute (ANSI) exist for all of these products[20] and require that they:

1. Not produce CO in excess of 400 ppm;
2. shut off when vent or flue is fully blocked;
3. shut off when blower door is not sealed properly (gas-fired central furnaces only); and
4. shut off if flames issue outside of the burner inlet openings.

CPSC expressed concern that the voluntary standards only address the issue of a completely blocked vent and do not address the following potential scenarios that would result in excessive CO production:

1. Disconnected or breached flues, vents, and chimneys;
2. partially blocked heat exchangers, flues, vents, and chimneys;
3. over-fired appliances; and
4. inadequate combustion air to appliances.

[20] Residential boilers, residential furnaces, and residential wall and floor furnaces are addressed by the following standards: ANSI Z21.13, *Standard for Gas-Fired Low Pressure Steam and Hot Water Boilers,* ANSI Z21.47, *Standard for Gas-Fired Central Furnaces, and* ANSI Z21.86, *Standard for Vented Gas-Fired Space Heating Appliances.*

(See the ANPR, 84 FR 42847, at p. 42851 for further discussion.)

CPSC has previously proposed to the ANSI Z21/83 technical committee[21] that the standards for residential gas furnaces (ANSI Z21.47, *Standard for Gas-Fired Central Furnaces*), residential gas boilers (ANSI Z21.13, *Standard for Gas-Fired Low Pressure Steam and Hot water Boilers*), and residential gas wall and floor furnaces (ANSI Z21.86, *Standard for Vented Gas-Fired Space Heating Appliances*) adopt the following requirements to address these areas[22]:

1. Require a means to limit:
    a. CO emissions to below 0.04%; or
    b. combustion conditions that result in CO emissions at or in excess of 0.04%; or
2. Require a means to shut-off in response to:
    a. CO emissions at or in excess of 0.04%; or
    b. combustion conditions that result in CO emissions at or in excess of 0.04%; or
3. Require a means to modulate operation to reduce CO emissions in response to:
    a. CO emissions at or in excess of 0.04%; or
    b. combustion conditions that result in CO emissions at or in excess of 0.04%.

Guidehouse considered and compared the proposal for this report. First, we note that the maximum allowable CO levels vary significantly. For the CPSC's proposal, a gas boiler would have to be able to either self-correct or shut down if CO production reaches 0.04% or have a means to maintain production levels below 0.04%. In the European standards, CO production is to be kept below 0.1% during normal operation and 0.2% during special cases such as incomplete combustion, which are notably much higher. As a result, it is not clear that the sensors and/or controls currently being used to meet the requirements of European standards are suitable to meet the requirements proposed by CPSC.

The European standards reference the use of CPSDs to shut down the boiler in the case of unsafe CO levels and GARCs that can adjust operation to ensure complete combustion as measures to combat excess CO, but does not explicitly require their use. GARC technology can be an indirect means to regulate CO production through supervision of the combustion to optimize air-fuel ratio, while CPSDs are a more direct CO measurement and control system. The technologies currently used to limit CO production in gas boiler in the European market are explored further in section 3 of this report.

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[21] ANSI Z21/83 Committee on Performance and Installation of Gas Burning Appliances and Related Accessories is responsible for developing standards for gas burning appliances.

[22] For more information see: https://www.cpsc.gov/Regulations-Laws--Standards/Voluntary-Standards/Gas-Appliances-CO-Sensors. The specific proposals are available at: https://www.cpsc.gov/s3fs-public/pdfs/blk_pdf_UpdatedCOShutoffProposal2014ANSIZ2113coverletter.pdf (gas boilers); https://www.cpsc.gov/s3fs-public/pdfs/blk_pdf_UpdatedCOShutoffProposal2014ANSIZ2186coverletter6bcleared.pdf (gas floor and wall furnaces; and https://www.cpsc.gov/s3fs-public/pdfs/blk_pdf_UpdatedCOShutoffProposal2014ANSIZ2147coverletter6bcleared.pdf (gas central furnaces).

Generally, the European standards require that the CO concentration "not exceed" the specified level during testing, which implies that either an automatic adjustment to maintain the CO concentration at an acceptable level, or shutting down before the CO concentration exceeds the specified level, would meet the requirement. This is similar to the CPSC proposals that would require either a means to limit CO production, a means to shut-off the burner when or before the CO concentration reaches the specified level, or a means to modulate operation when or before the CO concentration reaches the specified level.

The Japanese standards require that the CO concentration of the room or adjacent room not exceed 0.03% for certain water heater and that under normal conditions the CO concentration in the flue gases not exceed 0.14% for certain other types under normal operation and 0.28% under windy conditions. For the former requirement of 0.03% in the room, we note that the level of CO emitted from the unit can be greater than 0.03% while maintaining the CO concentration in the room below that level. Therefore, it is not clear what level CO concentration in those locations corresponds to the Japanese requirement of 0.03% in the room, making direct comparisons to the CO levels in the CPSC proposal difficult. In addition, the latter requirements for CO concentration in the flue gases provide for an allowable CO concentration that is notably much higher than the 0.04% level previously proposed. The Japanese standards require ICPDs as a method for controlling CO production, and the technologies currently used to limit CO production in gas boiler in the Japanese market are explored further in section 3 of this report.

For Japanese appliances required to be equipped with an ICPD, the Japanese standards specify that it must close the gas passage to the burner before the specified CO concentration is reached. This requirement would be more restrictive than the CPSC proposal as it essentially requires the unit to shut off the burner prior to the CO concentration exceeding the specified level. This is in contrast to the CPSC proposal which, as previously discussed, would allow for either means to limit CO production, a means to shut-off the burner when or before the CO concentration reaches the specified level, or a means to modulate operation when or before the CO concentration reaches the specified level.

3. TECHNOLOGIES USED TO LIMIT CARBON MONOXIDE PRODUCTION

After reviewing the applicable standards, Guidehouse next identified the technologies used in gas appliances in Europe and Japan to limit the production of CO. We reviewed manufacturer product literature, obtained feedback on products and technologies from manufacturers through survey responses and/or interviews, and obtained samples for teardown to physically examine the combustion control systems.

In gas space heating and water heating appliances, heat is generated by combustion and that heat is transferred to water or air via a heat exchanger. In vented appliances, after the hot combustion gases pass through the heat exchanger, they are exhausted outdoors. As discussed earlier in this report, CO can form during the combustion process when incomplete combustion occurs, usually as the result of an incorrect air-fuel ratio. During incomplete combustion, there is not enough oxygen present, so some of the carbon atoms are not completely oxidized, leading to the production of CO. If the appliance is not properly vented, or if the venting has deteriorated (e.g., due to corrosion) combustion exhaust gases can leak into the building, posing a potential hazard to building occupants.

In surveying the European and Japanese markets, we found that manufacturers limit the production of CO during combustion[23] through use of combustion safety systems, combustion control systems, and direct CO sensing. The combustion safety control systems focus on shutting down combustion under unsafe conditions, while the combustion control methods are capable of automatically adjusting combustion to ensure a proper air-fuel ratio, either through electronic or mechanical means. Direct CO sensing involves directly measuring the CO content of the flue gases via a sensor located downstream of the combustion chamber. The CO sensor provides input to the control system to allow the unit to adjust the combustion air-fuel ratio or shut off the unit if the amount of CO in the flue gases becomes elevated. In this section we first present an overview of the European and Japanese gas space and water heating markets in section 3.1. The technological approaches for different combustion systems are then described in sections 3.2, 3.3, and 3.4 below. We then present estimated manufacturing costs for incorporating the combustion controls and/or sensors in section 3.5, and compare the systems in use in Europe and Japan to combustion technologies found in the US market in section 3.6.

3.1 Market Overview

3.1.1 European Union

For the EU this report focuses primarily on gas-fired boilers used for space heating, as boilers are covered by the EN standards described in section 2.1 (i.e., EN 15502-1, EN 15502-2-1, and EN 15502-2-2). In addition, much of the technology used to control combustion and/or

[23] While the listed technologies limit CO production, we note these technologies are included in gas appliances primarily to improve efficiency or to allow for automatic adjustment for natural gas of varying quality/composition. Ensuring proper air-fuel ratio is associated with both improved combustion efficiency and reduced CO formation.

sense CO in boilers is transferrable to other types of heating equipment (e.g., water heaters) due to similarities in the combustion and control processes.

Boilers are the most popular type of domestic space heating equipment in Europe. Major manufacturers of boilers include Bosch Thermotechnik, Vaillant, Viessmann, BDR Thermea, and Ariston Thermo. In recent years, high efficiency, condensing[24] boilers with combustion fans and premix burners have dominated most of the market for new boiler sales. The move to these boilers has been driven by EU regulations on energy efficiency and emissions. In addition, many boilers currently available in Europe include technologies that are designed to allow for fuel flexibility, accommodating potentially changing gas characteristics based on the source of the gas (Norway, Russia, liquefied natural gas (LNG), etc.). Yet, even boilers that include a closed-loop control system that can adjust automatically for routine caloric content changes in the gas supply usually feature two general source-gas settings (liquified petroleum gas (LPG) vs. natural gas), suggesting that the technology does not make them completely source-gas agnostic.

During interviews, manufacturers indicated that there is a longer-term shift underway in the European market away from gas appliances toward gas/electric hybrid boilers, electric only (heat pump) boilers, and boilers using renewable fuels (e.g., green hydrogen). Several manufacturers also indicated that there has been a trend toward improved diagnostics with connectivity to the internet.

3.1.2 Japan

For Japan this report focuses on water heaters, as the Japanese standard reviewed (JIS-S-2109) applies to water heaters, and much of the technology used to control combustion and/or sense CO in water heaters is transferrable to other types of heating equipment (e.g., boilers) due to similarities in the combustion and control processes. In addition, gas-fired boilers and space heaters are less common than water heaters in Japan. Major manufacturers of water heaters in Japan include Rinnai, Noritz, Paloma, and Takagi. The majority of gas water heaters in Japan are installed outdoors. Outdoor models are installed outside the building, and thus, CO production is not considered to be a significant issue, as there is much less opportunity for combustion products to enter the building. For indoor units, manufacturers indicated during interviews that unvented models have significant market share, but power vent[25] and direct vent[26] models exist. During interviews, manufacturers generally indicated that the size of the gas space and water heating market in Japan is fairly stable, but that electric appliances are replacing gas in some

[24] Condensing gas appliances are designed to extract sufficient heat from the flue gases such that the flue gases are cooled below the dew point, causing condensation to occur and capturing latent heat. This technology significantly improves efficiency, but because the condensate is corrosive, requires use of corrosion-resistant materials in the vent and/or heat exchanger.

[25] Power vent models utilize a combustion fan.

[26] Direct vent models exhaust combustion gases to the outdoors and also draw combustion air from the outdoors. They may more may not be fan-assisted. These may also be labeled as “sealed” systems in that the combustion system is designed to be isolated from the room in which it is installed. This is in contrast to vented systems that are not direct vent, which draw combustion air from the room in which they are installed but expel flue gases outdoors.

situations. Some manufacturers also stated that recent shifts in the Japanese gas water heating market have included a change to more-efficient condensing models.

3.2 Combustion Safety Systems

Gas space heating and water heating appliances have historically used a variety of safety systems, ranging from basic thermocouples capable only of preventing gas flow without a flame to closed-loop air-ratio control combustion systems capable of continuously monitoring and adjusting combustion. The systems used in Europe or Japan – oxygen depletion sensors, direct CO sensing, flame ionization sensing systems, and combustion control systems – are discussed in the subsections below. Other combustion safety systems that are no longer in widespread use in Europe and Japan, but that are in use in the U.S., are discussed in section 3.6 to provide a point of comparison.

3.2.1 Oxygen Depletion Sensor

An oxygen depletion sensor (ODS) is a variation on the traditional thermocouple approach, in which a gas valve uses the energy generated by a thermocouple in contact with a standing pilot flame to enable gas flow through the gas valve. (See section 3.6.1.1 of this report for additional description of a thermocouple combustion control system.) An ODS consists of a precision pilot light and calibrated thermocouple that shuts the gas control valve when the oxygen in the room falls below a threshold.

During manufacturer interviews, some manufacturers indicated that Japanese water heating appliances that are installed indoors (specifically, power vent units) include an ODS to ensure the safety of building occupants and meet to the requirements of JIS 2109. Manufacturers indicated that ODS have been in use for several decades and have demonstrated ability to last the lifetime of a gas appliance into which they are installed. We note that the ODS only indirectly detects a drop in Oxygen levels, which may in turn lead to bad combustion, but it does not detect bad combustion.

3.2.2 Flame Ionization Sensing Systems

Basic flame ionization systems offer the same capabilities as traditional thermocouples. The presence of a flame is confirmed via the current streaming from the flame sensor rod to the gas burner. Should the signal no longer meet expectations, the combustion system will try to restart the flame and failing that, it will shut off gas flow.

In some ignition systems, the flame rod and ignitor can be combined into a single component next to the burner, while others feature a separate ignitor and flame rod. Among the European and Japanese boilers and tankless water heaters observed in our sample, units featured both approaches. Similarly, our samples included units with spark ignition systems that were external to the controller as well as integrated ones. All of the units in our reverse-engineering appliance cohort featured flame-ionization sensors.

Factors for the adoption of flame ionization sensor systems include energy efficiency (lower standby losses), higher reliability (the components used in flame ionization systems have been demonstrated as capable of lasting the lifetime of the appliance), the ability to monitor the quality of the flame, and the elimination of standing pilots (which can extinguish due to drafts, intermittent gas, orifice contamination, etc.). The elimination of standing pilots also allows the easier use of flue dampers, inducer blowers, etc., for some appliance categories. With the wider availability of low-cost, battery powered ignition systems, even standalone appliances, such as tankless water heaters, now commonly use spark ignitors and flame sensors.

How flame ionization sensors are used depends on the control system. Flame sensors can serve as a basic warning system (shutting the appliance down once unsafe conditions could not be mitigated), or as part of a feedback loop to control combustion (see section 3.3.1.2 for further discussion). In the former scenario, the flame ionization is used only as a safety measure to shut down the burner in absence of a steady flame, while in the latter scenario it can be used to adjust the burner and/or combustion fan to ensure complete combustion (thereby minimizing CO production).

3.3 Combustion Control

The following sections include discussion of the combustion systems currently in use in Europe or Japan. As noted previously, most gas space and water heating appliances in Europe and Japan use power burner systems with either pneumatic or closed loop control. In section 3.6, more basic combustion control systems that are common in the U.S. are discussed to provide a point of comparison.

3.3.1 Power Burner Appliances

A power burner blower is mounted at the intake of the combustion chamber. The power burner pressurizes and mixes the combustion air supply with the gas before it is combusted, typically through a ceramic burner tile, a perforated metal sheet, or a metal fiber burner. Most power burners only feature one burner whose output may be staged or modulated. Thus, the design lends itself to monitoring the performance of the flame across the entire burner with just one flame rod.

Power burners are very common for appliances designed in Europe and Japan, especially tankless water heaters and boilers (over 90% of homes in the EU use hydronic heating[27]). From a control point of view, power burner systems are relatively inexpensive appliances to upgrade from a simple flame sensor to a system that monitors the air-fuel ratio via the flame sensor, as most of the necessary components are already in place.

Additionally, with the right heat exchanger designs, power burners lend themselves more easily to variable input. For example, the burner system may feature a multitude of solenoid

[27] See Figure 5*, Assessment of the Space Heating and Domestic Hot Water Market in Europe—Open Data and Results*, Simon Pezzutto et. al. at https://www.mdpi.com/1996-1073/13/8/1894/pdf dated April 2020 and retrieved 2/2021

valves to stage the gas supply in many steps or modulating gas valves, which can continuously meter the gas flow across a range of outputs. Within the power burner cohort, two technologies are commonly used to modulate gas output.

- The pneumatic approach features a gas valve that opens and closes as a function of the air pressure that the power burner blower produces. Thus, the gas valve "follows" the burner on a fixed-ratio basis.
- Closed-loop control is also possible, where the controller operates the gas valve and blower system independently and uses feedback from a sensor to adjust the air-fuel ratio. Closed-loop control systems are typically found in higher-efficiency appliances.

3.3.1.1 Pneumatic Control

In the European market, many gas appliances utilize a GARC to control combustion. As discussed previously, EN 15502-1 defines a GARC as a device that automatically adapts combustion air rate to the gas rate or vice versa. During interviews, manufacturers indicated that pneumatic control systems are still the most prevalent type of burner control in Europe because it is less expensive to implement than closed-loop control.

Manufacturer feedback in survey responses and during interviews indicated that the gas valve/blower combinations typically last the lifetime of the appliance, and thus additional maintenance or repair costs for consumers is not a significant concern. In addition, manufacturers indicated that this technology is the most prevalent combustion control technology used in Europe, where power-burners are common. Figure 3-1 shows an illustration of a pneumatic gas valve and blower power burner system.

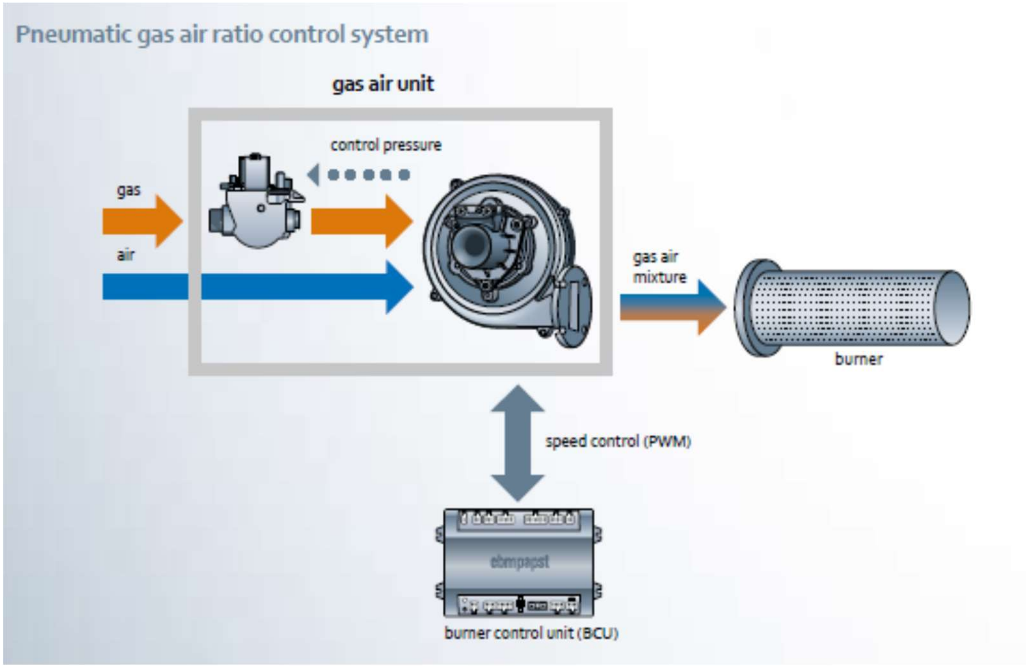


Figure 3-1: Illustration of a Pneumatic gas valve/blower combination

*Image from ebm-papst Condensing Boiler Technology Product Catalog 2019-03.

Pneumatically controlled systems will react to increases in static pressure, obstructions, etc., by reducing the input rate to a level commensurate with the remaining air flow. This approach assures continuous complete combustion during operation because the air-fuel ratio is adjusted to account for any changes to airflow.

Because the air-fuel ratio is set at the factory, pneumatically modulating systems benefit from being set up by the installer for local conditions using an electronic combustion gas analyzer (the installer fine-tunes the air-fuel ratio across all output capacities). However, even a perfect air-fuel ratio on the day of installation may deteriorate due to changes in the caloric value of the source gas, contamination, etc. A swap from one gas type to another (natural gas vs. LPG) also typically requires physical changes to the valve and recalibration thereof.

These systems typically include a flame ionization system, which may sense less-than-ideal combustion parameters but are incapable of automatically adjusting the burner or blower because the ratio of air to fuel is mechanically set. Thus, the unit cannot autonomously react to caloric changes in the gas being fed into the unit. However, as with less-sophisticated gas-fired appliances, the flame ionization system can be used to detect air-fuel ratios that are conducive to CO production, allowing it to initiate a unit shutdown.

3.3.1.2 Closed Loop Control

Closed-loop air-ratio control systems also utilize one or more flame ionization sensors which provides information on the flame quality. Unlike pneumatic systems, closed loop control allows the gas valve and the air supply to be adjusted separately. Thus, the controller can maintain an “ideal” air-fuel ratio even if the caloric value of gas changes. Figure 3-2 below shows a basic schematic (from Viessmann, a major European manufacturer) of how flame ionization sensors provide input for closed-loop control of the operation of their power burners.

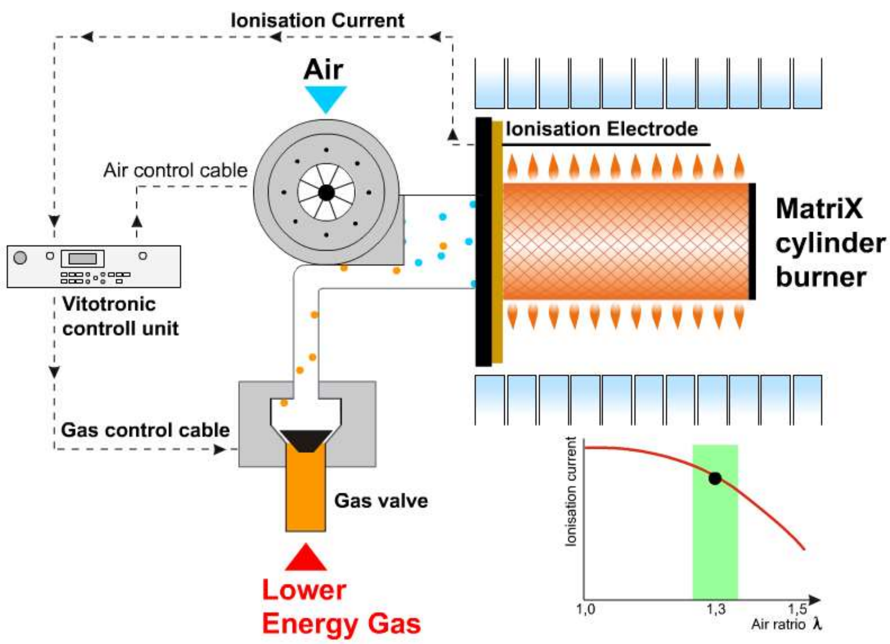


Figure 3-2: Schematic demonstrating the basic layout of a flame ionization sensor in a gas burning appliance (in particular, the Viessmann Lambda Pro)
*Image from Viessmann Vitodens 200, B2HA, B2HB – Product Introduction[28]

Closed-loop controllers typically perform a self-calibration on startup followed by continuously matching the air and the fuel to the current demand. This reduces the need for installers to fine-tune the appliance on installation, and allows the appliance to automatically compensate for any changes in caloric gas values. While systems with closed loop control may be able to accommodate switches from natural gas to propane and back without physical changes to the appliance, it is common for the gas type to be set in software.

Because of the feedback system, closed-loop control can enable safe operation with less excess air than a pneumatic system which has to incorporate an allowance for caloric gas changes and other factors. However, this greater level of control comes at a premium since independently controllable gas valves sell at a premium relative to the ones sold in pneumatically controlled systems. Hence, it is not surprising that closed loop control is typically only found in

[28] For more information see: https://www.viessmann.ca/content/dam/vi-brands/CA/pdfs/general/academy/webinars/vitodens_200_webinar.pdf/_jcr_content/renditions/original.media_file.download_attachment.file/vitodens_200_webinar.pdf.

premium, highest-efficiency appliances. The electronic components required for a closed loop control system have an expected lifetime that exceeds that of the appliance.

Within the cohort of reverse-engineering samples, two manufacturers supplemented their flame-ionization sensor with a dedicated CO sensor in the flue gas stream. Implementing a CO sensor on top of a flame-ionization system may have been done for safety reasons or to supplement the flame-ionization system in systems operating with minimal excess air.

3.4 Direct CO Measurement

Appliances that use direct CO measurement generally position a CO sensing device in the flue gas stream, downstream of combustion. The sensor is connected to the main control board of the appliance and is sensitive to the presence of CO or hydrocarbons in the flue gases. Once the sensor detects an elevated CO or hydrocarbon concentration in the combustion products, the controller either shuts down the appliance or (if fitted with a closed-loop control system) adjusts the air-fuel ratio).

Specific technologies used in the Japanese and European markets are discussed in the subsections that immediately follow. In addition to the technologies discussed immediately below, Guidehouse found other CO sensing technologies, such as infrared sensors, zirconium dioxide, and tin dioxide sensors, that could potentially be used in gas space heating and water heating appliances to limit CO production. However, because we did not identify any gas-fired space or water heating appliances on the European or Japanese markets that included these sensors at the time of this report, they were not examined further.

3.4.1 Catalyzed Pelletized Resistor Sensors

Catalyzed pelletized resistor (pellistor) sensors are currently used in Japanese water heaters to directly detect the amount of CO in flue gases and adjust or shut-down combustion when elevated CO levels occur in the flue gases. We did not identify any products available in the EU that utilize this technology. We identified one pellistor sensor being widely used in the Japanese market, which is designed to continuously monitor the flue gases of gas and oil fired domestic water and space heating appliances. The manual for this sensor explains the principles of its pellistor sensor operation as follows:

> *"A pellistor consists of a very fine coil of platinum wire, embedded within a ceramic pellet. On the surface of the pellet is a layer of a high surface area noble metal, which, when hot, acts as a catalyst to promote exothermic oxidation of flammable gases. In operation, the pellet and so the catalyst layer is heated by passing a current through the underlying coil. In the presence of a flammable gas or vapor, the hot catalyst allows oxidation to occur in a similar chemical reaction to combustion. Just as in combustion, the reaction releases heat, which causes the temperature of the catalyst together with its underlying pellet and coil to rise. This rise in temperature results in a change in the*

electrical resistance of the coil, and it is this change in electrical resistance which constitutes the signal from the sensor.”[29]

The sensor can detect levels of CO from 0 to 20,000 ppm (0 to 2%) with an accuracy of +/- 100 ppm (0.01%). It is advertised as being capable of operating in temperatures ranging from -20 °C to 200 °C, and at relative humidity ranging from 0 to 95%. The sensor includes a special resistor matrix mounted in a separate box, which allows for stable and reliable performance when mounted inside a flue and exposed to high temperatures. When the concentration of CO in the flue gases reaches a specified level, the signal from the sensor can be used to initiate a safety shutoff.[30]

According to the sensor’s manual, the sensor is designed to last at least ten years. During interviews, some manufacturers indicated that a common issue that shortens the lifespan of this sensor is exposure to combustion air tainted with silicon sealants often used in flues, which can reduce the sensor’s output or damage the sensor. Similarly, we note that silicone-aerosol in the combustion air supply (such as from silicone-containing cleaning supplies stored in the vicinity of the appliance) could result in a shortened lifespan for appliances that draw combustion air from around the unit. However, interviews with manufacturers that utilize this sensor indicated that this sensor is easily accessible for service or replacement, should failure occur before the life of the appliance.

Guidehouse obtained multiple samples of this sensor – one consisting of the sensor only (and attached wiring) and another sample that was installed in a Japanese water heater. We performed a reverse-engineering teardown analysis on these units to identify the materials, components, and processes used in their manufacture (see section 1 for additional description of the teardown analysis). Figure 3-4 shows photographs of the sensor in various stages of disassembly.

According to the sensor’s manual the optimum position should be away from other electronics to avoid interference. The sensor in the unit that we examined was mounted in a housing with a hole punched to allow flue gases to diffuse into it. Figure 3-3 below shows the sensor installed. In addition, the sensor was easily accessible for service or replacement, consistent with the comments from manufacturers discussed above.

We estimated the cost to implement the sensor on a per-unit basis and the estimated costs for incorporating this sensor based on the teardown analysis are discussed further in section 3.5.

[29] For more information see: https://af08ffaf-3437-4663-bb36-7f5fe31e84cb.filesusr.com/ugd/40199a_0ee41737ebbf4903888315030a43d5b0.pdf

[30] “NAP-78SU (High temp In-Stack Sensor).” *Nemoto Sensor Engineering Co., Ltd.* https://www.nemoto.eu/nap-78su-gas-sensor.

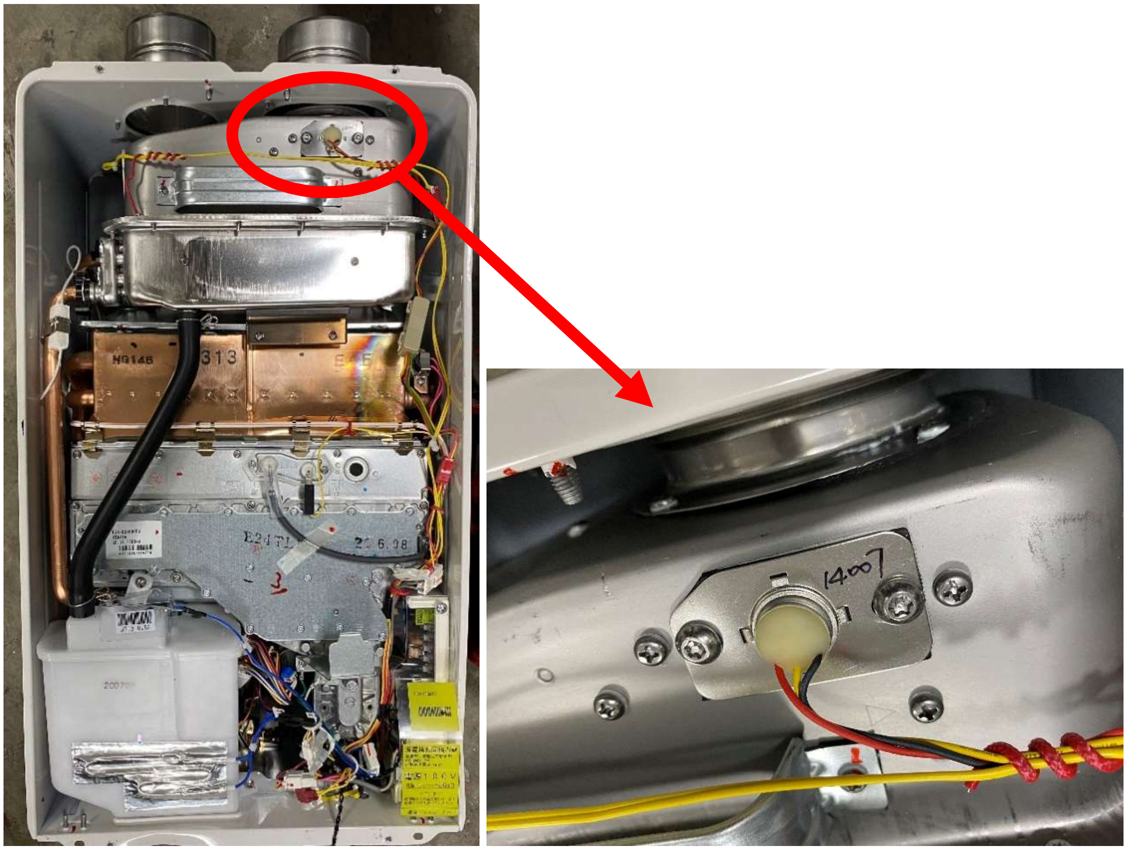


Figure 3-3: Images of a pellistor CO sensor mounted in the flue gas collector of a Japanese water heater.

Figure 3-4: Photos from a teardown analysis of a pellistor CO sensor.

3.4.2 Gallium Oxide Sensors

Various semiconducting metals' electrical properties are highly sensitive to small variations in its surrounding environment. Thus, sensors made from metal oxides such as gallium oxide (Ga_2O_3) can detect various gases. Compared to other metal oxides, gallium oxide offers especially excellent structural stability at very high temperatures and serves as an ideal candidate for gas sensing in harsh environments. Gallium oxide provides high levels of chemical resistance and thermal stability with the rated operation in temperatures of 100-500°C. (It is commonly used in its crystalline structure, β-Ga_2O_3 for high temperature applications and it is still very stable in this form). Guidehouse identified one manufacturer that uses gallium oxide sensors for sensing CO in the European market and is not aware of any manufacturers using this technology in Japan.

Gallium oxide's conductive properties are specifically sensitive to oxygen levels in its immediate environment, but its sensing capabilities are not limited to oxygen. These sensors are also sensitive to other gases such a H_2, CO, and CH_4 through surface redox reactions. When in the presence of CO, the resistance of the gallium oxide reduces proportionally to the CO concentration as shown in Figure 3-5. Doping the gallium oxide with other metals like gold and titanium can change the compounds electrical properties and allow it to be more sensitive to carbon monoxide or other gases.

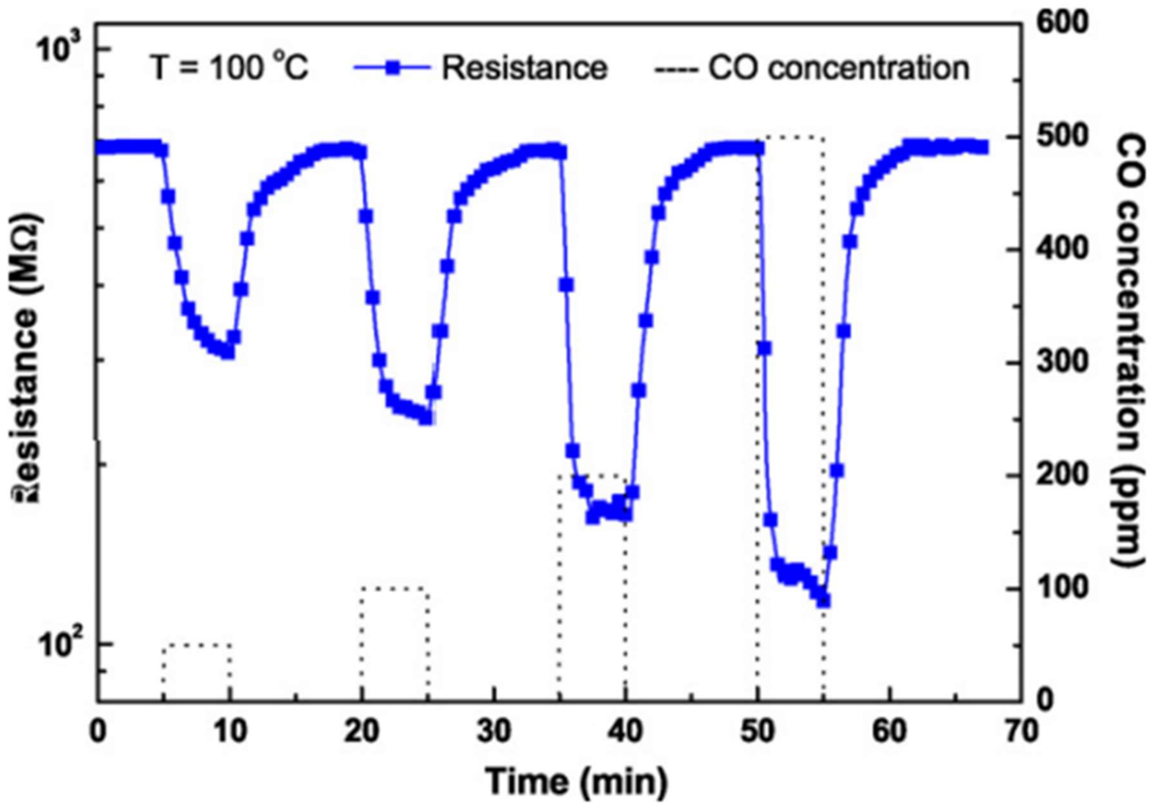


Figure 3-5: A gallium oxide sensor's reaction to CO at 100ºC

*Image from *Journal of Materiomics*, Volume 5, Issue 4, December 2019, Pages 542-557

The gallium oxide sensor we observed during teardown analysis of a European boiler was installed in the flue pipe near the outlet of the heat exchanger. The gallium oxide film is housed in a protective chamber which allows flue gas to diffuse through a permeable material into it. The resistance of the sensor varies based on the CO concentration and its signal is processed by the combustion controller. Signals from this sensor can be used to either modulate performance or initiate a safety shutdown of the appliance.

According to manufacturer survey responses, these sensors are designed to last the lifetime of the appliance. As with pellistor sensors described previously in section 3.4.1 of this report, these sensors are accessible for maintenance or replacement if necessary (i.e., if the sensor should fail before the life of the appliance). During teardown analysis of a unit that included a gallium oxide sensor, we confirmed that the sensor is easily accessible. Figure 3-6 shows an interior view of a boiler that we tore down that contained a gallium oxide sensor, and Figure 3-7 shows images of the sensor in various states of disassembly during the teardown analysis. The estimated costs for incorporating this sensor based on the teardown analysis are discussed further in section 3.5.

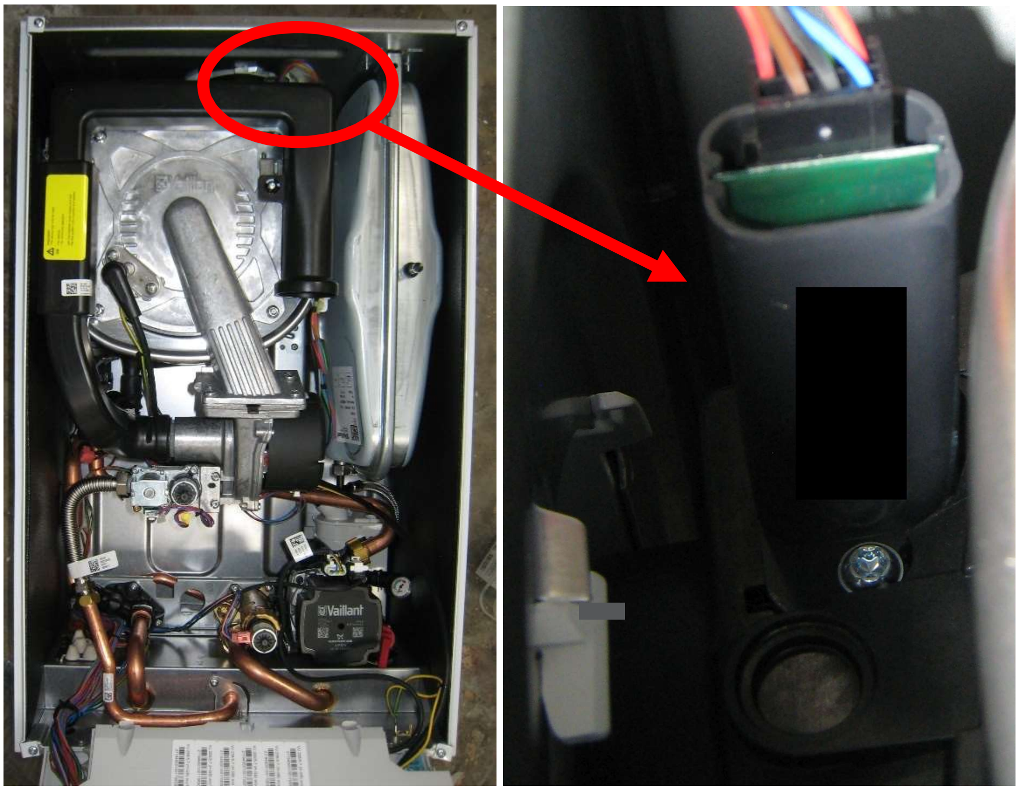
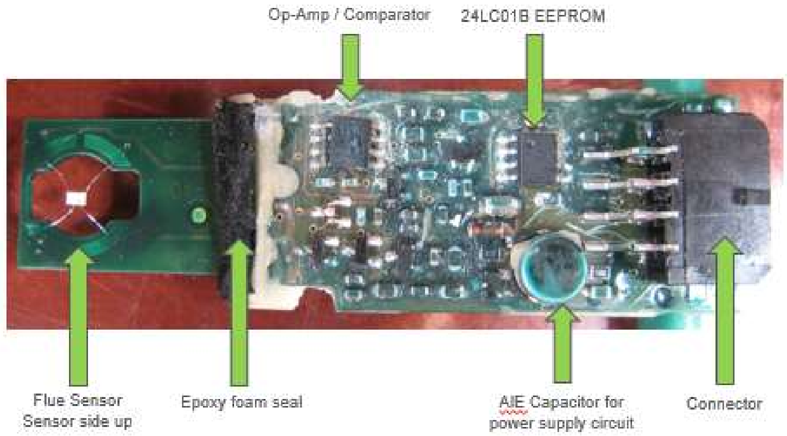


Figure 3-6: Interior view of a boiler with a gallium oxide combustion sensor. The sensor is mounted into the flue pipe collar.

Flue gas sensor casing split and removed.
Note thick epoxy foam covering circuit board.



Flue gas sensor circuit board after removal of several coats of protecting foam

Figure 3-7: Gallium oxide combustion sensor

Also notable is the use of an electrically erasable programmable read-only memory (EEPROM) chip on this sensor, suggesting that calibration values are factory set and then read by the combustion controller. Similarly, the pelletized resistor sensor (see section 3.4.1) appears to be manually calibrated at the sensor manufacturer, as the external potentiometer position is sealed with red lacquer and the outer plastic case holding it is further sealed with tape. Unlike the potentiometer, the EEPROM offers the opportunity to store a wider range of calibration values, etc., though at a higher cost.

3.5 Cost Analysis

As mentioned earlier in this report, Guidehouse obtained six units for teardown – three from Europe and three from Japan. One unit from Europe and one unit from Japan used dedicated CO sensing technology, with a CO sensor mounted in the flue gas post-heat exchangers. All of the units selected for reverse-engineering featured power burners with air-fuel-ratio sensing flame ionization systems.

As part of the teardown analysis, we examined the materials and processes, and the associated labor and overhead costs, used to manufacture the combustion control systems discussed in the previous sections to estimate a cost to the appliance manufacturer to include these systems and controls.

3.5.1 Flame ionization sensors

Flame ionization sensors are widely used throughout the European and Japanese markets to sense whether a flame is present. In many appliances they have replaced thermocouples as the flame sensor of choice, even though our research suggests that a flame ionization system costs more to implement than a thermocouple system. Our research further suggests that flame ionization systems offer longer lifetimes than thermocouple systems, reducing nuisance lockouts and warranty claims. Unlike thermocouple systems, flame ionization systems can run intermittently, eliminating the need for a standing pilot light. Additionally, they can recover from gas outages, power losses, etc., more easily than a thermocouple-powered gas valve (whose pilot light has to be manually relit every time the pilot light goes out).

Within the sample of units reverse-engineered, the average cost of an integrated flame ionization system capable of air-fuel ratio measurements was estimated to be $7.05 (minimum of $4.50 and maximum of $9.48) compared to $3.55 for a thermocouple system (at 1MM units p.a.). These costs include the flame rods, assorted wiring, and any data acquisition systems on controller PCBs but not shared components such as the microprocessor running the controller, non-dedicated power supplies, etc. Estimated costs for flame ionization sensor systems by purchase/manufacturing volumes are shown in Table 3-1.

Table 3-1: Estimated Manufacturing Cost for Flame Ionization by Purchase/Manufacturing Volume

Purchasing Volume (units pa)	Manufacturing Cost		
	Air-Fuel Ratio Measurement - Integrated		
	Minimum	Average	Maximum
1,000,000	$4.50	$7.05	$9.48
100,000	$5.64	$9.24	$12.72
10,000	$7.32	$12.71	$17.70

3.5.2 CO sensors

Team research suggests that the cost of CO sensors varies significantly from less than $6 to as much as $40 in single-unit quantities from electronics distributors. However, the allowable operating environment limits of these sensors as specified by their suppliers also vary significantly. Less expensive models are only being specified for use between -10 °C to 50 °C and a non-condensing, relative humidity (RH) of less than 90%. This precludes their use from inside flue systems due to exceeding the temperature and relative humidity limits. Additionally, many sensor datasheets specifically call out against use in corrosive environments (flue gas condensate has a pH of 4 (a pH of 4 or below is generally considered corrosive, whereas pH below 2 is generally considered highly corrosive)). This report focuses on CO sensors used inside the flue, as observed in the models from Europe and Japan that were examined. In our reverse-engineering cohort, we observed two examples of CO sensors installed directly in the flue gas stream, which serve as the basis for the estimates presented in this section. As noted, other sensors exist or have existed in the past, but due to their operational limitations or high cost, are not currently used in gas space or water heating appliances and therefore are not considered further in this report.

The flue gas sensors observed during reverse-engineering were connected with wiring to the PCB used by the appliance controller. Typically, the signal is processed by comparator and/or operational-amplifier before connecting to the microcontroller running the combustion process. As part of the reverse-engineering process, the team attempted to isolate all printed circuit board components associated with the CO sensor circuit on the controller PCB. Common circuit board infrastructure such as power supplies were assumed to be shared unless a voltage reference, regulator, etc., appeared within the confines of the PCB area where the CO signal appeared to be processed. Thus, this analysis focused on the marginal cost that the manufacturer would incur due to retrofitting a CO or flame-ionization sensor system to an existing controller platform. Past experience suggests that high-volume manufacturers will integrate such signal-processing capabilities directly into their control boards. All appliances with CO sensing abilities within the reverse-engineering cohort examined for this report featured integrated CO sensor circuits as part of their main control boards.

As previously discussed, the implementation cost is highly dependent on the specific CO sensor model and the requirements of the manufacturer. The team was only able to reverse-engineer two approaches, both of which showcased sensors capable of dealing with the most difficult operational conditions – continuously elevated temperatures combined with condensing conditions. As a result, the costs discussed below focus on measuring CO inside the flue gas stream of the appliance. We note that actual implementation costs across other appliances will vary somewhat as appliances have different dimensions, ideal mounting locations, etc.

At a volume of 1MM units per year for a given OEM, CO flue sensor and the necessary circuit components and circuitry integrated into controllers are estimated to cost the manufacturer an average of $16.27 per appliance as shown in Table 3-2.

Table 3-2: Estimated Manufacturing Cost for Integrated CO Sensors by Purchase/Manufacturing Volume

Purchasing Volume (units pa)	Manufacturing Cost		
	Integrated CO Flue Sensor Cost		
	Minimum	Average	Maximum
1,000,000	$12.21	$16.27	$20.33
100,000	$15.27	$19.68	$24.09
10,000	$26.64	$27.75	$28.85

3.6 US Market Comparison

The US residential heating and water heating appliance markets differ greatly from those in Japan and Europe. These differences are driven largely by differences in consumer expectations and regulations. As discussed in the subsections that follow the combustion safety systems and control strategies differ between the US and Europe and Japan.

3.6.1 System Types and Uses for Gas Heating

In Europe hydronic systems are commonly used for space heating. The market has transitioned almost entirely from atmospherically vented, non-condensing boiler systems to sealed, condensing systems that utilize premix burners and combustion fans. This transition was driven largely by the EU's Ecodesign Directive[31] and its requirements aimed at improving energy efficiency and reducing emissions. In the European residential boiler market, pneumatic gas valve/blower combinations are very common, but burner controls that utilize flame ionization with closed loop control are becoming more prevalent. Use of a carbon monoxide sensor in the flue is still rare in European boilers, and we were only able to identify a single manufacturer that currently employs a proprietary sensor solution. In the US, many atmospherically vented, non-condensing systems are still available. Pneumatic gas valve/blower combinations are employed in the US market, and Guidehouse also found some boiler models in the US having flame ionization control with closed loop feedback. We were not able to identify any models in the U.S. market that use a flue gas sensor to monitor CO levels.

In Japan, most gas water heaters are tankless outdoor models, and CO detection is not a priority, since any excess CO production would be exhausted to the atmosphere rather than to the residence. For indoor models in Japan, to meet the requirements of safety standards, water heater models may feature an oxygen depletion sensor and/or a CO sensor as described in sections 3.2 and 3.4, respectively. Vented indoor models more typically use CO sensors, while the oxygen depletion sensors are found mostly in unvented indoor models, but also sometimes in power vent models. The US water heater market is dominated by storage water heaters that heat and store hot water for later use; however, those products are beyond the scope of this report, which focuses only on tankless water heaters that heat water instantly on demand similar in design to those on the Japanese market. In the US most tankless water heaters are installed inside the residence and must be vented, although outdoor water heater models do exist. Venting systems for tankless water heaters are typically fan-assisted (e.g., power vent). Oxygen depletion sensors are not common on tankless water heaters in the US, although they are used widely on ventless gas heaters and ventless gas fireplaces in the US.

In the US, the market for gas-fired space heating appliances is dominated by central furnaces, which are not common in Europe or Japan. The design of US central furnaces differs significantly from the designs of boilers on the European market and tankless water heaters on the Japanese market that were reviewed for this report. Rather than a single pre-mix burner that is common in boilers and water heaters in Europe and Japan, respectively, a typical gas-fired central furnace in the US is comprised of several in-shot burners (the number of which depends on overall capacity), with each burner corresponding to an individual heat exchanger pathway through which the combustion gases flow. The heat exchanger pathways typically culminate in a collector box where the flue gases are combined before exiting through a single pipe. Typically,

[31] For more information on the EU ecodesign requirements for space and water heaters, see: https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/energy-efficient-products/space-and-water-heaters_en.

an inducer fan at the outlet of the heat exchanger assists the flue gases in moving through the heat exchanger.

While some US products use similar technologies to those being used in Europe and Japan for controlling combustion, there are a substantial number of models available that do not continuously monitor or control air-fuel ratio to ensure complete combustion. For many such products, integrating a CO sensor into the combustion controls and/or using a combustion system that continuously controls air-fuel ratio (and thus minimizes CO formation) could potentially be viable approaches to ensuring complete combustion and minimizing CO formation under a variety of conditions. During interviews and in surveys, however, manufacturers that have US operations (but which are also part of larger international companies having space and/or water heating operations in Europe and/or Japan) identified a number of potential concerns in employing these technologies more widely in the US market. After a brief discussion of combustion safety systems and combustion control strategies in use in the US, we discuss the potential issues with regard to implementing these technologies in the US, followed by an estimation of costs to implement them in various types of space and water heating appliances in the US.

3.6.2 Combustion Safety and Combustion Control Systems in the US

In sections 3.2 and 3.3 of this report, we describe combustion safety systems and combustion controls in widespread use in Europe and Japan. All of the combustion safety systems and combustion controls described in those sections are available to a certain extent in US appliances, while the direct CO sensors discussed in section 3.4 are not currently available in US appliances. Many line-powered gas-fired appliances sold in the US today use flame ionization sensor systems and either spark or hot-surface ignitors similar to those observed in European and Japanese products. However, in the US certain safety and control systems are still prevalent that are no longer widely available in Europe or Japan. Specifically, safety systems that employ a thermocouple with standing pilot are still used in the US in certain markets (e.g., wall furnaces). In addition, atmospherically-vented and induced draft appliances are also still common in certain markets (e.g., wall furnaces, boilers, and central furnaces, respectively).

3.6.2.1 Thermocouple / Standing Pilot System

In combustion systems that use a thermocouple and standing pilot, gas valves use the power generated by a thermocouple in contact with a standing pilot flame to enable gas flow through the main gas valve. Should the standing pilot flame extinguish, the main gas valve (supplying the burner and the standing pilot assembly) closes.

The benefits of a thermocouple / standing pilot system include low cost, standalone operation (no line power or batteries needed), and simplicity. However, the standing pilot flame has to burn continuously (requiring air and gas) and have a suitable flue pipe system. Thermopiles, which are basically multiple thermocouples stacked in series producing more power, can be used to power “digital” gas valves or limited controllers with additional features. Standalone gas valves using just thermocouples or thermopiles do not monitor for CO nor shut down due to excess CO. Their primary safety intent is for the gas valve to shut unless a steady pilot flame is present to ensure no unburnt gas leaks. As noted previously, these systems are not common in Japan and Europe, but are still in use in the US (for example, in wall furnaces).

ODS systems are a type of thermocouple / standing pilot system (as described in section 3.2.1) and are commonly found on vent-free appliances in the US and have been required on any ANSI-certified vent-free appliances since 1980.

3.6.2.2 Atmospheric Appliances

The simplest combustion devices do not use fans and instead rely on the higher buoyancy of combustion gases to rise and create a draft (the hotter the gases or the greater the input rate, the greater the draft). Typically using in-shot or upshot burners, a gas orifice meters out a fixed amount of gas at the nominally expected gas pressure inside the gas manifold to mix with ambient air and combust safely.

Depending on where the appliance is installed, the orifices may have to be exchanged by the installer to ensure the proper amount of fuel is supplied to match the available oxygen at that altitude (the installation manual will list the proper gas orifice internal diameter by altitude). Similarly, such appliances also require orifice and perhaps even burner changeouts when switching gas types (natural gas vs. propane).[32]

Typically, atmospherically vented appliances feature fixed output burners with a limited capacity, and total output is scaled by adding more burners. Hence, for a given product family, atmospherically vented appliances typically grow in one dimension as their output capacity increases.

Atmospheric vent appliances typically operate at low efficiency due to the allowances that designers have to make to ensure a good draft and mitigate potential combustion issues such as wind. Hence, these appliances tend to be designed with ample excess-air to ensure complete combustion. Simple thermocouple controls as described in section 3.6.2.1 are common in this appliance category.

3.6.2.3 Induced Draft Appliances

Induced draft appliances are frequently built similarly to atmospherically vented appliances but feature an inducer blower installed near the flue pipe exhaust. The blower induces a draft by pulling the flue gases through the heat exchanger and into a chimney or flue. An inducer allows the use of more energy-efficient heat exchanger designs and the ability to detect leaks in air-to-air heat exchangers (which improves product safety). Like the atmospheric-vented

[32] It is not uncommon for gas appliances (e.g., wall furnaces) to feature geographic stock keeping units (SKUs) that are pre-adjusted for an expected altitude at which the unit will be installed, or to offer high altitude conversion kits. Thus, appliances destined for areas with higher altitudes may feature factory-installed gas orifices that are different from the ones installed in water heaters destined for sea-level locations, or be field-convertible by the installer.

appliances from which they are derived, induced-draft appliances frequently use multiple burners in parallel to achieve a given output.

3.6.3 Potential Barriers to Combustion Control and CO Sensor Implementation in the US

3.6.3.1 Product Differences

As discussed in the preceding section, there are various differences in the gas space and water heating appliances available for sale in Europe and Japan as compared to the US. These design differences in the combustion systems are important in understanding potential challenges in implementing these devices in the US, which could necessitate significant redesigns of appliances. Whether the designs could be limited simply to controls and control board components, or would apply to the appliance generally would be a result of the design decisions made by manufacturers in implementing combustion control or CO sensing technologies.

In the short term, we expect manufacturers would attempt to minimize design changes to extant appliance platforms by adding CO sensors and/or controls. Longer term, manufacturers may explore a clean-sheet redesign to use flame ionization-based controls instead. This likely would necessitate broader changes to the burner and potentially to the heat exchanger. Between research & development, pilot production, long-term validation, etc., this effort would likely take significantly more time to implement than retrofitting a CO sensor into the flue gas stream of an existing product platform.

In Europe and Japan, the markets for gas boilers and gas water heaters, respectively, are dominated by high-efficiency, condensing products. This is a significant difference from the US where many gas space and tankless water heating appliances use less efficient, non-condensing technology. We note that non-condensing appliances have higher flue gas temperatures that may contribute to differing design constraints as compared to condensing products for sensor products.

In addition, as noted induced-draft and atmospheric-vent appliances are common in the US, whereas the power burner combustion systems dominate in Europe and Japan. Thus, while the implementation of the combustion control via closed-loop control has been demonstrated in Europe and Japan, and even on products in the US in certain markets that make significant use of power burners (e.g., condensing boilers), the feasibility of air-fuel ratio measurement via a single flame rod atmospherically-vented or induced-draft appliances has yet to be demonstrated.

It is unclear whether the flame ionization systems on non-power burners (i.e., on atmospheric or induced draft burners) can incorporate the kind of air-fuel ratio measurements and adjustments that correlate with combustion conditions conducive to limiting CO production. Another question is whether every burner in an appliance would need to be measured individually or whether a single flame sensor per appliance would suffice.

Our research suggests that if every flame has to be measured individually, the more cost-effective approach in a vented multi-burner appliance is to mount a single CO sensor in the flue gas stream (although as discussed above, such a solution has not yet been demonstrated in non-condensing appliances). Single-burner appliances, conversely, may be able to incorporate air-fuel sensing with relatively minor modifications.

3.6.3.2 Practices and Expectations Regarding Installation and Maintenance

Another potential concern for implementing these technologies in the US relates to differences in installation and maintenance practices for gas space and water heating appliances in the US compared to Europe and Japan. Manufacturers indicated that professional installations and annual inspections are more common in Europe and Japan than in the US, and in some areas are required. As a result, appliances are more likely to be properly installed and maintained in Europe and/or Japan as compared to the US, leading to lower likelihood of combustion issues.

The more common regular maintenance schedule practiced in Europe and Japan (as compared to the US) makes it more likely that any potential issues with appliances are detected and fixed before they become a more significant problem for the consumer.

3.6.3.3 Implementation issues

Requiring a broad range of products to infer or directly sense CO-production and shutting down as necessary is a significant change for many appliance designs in the US, which gives rise to concerns regarding implementation of such systems. Implementing a system that relies on air-fuel ratio measurements is much less concerning than implementing in-flue CO sensing, since the former is already widely practiced in some appliance categories; there are multiple suppliers, and standalone combustion controllers exist for low-volume gas appliance OEMs to buy.

Similar concerns may have existed in Europe and Japan before the widespread implementation of closed-loop control via flame ionization systems, and the more limited introduction of CO sensors that directly sense the amount of CO in the flue. However, as discussed, market forces including energy efficiency directives in Europe and Japan have largely driven manufacturers toward high-efficiency, condensing, pre-mix power burner designs, which lend themselves well to flame-ionization control systems. This contrasts with the US market, in which many gas space and water heating appliances still utilize non-condensing, atmospheric or induced-draft designs.

In addition, the variations in natural gas caloric content in different areas of Europe may have incentivized manufacturers to more widely implement closed-loop control via flame ionization, as these control schemes are often advertised as providing fuel flexibility and easier set up, rather than for their ability to reduce CO in the flue gases, thereby improving safety. Since such issues are less prevalent in the US, there has not been as much demand for such systems, and their implementation has thus far been somewhat limited.

Therefore, when examining the implementation of control schemes that either infer or directly sense CO-production in products in the US market, concerns exist that:

a) CO production limits established in the US may be stricter than what is achievable by sensors and combustion control strategies already demonstrated in Europe and Japan.

b) Significant capitalization will be necessary for the R&D, product certifications, and conversion costs necessary to redesign a large number of models to comply with any requirement to actively monitor and shut down and/or adjust combustion in the presence of excess CO. Constraints on capitalization will generally provide an advantage to larger manufacturers at the expense of smaller manufacturers, who have lower shipment volumes over which to spread capital expenditures. Similarly, larger manufacturers are more likely to have accredited in-house test facilities and better access to third-party test providers as well.

c) We only identified a single supplier of a commercially-available CO sensor currently being used in the European or Japanese gas-fired space and water heating appliance markets. While other CO sensors are commercially-available, to our knowledge they are not currently used to monitor CO in the flue gas of gas-fired space and water heating appliances either because of design constraints or cost constraints. Although CO sensors for similar applications have been commercially-available from other suppliers in the past, it is uncertain to what extent other sensor manufacturers would develop CO sensors that could be used in the flue gas stream. Given projected demand under a potential regulation it seems likely that other sensor manufacturers would enter the market, but the development, qualification, and certification process could take years.

d) If inclusion of a combustion control system or CO sensor significantly increases the product cost, which may be likely in the least sophisticated appliances currently for sale in the US, it could drive consumers to delay replacements by repairing old appliances, and fuel switch away from gas appliances all together.

e) As discussed earlier in this report, the US market includes many types of combustion system designs, including induced-draft and atmospherically vented products. Many of these products are mid-efficiency, non-condensing designs with significantly higher NO_x emissions than is produced by low-NOx power burners common in Europe and Japan, and for which the viability of a CO sensor or closed-loop combustion control has not been demonstrated. One concern expressed during interviews with manufacturers is that, in their experience with the commercially available CO sensor, the signal from the sensor degrades upon exposure to NO_x and varies based on the RH level in the combustion gases. We note that humidity level in the flue gases for condensing models is more predictable than in non-condensing models. Thus, technical challenges associated with these sensors may be lessened in European and Japanese products, where the NO_x levels are lower and the RH in the flue gases is more stable.

3.6.3.4 Incremental Manufacturer Cost Changes

In this section, we discuss expectations for product design changes in the US along with the associated costs by market segment. We note that the costs presented do not capture the R&D expenditures, or other capital expenditures that may be necessary, as those are outside the scope of this report. In addition, this analysis assumes that the combustion control and/or CO sensing implementations observed in the European and Japanese products would be capable of meeting a potential US requirement and that implementation in the US would include similar components, sensors, and associated controls. However, as discussed in the previous section that is currently uncertain pending the establishment of any requirements.

For the US market, we estimated the incremental costs to implement CO sensing or flame ionization-based combustion control systems (as appropriate) based on designs observed in the European and Japanese models, as well as our expectations of how CO sensing or flame ionization-based combustion control would be implemented in US products. As discussed earlier in this section, there are significant differences in the types of products available in the US market, as compared to the European and Japanese products that were part of the reverse engineering cohort analyzed for this report. The European and Japanese designs (premix power burner) lend themselves well to combustion control through flame ionization.

Similarly, in the US, some manufacturers of boilers and tankless water heaters already offer products with combustion systems that continually adjust air-fuel ratio based on flame ionization, thereby minimizing CO production, and for which the cost of complying with any new CO limitation could be effectively $0. On the other end of the spectrum, there are atmospheric and inducer-based systems for which neither CO sensors, nor flame ionization ionization-based air-fuel ratio measuring controls have been demonstrated in the US, Europe or Japan, and for which the costs are likely to be significant. The variability of product designs across industries and manufacturers, differences in purchasing quantities, and lack of demonstrated technologies results in much uncertainty on how manufacturers would choose to redesign such products to meet potential CO limit restrictions. However, the paragraphs below describe our assumptions with respect to the most likely approach and components necessary to convert different types of combustion control systems.

Because atmospheric-venting appliances typically feature the simplest control systems, they likely also have the highest cost to convert to a control system that can react to the presence of CO. For example a wall furnace may feature nothing more than a thermostatically-controlled on/off gas valve, a pilot light, and a thermocouple to control the burner operation.[33] To add a CO control system for such an appliance would likely require line power (or a very large battery pack), an enclosure with an controller, a sensor, etc., because there is no extant controller with which to share components, voltage busses, etc. All the units in the reverse-engineering cohort examined for this report featured blower systems, but we are very familiar with a wide scope of atmospheric vent units available in the US from having reverse-engineered over a hundred of them.

Due to the way that induced-draft systems typically are built, the flames (and the ionization signal being carried through them) may not be as stable as with the premix power burner systems found in the reverse-engineering cohort. Thus, adopting the same flame ionization strategy to measure the air-fuel ratio may not be feasible. With the exception of single-burner systems, most appliances using inducer-type combustion controllers would likely opt to

[33] Should the pilot light go out, a solenoid inside the gas valve closes, turning off the wall furnace until the pilot light is re-lit.

sense CO directly in the flue gases rather than try to measure a safe air-fuel ratio across multiple, parallel burners (each likely requiring a separate flame rod, signal wire, and comparator circuit).

Because they already feature a line-powered control system, the marginal cost of adding CO-limiting controls may be greatly reduced for single-burner, induced-draft appliances. Many induced-draft combustion controllers already use flame rods, so if CO production can be inferred by a less-than-ideal air-fuel ratio as measured by the flame rod, then the appliance can be shut down before it potentially produces excess CO. However, the scope of single-burner induced draft appliances is limited (e.g., clothes dryers) and such products may not be under consideration for CO requirements at the present time.

Barring significant redesign, most induced-draft systems and atmospheric systems would be expected to rely on measuring CO directly in flue gases, while we would expect power burner systems to rely on flame ionization. In the case of CO sensing, we envision two ways that could be implemented – as a component that is integrated into the design of the system controls and PCB (as was observed in some of the Japanese and European models that were reverse-engineered for this project), or as a standalone CO interlock. Past experience suggests that high-volume manufacturers will integrate the CO-sensor-related circuitry into their control boards, similar to the designs observed in the reverse-engineering cohort, while lower-volume manufacturers may opt for a stand-alone interlock.

Stand-alone CO interlock systems could be designed as a retrofit add-on to extant appliance control systems, allowing the manufacturer to upgrade their appliances to feature CO sensors with relatively minimal effort (instead of integrating the CO sensor package into the controller PCB). We expect this would be a common approach for low-volume manufacturers who lack the volume to justify designing electronics in-house. Instead, they would likely buy generic solutions (i.e., a combustion controller) that are made at higher volumes and sold into a wide scope of low-volume markets.

An illustrating example are ignition systems (i.e., the systems that generate sparks to start combustion). Some manufacturers integrate them into their main control boards, while some manufacturers buy standalone solutions that are energized on command by a relay. Separating the ignition system from the main PCB is quite sensible in case the ignition system is more prone to failure than the controller (swapping a standalone ignition system is much less expensive than replacing an entire control board). Within the cohort of reverse-engineering samples, some units featured integrated ignition systems some featured standalone systems.

The main downside to a standalone CO interlock as compared to an integrated CO sensor package is that some underlying supporting resources have to be duplicated, adding cost. For example, a standalone CO interlock would have to feature an AC-DC power supply, components to interface it with the main controller, as well as a casing, etc. As with generic ignition controllers, the main appeal of standalone CO interlocks is being able to consolidate the demand from many low-volume industries to allow multiple, competing suppliers to justify the expense of developing, certifying, and manufacturing at minimum efficient scale.

To our knowledge, there are presently no standalone CO interlock systems available on the market that are suitable for appliance use. Our research suggests that a standalone CO interlock would feature an external power input as well as two normally-open dry contacts as an output. The interlock would be added in series to other safety devices or using a dedicated set of contacts on an ignition control board. For example, it is not uncommon for pressure switches, spill switches, and like interlocks on furnaces to be arranged in a string that cuts off power to the gas valve if any one of the them is tripped. An illustrative wiring diagram is shown in Figure 3-8. If either spill switch opens, the pressure switch does not close (on an inducer model), or if the CO sensor interlock dry contact does not close, the gas valve will lack power and shut down.[34]

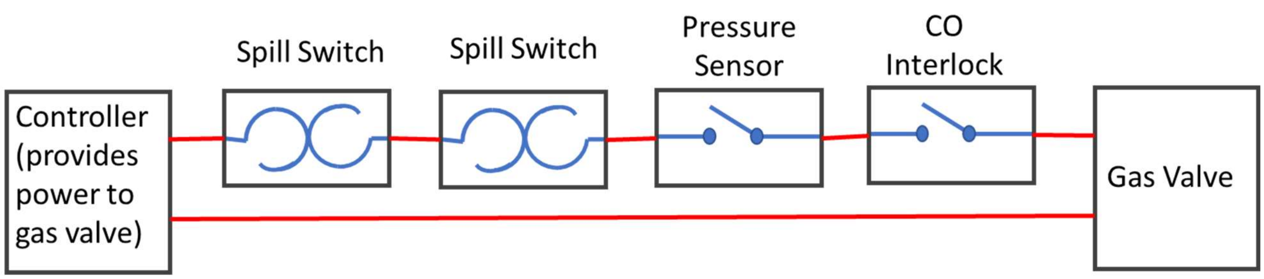


Figure 3-8: Illustrative Gas Valve Wiring

Excess CO or a lack of power to the package would open the dry contacts of the interlock, shutting the appliance down in a failsafe manner. Such functionality is similar to the temperature, flame-roll-out, and negative-pressure switches already commonly found in gas-fired appliances today. Hence, implementation could be relatively simple for all line-powered appliances though they would still require re-certification by applicable safety agencies to verify compliance.

Appliances without built-in line power supplies likely would require the addition of a regulated line power supply for the CO sensor interlock system.[35] Should line power be required, this could add significantly to the installation cost of the appliance or even make installation impossible, depending on the location. The simplest control systems (i.e., atmospheric vent systems featuring just a gas valve, standing pilot light, and thermocouple) may require a gas valve redesign or replacement, adding to R&D, certification and unit costs for the manufacturer. Table 3-3 shows the estimated cost for a standalone CO interlock both with and without an external power supply. Our cost estimates for an integrated sensor in the US market are the same as those previously presented in Table 3-2.

[34] Some ignition systems have these safety switches on a separate circuit or feature dedicated writing to/from each sensor to allow the controller to pinpoint the problem area. However, the operating principle is the same – any tripped sensors will cause the control system to shut the gas valve down.

[35] Power requirements for continuous monitoring and relay use likely exceed those sustainable by battery systems or thermopiles.

Table 3-3 Estimated Cost to Manufacturer for Standalone CO Interlock by Purchase/Manufacturing Volume

Purchasing Volume (units pa)	Cost to Manufacturer	
	Standalone CO Interlock	Ext. Powered CO Interlock
1,000,000	$28.68	$31.61
100,000	$33.88	$36.97
10,000	$40.62	$43.86

We estimate the manufacturing cost increase to induced draft appliances could be as low as $12.21 per unit for inclusion of an integrated CO sensor at high-volume (i.e., ~1,000,000+ units p.a.) to $40.62 per unit for a standalone CO interlock at low production volume (i.e., ~10,000 units p.a.). For atmospherically-vented products we similarly estimate a range of $12.21 per unit for inclusion of an integrated CO sensor at high-volume (i.e., ~1,000,000+ units p.a.) to $43.86 per unit for a standalone CO interlock with an external power supply at low purchase volume (i.e., ~10,000 units p.a.).

For power burner systems, we expect manufacturers would likely choose to use combustion control through flame ionization. Because all the components typically needed for air-fuel ratio measurements are already included in the appliance, we estimate the manufacturer implementation cost for CO-management will hence range from $0 if no additional components are needed to $41 for a standalone CO sensor at low purchase volumes (i.e., ~10,000 units p.a.; see section 3.5.2), depending on whether CO limits can be maintained with just a flame ionization system or whether a dedicated CO sensor has to be added to the flue system. The costs associated with atmospheric or inducer-based systems would likely be higher since such appliances typically do not incorporate combustion control via flame ionization measurements.

We emphasize once again that the costs presented represent the marginal increase in unit manufacturing cost and do not account for the additional research and development (R&D) expenses, capital expenditures, and training costs for servicers and installers that are typically incurred during product redesigns and would likely be required for a manufacturer to develop and implement these technologies in place of their current designs. The amount of these costs would vary widely depending on the design of the manufacturer's current products and could be significant.

These costs also do not include the cost of safety certification, without which products cannot be sold. If industry-wide CO-limit mandates were to be enacted, the ability of extant safety certification facilities and entities to meet the demand should be considered.

3.6.3.5 Incremental Price for the Consumer (US Market)

In addition to estimating manufacturer production costs changes, we estimated how the increase in manufacturer production cost translates into increased retail prices for consumers.

Typically, there are several participants in the distribution chain between the manufacturer and consumer (*e.g.*, the retailer, distributor, contractor, builder), each of which applies its own markup to cover their costs and profit. The markup varies by product due to various factors such as competition and how commoditized a product has become, among other factors.

To estimate the markups along the distribution chain, we relied on analysis performed by the US Department of Energy (DOE) in support of energy conservation standards rulemakings. In a 2010 final rule, the DOE estimated that the average overall markup for gas tankless water heaters in the US is approximately 2.31, including markups by all parties in the distribution chain from the manufacturer to the consumer (*e.g.*, the retailer, distributor, contractor, builder) and sales tax.[36] DOE also estimated the average overall markup for wall furnaces as 2.59 in the same analysis. DOE similarly estimated the average overall mark-ups for hot water boilers in a 2016 final rule analysis[37] and central furnaces in a 2016 supplemental notice of proposed rulemaking analysis[38] as 3.30 and 3.19, respectively. Applying these markups to the incremental price increases from the assumed CO control approach results in estimates for the change in retail price depending on the product type. These retail price increases are shown in Table 3-4.

As shown for some products (tankless water heaters and condensing boilers) the price can be as low as essentially $0 since many products use flame ionization-based combustion control systems or incorporate the components necessary to do so (assuming that proposed CPSC limits can be met with flame ionization sensors to measure the air-fuel ratio). However, for most products, implementation of a CO sensor would be the most likely approach, which could add over $100 to the retail price for some products. The incremental cost and price increases shown in Table 3-4 reflect assumed purchase volumes ranging from 10,000 to 1,000,000 units p.a. depending on the market size for the given product (e.g., central furnaces were assumed to have purchase volume of 1,000,000+ p.a., while wall furnaces were assumed to have 10,000 p.a.).

Table 3-4: Estimated Incremental Retail Price Increase in US Appliances from Inclusion of Continuous CO Control, excluding R&D, Capital expenditures, and Certification Costs.

Product	Assumed CO Control Approach	Incremental Cost Increase		Overall mark-up	Incremental Retail Price Increase	
		Min.	Max.		Min.	Max.
Central furnaces	CO Sensor	$12.21	$28.68	3.19	$38.95	$91.48

[36] For more information on the markups estimated by the US DOE for residential water heaters, see chapter 6 of the 2010-04-08 Final Rule Technical Support Document Chapters 1 through 16. Available online at: https://www.regulations.gov/document?D=EERE-2006-STD-0129-0149.

[37] For more information on the markups estimated by the US DOE for residential boilers, see chapter 6 of the Final Rule Technical Support Document for Residential Boilers (Dec. 22, 2015), available online at: https://www.regulations.gov/document?D=EERE-2012-BT-STD-0047-0070.

[38] For more information on the markups estimated by the US DOE for residential furnaces, see chapter 6 of the Supplemental Notice of Proposed Rulemaking Technical Support Document, available online at: https://www.regulations.gov/document?D=EERE-2014-BT-STD-0031-0217.

Most Tankless water heaters	flame sensor*	$0.00	$20.33	2.31	$0.00	$46.96
Non-condensing boilers	CO Sensor	$15.27	$33.88	3.30	$50.40	$111.81
Most Condensing Boilers	flame sensor*	$0.00	$24.09	3.30	$0.00	$79.50
Wall furnaces (fan type)	CO sensor	$40.62	$43.86	2.59	$105.22	$113.61
Wall furnaces (gravity type)	CO sensor	$43.86	$43.86	2.59	$113.61	$113.61
Floor furnaces	CO sensor	$40.62	$43.86	2.52	$102.37	$110.54

*Because the components typically needed for air-fuel ratio control are already included in the appliance, the manufacturer implementation cost for CO-management could be as low as from $0. However, if CO limits could not be maintained with just a flame ionization system and a dedicated CO sensor is required, additional cost may be incurred. The upper bound of this range represents the latter possibility.

3.6.4 Conclusion

Because European and Japanese combustion appliances commonly use power burners, it is not surprising that all of the teardown samples used power burner systems. In the US, however, many gas-fired appliances are built with atmospheric or inducer-based combustion systems. If a CO-safety system mandate were adopted in the US, it is our expectation that in the short term most appliance manufacturers making atmospheric or inducer-based products will opt to retrofit CO sensors, with the longer-term possibility of less-expensive flame-ionization approaches being used if appliances can be economically redesigned, certified, qualified, etc. For manufacturers of products with power burners, we expect the cost of including combustion control would be minimal since many products use flame ionization-based combustion control systems or incorporate the components necessary to do so.

4. EFFECTIVENESS OF TECHNOLOGIES IN REDUCING FATALITIES AND INJURIES ASSOCIATED WITH THE USE OF DOMESTIC GAS HVAC APPLIANCES IN EUROPE AND JAPAN

As a final step in this project, Guidehouse investigated the trends in CO-related injuries and deaths in an attempt to gauge the effectiveness of CO regulations, and the subsequent implementation of CO limiting technologies, in Europe and Japan. The effectiveness of the standards was evaluated based on whether evidence exists of a reduction in CO-related incidents (deaths and injuries) from domestic HVAC appliances after the implementation of requirements intended to limit CO production from gas space heating and water heating appliances. The data presented in the following sections shows that deaths and injuries from CO due to gas appliances are declining in both Europe and Japan, which could indicate that the regulations have been effective in driving the reductions in CO incidents in Europe and Japan. We note, however, that various other initiatives and market changes were occurring over a similar timeline that could also have been at least partially responsible for the decrease in CO-related incidents that has been observed.

4.1 Europe

When researching the CO incidences in the European market, we were unable to obtain data that would allow for a sufficient assessment of CO-related incidents over time for all of the European Union, despite attempts to locate publicly available information online, as well as attempts to contact government agencies directly. While we were able to find reports such as the World Health Organization's "Mortality associated with exposure to carbon monoxide in European Member States," these data sources did not provide the data needed to indicate effectiveness because they did not show how CO-related deaths and/or injuries changed over time. Table 4-1 is an example of the information provided in the WHO report, which provides CO deaths for specific time intervals. While useful in understanding the magnitude of CO-related deaths in various EU member states, because the data is not provided by year, we were unable to analyze trends or draw any conclusions about the effectiveness of regulations intended to reduce CO-related incidents from this data.

Table 4-1: CO deaths by European Member States (taken from WHO report: "Mortality associated with exposure to carbon monoxide in European Member States")

Country	Reporting Period	Reporting years	Deaths in responding period	Average number of deaths per year	Annual death rate (per 100,000 people)	Range of annual death rates in reporting period
Andorra	1994–2007	14	4	0.3	0.41	0–1.56
Austria	1980–2008	29	922	31.8	0.4	0.15–0.74
Azerbaijan	1982–2008	27	48	1.8	0.02	0–0.08

Belarus	1999–2008	10	11,809	1180.9	11.99	8.61–14.64
Belgium	1995–2008	14	553	39.5	0.38	0.12–0.60
Bosnia and Herzegovina	2003–2008	6	49	8.2	0.21	0.13–0.44
Croatia	1998–2007	10	314	31.4	0.7	0.35–0.97
Cyprus	2005–2007	3	6	2	0.25	0.13–0.35
Czech Republic	1986–2008	23	6203	269.7	2.62	0.87–6.00
Denmark	1980–2006	27	4458	165.1	3.16	0.76–5.73
Estonia	2008	1	82	82	6.16	-
Finland	2000–2007	8	917	114.6	2.19	1.66–2.55
France	1985–1998, 2001–2002	16	977	61.1	0.11	0.05–0.21
Georgia	1999–2002	4	8	2	0.04	0.02–0.069
Germany	1980–2007	28	43153	1541.2	1.91	0.34–4.38
Hungary	1996–2004	9	1166	129.6	1.27	0.91–1.61
Latvia	1996–2008	13	758	58.3	2.48	1.22–3.86
Lithuania	2000–2008	9	114	12.7	0.37	0.33–0.41
Luxembourg	1998–2007	10	44	4.4	0.98	0.21–1.81
Malta*	1991–2008	18	20	1.1	0.29	0–1.05
Republic of Moldova	1991–2008	18	4306	239.2	5.83	3.43–9.93
Russian Federation	2005–2007	3	54778	18259.3	12.81	11.32–14.07
Slovakia	1992–2008	17	719	42.3	0.79	0.59–1.07
Slovenia	1980–2007	28	1351	48.3	2.44	1.09–3.48
Spain	1981–1998	18	1932	107.3	0.28	0.20–0.38
Sweden	1980–2007	28	5449	194.6	2.24	0.89–3.81
Switzerland	1995–2007	13	266	20.5	0.28	0.15–0.44
Turkey	2008	1	84	84	0.11	–
Total		405	140490	346.9	2.24	0.60–7.05

According to the Department of Forensic Medicine and Pathology Hospital of Montenegro, there were 30 lethal cases of CO poisoning in 1993–2006. However, data cannot be provided by year and underreporting may have occurred.
*Malta data are restricted as CO reporting is limited to one large hospital. Underreporting is possible but in case of poisoning cases expected to be marginal

Another problem with WHO data in the context of this analysis is that the cause of the CO poisoning death is not indicated. CO-related deaths can be caused be a number of circumstances, many of which are unrelated to unintentional poisoning due to malfunctioning gas water and/or space heating appliances (such as incidents caused by automobiles, generators, house fires). However, accidental CO-related deaths and injuries caused by faulty residential gas space and water heating appliances were the only CO-related incidents relevant to this report. Thus, although we were able to find some limited data on CO deaths from accidental CO exposure for many European countries via the WHO report, the data were not particularly useful in determining effectiveness of changes to European standards.

We then investigated whether data on CO poisoning deaths and injuries for individual EU member states was available. We found publicly available data on CO incidents in the UK, which until recently was a member state of the European Union.[39] While these data are not certain to be reflective of trends through the entire EU, they are presented here as a potential proxy for CO-related death and injury trends in the broader EU, because the UK would have been subject to the same CO regulations and standards (as discussed in section 2.1 of this report) as the other EU member states. In the UK, the Health and Safety Executive publishes annual incident data for deaths and injuries caused by CO poisoning.[40] Figure 4-1 shows that between 2008 and 2019, CO incidents, deaths, and injuries have generally trended downward, with a peak occurring in the 2010/2011 reporting year.[41]

[39] The United Kingdom withdrew from the European Union on January 31, 2020. See: https://europa.eu/european-union/about-eu/countries_en.

[40] The HSE website currently publishes data spanning from 2014 to 2019 on its website, which is available here: https://www.hse.gov.uk/statistics/tables/index.htm. To supplement this data, we located external websites that had reproduced earlier HSE data: https://dmgdelta.co.uk/are-you-carbon-monoxide-aware-its-not-just-a-domestic-boiler-problem/ and http://www.co-gassafety.co.uk/wp-content/uploads/2015/07/Statistics-sheet-presspack-Jan2017-from-Amy-07.01.17-.

[41] HSE presents CO-incident data from April through March of the following year. Thus, for example, the 2010/2011 data includes CO incidents from April 1, 2010 through March 31, 2011.

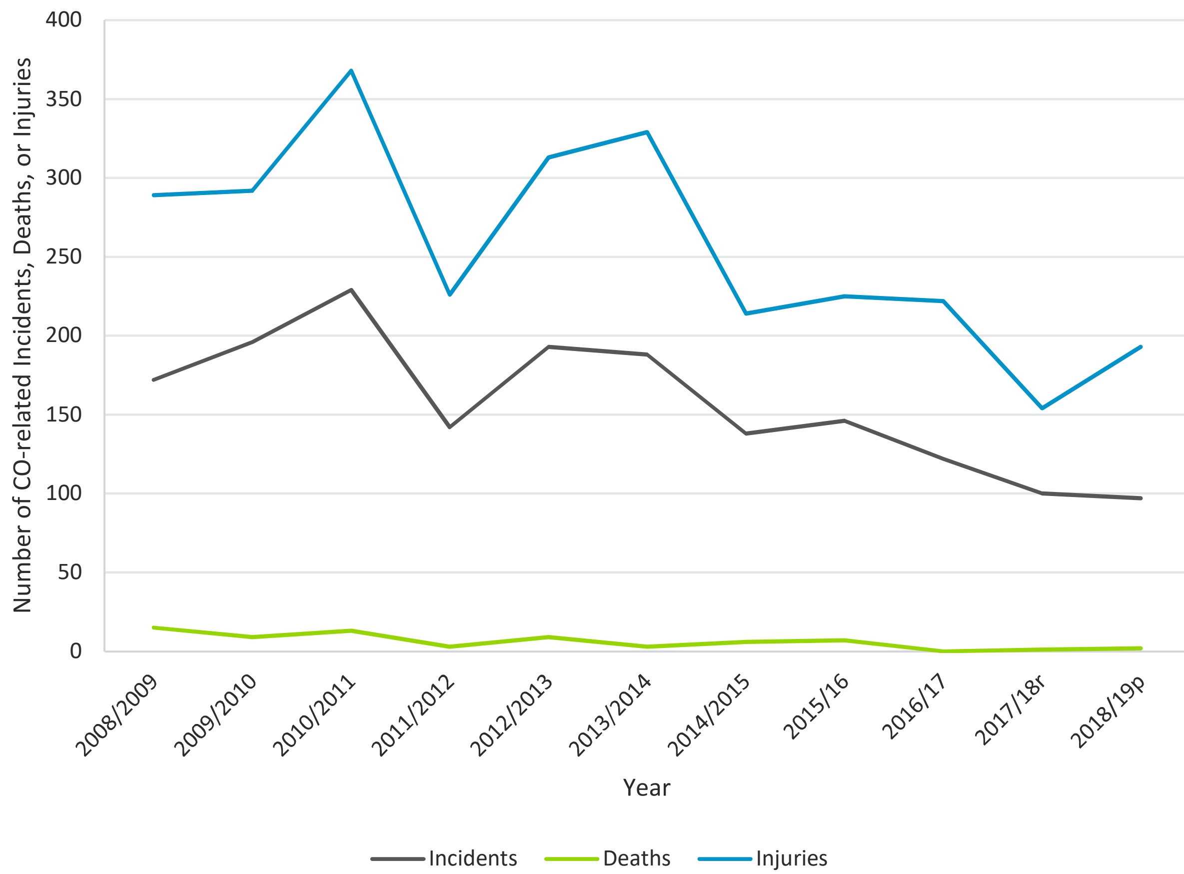


Figure 4-1 CO-related Incidents, Deaths, and Injuries as Reported by the HSE

Additionally, there are several independent and charitable organizations focused on reducing CO-related injuries in the UK, including the Gas Safe Charity,[42] Gas Safety Trust,[43] and the Carbon Monoxide and Gas Safety Society ("CO-Gas Safety").[44] The latter two organizations publish data on CO poisonings on their respective websites, providing incident reports with details including the date, fuel, appliance type, property type, region in which the incident occurred, and details on the affected person(s). The Gas Safety Trust publishes CO incident data of reported casualties of CO since 1996 provided by the HSE, British Gas and the Gas Safe Register. Guidehouse gathered the data from their website and filtered the data to examine trends in the deaths and injuries caused by gas space and water heating appliances using piped natural gas in residences. CO-Gas Safety collects information on unintentional poisoning caused by CO produced by combustion appliances, not including deaths or injuries from CO that is produced by unintentional fire or flames (often smoke inhalation in domestic fire accidents). We similarly gathered data from the CO-Gas Safety website and filtered the data to examine CO-related

[42] For more information see: https://www.gassafecharity.org.uk/.

[43] For more information see: http://www.gassafetytrust.org/.

[44] For more information see: https://www.co-gassafety.co.uk/.

deaths and incidents that resulted in at least one death[45] that were caused by non-portable gas space and water heating equipment (e.g., central heating boilers, water heaters) in residential settings.[46] Figure 4-2 shows the trend in CO-related injuries and deaths over time based on data gathered from the Gas Safety Trust website and Figure 4-3 trends in deaths and incidents resulting in at least one death based on data gathered from the CO-Gas Safety website.

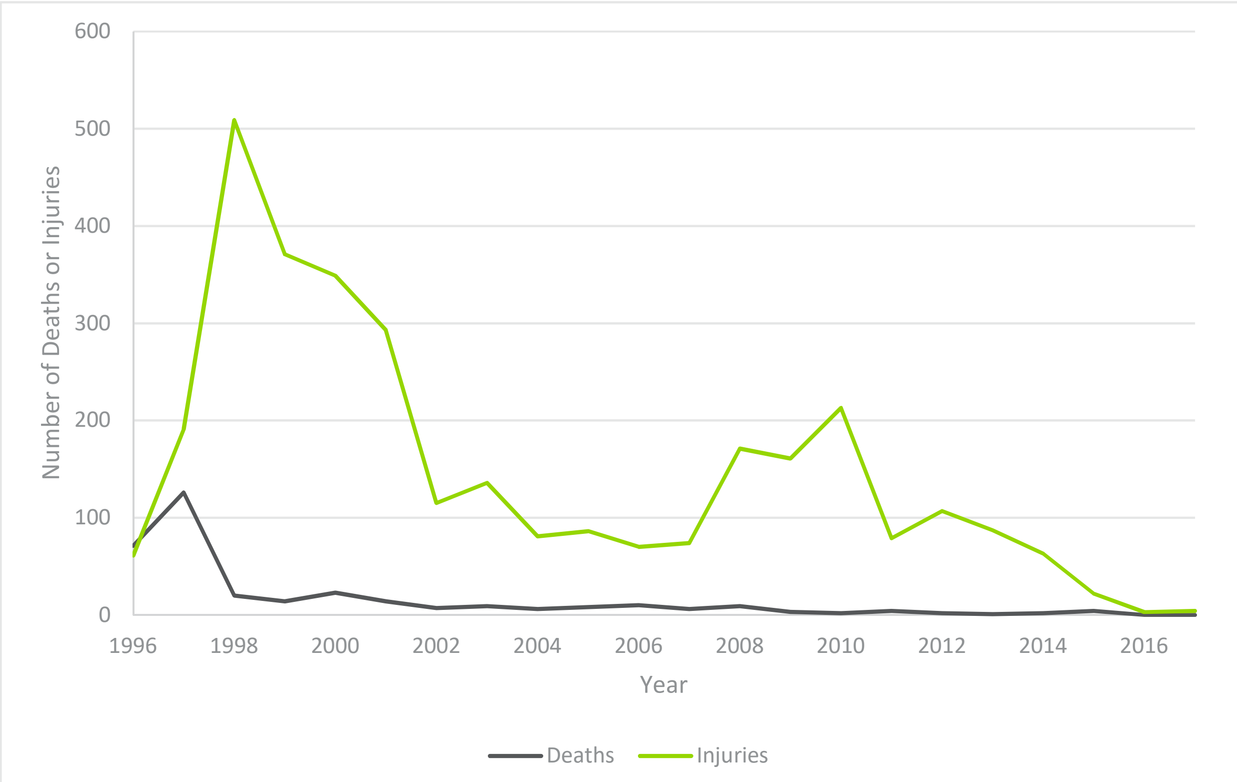


Figure 4-2 CO-related Deaths and Injuries from Residential Gas Space and Water Heating Appliances as Reported by Gas Safety Trust

[45] Although the CO-Gas Safety data do not group multiple deaths into incidents, we assumed that when multiple deaths occurred on the same date, in the same location, with the same type of dwelling, and due to the same cause, they were a singular incident.

[46] Specifically, this dataset includes incidents where the fuel type is mains gas, the type of residence is listed as a flat, house, or bedsit, and the appliance type is a water heater, central heating boiler, back boiler, or room heater.

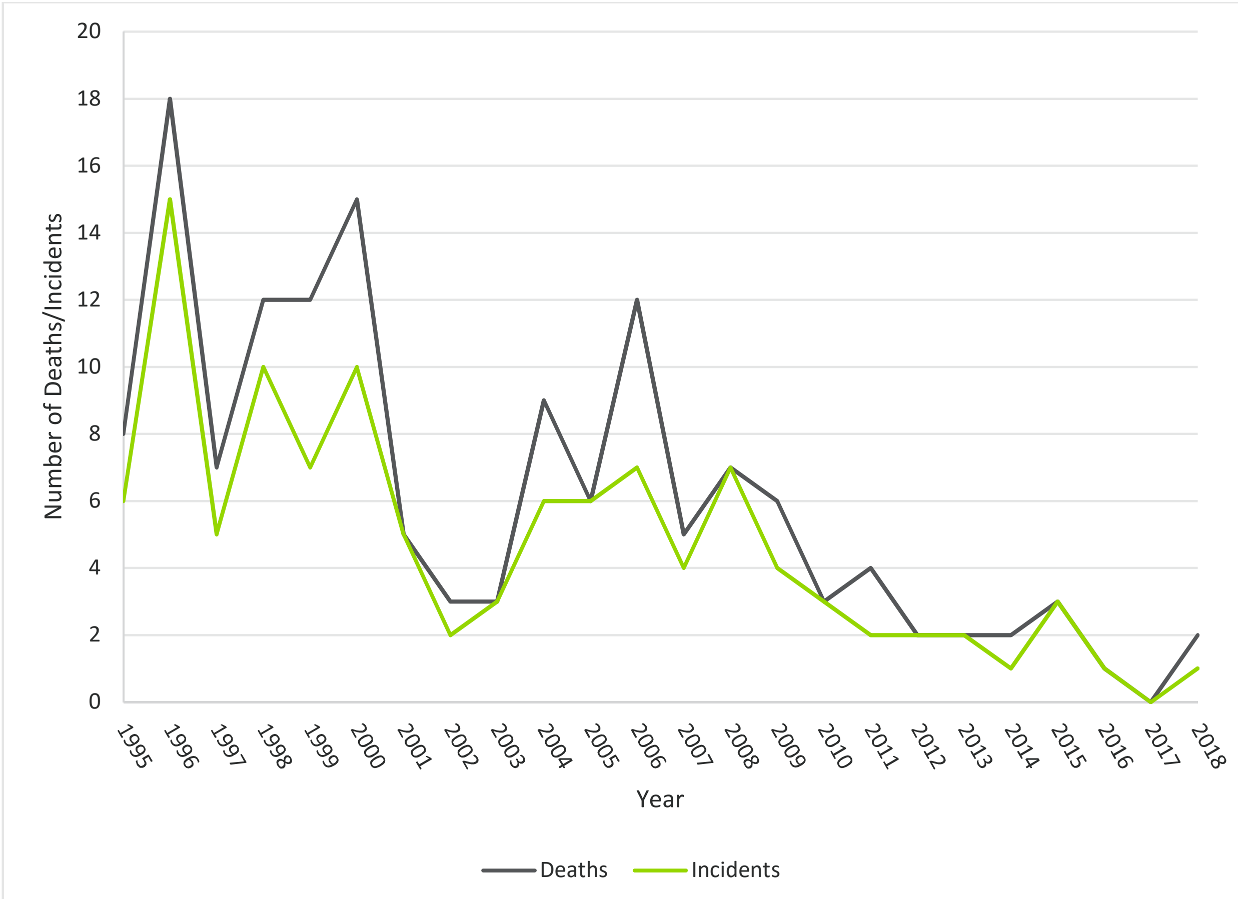


Figure 4-3 CO-related Deaths and Incidents from Residential Gas Space and Water Heating Appliances as Reported by CO-Gas Safety

As with the data published by HSE, the Gas Safety Trust and the CO-Gas Safety data show an overall downward trend in the number of CO-related deaths and injuries (Gas Safety Trust) and incidents and deaths (CO-Gas Safety) per year. Both the Gas Safety Trust and the CO-Gas Safety dataset include earlier years than the HSE data, and show higher peaks in the mid-to-late 1990s, several smaller peaks in the mid-to-late2000s, and a downward trend to the most recent years.

Despite the lack of publicly available data on the effectiveness of CO regulations and technology implementation for the entire EU, we captured anecdotal impressions during manufacturer interviews by asking about this issue. The responses from manufacturers indicated that CO-related injuries and deaths in the EU were trending downward, which comported with the data observed in the UK. However, as discussed later in this section, manufacturers offered various explanations for this decrease.

Regulations for the safe operation of gas appliances were initially established by the European Economic Community (EEC) in Council Directive 90/396/EEC of 29 June 1990 on the approximation of the laws of the Member States relating to appliances burning gaseous fuels.[47] Relevant to this report, the Directive applied to appliances burning gaseous fuels used for heating and hot water production (among other products), and generally required that member states ensure that these appliances are safe for persons, domestic animals, and property before being placed on the market and put into service. In addition, the Directive included a number of specific requirements related to the construction and safe operation of gas appliances. Particularly relevant to this report, the Directive required that appliances must be so constructed that, when used normally, flame stability is assured and combustion products do not contain unacceptable concentrations of substances harmful to health, and there will be no accidental release of combustion products. Member States were to presume compliance with the safety requirements of appliances and fittings when they conform to the national standards applicable to them, implementing the harmonized standards whose reference numbers have been published in the Official Journal of the European Communities. The Directive was modified in 1993 by Directive 93/68/EEC[48] to make it a formal "CE Marking" directive and to make the conformity assessment modules more consistent with the other CE marking directives. Subsequently, Directive 2009/142/EC[49] of The European Parliament and of the Council of 30 November 2009 relating to appliances burning gaseous fuels combined original text of 90/396/EC and its amendments into a single document, and simplified some of the language. Most recently, Directive 2009/142/EC was replaced with Regulation (EU) 2016/426 of the European Parliament and of the Council of 9 March 2016 on appliances burning gaseous fuels and repealing Directive 2009/142/EC.

The timing of the Directive and subsequent updates in the EU, when viewed along with the data presented above in Figure 4-1, Figure 4-2, and Figure 4-3, suggest that the implementation of the Directive and its updates, along with the related prevalent compliance with the standards discussed in section 2.1 of this report, played a role in reducing carbon monoxide poisonings in the UK from the mid-1990s to present. As noted, the Directive became effective in the early 1990s, and data shows a decreasing trend in CO incidents starting in the mid-1990s, the earliest time from which data were available. It is logical that decreases would be seen in the years following the implementation of the requirements, as it would take time for the installed stock to turn over with newer, presumably safer, products. However, as noted previously, during manufacturer interviews, manufacturers discussed a multitude of factors that could contribute to lowering accidental CO poisoning by residential HVAC equipment beyond the requirements in the directives and associated compliance with standards. First, manufacturers pointed to the increased use of direct venting as a potential contributing factor to the decrease, because these systems bring fresh combustion air in from outside and are generally "sealed" in that they isolate the combustion process from the space in which it is installed, rather than use air surrounding the unit for combustion air. Because these systems are sealed off from the room in which they are installed, in the event that an appliance produces excess CO, there is no avenue for the gases to enter the space when the appliances are installed properly. In addition, manufacturers discussed the increased use of improved combustion controls allowing units to maintain an appropriate air-fuel ratio, helping to prevent excessive CO production during the

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[47] https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A31990L0396
[48] https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A31993L0068
[49] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0142#ntr4-L_2009330EN.01001001-E0004

combustion process. Manufacturers also noted that beyond these strides in combustion technology, Europe is also experiencing increased electrification, and electric heat pumps are being used in place of gas and oil appliances whenever possible in many regions of Europe. Some manufacturers stated that the overall downward trend in the number of fossil fuel burning HVAC appliances in Europe is a contributing factor to any reduction in CO-related incidents. Lastly, some manufacturers suggested that improved installation practices and local requirements could be partially responsible for the downward trend in CO-related incidents. Thus, it is likely that a confluence of factors has contributed to the decline in CO-related incidents observed in the UK data and described anecdotally by manufacturers.

4.2 Japan

To investigate the trends in CO incidents and evaluate the effectiveness of CO-related regulations in Japan, we relied upon information provided by Japan's National Institute of Technology Evaluation (NITE), which is a division of the Ministry of Economy, Trade, and Industry (METI).[50] NITE provided us with records of CO incidents between 1996 and 2018 broken down by severity (death, serious injury, or minor injury) and the cause of the incident (gas appliances, kerosene appliances, generators, or "other," which includes, for example, portable cooking stoves). Figure 4-4 shows the total number of CO injuries and deaths in Japan from 1996 to 2018 by incident cause. The total number of recorded incidents in Japan between 1996 and 2018 was 315, the vast majority of which (70%) were caused by gas appliances. In addition, gas appliances were determined to be the cause of 57 of 111 (51%) CO-related deaths in Japan during this period.

[50] For Consumer Product Safety, NITE's website includes the following mission statement: "The consumer products we encounter in our daily lives are many and varied. Meanwhile, product-related accidents occur in familiar situations. NITE collects information on those accidents, analyzes them, and investigates their causes. By making the results public, NITE helps to prevent accidents from recurring and assists businesses to develop and supply safe products." For more information, visit: https://www.nite.go.jp/en/jiko/index.html.

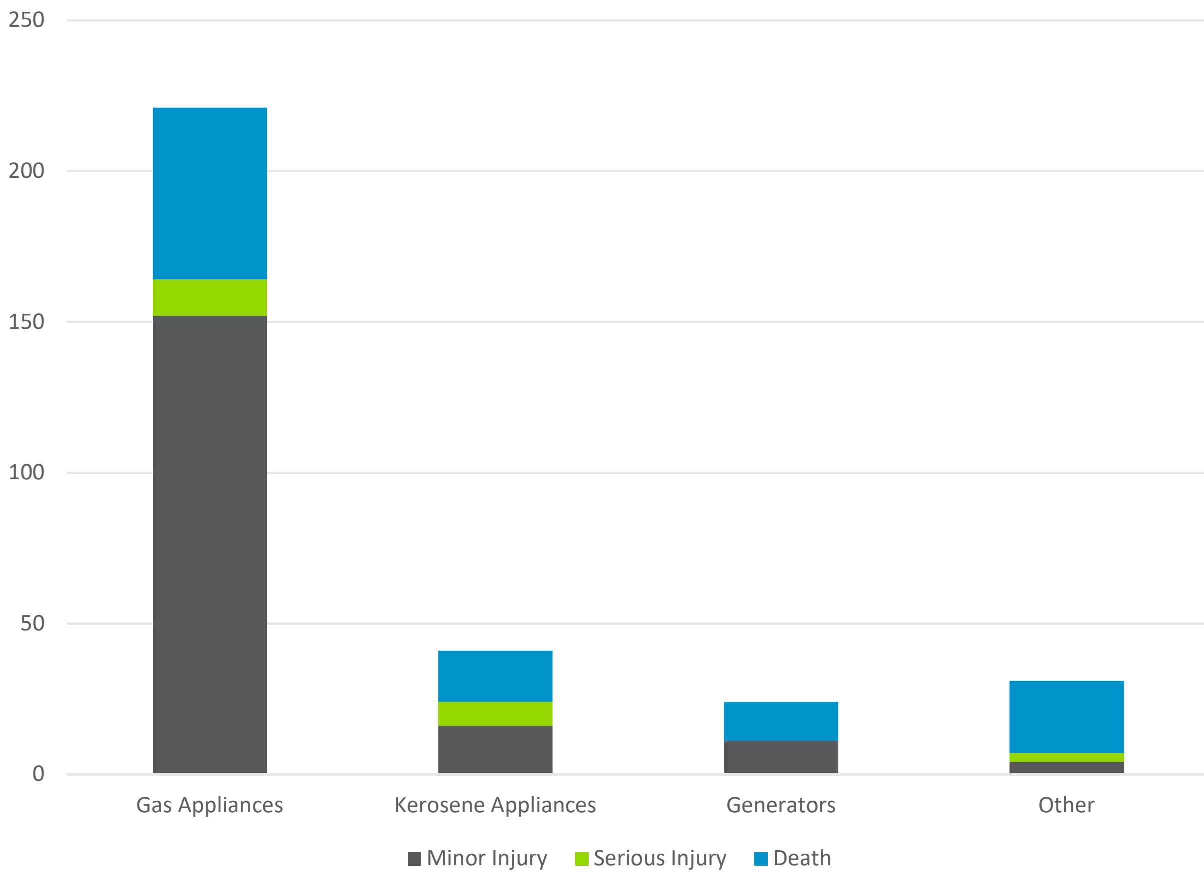

Figure 4-4: Total Carbon Monoxide Injuries and Deaths in Japan from 1996 to 2018 by Cause

In response to survey questions, NITE indicated that gas space and water heating appliances are regulated by the Gas Business Act and the Act on the Securing of Safety and the Optimization of Transaction of Liquefied Petroleum Gas. NITE stated that CO concentration in exhaust gas was regulated to require that the ratio of CO to CO_2 in the gas be equal to or less than 0.02 under the technical standards of the Ministerial Ordinance on Examination for Gas Equipment since 1971. In addition, NITE stated that the allowable CO concentration in exhaust gas was changed to require less than 0.28% since 1996, which was theoretically equivalent to the previous requirement. In 2000, the name of the Ministerial Ordinance was changed to "Ministerial Ordinance on Technical Requirements for Gas Equipment" and in 2008 updated to require the CO concentration to be 0.14% or less. Finally, NITE stated that an incomplete combustion preventing device has been required to be mounted in vented type gas appliances since 2007 and in unvented gas appliances since 1989. Compliance with these regulations is generally demonstrated through certification to the applicable standards discussed in section 2.2. As discussed in section 2.2, the ICPD must stop the appliance from operating before the CO concentration in adjacent rooms exceeds 300 ppm. As shown in Figure 4-5, there has been a decline in CO-related deaths in Japan caused by gas appliances since 2007, and in total CO-related incidents since 2009. Between 1996 and 2007, the average number of CO-related deaths caused by gas appliances was 3.9 per year, and between 2008 and 2018 the average number of

CO-related deaths per year dropped to 0.9. In addition, Figure 4-6 shows the trend in total CO-related incidents (injuries and deaths) between 1996 and 2018 for all other causes – kerosene appliances, generators, and other, as a point of comparison. As shown in Figure 4-6, CO-related incidents from causes other than gas appliances have remained relatively steady aside from peaks in 2005 and 2008. Although there are peaks in 2005 and 2008, the number of incidents in 1996 remains similar to those in 2018. Comparing this to CO-related incidents caused by gas appliances over the same period, other non-gas-appliance causes accounted for an average of 4.5 CO-related incidents between 1996 to 2007, which dropped to an average of 3.9 CO-related incidents between 2008 and 2018. As a result, the percentage of deaths caused by CO exposure from gas appliances has been reduced over these periods. From 1996 to 2007, the percentage of CO-related injuries and deaths caused by gas appliances was 74.4% and 53.9% respectively. From 2007 to 2018, those percentages went down to 61.5% (-12.7%) and 45.7% (-8.2%), respectively. The data suggest that the relative decrease in CO-related incidents for gas appliances compared to other causes could be due in part to the requirement for inclusion of an ICPD. However, as with the European market, we note that other factors, aside from the requirement for ICPD, may have contributed to the decline in CO incidents. These factors could include increased usage of CO alarms and increased education regarding the dangers of CO poisoning. NITE indicated that although CO detectors are not mandatory in Japan, fire alarms and gas leak alarms are, and the use of multifunctional alarms that also include a CO alarm has increased their use. In addition, NITE provided information on programs by the Gas Safety Office of METI, as well as other associations and organizations in Japan that promote awareness of CO poisonings. Therefore, similar to the EU (as discussed in section 4.1), while the regulatory requirements to limit CO productions in gas appliances likely contributed to the overall decline in CO-related incidents, there is likely a confluence of factors that have contributed to the decline in CO-related incidents.

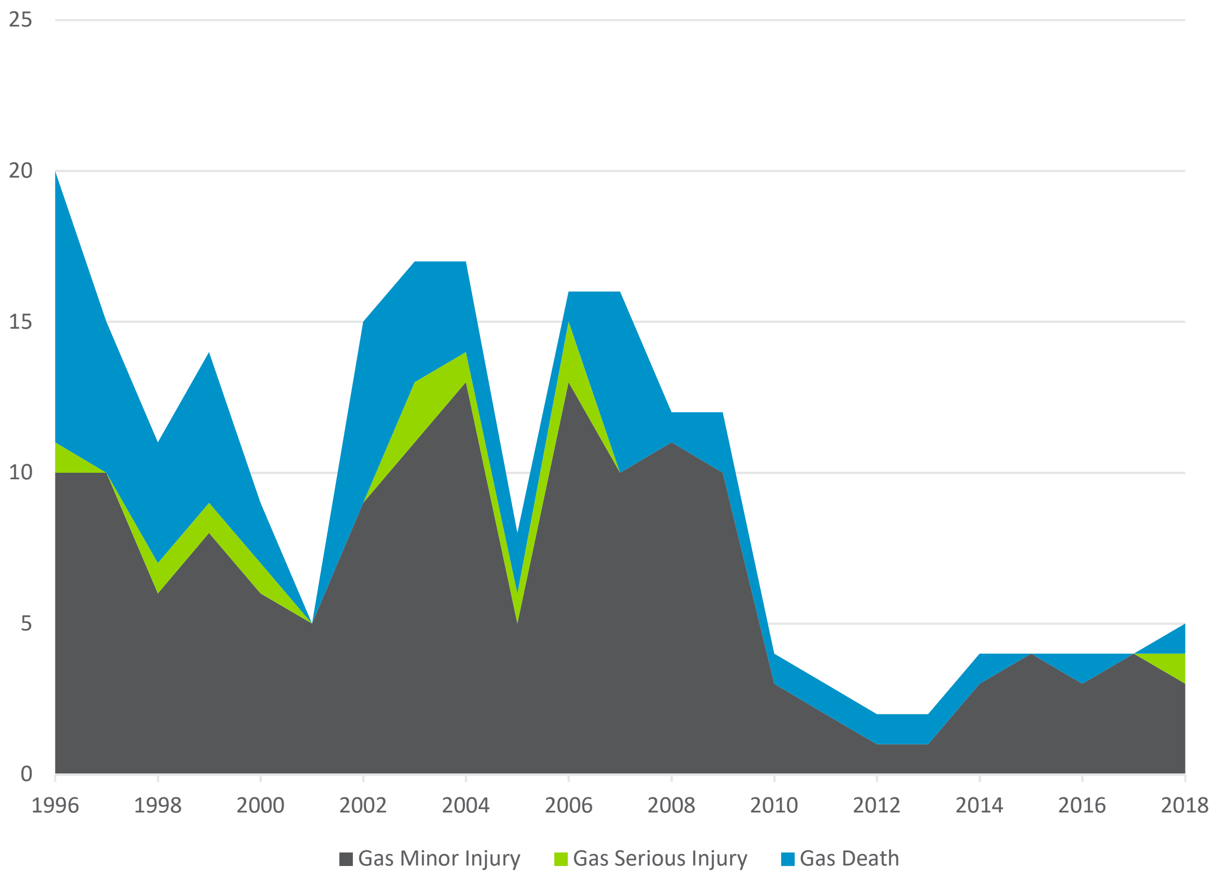

Figure 4-5 Carbon Monoxide Injuries and Deaths Caused by Gas Appliances in Japan from 1996 to 2018

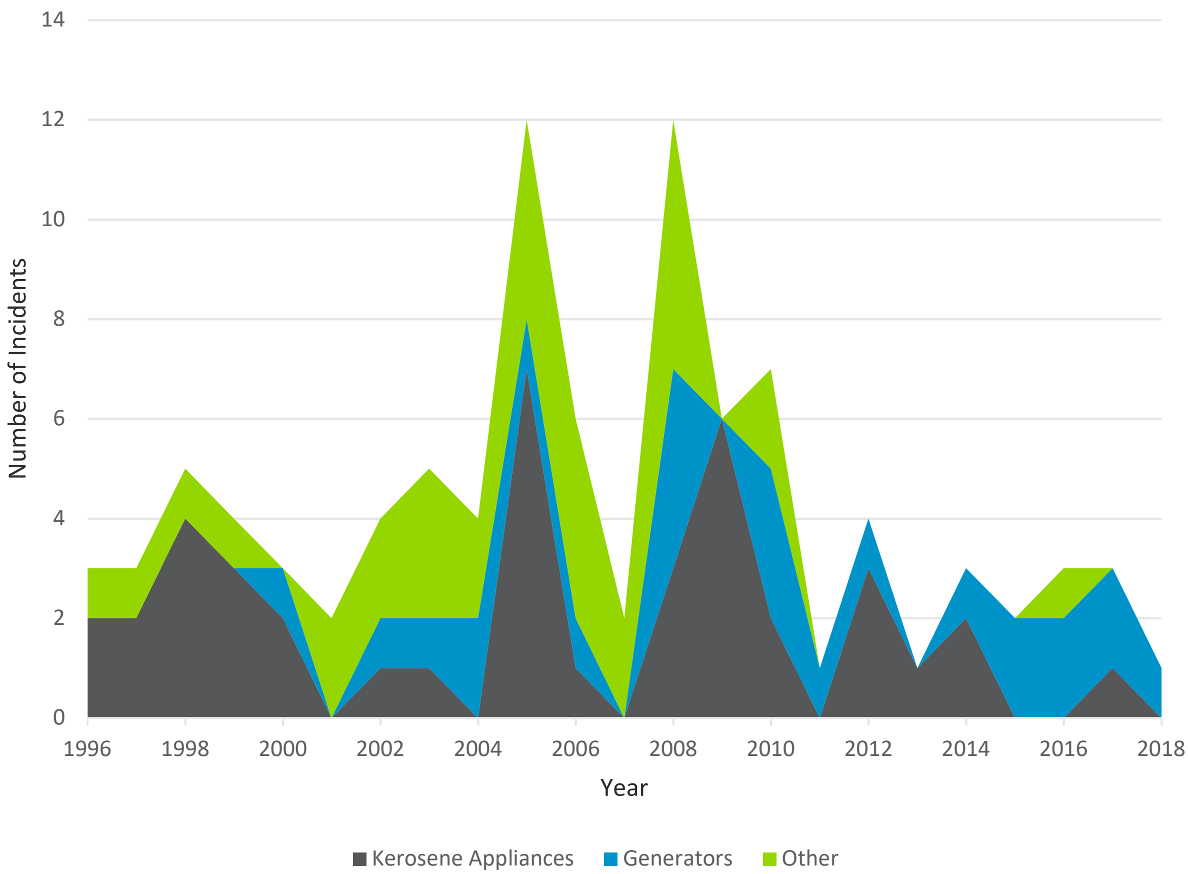

Figure 4-6 Carbon Monoxide Incidents (Injuries and Deaths) Caused by Kerosene Appliances, Generators, and Other Causes in Japan from 1996 to 2018

APPENDIX A. MANUFACTURER INTERVIEW GUIDE FOR COMBUSTION CONTROL AND CO SENSING TECHNOLOGIES: EUROPE

Background:

Guidehouse is working with the Consumer Product Safety Commission (CPSC) to examine the requirements for and use of combustion control or CO sensing technologies for monitoring and limiting carbon monoxide (CO) production in gas appliances in the European and Japanese markets. In doing so, we also recognize that some requirements that are designed to ensure the energy efficiency of gas appliances (e.g., through combustion control or air/fuel ratio control) may also help limit or respond to excessive CO production. Through this interview Guidehouse seeks to gain a better understanding of the design and implementation of gas/air ratio controls and/or combustion product safety devices or other devices intended to ensure energy efficiency, particularly combustion efficiency, or to limit the production of CO in residential gas boilers; the costs, performance, and lifetimes associated with these combustion control or CO sensing technologies; any potential market barriers to the implementation of such devices; and the effectiveness of these devices in preventing CO-related incidents. In addition, there are several standards that provide requirements for the safety, rational use of energy, and fitness for purpose of gas-fired boilers and safety/control devices in the EU, which are listed in the table below.

Table 1. European Union Standards for Safety and Control Devices and Gas-fired Central Heating Boilers

Standard	Summary of Relevant Provisions
EN 13611: Safety and control devices for burners and appliances burning gaseous and/or liquid fuels—General requirements	• Includes general requirements for all safety control devices for gas and or liquid fuel burning appliances • Includes test criteria for such devices • This code is meant to be used in conjunction with the other codes of interest
EN 16340: Safety and control devices for burners and appliances burning gaseous or liquid fuels—Combustion product sensing devices	• Provides specific information regarding the performance of combustion product-sensing devices (CPSD) • Includes test procedures allowable tolerances for CPSDs
EN 12067-2: Gas/air ratio controls for gas burners and gas burning appliances—Part 2: Electronic types	• Includes the performance standards for gas/air ratio controls (GARCs) in gas burners and gas burning appliances • Defines GARC as: a closed loop modulating system consisting of the electronic control, actuating elements for the gas flow and air flow as a minimum, and allocated feedback signal(s) • Requires that GARCs have the ability to initiate safety shutdowns

EN 15502-1: Gas -fired heating boilers – Part 1: General requirements and tests	• Requires boilers with fans to check supply of combustion air, one of the ways listed is the use of a GARC • CO levels are cited to not exceed 0.10% (1,000 ppm) during "limit conditions" and 0.20% (2,000 ppm) during "Special conditions" (incomplete combustion and flame lift)
EN 15502-2-1: Gas-fired central heating boilers, Part 2-1: Specific standard for type C appliances and type B2, B3 and B5 appliances of a nominal heat input not exceeding 1000 kW	• Includes instructions for monitoring of CO and other combustion products during testing • Separate CO testing for gas appliances with and without GARCs • CO thresholds remain consistent with EN 15502-1 • Requires that CO not reach specific values under test conditions including blocked air inlets, blocked vents, and internal recirculation • Includes alternative supervision strategies for air proving including continuous (shutting down if CO reaches 2000 ppm) and start-up supervision (no start if CO reaches 1000 ppm).
EN 15502-2-2: Gas-fired central heating boilers, Part 2-2: Specific standard for type B1 appliances	• CPSDs shall be designed such that they can withstand the thermal stress resulting from spillage of combustion products • Defines a combustion products discharge safety device as: a device that at least causes safety shutdown of the main burner when there is an unacceptable spillage of combustion products at the draft diverter. • Requires continuous supervision of combustion air rate or combustions product rate for type B_{12} and B_{13} boilers • CO thresholds remain consistent with EN 15502-1 • Requires that CO not reach specific values under test conditions including blocked air inlets, blocked vents, and internal recirculation • Includes alternative supervision strategies for air proving including continuous (shutting down if CO reaches 2000 ppm) and start-up supervision (no start if CO reaches 1000 ppm). • References EN 14459:2007 Annex 1 "For specific endurance requirements and tests on electronic Combustion Products Safety Discharge Devices and their sensors"

1. Overall Market and Regulatory

1.1 Who are the manufacturers with the largest market shares in the European residential gas boiler market?

1.2 What are the overall market trends in the European residential gas boiler market?

1.3 What are the most common designs of new gas boilers sold in the EU?

1.3.1 Do most boiler designs include combustion air fans/motors?

1.3.2 During burner operation, do most gas boilers monitor and control:

- Production of CO;
- Proper combustion or air/fuel ratio?

1.4 Is compliance with EN 15502-1 required for gas central heating boilers in the EU? Are requirements different for different countries within the EU?

1.5 EN 15502-2-1 and 15502-2-2 state that GARCs as certified to EN 12067 are an option for monitoring the combustion air supply in certain gas boilers to ensure appropriate gas/air ratio during combustion.

1.5.1 Continuous supervision of combustion air using a GARC is one of the two alternative methods for monitoring combustion air supply (the other being the start-up only monitoring). How commonly do products include GARCs as the method for monitoring the combustion air supply?

1.5.2 Many GARCs include O2 sensors to monitor the proper gas/air ratio. Do the GARCs that you include use O2 sensors or another means of regulating the gas/air ratio?

1.5.3 What is the motivation for including such devices (e.g., increasing safety of combustion versus increasing combustion efficiency or other reasons)?

1.6 Do you offer products that include combustion product sensing devices (CPSD) that are certified to EN 16340?

1.7 Do you sell gas boilers in both the European and US markets? If so, are there typically any significant design differences? In particular, do your boiler designs for the US market contain the same combustion controls or sensors (e.g., GARC or CPSD) as those sold in the EU market?

2. Combustion Control and CO Sensing Technologies

Combustion control devices (GARCs) found through market research include: Lambda Pro Control Plus (Viessman), Lambda-Gx (Rotex), “MC2 Multi Combustion Control” (Ferroli), SCOT technology (Weishaupt), EVO (Broetje), and Gallium Oxide semiconductor sensors (Vaillant).

2.1 What strategy(ies) do you use to monitor and control combustion efficiency or air/fuel ratio, or CO production of your gas boilers and/or vented space heaters?

2.1.1 What other strategies are you aware of competitors using?

2.2 Does your company purchase combustion control or CO sensing technologies or produce them in house? To the best of your knowledge, do your competitors generally purchase or produce in house?

2.2.1 If combustion control or CO sensing technologies are typically purchased, who are the major producers of these devices?

2.2.2 If you purchase your combustion control or CO sensing technologies, are they all purchased from the same sensor manufacturer and/or supplier, or do you use multiple suppliers?

2.3 What is the typical approximate cost of combustion control or CO sensing technologies (either to produce or purchase)?

2.3.1 How much does the addition of combustion control or CO sensing technologies add to the total cost of manufacturing, including the cost of the sensor, labor for assembling it, and any other associated costs?

2.3.2 What are the maintenance costs and the replacement costs associated with combustion controls and CO sensing technology?

2.3.3 Are there other associated costs not previously mentioned?

2.4 What is the typical sensitivity of the combustion control or CO sensing technologies that you manufacture/purchase? Can these be adjusted to detect whether CO levels above or below 400ppm or some other threshold?

2.5 What is the expected lifetime of the combustion control or CO sensing technologies? How does this compare to the expected lifetime of your boiler products?

2.5.1 Is there a mandatory lifetime for combustion control or CO sensing technologies that is required by the appliance manufacturer, standards, or a regulatory agency?

2.5.2 For expected or mandatory lifetime for combustion control or CO sensing technologies, how is the lifetime determined? Is there a test method or standard used to determine lifetime?

2.5.3 Are combustion control or CO sensing technologies typically required to be repaired or replaced prior to the lifetime of the boiler, or are they expected to last for the lifetime of the boiler or longer?

2.5.4 Are they generally accessible and able to be repaired or replaced?

2.5.5 Does the sensor's sensitivity (effectiveness in sensing CO or other target gas levels) degrade over its lifetime?

2.6 Are there any other barriers to inclusion of combustion control or CO sensing technologies in gas boilers and/or vented space heaters?

3. Effectiveness of Combustion Control and CO Sensing Technology

3.1 How effective has the incorporation of combustion control or CO sensing technologies, including those designed to ensure combustion efficiency or an optimal air/fuel ratio, been in reducing CO-related injuries or casualties of consumers using your products?

3.1.1 After first implementing these technologies in your products, did you notice a reduction in CO poisoning incidents reported?

APPENDIX B. MANUFACTURER INTERVIEW GUIDE FOR COMBUSTION CONTROL AND CO SENSING TECHNOLOGIES: JAPAN

Background:

Guidehouse is working with the Consumer Product Safety Commission (CPSC) to examine the requirements for and use of sensors for monitoring and limiting carbon monoxide (CO) production in gas appliances in the European and Japanese markets. In doing so, we also recognize that some requirements that are designed to ensure the energy efficiency of gas appliances (e.g., through combustion control or air/fuel ratio control) may also help limit or respond to excessive CO production. Through this interview Guidehouse seeks to gain a better understanding of the design and implementation of gas/air ratio controls or combustion safety devices or other devices intended to ensure energy efficiency, particularly combustion efficiency, or limit the production of CO in residential vented gas water heaters, boilers, and space heaters ; the costs, performance, and lifetimes associated with these sensors; any potential market barriers to the implementation of such sensors; and the effectiveness of these sensors in preventing CO-related incidents. In addition, the standards for gas-fired water heaters, boilers, and space heaters are listed in the table below with several requirements in relation to CO.

Table 1. Japanese Standard for Gas Burning Water Heaters for Domestic Use, Gas Hydronic Heating Appliances for Domestic Use, and Gas burning Space Heaters for Domestic Use

Standard	Summary of Relevant Provisions
JIS S 2109: Gas burning water heaters for domestic use	• Maximum allowable CO levels specified for various operational conditions and types of water heaters. Requirements for CO produced and CO concentrations in the room and adjacent room. • When CO reaches the cut off, requires activation of the incomplete combustion preventative device (ICPD) • Test conditions including incomplete ventilation, incomplete combustion, windy conditions in exhaust pipe, and exhaust air being shut off to simulate worst case scenarios for CO production
JIS-S-2112: Gas hydronic heating appliances for domestic use	• Maximum allowable CO levels specified for various operational conditions and types of water heaters. Requirements for CO produced and CO concentrations in the room and adjacent room. • When CO reaches the cut off, requires activation of the ICPD • Test conditions including incomplete ventilation, incomplete combustion, windy conditions in exhaust pipe, and exhaust air being shut off to simulate worst case scenarios for CO production
JIS-S-2122: Gas burning space heaters for domestic use	• Maximum allowable CO levels specified for various operational conditions and types of water heaters. Requirements for CO produced and CO concentrations in the room and adjacent

	room. • When CO reaches the cut off, requires activation of the ICPD • Test conditions including incomplete ventilation, incomplete combustion, windy conditions in exhaust pipe, and exhaust air being shut off to simulate worst case scenarios for CO production

1. Overall Market and Regulatory

1.1 Who are the manufacturers with the largest market shares in the Japanese vented residential gas water heater, boiler, and space heater markets?

1.2 What are the overall market trends in the Japanese vented residential gas water heater, boiler, and space heater markets?

1.3 What are the most common designs for new vented residential gas water heaters, boilers, and space heaters sold in Japan?

1.3.1 Do most or all vented residential gas water heaters, boilers, and space heaters monitor or limit production of CO or proper combustion or air/fuel ratio during burner operation?

1.4 Is JIS-S-2109 a mandatory standard that manufacturers are required to comply with? If not, do the majority of manufacturers voluntarily sell products that comply with this standard?

1.5 Are JIS-S-2112 and JIS-S-2122 mandatory standards that manufacturers are required to comply with? If not, do a majority of manufacturers voluntarily sell products that comply with these standards?

1.5.1 Are the requirements for JIS-S-2112 and JIS-S-2122 for hydronic heating and domestic space heaters similar to JIS-S-2109 with regard to the requirements for allowable CO production and incomplete combustion preventive devices?

1.6 How does your company typically incorporate the Incomplete Combustion Preventive Devices (ICPD) device into your products? Is it usually contained inside the combustion chamber, flue, vent pipe or cabinet of the appliance, or is it installed outside of the product? Of your products that incorporate ICPDs, what percentage locate the ICPD inside the combustion chamber, flue, vent pipe, or cabinet of the appliance? What percentage of the appliances that incorporate ICPDs are vented and what percent are unvented?

1.6.1 Is it provided by the manufacturer or obtained by the installer as an aftermarket part?

1.6.2 If installed within the combustion chamber, flue, vent pipe or cabinet of the appliance, what level of CO do these ICPDs detect before being activated and shutting down the appliance? Are these CO measurements being made within the combustion chamber, flue, vent pipe or cabinet of the appliance or outside of the appliances or in another room?

1.7 Do you sell gas water heaters, boilers, and space heaters in both the Japanese and US markets? If so, are there typically any significant design differences? In particular, do your water heater, boiler, and space heater designs for the US market contain the same combustion controls or CO sensors as those sold in the Japanese market? If not, why not?

2. Combustion Control and CO Sensing Technologies

Incomplete Combustion Preventative Devices found through market research include: CO/H2 sensors (Rinnai), Incomplete Combustion Avoidance Device (Paloma & Rheem), and Air/Fuel Ratio sensors (Takagi).

2.1 What strategy(ies) do you use to control combustion efficiency or air/fuel ratio, and CO production of your gas water heaters, boilers, and space heaters? What other strategies are you aware of competitors using?

2.2 Does your company purchase combustion control and CO sensing technologies or produce them in house? To the best of your knowledge, do your competitors generally purchase or produce in house?

2.2.1 If combustion control and CO sensing technologies are typically purchased, who are the major producers of the sensors?

2.2.2 If you purchase combustion control and CO sensing technologies, are they all purchased from the same manufacturer or supplier, or do you use multiple suppliers?

2.3 What is the typical approximate cost of combustion control and CO sensing technologies (either to produce or purchase)?

2.3.1 How much does the inclusion of combustion control and CO sensing technologies add to the total cost of manufacturing, including the cost of the combustion control and CO sensing technologies, labor for assembling it, and any other associated costs?

2.3.2 What are the maintenance costs and the replacement costs associated with combustion controls and CO sensing technology?

2.3.3 Are there other associated costs not previously mentioned?

2.4 What is the typical sensitivity of the combustion gas sensors or combustion control technology that you manufacture/purchase?

2.5 What is the expected lifetime of combustion control and CO sensing technologies? How does this compare to the expected lifetime of your water heaters, boilers, and space heaters?

2.5.1 Is there a mandatory lifetime for combustion control and CO sensing technologies that is required by the appliance manufacturer, standards, or regulatory agency?

2.5.2 For expected or mandatory lifetime for combustion control and CO sensing technologies, how is the lifetime determined? Is there a test method or standard used to determine lifetime?

2.5.3 Are combustion control and CO sensing technologies typically required to be repaired or replaced prior to the lifetime of the water heater, or are they expected to last for the lifetime of the water heater or longer?

2.5.6 Are they generally accessible and able to be repaired or replaced?

2.5.7 Does the sensitivity (effectiveness in sensing CO or other combustion gas conditions) of combustion control and CO sensing technologies degrade over its lifetime?

2.6 Are there any other barriers to inclusion of combustion control and CO sensing technologies in gas water heaters, boilers, or vented space heaters?

3. Effectiveness of Combustion Control and CO Sensing Technology

3.1 How effective has the incorporation of combustion control and CO sensing technologies, including those designed to ensure combustion efficiency or an optimal air/fuel ratio, been in reducing CO-related injuries or casualties of consumers using your products?

3.1.1 After first implementing these technologies, did you notice a reduction in CO poisoning incidents reported?

APPENDIX C. INTERVIEW GUIDE FOR COMBUSTION CONTROL AND CO SENSING TECHNOLOGIES: REGULATORY AGENCY

Background:

Guidehouse is working with the Consumer Product Safety Commission (CPSC) to examine the requirements for and use of Combustion Control and CO Sensing Technologies for monitoring and limiting carbon monoxide (CO) production in gas appliances in the European and Japanese markets. In doing so, we also recognize that some regulations that are designed to ensure the energy efficiency of gas appliances (e.g., through combustion control or air/fuel ratio control) may also help limit or respond to excessive CO production. Through this interview Guidehouse seeks to gain a better understanding of the requirements of regulatory standards for gas appliance energy efficiency and safety and the effectiveness of these standards in preventing CO-related incidents.

1. What are the standards and regulations in your region/country that govern the safety of and production of CO from gas appliances?

    1.1. Are the standards and regulations mandatory or voluntary?

    1.2. If voluntary, how prevalent is compliance?

    1.3. When did the standards/regulations governing the production of CO from gas appliances go into effect?

2. What are the standards or regulations in your region/country that govern the energy efficiency, particularly combustion efficiency, of gas appliances?

    2.1. Are the standards and regulations mandatory or voluntary? If voluntary, how prevalent is compliance?

    2.2. Are these energy efficiency standards and regulations also designed to prevent excessive CO production?

    2.3. When did the standards/regulations governing the energy efficiency, particularly combustion efficiency, of gas appliances go into effect?

    2.4. Do you believe that if the combustion efficiency or optimal air/fuel ratio of a gas appliance can be established and maintained, then the appliance will not produce excessive levels of CO?

3. Are the energy efficiency standards and regulations designed to accomplish that outcome?

    3.1. Do you have listings of all gas appliances that are certified to meet any of the above referenced standards and regulations?

    3.2. How do you measure effectiveness of the safety standards/regulations (e.g., reduced CO-related incidents, deaths, injuries, etc)?

3.3. How do you measure the effectiveness of the energy efficiency standards/regulations? (e.g., improved energy efficiency, improved combustion efficiency, etc)

4. Have you noticed trends in CO-related incidents following the adoption of the CO safety or energy/combustion efficiency standards/regulations?

4.1 For any trends observed, are there other factors, aside from the standards/regulations that could explain or account for the trend? (For example, if an overall reduction is observed, could it be due to other factors, such as a declining market overall, use of CO alarms, or consumer/first responder/medical authority education?)

4.2 Does statistical data exist showing the effects of the standards or regulations for CO production?

4.3 Do you have statistical data on the annual or periodic number of CO deaths and injuries caused by all consumer products in general, and gas appliances in particular?

4.4 Do you have statistical data on the annual or periodic number of medical appointments, emergency room visits, or hyperbaric oxygen chamber treatment visits associated with CO exposure from gas appliances?

ATTACHMENT 2

Project Number: DfR16-0694 | **Date:** 10/19/2022
V4

Performance and Accelerated Life Testing of Carbon Monoxide and Combustion Sensors

For Submission to

Consumer Product Safety Commission (CPSC)
By way of
Department of Health and Human Services

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Executive Summary

Accelerated life testing (ALT) was conducted on three commercially available combustion gas sensors. The goal was to obtain an assessment on the performance and reliability of the sensors in three common application areas of a residential gas furnace. The operating and environmental conditions for these application areas were based on the U.S. Consumer Product Safety Commission's Performance Work Statement to DfR Solutions and common duty cycle rates derived from the Federal Test Procedures for Residential Furnaces and Boilers[1].

From the application field conditions and the sensor design and material limitations, two main tests were performed to induce the expected failure mechanisms:

- Temperature Cycling (TC) – generally used for thermo-mechanical induced cracking and fretting
- Temperature Humidity Bias Testing (THB) – generally used for temperature-humidity induced corrosion, oxidation, and hydrolysis

The tests were conducted to demonstrate 85% reliability with an 80% confidence level. Industry standard reliability acceleration models were used for determining acceleration factors from field and test conditions. Test sample quantity and test durations were part of test parameter development using ReliaSoft Weibull++ software. Results in test were correlated back to equivalent field life based on meeting or exceeding the prescribed test parameters.

Hard failures were defined as a severely degraded or absent sensor signal output, in which the sensor is unable to detect some level of its intended target gas range. In cases where the number of hard failures exceeded that allowed for the test, a life data analysis was performed in Weibull++. Acceleration factors were used to determine the expected equivalent field life from the Weibull++ analysis results in test.

Table 1 shows the results from Sensor A, a dual-channel CO2 sensor module. The sensor met the test parameter metrics to demonstrate over 20 years equivalent field life for thermo-mechanical failure mechanisms.

Table 1: Sensor A Equivalent Field Life Results

Application Area	Test	Equivalent Field Life	Comments
Vent Pipe	TC	30.4 yrs	2 hard failures out of 8 samples.
	THB	4.1 yrs (3.2 – 5.1 yr range)	22 hard failures out of 48 samples.

Under THB testing, results fell significantly short of the desired life. Constant non-zero signal output and varying signal output, both occurring with no gas concentration present, were the main failure modes. Recommendations for sensor re-design to minimize humidity ingress into the sensor area and to use a more robust bypass capacitor are proposed based on the failure analysis.

[1] DOE, Energy Conservation Program for Consumer Products: Test Procedures for Residential Furnaces and Boilers; Final Rule. Federal Register, Vol. 81, No. 10, Part V, January 15, 2016.

Based on the results of both tests, while accuracy and stability may drift over the expected lifetime of the sensor, sensors are expected to function over that period by responding to their target gas concentrations. The manufacturer recognizes the need for calibration by incorporating programming that allows the sensor to periodically self-calibrate.

The manufacturer has developed new sensors with a protective enclosure around the infrared detector. This was implemented to prevent humidity ingress and infrared detector failure. Those sensors will undergo TC and THB reliability testing by DfR Solutions as a separate project and report.

Table 2 shows the results from Sensor B, a COe sensor module. Due to use of extended dwell times in TC testing, the 1-yr test duration constraint had been reached before the required number of test cycles were accumulated to demonstrate 10-yr equivalent field life. Sensor signal output decayed >25% over time. However, sensors remained above 100 mV after decaying from their peak output at the start of exposure to each gas concentration. This phenomenon was investigated and discussed with the manufacturer, but it is not clearly understood.

Table 2: Sensor B Equivalent Field Life Results

Application Area	Test	Equivalent Field Life	Comments
Secondary Heat Exchanger	TC	Not completed	1 hard failure out of 7 samples. Sensors only tested to 2.6 years equivalent field life.
	THB	0.8 yrs (0.6 – 1.1 yr range)	7 hard failures out of 8 samples. Back half of sensor compromised, leading to early failure.

Under THB testing, the back half of the sensor was compromised due to the highly accelerated stress test (HAST) conditions applied. Despite material evaluation and initial temperature pre-testing, these conditions were too extreme of a stressor on the back half of the sensor. This part of the sensor is only designed for the ambient conditions external to the heat exchanger. This led to early and intermittent failure modes of fluctuating or no signal output, mainly attributed to degradation in the internal connection between the back half and front half of the sensor. As a result, the equivalent field life of just under a year is not reflective of the actual expected field life.

Recommendations to improve the robustness of the design are proposed. One suggests changing the material and geometry of the strain relief. The other suggests adding a restraint on the internal spring leads to assure positive contact with the electrode and heater pads.

The manufacturer has developed new sensors with improved strain relief. A set of new sensors will be tested to demonstrate up to 15 years equivalent field life within a 1-yr period. Power cycling the heater in the units is proposed to achieve the same temperature changes as in thermal cycling, but in a shorter time. There is no indication that the new sensors could not achieve a 15-yr expected field life for thermo-mechanical induced failure mechanisms.

The new sensors will also undergo THB testing with a different approach recommended. The front half of the sensor will be isolated from the back half in two separate THB tests. These tests will be performed by DfR Solutions as a separate project and report.

Decay in sensor signal output is expected, but Sensor B is expected to functionally respond to its target gas concentrations. The brief response to the targeted gas concentration before decaying in signal output would have to be resolved in order to reliably use a time-weighted average algorithm and not indicate a false negative.

Table 3 shows the results from Sensor C, a CO sensor module. Due to the extended dwell times in TC testing, the required number of test cycles needed to demonstrate 10-yr equivalent field life were not reached. These sensors will be put back in test with the prescribed 10-minute dwell times to complete the testing within a 10-month period.

Table 3: Sensor C Equivalent Field Life Results

Application Area	Test	Equivalent Field Life	Comments
Primary Heat Exchanger	TC	Not completed	No hard failures out of 48 samples. Sensors only tested to 1.6 years equivalent field life.
	THB	3.5 yrs	20 hard failures out of 20 samples.

Under THB testing, the reliability results fell significantly short of the planned demonstrated life of 8 years. Potential for excessive overstress existed on the back half of the sensor, despite test conditions remaining within the material limitations and published specifications. The humidity conditions in test were well above what it would normally experience in the field. A common concern in using HAST systems is the potential to increase stresses beyond the limitation of the device materials and induce failure mechanisms that are not seen or relevant in the field.

The potential for sensor poisoning existed. Poisoning is a common risk where compounds begin to decompose on the catalyst to form a dense barrier. Silicone and organic lead are common poisons. Silicone wire was used in the new high-temperature MIL-standard test connector in the HAST autoclave. While the silicone and connector are rated for use in higher temperatures than used in test, it is not clear if there was any correlation between the silicone introduction and the subsequent failures after subsequent THB exposure. Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS) was performed on the compensator and detector elements. Surface depletion of tin (Sn) was noted in the detector. Higher concentration of silicone was noted also but was not consistent with another failure observed. The results of THB testing are not conclusive. The manufacturer reports that the failure is not something they have seen. They have tested sensors exposed to 10 ppm Hexamethyledisiloxane (HMDS), a commonly encountered silicone known to poison noble metal catalysts, with acceptable span and sensitivity results. Results were shared with them, and feedback is pending as of the submission of this report.

The expected equivalent field life of 3.5 years for THB-induced failure mechanisms is likely not reflective of actual expected field life. Per the manufacturer's data sheet and technical manual, Sensor C utilizes the most widely used method of detecting flammable gases in industry with the catalytic pelletized resistor ("pellistor") invented over 40 years ago. The "pellistor" has been used in the combustion chambers of instantaneous gas water heaters in Japan since about 2001. The manufacturer rates the sensor to over 10 years expected life.

Similar for both thermal cycling and THB exposure, while accuracy and stability at "zero" may drift, the sensors are still expected to function over their expected life time by responding to their target gas concentrations. The relatively high number of sensors exceeding the accuracy (repeatability) tolerance could be less if they were allowed to reach a final stable value in test. Stability in the field may be better without the movement associated with handling and testing.

Accuracy and sensitivity to physical movement seemed to lead to drift or shifts in the signal output of Sensor C. The manufacturer of this sensor indicates that this drift can easily be compensated for by the appliance's software carrying out a routine zero correction calibration just before the burner is ignited.

In general, manufacturers could develop algorithms to respond appropriately to sensor output and allow for self-calibration and zeroing, mitigating effects of fluctuation, spikes, or drift.

1 Introduction

The U.S. Consumer Product Safety Commission ("CPSC") staff contracted the services of DfR Solutions to conduct performance and quantitative accelerated life testing (ALT) of carbon monoxide (CO) and combustion sensors in accordance with generally accepted practices established within the field of Reliability Engineering.

The purpose of this test program was to accelerate the aging of the three (3) different CO and combustion gas sensors under examination in order to estimate their life span within the operating environment of a residential gas furnace or boiler.

1.1 Background

Residential gas furnaces and boilers are among the leading causes of annual, non-fire related CO poisoning deaths among all consumer products in the United States. Currently, the governing voluntary standards for these appliances do not require protection against many of the failure modes known to cause or contribute to the leakage of unsafe levels of CO into the living space of a residential structure.[2] CPSC staff has demonstrated the concept of using CO or other combustion gas sensors in the heat exchangers, flue passageways, and vent pipes of gas furnaces to detect unsafe levels of CO in these areas of the appliance and cause the shutdown of the appliance in response.[3,4,5] The gas appliance voluntary standards community has expressed concern about sensors having the durability and longevity to operate within the operating environments of these appliances for the lifespan of the appliance (estimated to range from 15-20 years).

In Japan, incomplete combustion devices have been required by the Japanese Industrial Standards (JIS) in residential gas water heaters to protect against CO poisoning since approximately 2001.[6] In Europe, the Committee for European Standardization (CEN) published a standard for combustion product sensing devices (CPSD) for usage within residential gas boilers to help maintain the proper air-fuel ratio of these appliances.[7] The United States does not presently require CO or combustion gas sensors to be installed in residential heating appliances.

1.2 Accelerated Life Testing (ALT)

ALT is a method of test that accelerates failures in devices in order to quantify life characteristics in normal use conditions, known as the field environment. Acceleration of damage accumulation (failures) typically requires the application of stresses above that which the device will see in a typical field environment.

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[2] ANSI Z21.47, *Standard for Gas-Fired Central Furnaces*; ANSI Z21.13, *Standard for Gas-Fired Low Pressure Steam and Hot Water Boilers*; and ANSI Z21.86, *Standard for Vented Gas-Fired Space Heating Appliances*.
[3] *Furnace Combustion Sensor Test Results*, R. Jordan, U.S. Consumer Product Safety Commission (2001).
[4] *Combustion Sensor Test Results*, R. Jordan, U.S. Consumer Product Safety Commission (2004).
[5] *Evaluation of the Durability and Longevity of Chemical Sensors Used In-Situ for Carbon Monoxide Safety Shutdown of Gas Furnaces,* R. Jordan, R. Butturini, U.S. Consumer Product Safety Commission (2012).
[6] JIS-S-2109, *Japanese Industrial Standard for Gas burning water heaters for domestic use*
[7] EN 16340, *Safety and control devices for burners and appliances burning gaseous or liquid fuels–Combustion product sensing devices.*

ALT requires the application of an acceleration factor, which is the ratio of time in field to time in test. Higher acceleration factors equate to shorter test times. However, increasing these stresses beyond the limitations of the device materials will induce failure mechanisms that are not seen or relevant in the field. Therefore, these material limitations serve as constraints on the amount that any test can be accelerated.

The stresses used in test (e.g., temperature, humidity) are chosen to accelerate the failure modes of interest in the field environment. Higher stresses equate to higher rates of damage accumulation in test, resulting in test times shorter than the anticipated life of the devices under test:

$$\text{Total Test Time} = \text{Field Life} / \text{Acceleration Factor}$$

Additional parameters that impact the life expectancy of a device, in addition to the stresses applied during test, include:

- Environmental duty cycle for the devices
- Reliability factor that the test will strive to demonstrate (essentially, the percentage of sensors expected to perform their intended function for the anticipated life expectancy)
- Confidence level factor that describes how accurate the predicted reliability is (defining the range of certainty around the predicted reliability)

Time-to-failure data obtained from the higher-stress acceleration testing under the specified conditions is used to extrapolate to field conditions, thereby providing a prediction of life expectancy.

2 Test Plan

The test plan identifies the ALT conditions prescribed for each of the chosen CO and combustion gas sensors, including environmental conditions and electrical requirements. Also, a strategy for monitoring and measuring sensor degradation within the environment, through in-situ testing and periodic removal and characterization to gas sensitivity, is described.

The approach taken first identifies the operating and environmental conditions for the sensors and their application requirements. A construction and design evaluation is performed to assess the device's specifications and capability against the requirements, and help identify critical areas that would impact the reliability. Failure mechanisms can then be determined and appropriate failure acceleration models utilized to develop the final test parameters.

2.1 Operating and Environmental Conditions

Representative conditions found in typical use (field) environments for residential gas furnaces are shown in Table 4[8].

Table 4: Normal (Typical) Operating Ranges of a Residential Gas Furnace

Area of Furnace	Temperature On-Cycle	Humidity On-Cycle	Temperature Off-Cycle	Humidity Off-Cycle
Primary Heat Exchanger	149-260°C	0-50% RH	65.5-121°C	50-75% RH
Secondary Heat Exchanger	60-121°C	90-100% RH	37.8-65.5°C	75-90% RH
Vent Pipe	32.2-48.8°C	90-100% RH	23.8-37.8°C	75-90% RH

Based on the assumptions in the Federal Test Procedures for Residential Furnaces and Boilers[9], the duty cycle rates are shown in Table 5.

Table 5: Duty Cycle Rates

		ON (min)	OFF (min)
Gas Furnace	Single-stage	3.87	13.3
	Multi-stage	10	10
Gas Boiler	Single-stage	9.68	33.26
	Multi-stage	15	15

[8] U.S. Consumer Product Safety Commission, Performance Work Statement, "Performance and Accelerated Life Testing of Carbon Monoxide and Combustion Sensors," p. 11, October 3, 2016

[9] DOE, Energy Conservation Program for Consumer Products: Test Procedures for Residential Furnaces and Boilers; Final Rule. Federal Register, Vol. 81, No. 10, Part V, January 15, 2016.

The following additional parameters impacting life expectancy are defined, with reliability and confidence levels reasonable for the application and industry:

- Field life: Up to 20 years desired for combustion gas sensors (test duration constraints limited to 12 months can decrease the field target life attainable to less than 20 years)
- Heating load hours: 2080 hours based on the national average per year[10] (furnace burn time, or ON time)
- Heating season: 4160 hours (about 5.7 months) based on a ratio of 2 for the average length of the heating season to the average heating load hours[10]
- Reliability factor: 85% or better
- Confidence level factor: 80% or better

The number of thermal cycles experienced in the field was based upon the heating season indicated above and the duty cycle of a multi-stage gas furnace. While they may not be as commonly used as single-stage furnaces, multi-stage furnaces are typically more efficient and would be expected to increase in usage for the future with lower overall energy costs. A multi-stage furnace's total cycle time is a little more than that for a single stage furnace, as it has a significantly longer ON time. This equates to slightly fewer thermal cycles per year than for single stage furnaces, but significantly more cycles than that experienced with gas boilers.

For a multi-stage gas furnace, a total of 12,480 cycles per year is determined for a heating season of 4160 hours and the duty cycle indicated in Table 5.

2.2 Construction/Design Evaluation

Three different types of CO and combustion gas sensors were evaluated to undergo ALT. Reference to the manufacturer and model of these sensors are omitted in the text and graphics (via greyed-out boxes) for anonymity reasons.

- Sensor A: CO_2 Sensor Module
- Sensor B: Combustion Gas Sensor Module
- Sensor C: CO/H_2 Sensor Module

An evaluation of each sensor design was conducted to assess the limitations of the materials used to construct each sensor. One of each sensor type was destructively analyzed to better examine the construction materials and overall design, using various tools such as optical microscopy, Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS), and Fourier Transform Infrared Spectroscopy (FTIR).

2.2.1 Sensor A

Sensor A (Figure 1) is a dual-channel CO_2 module. Per the manufacturer's specifications, it is designed for high concentration measuring applications and uses a dual-channel non-dispersive infrared (NDIR) optics technology for diffusion or flow-through sampling.

[10] DOE, Energy Conservation Program for Consumer Products: Test Procedures for Residential Furnaces and Boilers; Final Rule. Federal Register, Vol. 81, No. 10, Part V, p. 2653, January 15, 2016.

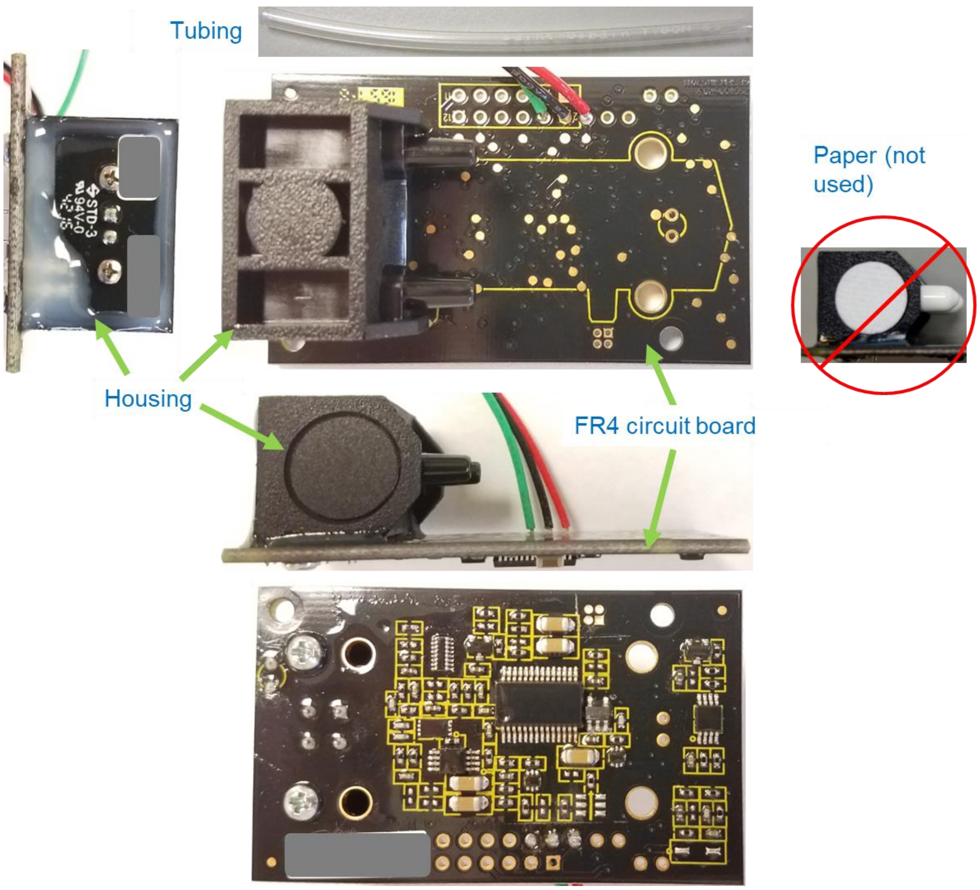


Figure 1: Sensor A

The IR lamp modulates on and off, and the filtered IR detector below monitors the intensity depending upon how much IR is absorbed by the measured gas (Figure 2). One channel measures CO_2 gas concentrations, and the other serves as a reference channel for the sensor signal intensity. The sensor has a 0 to 4 V output corresponding to a measurement range of 0 to 12% CO_2. Operating conditions are indicated at 0°C to 50°C and 0 to 95% RH (non-condensing), and the device operates off of 5 V_{dc} power supply.

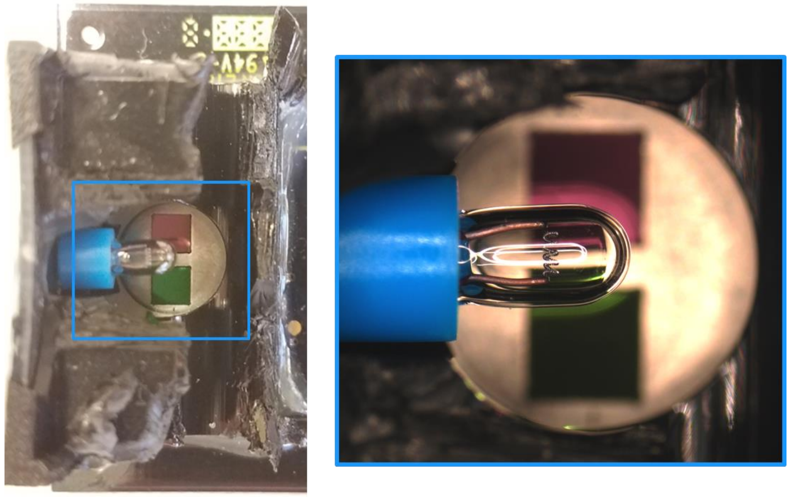


Figure 2: Sensor A Detector Element in Housing with IR Source Lamp

The normal operating environment for Sensor A is in the vent pipe temperature range identified in Table 4, and the sensor is designed to be installed entirely inside the field environment (diffusion sampling) or with only tubing into the field environment (flow-through sampling). Flow through rate is 250 mL/min maximum through the ports in the housing.

The thermal stability of the materials comprising Sensor A were evaluated through the destructive analysis and manufacturer-provided specifications in relation to the vent pipe application temperature range (Table 4), and determined to be as follows:

Materials exposed to the environment: Thermal stability range

- Tubing, polyvinyl chloride (PVC) (Tygon S3 B-44-4X): maximum 74°C
- Housing, polycarbonate (PC): maximum 170°C
- FR4 circuit board: maximum 140°C
- Paper: maximum 200°C (*Note – Actual units tested had cover with 3M 200MP adhesive (rated at 149°C) in place of paper (for use as flow-through sampling instead of diffusion sampling)*).
- Integrated circuits: maximum 125°C
- Infrared source lamp: -40°C to 105°C
- Infrared detector: -20°C to 120°C

Allowable test temperature range based on the above:

- Minimum temperature: -20C
- Maximum temperature: 105C (substituting silicone tubing for PVC tubing for higher temperature capability in test)

2.2.2 Sensor B

Sensor B (Figure 3) is a mixed potentiometric chemical sensor module. Per the manufacturer's specification, it can detect multiple oxidizable gaseous substances (COe), like CO and H_2, in the measured gas (up to 3000 ppm CO/H_2, with ideal resolution up to 1000 ppm).

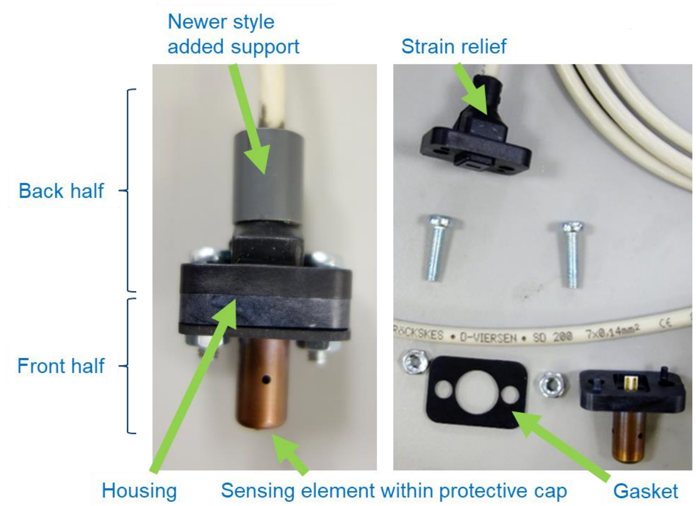


Figure 3: Sensor B

The sensor element (Figure 4) consists of: ZrO_2 ceramic (electrode substrate), Al_2O_2 ceramic (carrier substrate), and noble metals (sensing electrode material). A heating element exists on the back side of the substrate, as the sensor voltage output is very temperature dependent. The sensor element requires operation around 650°C (between 450°C to 700°C possible operating range), in addition to requiring a minimum level of oxygen of about 0.5% to 1% to maintain the chemical reaction of the electrodes. Power is supplied to the heater element only. A separate power supply controller box keeps the resistance of the heater at a constant value in the field (equal to the value that consumes 2.8 W to 3 W power in air with no airflow).

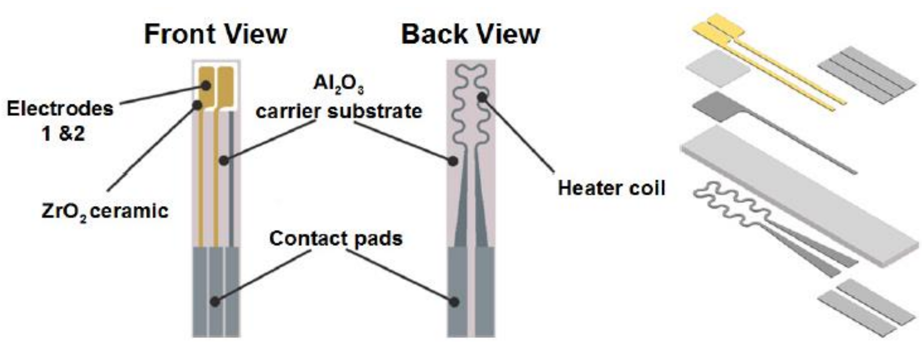


Figure 4: Sensor B Element Design (from manufacturer's specification)

The contact pads make electrical connection with the back half of the sensor through leads (interconnect) that deflect upon insertion of the pads (Figure 5).

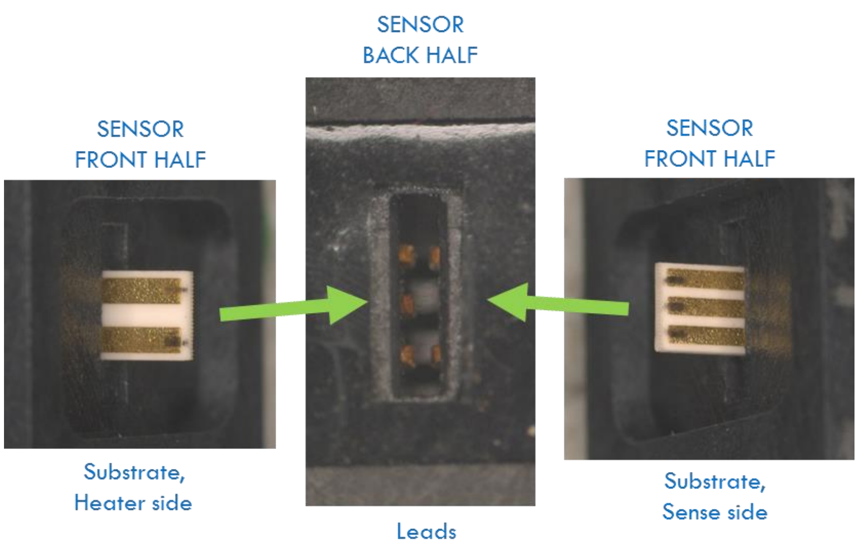


Figure 5: Sensor B Interconnect

The normal operating environment for this device is in the secondary heat exchanger temperature range identified in Table 4. The device has a rated temperature range of -20°C to 150°C (with short peaks up to 200°C). It is considered immune to condensing humidity and is suitable for condensing boilers and the exhaust of fuel cells. The sensor is designed to be installed with only the sensor element exposed to the field environment.

The thermal stability of the materials comprising Sensor B were evaluated through the destructive analysis and manufacturer-provided specifications in relation to the secondary heat exchanger application temperature range (Table 4), and determined to be as follows:

Material exposed to the environment: Thermal stability range

- Sensing element (ceramic ZrO_2): melting point of 2700°C
- Cap, stainless steel: 930°C or higher

Materials not exposed to the environment: Thermal stability range

- Housing, main body, Vectra® liquid crystal polymer (LCP): -40°C to 216°C
- Connector gasket: - 200°C to 215°C
- Gasket, Viton elastomer: maximum 200°C
- Strain relief: -40°C to 100°C
- Cable: -30°C to 80°C (worst case 100°C)

Allowable test temperature range based on the above:

- Minimum temperature: -20°C
- Maximum temperature: 150°C

Heat generated from the roughly 650°C operating temperature of the heater element, combined with the high temperatures in the operating secondary heat exchanger environment, is conducted to the back half of the sensor. This is where lower temperature-limited materials are used, and so the rated maximum operating temperature of 150°C should not be exceeded.

2.2.3 Sensor C

Sensor C (Figure 6) is a CO and H_2 combustion gas sensing module that utilizes a catalyzed pelletized resistor (pellistor). It can detect 0-2% carbon monoxide (0-20,000 ppm CO).

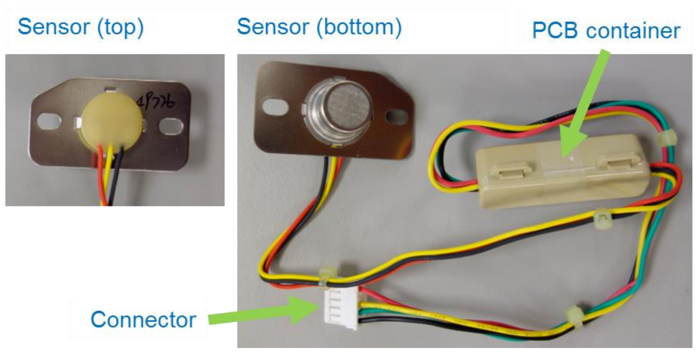


Figure 6: Sensor C & PCB Container

Per the manufacturer's data sheet and technical manual, the sensor element (Figure 7, with stainless steel enclosure removed) consists of a pair of pellistors: a detector and a compensator. The detector has an active catalyst layer on the ceramic pellet (Figure 8), while the compensator has no catalyst layer for flammable gas to oxidize. It is used as a reference resistance to which the detector's signal is compared, removing the effects of environmental factors other than the presence of a flammable gas. Each pellistor is attached to the sensor through a welded bond (platinum wire to the nickel-alloy pin).

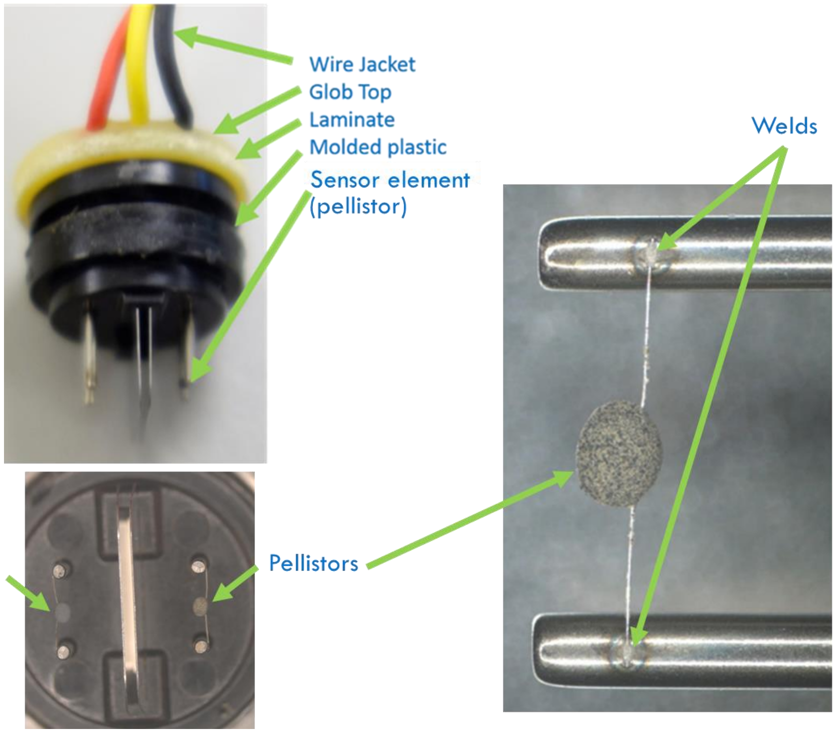


Figure 7: Sensor C Element

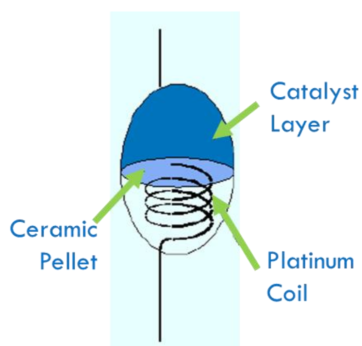


Figure 8: Sensor C Pellistor Design (from manufacturer's data sheet and technical manual)

The catalyst layer on the surface of the detector pellistor mainly consists of tin (Sn) and carbon (C) (beyond the presence of oxygen (O) detected). This is apparent in the EDS mapping of the SEM image shown in Figure 9. This catalyst layer is heated by electric current run through the platinum coil. Exposed to a flammable gas, the heated catalyst allows oxidation to occur. This is an exothermic reaction that raises the temperature of the ceramic pellet and coil within, which changes the electrical resistance of the coil as measured by the sensor signal.

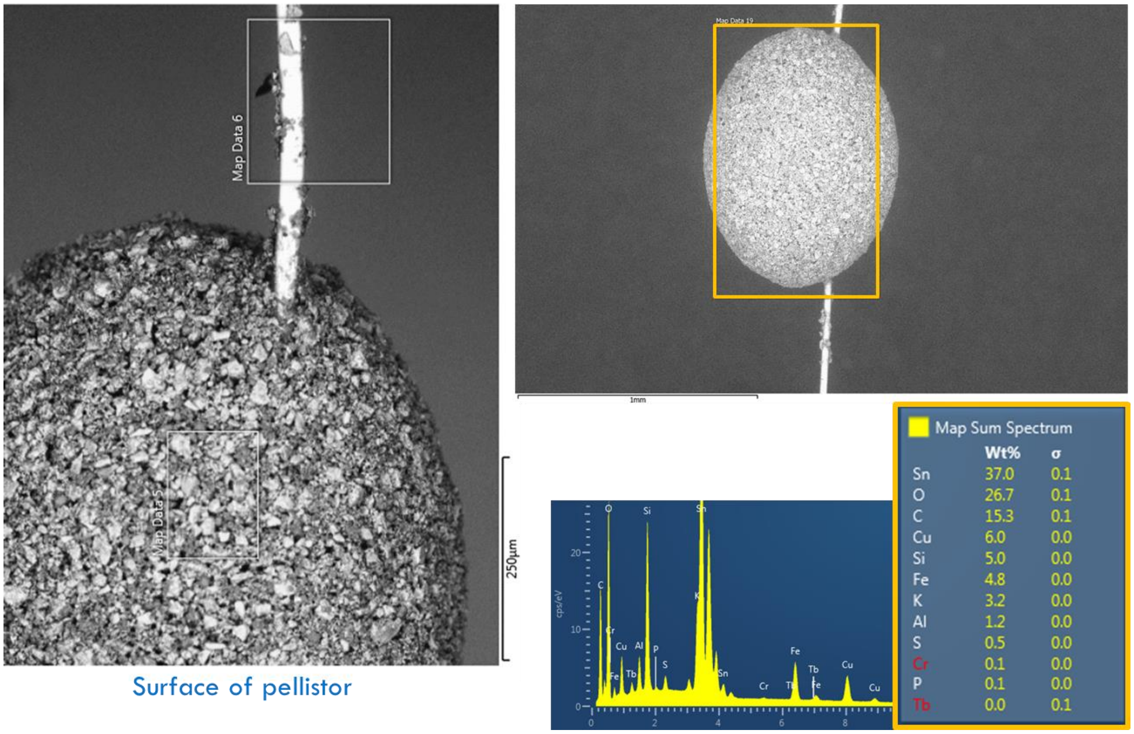


Figure 9: Sensor C Detector Catalyst Layer

The PCB container houses the resistor matrix (Figure 10). The PCB contains two other resistors to balance the Wheatstone bridge setup. A variable resistor also exists to adjust the zero offset.

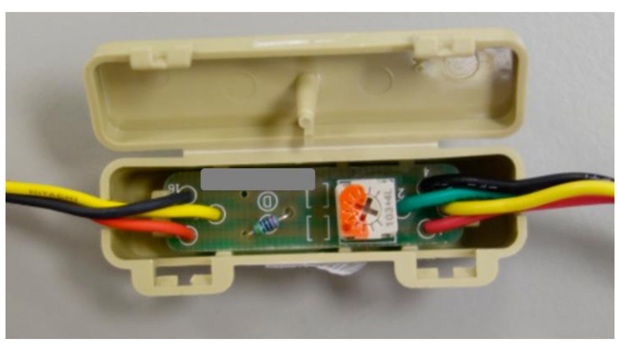


Figure 10: Sensor C PCB Container

The normal operating environment for this device is in the primary heat exchange temperature range identified in Table 4, monitoring flue gases generated by gas- or oil-fired domestic hot water and central heating boilers. The device has a rated temperature range of -25°C to 200°C (max. 260°C) inside the flue duct, and -25°C to 150°C outside, with a rated humidity range of 0 to 99% RH. The sensor is designed to be installed with only the sensing element exposed to the field environment, and it operates off of 2 V_{dc} power supply.

The thermal stability of the materials comprising Sensor C were evaluated through the destructive analysis and manufacturer-provided specifications in relation to the primary heat exchanger application temperature range (Table 4), and determined to be as follows:

Materials exposed to the environment: Thermal stability range

- Sensor is comprised of a stainless steel enclosure and mesh, nickel alloy pins, heat-resistant phenolic base mount, platinum wire, and ceramic pellet: -30°C (based on manufacturer's storage temperature tests) to maximum 260°C

Materials not exposed to the environment: Thermal stability range

- Wire jacket ETFE (ethylene tetrafluoroethylene):
    - 3-wire, PCB-Sensor: maximum 200°C
    - 4-wire, Connector-PCB: maximum 200°C
- Cable ties: maximum 105°C
- Glob top epoxy: maximum 177°C
- Laminate epoxy: maximum 177°C
- PCB container, Nylon66: maximum 180°C

Allowable test temperature range based on the above:

- Minimum temperature: -30°C
- Maximum temperature: 260°C for material exposed to environment. For exterior to environment, temperature is limited to 177°C (with removal of cable ties).

2.3 Failure Mechanisms

The CO and combustion sensors used in residential gas furnaces experience a combination of high temperatures and high humidity in use. With a duty cycle of 50%, these environmental extremes are cyclical in nature. The stress conditions could also include power cycling stresses if they powered on and off with the furnace (e.g. 10 minutes on and 10 minutes off cycles) and possible corrosion caused by a typical residential gas furnace. However, these sensors are intended to remain powered ON during the heating season and therefore would not experience power cycling.

Based on the material characteristics of each sensor, temperature cycling can drive mechanical fatigue due to thermo-mechanical loading. Any time two different materials are connected to one another in electronics assemblies, there is a potential for a coefficient of thermal expansion (CTE) mismatch to occur. Some of these CTE mismatch interactions can be quite complicated due to the different mechanical properties of materials, complex geometries, and competing material behaviors. Solder durability/fatigue and material fatigue (e.g. component packaging, interconnections) become of concern for overall reliability. This type of failure mechanism is often replicated through temperature cycling, and is typically applied to induce cracking in permanent interconnects (solder joints, wire bonds, vias, die attach, etc.) and fretting in separable connectors (as between the front and back half of the Sensor B samples).

Humidity exposure can induce corrosion, metal migration, oxidation of exposed metal surfaces, or hydrolysis of polymers. For these sensors, electrical parameter shifts, absorption or adsorption of materials, and potential shorting are all potential failure mechanisms typically associated with a temperature humidity bias (THB) stress, where the bias is the power source. Corrosion from external gases and humidity are also a potential failure mechanism that could affect these types of sensors given their typical use environments.

2.4 Acceleration Models for Testing

Accelerated life tests were devised to expose the sensors to stressors associated to their field use, compressing the time for testing through overstress acceleration. Acceleration factors were determined for each ALT test based on the failure mechanisms identified (brought on by temperature cycling and THB exposure) and the associated models for acceleration.

2.4.1 Temperature Cycling Model

In temperature cycling, sensors are subjected to high and low temperature extremes. The intent is to create cyclic stresses due to thermal expansion and contraction of the various materials comprising the sensors. For ductile metals (such as solder), the most common approach is to use the Coffin-Manson equation. The assumption is that the failures will be due to fatigue from cyclic strain dependent upon the number of applied temperature cycles. This strain is in the inelastic and creep regions for soldered interconnects on Sensor A, as well as the external half of Sensor B and Sensor C. The spring-loaded leads in Sensor B can also experience stress relaxation. The equation shown in Figure 11 illustrates this computation.[11]

$$A_{TC} = \frac{N_{Use}}{N_{Stress}} = \left(\frac{\Delta T_{Stress}}{\Delta T_{Use}}\right)^{K}$$

$$Ln(N_f) = C - K \; Ln(\Delta T)$$

Notation

A_{TC}	=Temperature cycle acceleration factor
N_{Stress}	=Number of cycles tested
N_{Use}	=Equivalent number of field cycles
ΔT_{Stress}	=Temperature cycle test range
ΔT_{Use}	=Nominal daily temperature change in the field
K	=Temperature cycle exponent
N_f	=Number of cycles to failure
C	=Constant

Figure 11: Temperature Cycle Acceleration Linearized Cycles to Failure Model

[11] "Design for Reliability-Concepts in Accelerated Testing," http://www.dfrsoft.com/DfRSoft%20Accel%20Testing.pdf, January 8, 2017

Acceleration factors are very sensitive to the value of the K exponent. Values between 2 and 4 for this exponent have been used in the industry. A value of 2.4 is applied based on the soft ductile material used in lead-free solder interconnects[12].

The temperature delta in the field is a driving factor in the temperature cycling acceleration model. This temperature delta is taken as the difference between the maximum field temperature in the ON-cycle and the maximum field temperature in the OFF-cycle. It is considered less likely for a temperature delta to occur between the maximum and minimum extremes of the ON- and OFF-cycles, respectively. The temperature delta between the maximum ON- and OFF-cycle temperatures is also larger than that between the minimum ON- and OFF-cycle temperatures, and therefore is more conservative in applying real-world field conditions.

Because Sensor C has a rated temperature range limited to 200°C under normal use, it is not expected to be installed in furnaces where the temperature within the primary heat exchanger would exceed this amount. The maximum field temperature for this sensor in the ON-cycle condition (reference Table 4) was therefore taken as 200°C. This temperature is close to the average of the ON-cycle temperature range, and so the average of the OFF-cycle temperature range (93.25°C) was used to determine the overall field temperature delta. The other two sensors tested were rated for the entire temperature ranges listed for their respective use areas within the furnace.

2.4.2 Temperature-Humidity-Bias (THB) Model

In THB testing, sensors are placed at elevated temperatures and humidity for an extended period of time. The model includes a relationship between life and temperature (Arrhenius Model) and life and humidity (Peck's Law Model).[13] The product of these two separate models generates an overall acceleration factor that must be greater than 1 for the model to be valid. Figure 12 delineates the equations used for this model[14].

[12] Blish R, Temperature Cycling and Thermal Shock Failure Rate Modeling, 1997 IEEE International Reliability Physics Symposium Proceedings. 35th, April 8-10, 1997
[13] Peck, D. Stewart, A Comprehensive Model for Humidity Testing Correlation, 1986
[14] "Design for Reliability-Concepts in Accelerated Testing," http://www.dfrsoft.com/DfRSoft%20Accel%20Testing.pdf, January 8, 2017

$$A_T = Exp\left\{\frac{E_a}{K_B}\left[\frac{1}{T_{Use}} - \frac{1}{T_{Stress}}\right]\right\}$$

$$A_H = \left(\frac{R_{Stress}}{R_{Use}}\right)^m$$

$$A_{TH} = A_T A_H$$

$$Ln(t_f) = C + \frac{E_a}{K_B T} - m \ Ln(R)$$

Notation

A_H = Humidity acceleration Factor
A_T = Temperature acceleration factor
A_{TH} = Temperature-Humidity acceleration factor
RH_{stress} = Relative humidity of test
RH_{use} = Nominal use relative humidity
T_{stress} = Test temperature
T_{use} = Nominal use temperature
m = Humidity constant
E_a = Activation energy
t_f = Time to Fail
C = Constant

Figure 12: THB Model Equations

The failure mechanism's activation energy, E_a, is assumed to be 0.7 eV (an industry standard for conservatively estimating test times)[15] for the sensors based on the materials and composition. Boltzmann's constant, K_B, is given as 8.617×10^{-5} eV/K. A humidity constant, m, of 2.66 is also assumed (typical industry value).

For THB exposure, the low percent relative humidity values are taken at the ON- and OFF-cycle maximum temperatures (reference Table 4). While this provides a slightly higher acceleration factor, it is less likely for the highest humidity conditions to occur during the highest temperature conditions. For Sensor C, the ON- and OFF-cycle field temperatures are taken at or close to the average of the temperature ranges for the primary heat exchanger. The corresponding relative humidity values are therefore taken at the average of their respective ranges in the ON-cycle and OFF-cycle. Overall, this represents a more realistic field condition for the acceleration model.

2.4.3 Acceleration Factor Examples

As an example for the THB acceleration factor model, Sensor A used in the vent pipe is exposed to an ON-cycle field temperature and humidity level range based on the values described in Table 4. For the ON-cycle, we take the high temperature and low humidity level of the ON-cycle range, using a maximum temperature of 48.8°C with 90% RH for the field conditions (for the

[15] Bayle, Franck; Mettas, Adamantios; Temperature Acceleration Models in Reliability Predictions: Justification and Improvements, 2010, IEEE RAMS Conference

OFF-cycle, we would take the corresponding high temperature and low humidity level of the OFF-cycle range).

We assume a test temperature of 85°C and a test relative humidity of 98% (within the allowable test temperature range for the sensor determined from the construction/design evaluation).

The following equation calculates the temperature acceleration factor (where the conversion from °C to Kelvin (K) is through adding 273.15 to °C):

$$A_T = \exp\{(0.7eV/8.617\times10^{-5}\ eV/K)*[1/(85+273.15) - 1/(48.8+273.15)]\} = 12.80$$

The next equation calculates the humidity acceleration factor:

$$A_H = (98\%RH/90\%RH)^{2.66} = 1.25$$

The combined temperature-humidity acceleration is the product of these two calculations:

$$A_{TH} = A_T\ A_H = 16.05$$

For this example, and assuming a time in the field, T_{Field}, of 41,600 hours (10 years of heating seasons) of life expectancy (approximate amount of cumulative OFF time over the sensor's life), the test duration, T_{Test}, would be determined as:

$$T_{Test} = T_{Field} / A_{TH} = 41{,}600\ \text{hrs} / 16.05 = 2{,}592\ \text{hrs}\ (1\ \text{day} / 24\ \text{hrs}) = 108\ \text{days}$$

However, this does not account for the required reliability and confidence level factors (using an assumed reliability distribution), nor the number of samples to be tested. That is discussed next in Section 2.5.

2.5 Test Parameter Development

With the acceleration factors determined from the appropriate acceleration models associated with the failure mechanisms identified, the test durations and sample sizes can then be developed. This is done for each ALT performed on each sensor type. The field life (time or number of cycles), reliability factor, and confidence level factor are already defined in Section 2.1. The following additional general parameters are needed:

- Assumed reliability distribution (including the Beta, β, parameter for the commonly used parametric binomial Weibull distribution)
- Number of test samples desired – OR – Test duration desired

The acceleration factor is used in ReliaSoft Weibull++ software to determine test duration with "*n*" test samples to achieve the field target life with the prescribed percent reliability and confidence level. Alternatively, the test duration can be calculated based on the number of test samples desired.

The Beta, β, value is known as the shape parameter, and represents the slope of the unreliability curve vs. time. It can be determined based on failure history (calculated based on a time- or cycles-to-failure plot if known) or expected failure along the typical reliability bathtub curve of failure rate vs. time (Figure 13). Along this curve, β<1 for infant mortality, β=1 for constant failure rate (random failures), and β>1 for wear-out failures.

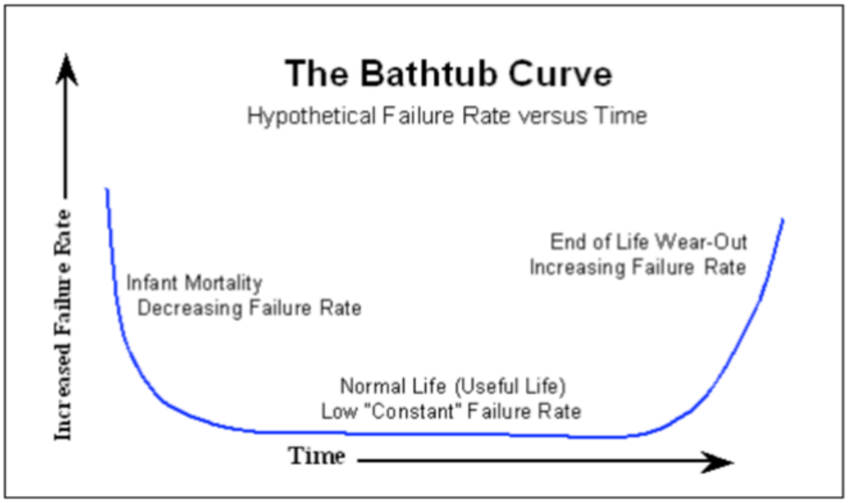


Figure 13: Reliability Bathtub Curve

Using the THB acceleration factor example in section 2.4.3, Weibull++ software is run with a 85% reliability factor, 80% confidence level factor, and a Beta value of 3. The Beta value chosen is reasonable for wear-out failure mechanisms, and is just beyond the influence of random latent defects (where β<2.5). With a sample size of 48, the calculated test duration in the ON-cycle, assuming 0 failures occur, is 1532 hours, or 64 days (Figure 14).

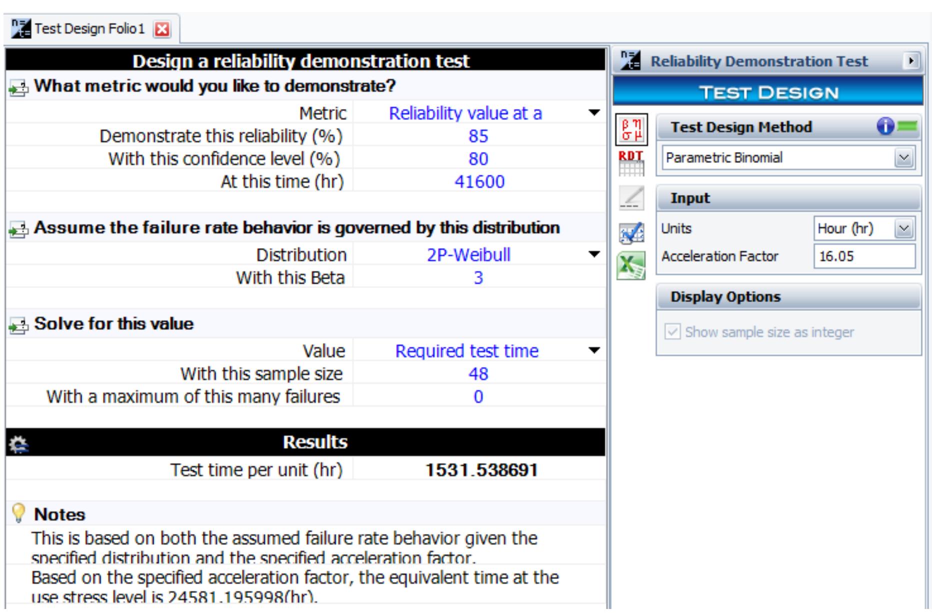


Figure 14: Weibull++ 11 Program

The reliability and confidence level factors, the number of failures permitted, and the sample size can all be varied to define the appropriate test structure.

2.5.1 Importance of Sample Size

Weibull++ software was used to determine the relative impacts of reliability, confidence level, sample size, and failures on test durations. As an example, Figure 15 shows the relative test durations (days) obtained for a hypothetical application with a given field life requirement and the following parameter changes: the reliability factor was ranged from 85-95%, the confidence level factor from 80-90%, and the sample size from 8-32 pieces.

			Test Duration	
Sample Size	Reliability	Conf	0 Fail	1 Fail
8	85	80	111	157
	90	80	138	195
	95	80	198	280
	85	85	120	166
	90	85	150	207
	95	85	215	297
	85	90	133	179
	90	90	165	222
	95	90	236	318
16	85	80	78	109
	90	80	98	135
	95	80	140	194
	85	85	85	115
	90	85	106	143
	95	85	152	206
	85	90	94	124
	90	90	116	154
	95	90	167	221
32	85	80	55	76
	90	80	69	95
	95	80	99	136
	85	85	60	81
	90	85	75	100
	95	85	107	144
	85	90	67	87
	90	90	82	108
	95	90	118	155

Figure 15: Hypothetical Results of Temperature Cycling Calculations

Clearly, from the example calculations performed, it can be seen that the number of samples available can have a profound impact on the achievable reliability, the confidence in that determination, and the test duration. Sample size is important because in a study of this nature, the goal is to make inferences about the population of sensors based on the sample size tested. For example, increasing the sample size will decrease the width of the confidence interval because it reduces the standard error involved. The sample size will also help in defining the amount of error one can accept. Thus, the larger the sample size, the higher the confidence in the results.

Conversely, as reliability and confidence level factors increase, so do the number of test samples required to demonstrate those increased factors in the same amount of test time. Addition of failures allowed in test also requires an increase in test duration to achieve the same reliability and confidence level goals.

2.6 Test Approach

Temperature cycling and THB testing were the two ALT's assigned to accelerate the failure mechanisms identified previously. The final test parameters were developed for these two tests, taking the following parameters into account:

- Available number of samples
- Material limitations
- Budget and timeline constraints

Acceleration of damage accumulation typically requires the application of stresses in excess of what the product would see in the use environment. However, increasing these stresses beyond the limitations of the sensor materials would induce failure mechanisms that are not relevant in the field (i.e., would not normally have occurred). Due to these constraints, DfR Solutions developed test conditions to accelerate the tests as much as possible without causing unrepresentative damage.

The test conditions were unique for each of the three sensors, and included environmental conditions, electrical requirements, recommended sample size, and periodic gas sensitivity checks. The frequency of performing gas sensitivity tests correlated to about every 1 to 2 years equivalent in the field. Failures observed during those tests could then be correlated back to an expected point in time in the field.

If no failures were observed during testing, then the prescribed reliability and confidence level factors will have been demonstrated for the sensors and the associated failure mechanisms discussed. If failures were observed before the planned test duration was achieved, there are two scenarios that can occur:

1.) The test is continued the additional number of cycles (for temperature cycling testing) or additional time (for THB testing) per the planned number of failures allowed.
2.) The test is stopped if the number of failures exceed that allowed, and the cycles- or time-to-failure data is plotted and fit to the 2-parameter binomial Weibull distribution, using the measured Beta value from the test population, with Weibull++ software.

Characteristic life can then be determined (time to failure for 63% of the test population). The original reliability and confidence level factors can be applied to determine the expected lifespan in the field.

Based on the test parameter development and test plan approach presented, DfR Solutions recommended the number of CO and combustion gas sensor test samples as shown in Table 6 for temperature cycling and THB testing. A Beta value of 3 was used in the reliability calculations for test durations and sample sizes. The number of failures allowed for each test was 2 qty. This is reasonable for the sample sizes and the additional time required to demonstrate the 85% reliability and 80% confidence level goals.

Table 6: Sample Size Per Test

Sensor	# for Temperature Cycling Test	# for THB Test	Total # Sensors Required
A	8	48	56
B	8*	8	16
C	48	20	68

* Reduced to 7 samples at start of test (reference Section 4.2.1)

2.7 Temperature Cycling Conditions

DfR Solutions performed three unique temperature cycling tests based on the environmental conditions found in Table 4, the duty cycle for a multi-stage furnace in Table 5, and the allowable test temperature ranges determined for each sensor. Sensor A units were tested within the lower temperature ranges found in the vent pipe. Sensor B units were tested within the mid temperature ranges typically found in the secondary heat exchanger. Sensor C units were tested within the higher temperature ranges that typically exist in the primary heat exchanger.

The minimum and maximum test temperatures for each sensor were selected based on a calculated acceleration factor and corresponding reasonable test duration (number of days given an achievable cycle rate in test) for the sample sizes shown in Table 6. The test conditions are a balance between not creating an excessively over-stressed environment based on the thermal properties of the sensor materials, while still achieving an economical and timely approach to test completion. For Sensor B units, field expectancy was limited to 10 years given the lower acceleration factor and corresponding test duration exceeding 1 year with 1 failure. Similarly, Sensor C units were limited to demonstrating 10 years in the field given the lower acceleration factor and corresponding test duration exceeding 1 year with 2 failures. These conditions were applied to the test plan to stay within the 1-year test duration constraint.

2.7.1 Sensor A Temperature Cycling

DfR Solutions recommended the test parameters outlined in Table 7 to meet the desired reliability, confidence, and life expectancy goals for Sensor A. Although the sensor had an operating temperature rating of 0-50°C, the sensor's determined allowable temperature range based on the design evaluation was not exceeded. The entire device was subjected to the environmental conditions for temperature cycling stress testing.

Table 7: Sensor A Temperature Cycling Test Parameters

20-Year Equivalent Life Expectancy (249,600 field cycles) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
8	85%	80%	866 cycles (73 days)[A]	1090 cycles (91 days)[A]	1261 cycles (106 days)[A]
Number of sensitivity readings following baseline check[B]:			8	9	11
Test Conditions -					
Min Field Temperature	**Max Field Temperature**	**Min Test Temperature**	**Max Test Temperature**	**Acceleration Factor**	
37.8°C	48.8°C	-20°C	100°C	309.5	

[A] Test duration in days is based on 2.00 hr cycles (10°C/min ramp rate and 48 min. dwell)
[B] Sensitivity readings are based on 10-day intervals (1.9-yr field equivalency for test duration with 2 failures)

2.7.2 Sensor B Temperature Cycling

DfR Solutions recommended the test parameters outlined in Table 8 to meet the desired reliability and confidence goals, with 10-year life expectancy (to keep within the 1-year test time constraint), for Sensor B. Only the sensing portion (front half) of the device was subjected to the environmental conditions for temperature cycling stress testing. The upper test temperature was limited to 135°C in order to minimize excessive heat conduction to the back half of the sensor. Sensitivity intervals were closer to 1 year since no power supply for signal output was used on this type of sensor to continuously monitor in situ (although the passive sensor output was continuously monitored). Test durations beyond 1 failure are not indicated since the 1-year test duration constraint is already exceeded at this point.

Table 8: Sensor B Temperature Cycling Test Parameters

10-Year Equivalent Life Expectancy (124,800 field cycles) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
8	85%	80%	11,395 cycles (322 days)[A]	14,340 cycles (405 days)[A]	n/a
Number of sensitivity readings following baseline check[B]:			10	12	n/a
Test Conditions -					
Min Field Temperature	**Max Field Temperature**	**Min Test Temperature**	**Max Test Temperature**	**Acceleration Factor**	
65.5°C	121°C	-20°C	135°C	11.76	

[A] Test duration in days is based on 0.68 hr cycles (15°C/min ramp rate and 10 min. dwell)
[B] Sensitivity readings are based on 35-day intervals (1.1-yr field equivalency for test duration with 0 failure)

2.7.3 Sensor C Temperature Cycling

DfR Solutions recommended the test parameters outlined in Table 9 to meet the desired reliability and confidence goals, with 10-year life expectancy (to keep within the 1-year test time constraint), for Sensor C. Only the sensing portion of the device was subjected to the environmental conditions for temperature cycling stress testing.

Table 9: Sensor C Temperature Cycling Test Parameters

10-Year Equivalent Life Expectancy (124,800 field cycles) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
48	85%	80%	6698 cycles (273 days)[A]	8267 cycles (337 days)[A]	9346 cycles (381 days)[A]
Number of sensitivity readings following baseline check[B]:			10	12	14
Test Conditions -					
Min Field Temperature	**Max Field Temperature**	**Min Test Temperature**	**Max Test Temperature**	**Acceleration Factor**	
93.25°C	200°C	-30°C	260°C	11.01	

[A] Test duration in days is based on 0.98 hr cycles (15°C/min ramp rate and 10 min. dwell)
[B] Sensitivity readings are based on 28-day intervals (1.0-yr field equivalency for test duration with 0 failure)

2.8 Temperature-Humidity Bias (THB) Conditions

Conventional humidity chambers have a maximum operating temperature of 85°C and a maximum humidity level of 98%, which became a limiting factor with respect to the Sensor B and Sensor C units. To be able to complete the tests for these two sensors within the available year of test time, it was necessary to be able to achieve test temperatures up to 135°C with the use of an autoclave type chamber.

2.8.1 THB Split Test Methodology

With respect to the THB testing, DfR Solutions recommended performing a split year equivalent test based on the 50% duty cycle for multi-stage gas furnaces. By doing so, the tests were able to assess the impact that both the OFF and ON cycles had on the sensors undergoing low and high temperature and relative humidity ranges. By aggregating the two elements of the test, DfR Solution's approach provided a meaningful assessment of the life expectancy of the sensors over their entire operating range. Testing for the OFF-cycle and the ON-cycle conditions in series was the most advantageous way to conduct the test within the available time.

2.8.2 Sensor A THB

Sensor A testing was conducted in a traditional THB chamber. The test conditions for 10-year life for each the OFF-cycle and the ON-cycle were performed in series to achieve 20-year equivalent life. DfR Solutions recommended the test parameters outlined in Table 10 and Table 11 to meet the desired reliability, confidence, and life expectancy goals for Sensor A. Although the sensor had an operating temperature rating of 0-50°C, the sensor's determined allowable temperature range based on the design evaluation was not exceeded. The 98% RH test condition was not considered an excessive overstress relative to the maximum operating rating of 95% RH, as long as it remains non-condensing. The entire device was subjected to the environmental conditions for THB stress testing.

Table 10: Sensor A THB Off Cycle Test Parameters

OFF-cycle, 10-Year Equivalent Life Expectancy (41,600 hrs) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
48	85%	80%	387 hrs (17 days)	477 hrs (20 days)	539 hrs (23 days)
Number of sensitivity readings following baseline check[A]:			8	10	12
Test Conditions -					
Field Temperature	**Field Humidity**	**Test Temperature**	**Test Humidity**	**Acceleration Factor**	
37.8°C	75%	85°	98%	63.64	

[A] Sensitivity readings based on 2-day intervals (1.2-yr field equivalency for test duration with 0 failure)

Table 11: Sensor A THB On Cycle Test Parameters

ON-cycle, 10-Year Equivalent Life Expectancy (41,600 hrs) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
48	85%	80%	1532 hrs (64 days)	1891 hrs (79 days)	2137 hrs (90 days)
Number of sensitivity readings following baseline check[A]:			6	7	8
Test Conditions -					
Field Temperature	**Field Humidity**	**Test Temperature**	**Test Humidity**	**Acceleration Factor**	
48.8°C	90%	85°C	98%	16.05	

[A] Sensitivity readings based on 12-day intervals (1.9-yr field equivalency for test duration with 0 failure)

2.8.3 Sensor B and Sensor C THB

During the ON-cycle, field temperatures of 121°C (Sensor B) and 200°C (Sensor C) and associated humidity levels at those extremes limit the acceleration factors achievable with the allowable test conditions. This prevented getting test duration times below one year for even a 10-year equivalent life expectancy test (5 years OFF, 5 years ON) using a reasonable number of test samples. Therefore, DfR Solutions recommended testing Sensor B and Sensor C for 8-year life equivalent (4 years OFF, 4 years ON) using the test parameters outlined in Table 12 and Table 13 for Sensor A units, and Table 14 and Table 15 for Sensor C units. The OFF-cycle and ON-cycle test conditions were conducted in series to meet the desired reliability and confidence level goals, with 8-year life expectancy, while keeping within the 1-year test time constraint.

2.8.3.1 Sensor B THB

Only the front and the modified back half of Sensor B was subjected to the environmental conditions for THB stress testing. Partial sensor placement inside the test environment was not feasible due to limitations of the HAST humidity chamber when pressurized for high temperature and humidity conditions (i.e., no physical pass-through capability existed for the front and back half of the sensor). However, the determined allowable temperature range based on the design evaluation was not exceeded for the back half of the sensor. Test durations beyond 1 failure are not indicated for ON-cycle testing since the 1-year test duration constraint is already exceeded at this point.

Table 12: Sensor B THB Off Cycle Test Parameters

OFF-cycle, 4-Year Equivalent Life Expectancy (16,640 hrs) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
8	85%	80%	717 hrs (30 days)	902 hrs (38 days)	1043 hrs (44 days)
Number of sensitivity readings following baseline check[A]:			5	7	8
Test Conditions -					
Field Temperature	**Field Humidity**	**Test Temperature**	**Test Humidity**	**Acceleration Factor**	
65.5°C	75%	105°C	98%	24.94	

[A] Sensitivity readings based on 6-day intervals (0.8-yr field equivalency for test duration with 0 failure)

Table 13: Sensor B THB On Cycle Test Parameters

ON-cycle, 4-Year Equivalent Life Expectancy (16,640 hrs) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
8	85%	80%	7035 hrs (294 days)	8853 hrs (369 days)	n/a
Number of sensitivity readings following baseline check[A]:			8	10	n/a
Test Conditions -					
Field Temperature	**Field Humidity**	**Test Temperature**	**Test Humidity**	**Acceleration Factor**	
121°C	90%	135°C	98%	2.54	

[A] Sensitivity readings based on 38-day intervals (0.5-yr field equivalency for test duration with 0 failure)

2.8.3.2 Sensor C THB

The entire Sensor C device (sensor and power/signal wires between sensor and PCB container) was subjected to the environmental conditions for THB stress testing. Partial sensor placement inside the test environment was not feasible due to limitations of the HAST humidity chamber when pressurized for high temperature and humidity conditions (i.e., no physical pass-through capability existed for the front and back half of the sensor). However, the determined allowable temperature range based on the design evaluation was not exceeded for the back half of the sensor and the connected wires mounted outside of the field environment.

Table 14: Sensor C THB Off Cycle Test Parameters

OFF-cycle, 4-Year Equivalent Life Expectancy (16,640 hrs) -			Test Duration		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
20	85%	80%	1957 hrs (82 days)	2427 hrs (102 days)	2759 hrs (115 days)
Number of sensitivity readings following baseline check[A]:			7	9	10
Test Conditions -					
Field Temperature	**Field Humidity**	**Test Temperature**	**Test Humidity**	**Acceleration Factor**	
93.25°C	62%	105°C	98%	6.73	

[A] Sensitivity readings based on 12-day intervals (0.6-yr field equivalency for test duration with 0 failure)

Table 15: Sensor C THB On Cycle Test Parameters

ON Cycle, 4-Year Equivalent Life Expectancy (16,640 hrs) -			Test Duration		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
20	85%	80%	5352 hrs (223 days)	6639 hrs (277 days)	7547 hrs (315 days)
Number of sensitivity readings following baseline check[A]:			6	8	9
Test Conditions -					
Field Temperature	**Field Humidity**	**Test Temperature**	**Test Humidity**	**Acceleration Factor**	
200°C	25%	135°C	98%	2.46	

[A] Sensitivity readings based on 38-day intervals (0.7-yr field equivalency for test duration with 0 failure)

2.9 Sensor Power Conditions

All three sensor types were powered during temperature cycling and THB testing (Sensor B signal output is passive, but its heater element was powered for proper operation). Input voltage and current to the sensor was continuously monitored and recorded, as was output voltage from the detector. This allowed for capture of degradation and time of occurrence.

2.9.1 Sensor A Power

Sensor A units required 5 V_{dc} (±5%) applied to pin C and ground connected to pin 2 during testing (Figure 16). Power consumption is rated at 0.165 W average and 0.90 W peak (using 33 mA average and 180 mA peak). In THB testing, this power provided the bias necessary for electrochemical migration, if it were to occur.

Connector Pinout	Function
A	TX (UART)
B	RX (UART)
C	V+ (5 VDC)
1	V+ (5 VDC)
2	GND
3	GND
4	AV OUT (0 to 4 VDC)
5	I2C SCL
6	No Connect
7	I2C SDA
8	No Connect
9	No Connect
10	TX (UART)
11	RX (UART)
12	GND

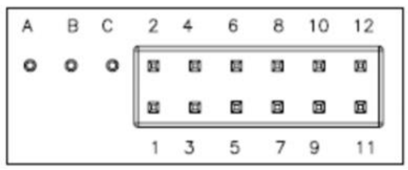


Figure 16: Sensor A Pin Designations (per manufacturer's specification)

2.9.2 Sensor B Power

For Sensor B units, only the heating element was powered (the sensor element is passive by design, and therefore not supplied with a voltage bias in the field). The sensor element can output up to about 700 mV signal passively depending upon the CO/H_2 gas concentrations to which it is exposed. This self-generated voltage could be simulated in test during the aging process, but small voltages of even 100mV would continuously force O2- ions to cross any electrolyte and simulate an amperometric oxygen sensor, potentially changing the electrode and its nominal behavior over time. Going to a duty cycle for this type of bias is less of a concern for this issue, but it would not be significant for promoting electro-chemical migration (ECM). Therefore, no voltage bias was applied to the sensor element in test.

The Sensor B units come with an external power control box that provides 10-12 V_{dc} that is pulse width modulated (PWM) at 50 Hz (and at about a 33% duty cycle) (Figure 17). The stock power control box keeps the resistance of the heater at a constant value (equal to that which provides 2.8-3 W heating power in air with no airflow) by regulating the power supplied to the heater element, and therefore maintaining its temperature. However, this power control box was cost prohibitive to utilize for each of the 16 quantity sensors designated for TC and THB testing.

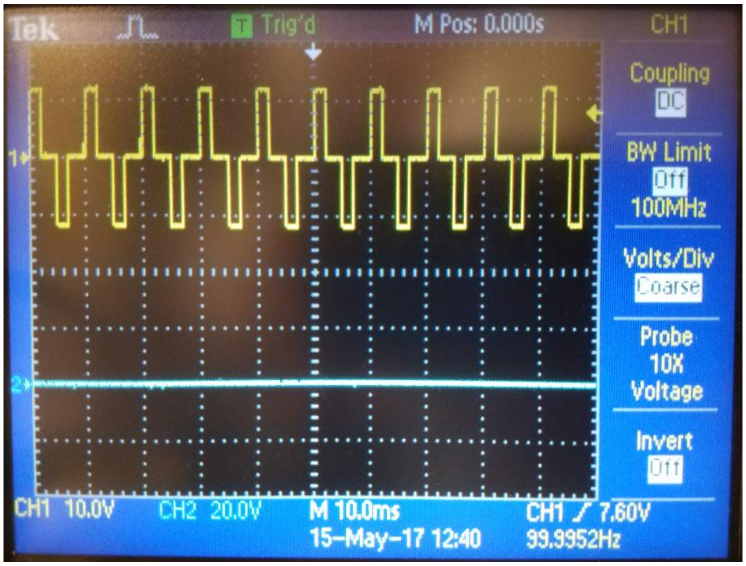


Figure 17: Sensor B Stock Power Supply Trace (Voltage vs. Time)

An alternative approach was used instead to power the heater elements with a single power source for each test. A variable AC power supply at 60 Hz was set to a voltage that would achieve about 2.8-3 W power across the heater element in ambient air with no airflow (Figure 18). The root mean squared (rms) voltage and current across the heater element were determined by measuring the voltage drop across a 5 Ohm sense resistor added to an external breakout board. From a cold startup, voltage had to be slowly increased so that the current was less than 0.5 A (starting at 1 W and increasing slowly to 3 W within minimum 30 sec.), and so that heater power did not exceed 6 W per the manufacturer. Power higher than 4 W continuously may alter the sensor electrodes. Normal operating current was expected to be around 0.35 A_{rms}. With 2.8-3 W power supplied to the heater element, monitored by recording the voltage and current across it, the sensor was ensured to reach and maintain is required operating temperature throughout testing.

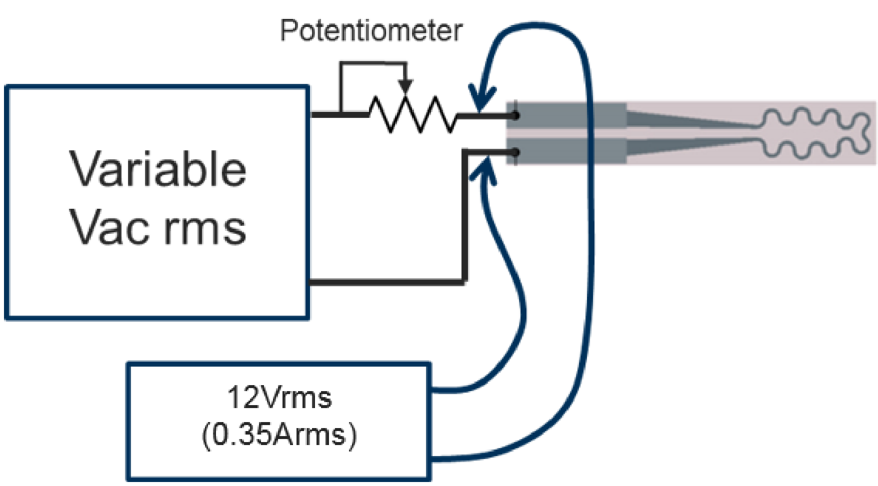


Figure 18: Bias Structure for Sensor B Heating Element

The two sense lines (U_{sen1} and U_{sen2}, Figure 19) were monitored during aging and during the gas sensitivity testing (at test intervals equivalent to about 1 year).

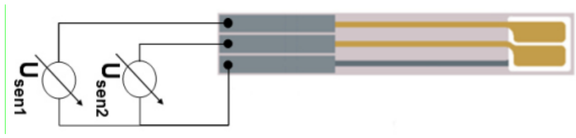


Figure 19: Sensor Electrodes Signal Outputs for Sensor B

2.9.3 Sensor C Power

Sensor C units required 2 V_{dc} ($\pm$0.1 V_{dc}) applied to pin 1 (power) and ground/return connected to pin5 (GND) (Figure 20). Current consumption is rated at 130-150 mA.

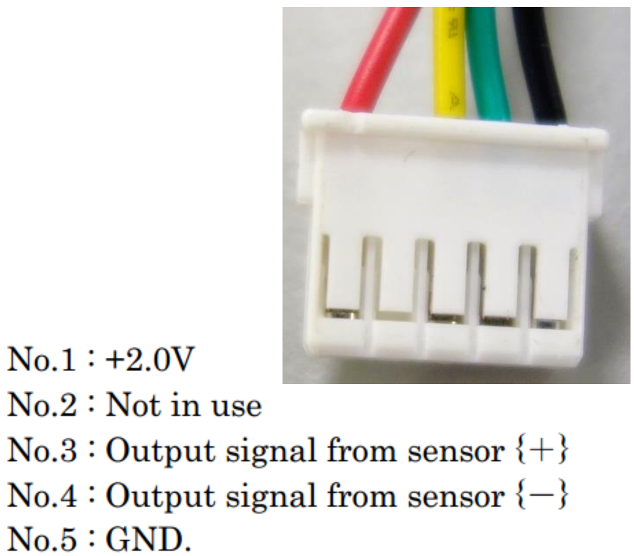


Figure 20: Sensor C Connector

2.10 Gas Sensitivity Performance

To assess the performance of the sensors when exposed to temperature cycling and THB stresses, DfR Solutions monitored and recorded the sensors for functional degradation through periodic sensitivity testing to known gas concentrations. A total of 5 certified gas concentrations were utilized, each progressively more concentrated in CO, H_2, and CO_2 than the first (Table 16). These concentrations capture the capability of the sensors tested. DfR Solutions performed these gas checks at time intervals that equate to about 1-2 years in the field.

Table 16: Gas Sensitivity Concentrations in Test

Tank	CO (ppm)	H2 (ppm)	CO2 (%)	O2 (%Mol/Mol)	N2
1	350	175	8% (80,000 ppm)	3%	Bal
2	400	200	9% (90,000 ppm)	3%	Bal
3	700	350	10% (100,000 ppm)	3%	Bal
4	1000	500	11% (110,000 ppm)	3%	Bal
5	1500	750	12% (120,000 ppm)	3%	Bal

2.10.1 Sensor A Sensitivity Performance

Sensor A units were tested in the flow-through mode at room temperature conditions (after minimum 24 hours for unit to self-calibrate at room temperature). Sensor signal output is 0-4 V depending upon the gas concentration. Sensor output temperature dependence is 0.4% FS per °C from calibration temperature, and pressure dependence is 0.135% of reading per mmHg. Sensor specifications evaluated are indicated in Table 17 below.

Table 17: Sensor A Performance Specifications

Parameter	**Specification**
Accuracy	±5% reading (from 3-20% concentration)
Stability over life of sensor (rated at 10 yrs)	<5% FS or <10% reading, per year

2.10.2 Sensor B Sensitivity Performance

Sensor B units were tested with only the sensor tips exposed to the gas environment. There are no specifications for accuracy, but the manufacturer indicated it is essentially a binary sensor. If bad combustion occurs in the furnace in which it is installed, the sensor will output above 100 mV signal. If there is more than 25% variation after aging, it is a sign that something could have degraded. A characteristic sensor response curve from the manufacture's published literature is shown in Figure 21 below.

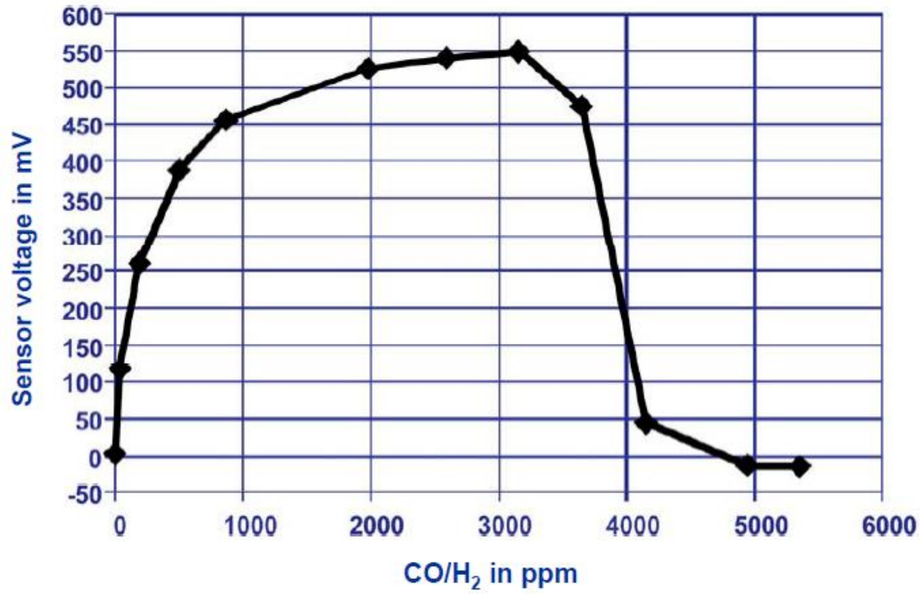


Figure 21: Sensor B Characteristic Sensor Output

2.10.3 Sensor C Sensitivity Performance

Like the Sensor B units, the Sensor C units were tested with only the sensor tips exposed to the gas environment. It has a typical output sensitivity of 6 mV ±1 mV at 23°C for a gas mixture equivalent to Tank 4 in Table 16 used in test (1000 ppm CO / 500 ppm H_2). Sensor specifications evaluated are indicated in Table 18 below. A characteristic sensitivity curve to an exposure of CO/H_2 in a 2:1 gas mixture (ppm) from the manufacturer's published literature is shown in Figure 22.

Table 18: Sensor C Performance Specifications

Parameter	**Specification**
Accuracy (measured as repeatability)	±0.5 mV for Zero and Gas Sensitivity
Stability, long term (rated over 10 yrs life)	±2 mV per year for Zero ±2 mV per month for Gas Sensitivity

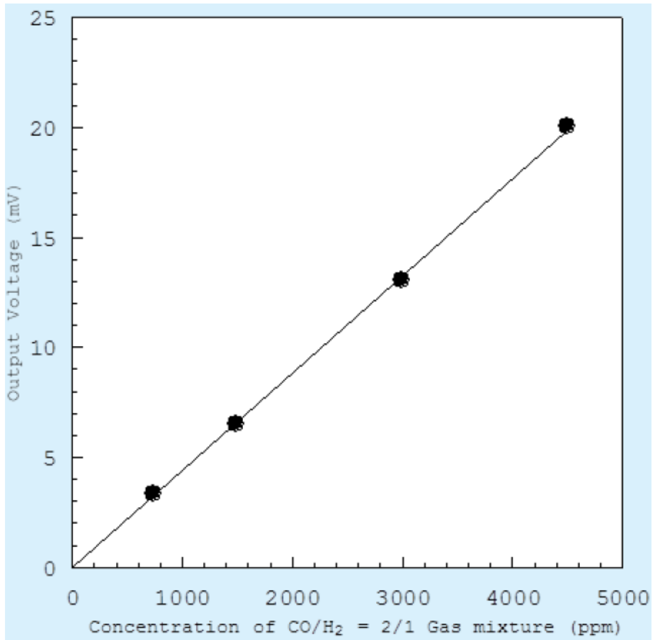


Figure 22: Sensor C Characteristic Sensor Output

2.11 Failure Criteria

DfR Solutions accumulated several types of data during exposure to temperature cycling and THB testing, as well as periodic gas sensitivity testing. Input voltage and current were continuously monitored and recorded to each sensor during exposure testing and gas sensitivity testing to provide evidence of any degradation in performance. Sensor signal output voltage was also continuously monitored and recorded to observe for any unexpected changes or anomalies during exposure testing, and for repeatability and stability during periodic gas sensitivity checks relative to the initial baseline results. Changes in voltage provided evidence as to whether the sensors operated according to manufacturer's specifications or degraded to a point where they could no longer be effective in sensing gas concentrations.

Failures were characterized among two criteria:

1. Soft Failures: Sensor signal output voltage did not meet the accuracy or stability specifications outlined in Section 2.10. However, an output signal is present, detecting some level of its intended target gas range.
2. Hard Failures: Sensor signal output voltage severely degraded or absent, unable to detect some level of its intended target gas range.

If a sensor was a hard failure, it was generally kept in test to see if it recovered in subsequent gas sensitivity checks. If it did not, it was removed from test. A failure analysis was to be conducted on up to 3 failed samples from each sensor type.

3 Test Setup and Procedure

The test setup and procedure followed for temperature cycling and THB testing, as well as the periodic gas sensitivity checks, were unique to each of the three sensors. The sensor's geometry, the allowable test temperature ranges determined for each, and the equipment used to achieve the prescribed test conditions all influenced how the sensors were tested.

3.1 Thermal Cycling Setup

The temperature limitations on the sensor materials influenced how and where each sensor was tested in the thermal cycle chambers. Sensor A units were placed completely inside the chamber because its materials could withstand the test temperatures. However, the Sensor B and Sensor C units were installed such that only the sensor tip was exposed to the test temperatures to avoid damaging parts of the sensor that are not exposed to the most severe operating temperatures. This setup replicates the sensor environment in the field, where part of the sensor is inside the high stress environment and part is outside (e.g., sensor mounted through the wall of the primary heat exchanger and electronic controls mounted outside of the furnace).

3.1.1 Sensor A TC Setup

Sensor A units were placed in a small Sun Systems thermal chamber (EC10, 0.7 cu-ft) for exposure testing. The 8 sensors were connected in series in two groups of 4 via high-temperature silicone tubing (3/32" ID (same as stock) and 1/16" wall) connected to the inlet and outlet ports of each sensor (Figure 23). This allowed gas sensitivity checks to be performed in-situ in the flow-through mode, while limiting the number of sensors checked in series simultaneously (gas flow through the sensor starts to be affected if a much larger number of daisy-chained samples are used).

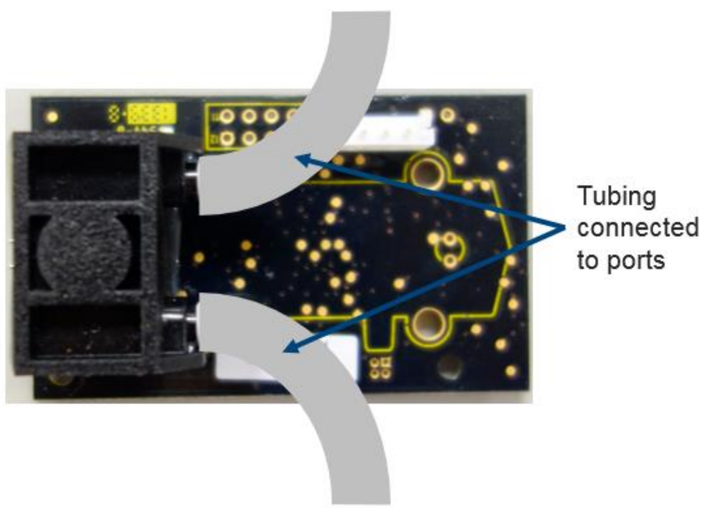


Figure 23: Tubing Connections for Flow-Through Mode

Samples were suspended from a rack within the chamber using cable ties, keeping adequate space in between for proper air circulation and temperature distribution within the chamber (Figure 24). The chamber was started in the cold cycle and set to -20°C and 98.5°C to achieve the temperature conditions in Section 2.7.1 based on the thermal profile of the chamber (Figure 25).

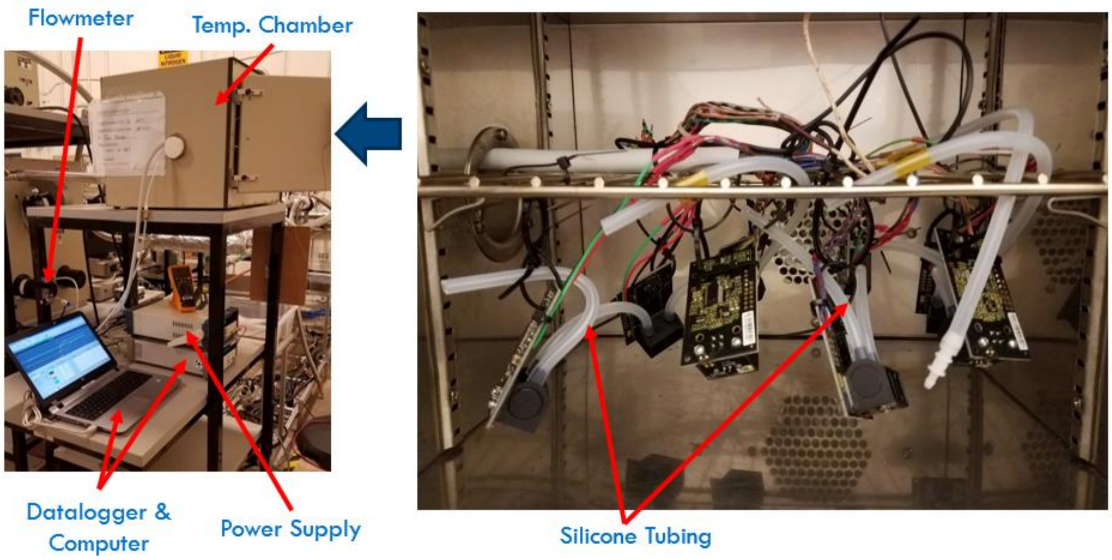


Figure 24: Sensor A TC Setup

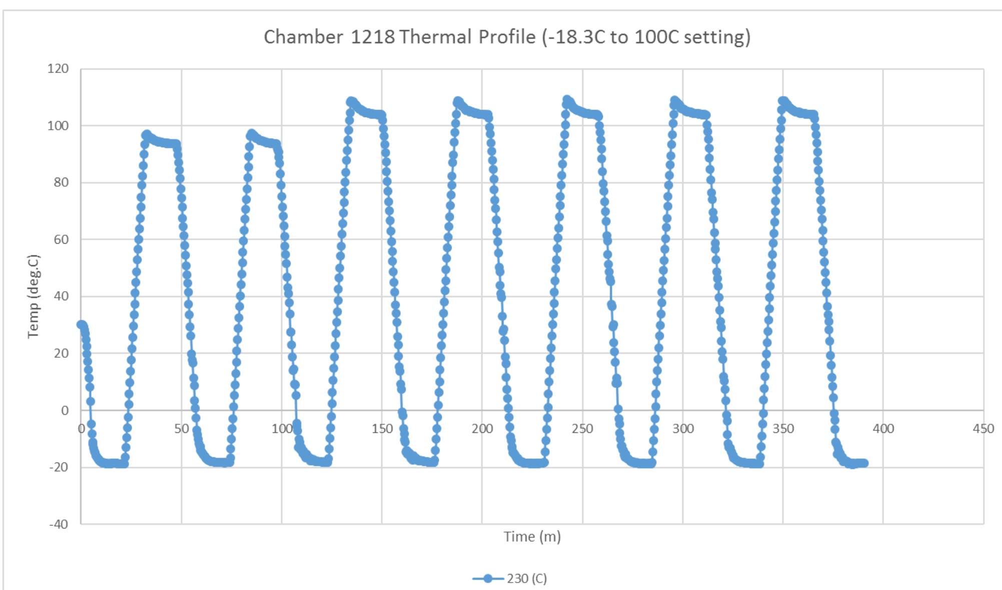


Figure 25: Sensor A TC Chamber Thermal Profile

The samples were continuously powered per the requirements in Section 2.9.1 and continuously monitored for input power (voltage and current) and signal output voltage via the datalogger and computer. A separate break-out board with 0.5 ohm sense resistors was used for these measurements, allowing determination of the input current by measuring the voltage drop across the known 10 ohm resistance (Figure 26). The wiring diagram for this setup is shown in APPENDIX A: Sensor A TC and THB wiring diagram.

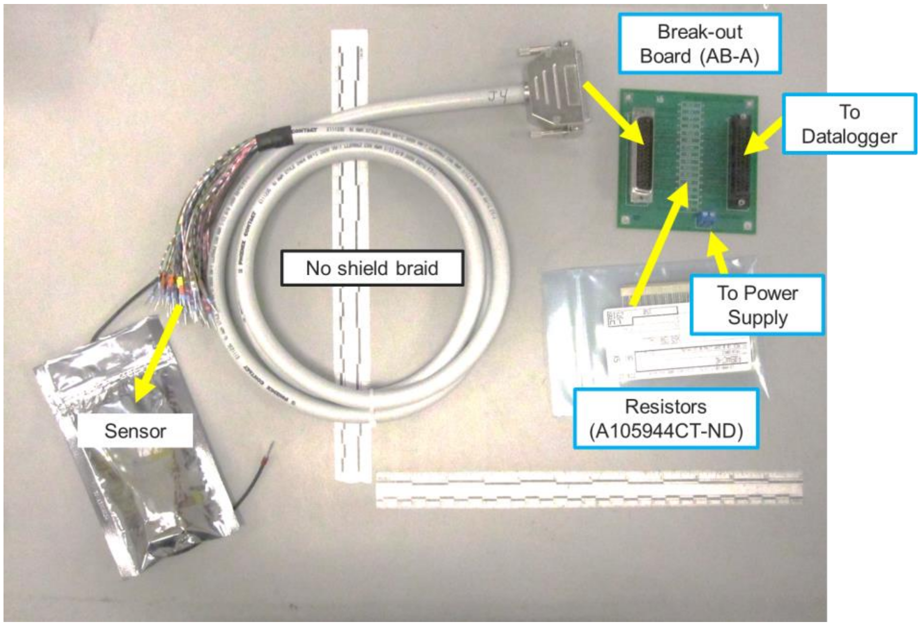


Figure 26: Sensor A TC Break-out Board for Data Monitoring

3.1.2 Sensor B TC Setup

Initially, 8 Sensor B units were placed into a custom door that was fitted to a small Sun Systems thermal chamber (EC10, 0.7 cu-ft) for exposure testing (Figure 27). The custom door allowed for only the sensing portion (front half) of the device to be exposed to the chamber environmental conditions. Additional strain relief was not initially used on the stock white cables extending from the backs of the sensors. One of the sensors was removed due to pre-mature failure (no heater power due to compromised engagement between contacts on the front and back halves of the sensor). Testing was setup to start with 7 samples instead.

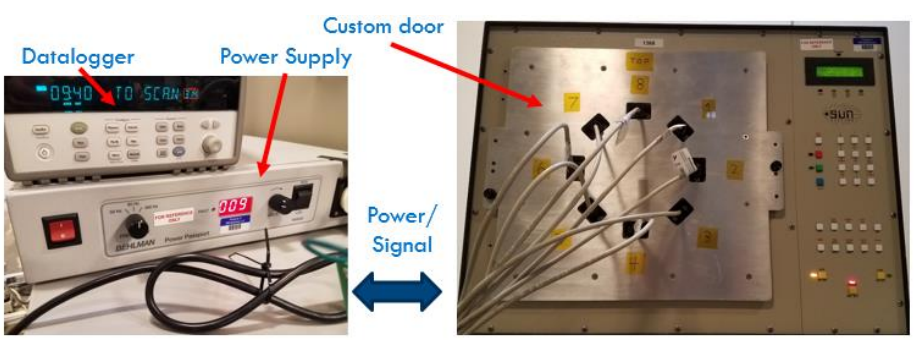


Figure 27: Sensor B TC Setup

The chamber was started in the cold cycle and set to -21°C and 135.5°C to achieve the temperature conditions in Section 2.7.2 based on the thermal profile of the chamber (Figure 28).

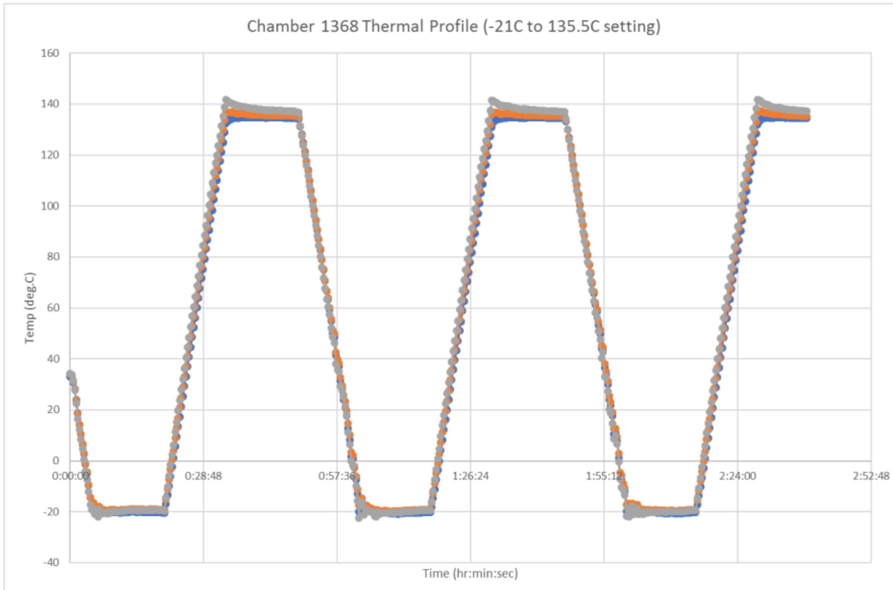


Figure 28: Sensor B TC Chamber Thermal Profile

The custom door was made of stamped and welded steel (with white high-temperature (>300°C) spray paint applied), which was exposed to the inside of the chamber and to which the sensors were attached Figure 29. The outside (non-exposed portion) of the door was made of machined aluminum. A very high-temperature mineral wool insulation was used in between the inner and outer portions of the door to help maintain the thermal conditions inside the chamber, along with a high-temperature silicone foam strip that sealed the custom door to the outside front surface of the chamber. While silicone-based materials should not be used near the sensor per the manufacturer, the closed cell silicone door seal was acceptable given its location relative to the samples and minimal surface exposed to the test environment.

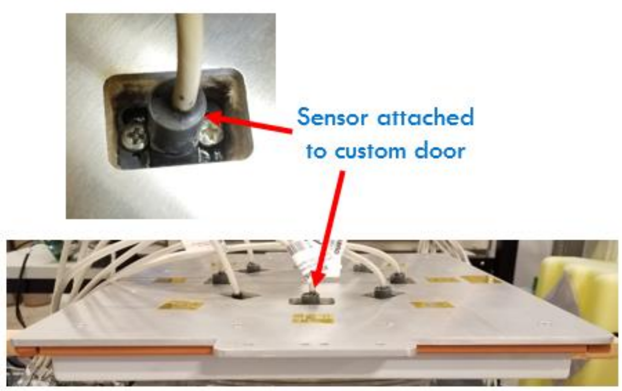


Figure 29: Sensor B TC Custom Door

The samples were continuously powered per the requirements in Section 2.9.2 and continuously monitored for input power (voltage and current) and signal output voltage (U_{sen1} and U_{sen2}) via the datalogger and computer. A separate break-out board with 5 ohm sense resistors was used for these measurements, allowing determination of the input current by measuring the voltage drop across the known 5 ohm resistance (Figure 30). The power consumed by the heater element and its resistance could then be calculated from the current and voltage measured across it (Power = Current x V_{heater}, and Resistance = V_{heater} / Current). Braided sheath and aluminum foil tape was wrapped around the cable from the breakout board up to where each sensor cable wire separates out to the individual sensor (to mitigate any potential interference on the low voltage signal output). The wiring diagram for this setup is shown in APPENDIX B: Sensor B TC and THB Wiring Diagram.

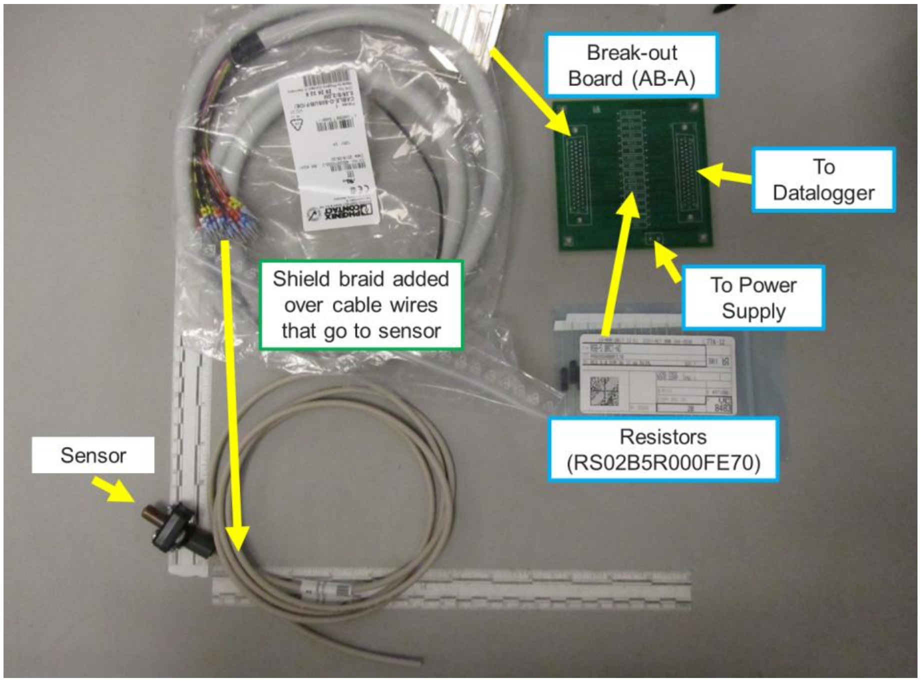


Figure 30: Sensor B TC Break-out Board for Monitoring

Preliminary testing in setup indicated that power consumption at high temperature is very similar to that at room temperature. However, at lower temperatures, resistance of the heater decreases and therefore power consumption increases (by 1/R, where R is the resistance). This increase was found to be about 0.15 to 0.20 W at -20°C. To account for this increase at cold temperature, the power consumption was set closer to 2.8 W at room temperature.

3.1.3 Sensor C TC Setup

The 48 Sensor C units were placed into a custom door that was fitted to a large Sun Systems thermal chamber (EC16HA, 6.16 cu-ft) for exposure testing (Figure 31). The custom door allowed for only the sensing portion of the device to be exposed to the chamber environmental conditions. The sensors as-received were around 30 mV output with a span of about 5 mV variation. Prior to testing, all 48 sensors were zeroed within ±0.5 mV using the adjustment screw within the PCB container (refer to Figure 10). Zeroing would likely be done in a field installation, and also facilitated identifying variation from the baseline checks during testing.

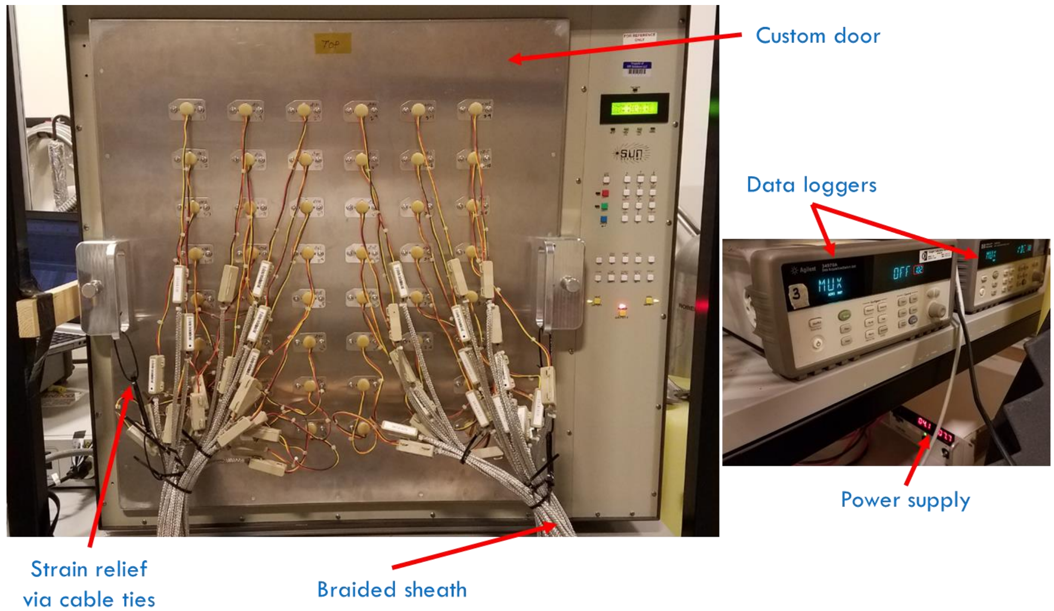


Figure 31: Sensor C TC Setup

The chamber was started in the hot cycle and set to -29.5°C and 260°C to achieve the temperature conditions in Section 2.7.3 based on the thermal profile of the chamber (Figure 32).

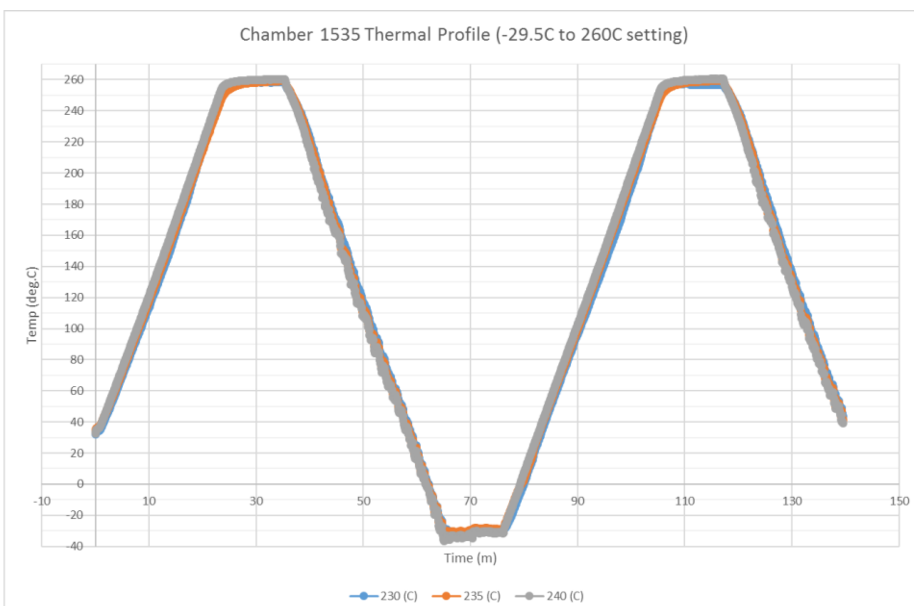


Figure 32: Sensor C TC Chamber Thermal Profile

The custom door was made of aluminum and stainless steel sheet metal that encased an alumina ceramic insulator (Figure 33). The sensors were mounted to the aluminum sheet and protruded through the insulator, which helped maintain the thermal conditions inside the chamber. An ultra high-temperature rope flange seal served to close the gap with the front surface of the chamber.

Due to the high temperature reached inside, the thermal chamber was vented via the exhaust port under slight suction.

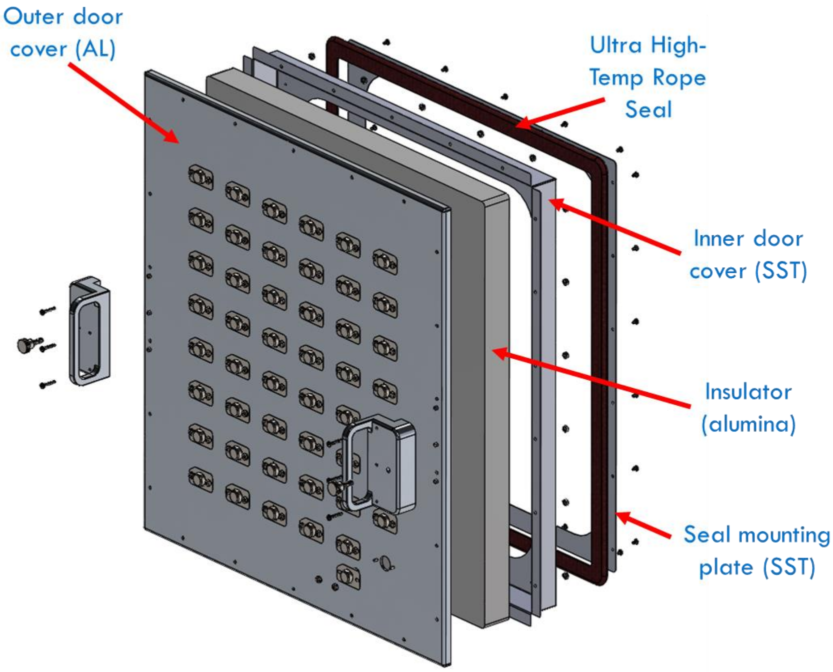


Figure 33: Sensor C TC Custom Door

The samples were continuously powered per the requirements in Section 2.9.3 and continuously monitored for input power (voltage and current) and signal output voltage via the datalogger and computer. A separate break-out board with 10 ohm sense resistors was used for these measurements, allowing determination of the input current by measuring the voltage drop across the known 10 ohm resistance (Figure 34). The wiring diagram for this setup is shown in APPENDIX C: Sensor C TC and THB Wiring Diagram.

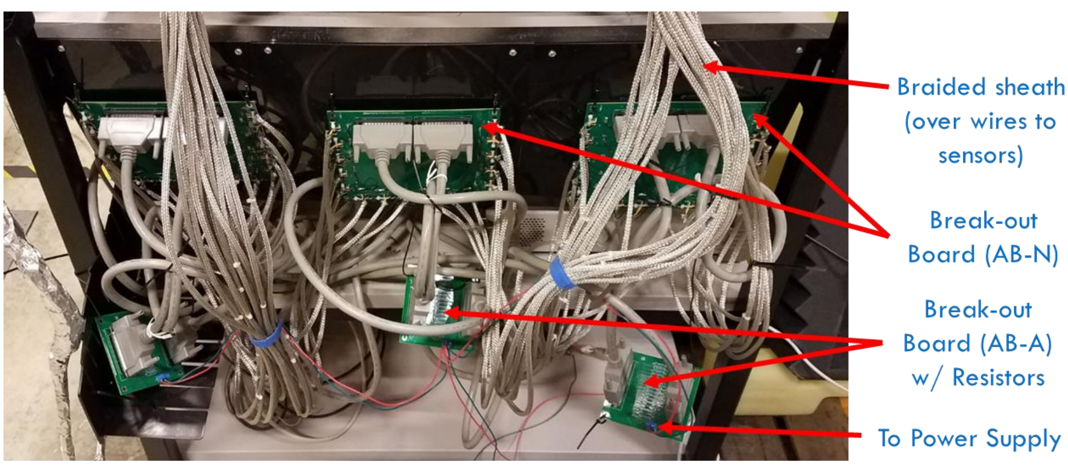


Figure 34: Sensor C TC Break-out Boards for Monitoring

3.2 THB Setup

Similar to temperature cycling testing, the Sensor A units were placed completely inside the environmental chamber. The Sensor B and Sensor C units were also placed completely inside the autoclave, with some modifications to Sensor B for connections to the back half. For Sensor B and Sensor C units, testing was conducted with the use of a single autoclave (testing to the same temperature and humidity conditions for both).

3.2.1 Sensor A THB Setup

Sensor A units were placed in an ESPEC thermal humidity chamber (EPL-3H, 14 cu-ft) for exposure testing. This chamber has the ability to achieve 98% RH up to 85C. As in TC, the 48 sensors were connected in series in 12 groups of 4 via high-temperature silicone tubing (3/32" ID (same as stock) and 1/16" wall) connected to the inlet and outlet ports of each sensor.

Samples were suspended from a rack within the chamber using cable ties, keeping adequate space in between for proper air circulation and temperature/humidity distribution within the chamber (Figure 35). To prevent condensation from forming on the sensors, the chamber was programmed to ramp up temperature first to allow sensors to come to equilibrium with chamber air temperature (in about 1 hour), and then ramp up the humidity to the prescribed conditions in Section 2.8.2 (in about 2 hours). Similarly, the humidity was ramped down prior to lowering temperature when returning back to room temperature conditions for periodic gas sensitivity checks made in-situ.

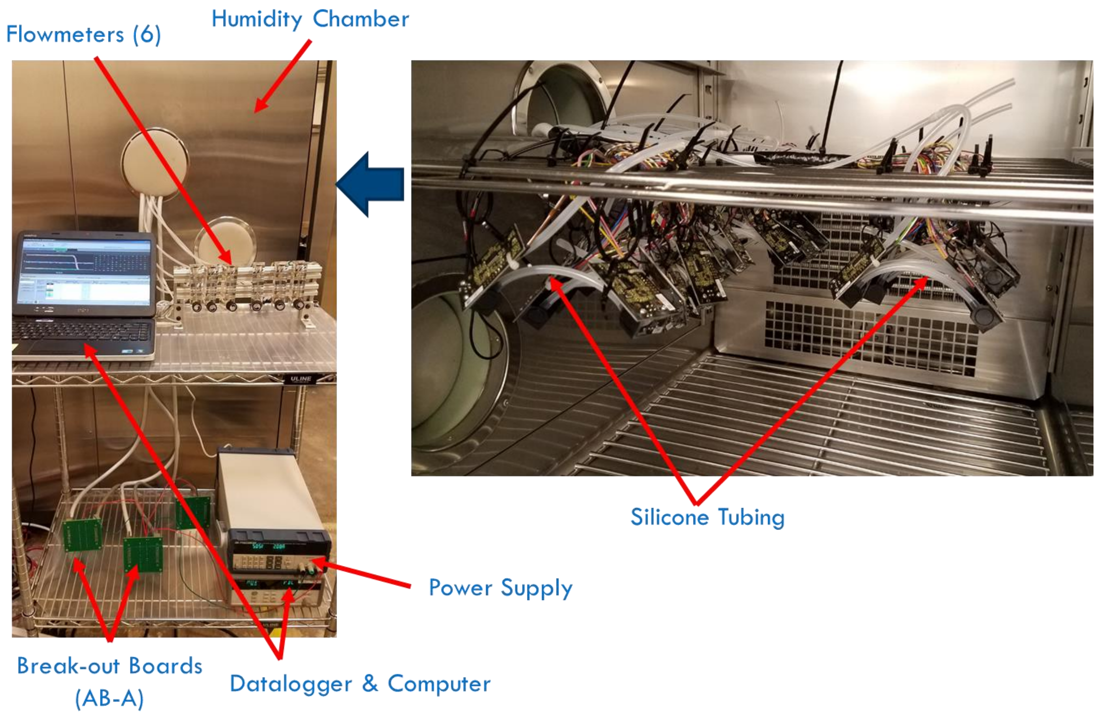


Figure 35: Sensor A THB Setup

The samples were continuously powered per the requirements in Section 2.9.1 and continuously monitored for input power (voltage and current) and signal output voltage via the datalogger and computer. Separate break-out boards with 0.5 ohm sense resistors were used for these measurements, allowing determination of the input current by measuring the voltage drop across the known 10 ohm resistance. The wiring diagram for this setup is shown in APPENDIX A: Sensor A TC and THB wiring diagram.

3.2.2 Sensor B and Sensor C THB Setup

The 8 Sensor B units and 20 Sensor C units were placed in an ESPEC HAST System chamber (EHS-221M, 1.6 cu-ft) for exposure testing (Figure 36). This chamber has the ability to achieve 75% to 100% RH relative humidity at temperatures of 105.0°C to 142.9°C (in unsaturated control mode). Integrated into the chamber are shelves which stowed the AC and DC power supplies, dataloggers, and break-out boards. Due to the heat load generated within this cabinet area, a fan was positioned for forced air cooling across the powered equipment.

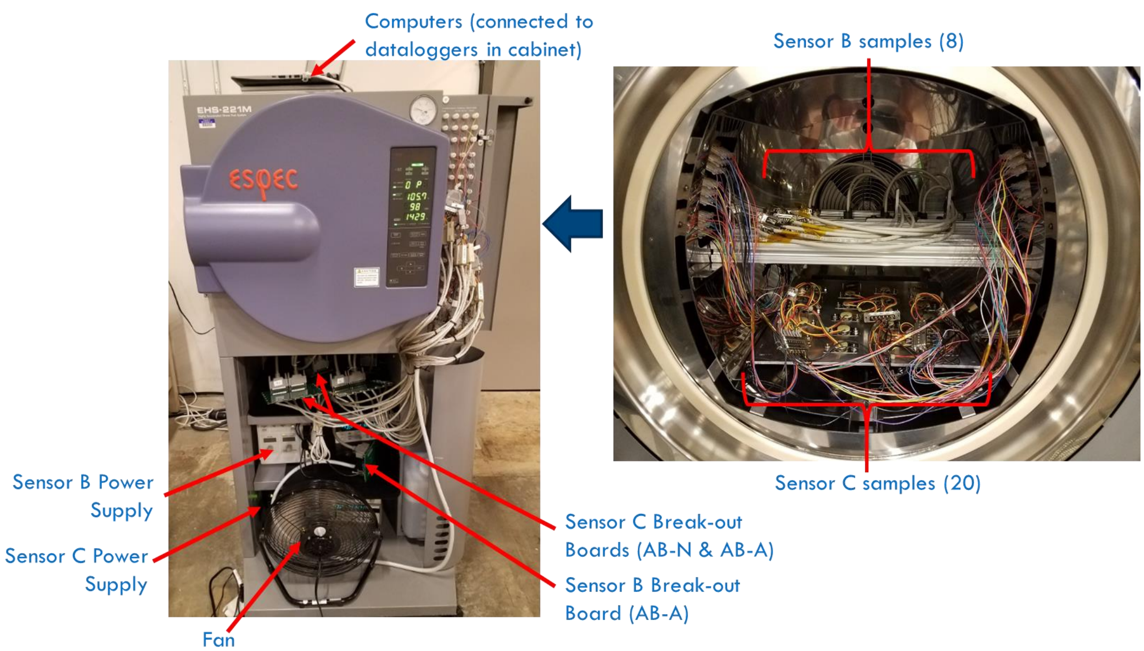


Figure 36: Sensor B & Sensor C THB Setup

The autoclave chamber was configured to the maximum number of input/output pin terminals (72 qty.) in the wall of the chamber for interconnecting to power and monitoring electronics during testing (Figure 37). Each pin was limited to about 1 A current. The number of Sensor B and Sensor C samples tested together reached the limit of the chamber's capability given both the number of pin terminals availble and the electrical current constraint.

Figure 37: ESPEC Autoclave Signal Terminals

The Sensor C units as-received were around 30 mV. Prior to testing, all 20 of these sensors were zeroed within ±0.5 mV using the adjustment screw within the PCB container (refer to Figure 10). Zeroing would likely be done in a field installation, and also facilitated identifying variation from the baseline checks during testing.

The autoclave was operated in the unsaturated control mode to the prescribed temperature and humidity conditions in Section 2.8.3. It automatically ramped up temperature, pressure, and humidity to control to the setpoints and prevent condensing conditions. Drip loops were established within the chamber from the signal terminals inside to mitigate any condensation on sensors (Figure 38). The chamber was set to 105.7°C to achieve 98% RH in the OFF-cycle condition, and 133.6°C to achieve 98% RH in the ON-cycle condition.

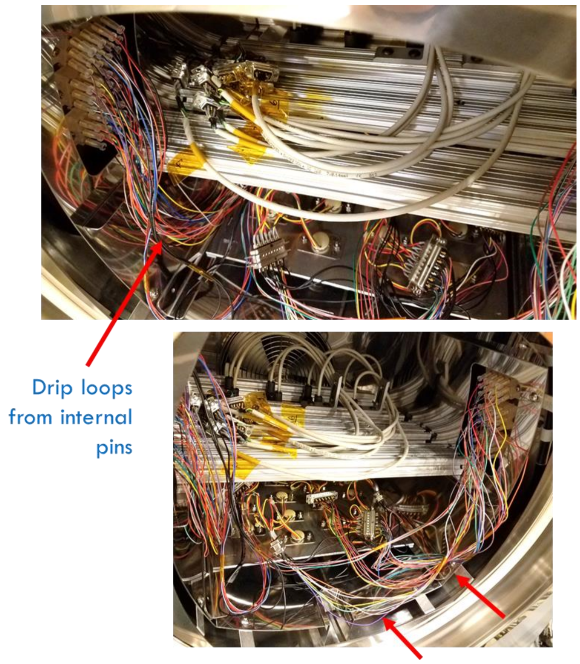


Figure 38: Drip Loops within Autoclave

3.2.2.1 Sensor B THB Mounting Plate and Connections

A custom mounting plate, made of aluminum sheet metal, served to fixture the 8 Sensor B units and provide strain relief on the cables to place them securely on the upper shelf brackets within the autoclave (Figure 39). Standard 1” T-slotted extruded rails served as the supports that spanned across the brackets. The samples were positioned vertically to minimize any chance of moisture condensing on the surrounding fixture and collecting inside the sensing element. Nylon cable ties used on aluminum brackets, while rated to only 82.2°C, have been used successfully in high humidity test applications if not flexed in use. Their heat defection temperature and melt temperature, based on common Nylon 66, are well above the maximum test temperature used in the autoclave.

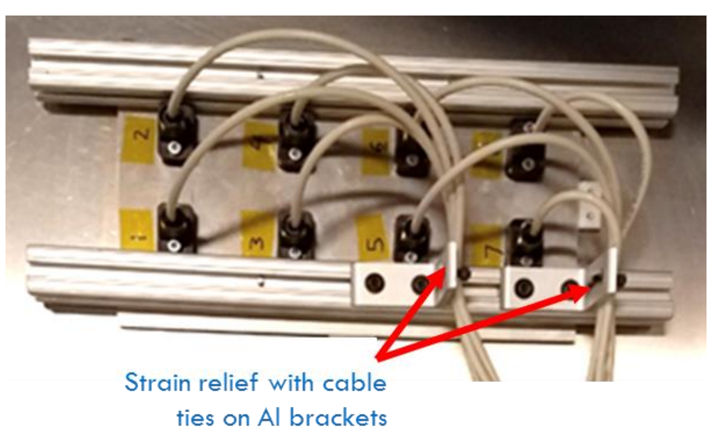


Figure 39: Sensor B THB Mounting Plate

Dsub9 connectors (male and female) were used to connect from the ends of the Sensor B cables to the wires connected to the pin terminals within the autoclave. Initial connectors used were 8 micro-inch (0.20 micron) gold plated. This gold plating minimizes corrosion of contacts in connectors with limited usage. These were later replaced with 30 micro-inch (0.76 micron) gold plated Dsub9 connectors for improved robustness in the harsh temperature and humidity environment within the autoclave (discussed in the test results of Section 4.2.2).

The samples were continuously powered per the requirements in Section 2.9.2 and continuously monitored for input power (voltage and current) and signal output voltage (U_{sen1} and U_{sen2}) via the datalogger and computer. A separate break-out board with 5 ohm sense resistors was used for these measurements, allowing determination of the input current by measuring the voltage drop across the known 5 ohm resistance. The power consumed by the heater element and its resistance could then be calculated from the current and voltage measured across it (Power = Current x V_{heater}, and Resistance = V_{heater} / Current). The wiring diagram for this setup is shown in APPENDIX B: Sensor B TC and THB Wiring Diagram.

3.2.2.2 Sensor B THB Cable Replacement

Initial concern existed over the use of the cables on the back half of the sensor in the autoclave. From the design evaluation, they were rated only to 80°C, with a worst case temperature of 100°C. Preliminary testing of a section of the cable at elevated temperatures and un-powered for one week showed promise with no real physical change or shorting of the wired bundle. However, at the second gas sensitivity check following the initial baseline check on the 8 sensors, the back half of the sensor showed signs of softening and displacement. They had been exposed to the OFF-cycle THB test conditions for 12 days. The wire and wire insulation had deteriorated, and were brittle and frayed easily with handling (Figure 40).

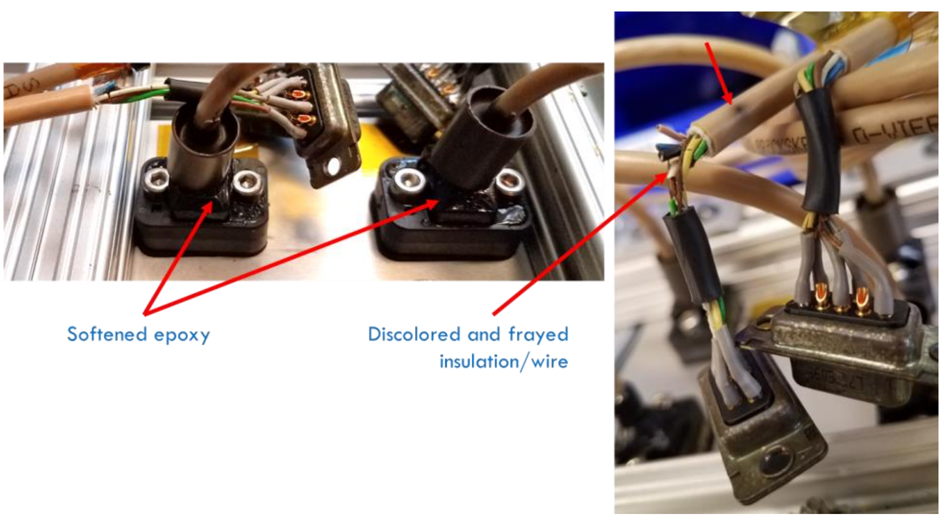


Figure 40: Sensor B THB Cable Deterioration

To prevent further deterioration and loss of power and signal lines, the stock Sensor B cables and their connection to the back half of the sensor were replaced with high-temperature silicone ribbon cable wire. Only one of the eight sensors was the previous style with no barrel and epoxy applied by the manufacture to strengthen the connection. That sensor and the remaining 7 sensors all had the black plastic and epoxy physically removed (Figure 41). Flux-Remover (Puretronics) was sprayed on back half, brushed as needed, rinsed with alcohol, and followed by N2 and/or canned compressed gas, followed by overnight air dry. During the cleaning process, the units were held upright as best as possible to help prevent, with the aid of gravity, liquid ingress towards the sensor element.

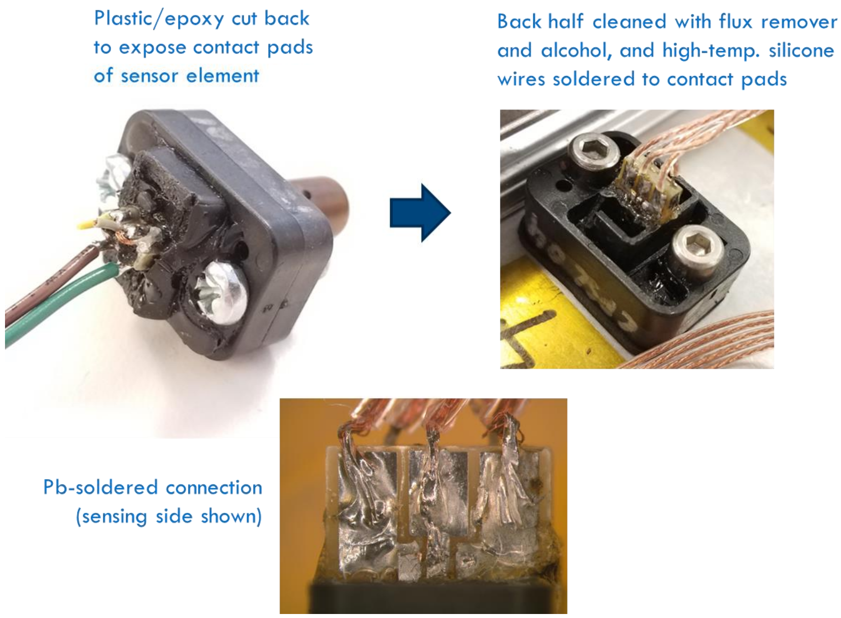


Figure 41: Sensor B THB Cable Replaced with Silicone Cable

Resistance measurements of the heater element, unpowered at room temperature, were taken at the Dsub9 connector at the end of the original Sensor B cable, and then at the same connection at the end of the silicone cable after re-work (Table 19). Only a slight decrease in resistance (3%) was observed, likely due to the decreased length.

Table 19: Sensor B THB Heater Element Resistance after Cable Replacement

Sensor	Original Setup: Heater Resistance (Ohm)	New Setup with Silicone Cable: Heater Resistance (Ohm)	Delta (Ohm (%))
1	10	9.7	0.3 (3%)
2	10.3	10.0	0.3 (3%)
3	10.1	9.8	0.3 (3%)
4	10.2	9.8	0.4 (4%)
5	10.1	9.8	0.3 (3%)
6	10.2	9.8	0.4 (4%)
7	9.3	9.0	0.3 (3%)
8	9.5	9.2	0.3 (3%)
Avg.:	9.96	9.64	0.32 (3%)

An aluminum "L" bracket was also added to the mounting panel to fixture the Dsub9 connectors (Figure 42). This helped minimize the strain on the silicone cables when connecting and disconnecting for periodic gas sensitivity checks.

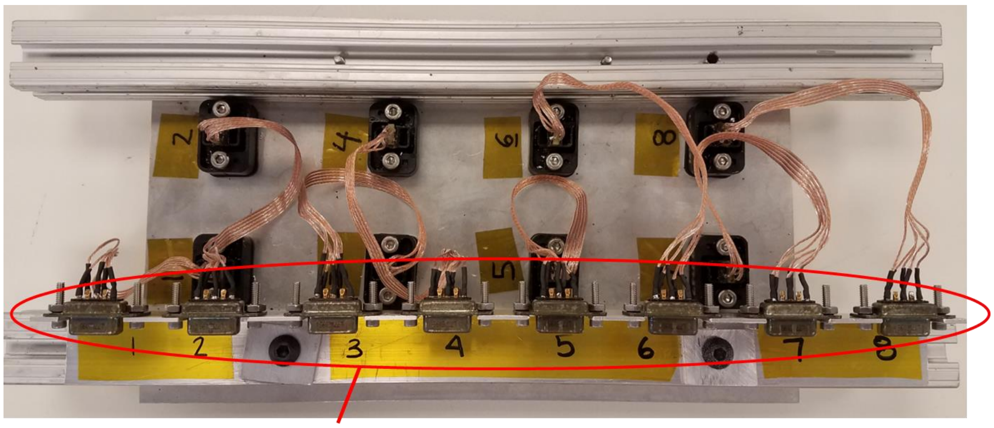


Figure 42: Sensor B THB Updated Mounting Plate and Cables

3.2.2.3 Sensor C THB Mounting Plate and Connections

A custom mounting plate, made of aluminum sheet metal, served to fixture the 20 Sensor C units (Figure 43). The samples were positioned vertically to minimize any chance of moisture condensing on the surrounding fixture and collecting inside the sensing element.

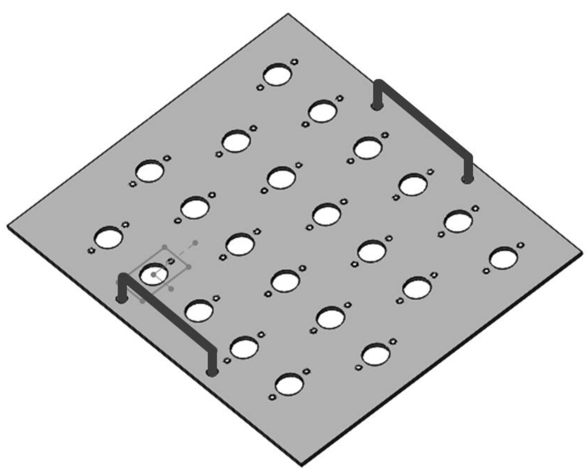


Figure 43: Nemto THB Mounting Plate

The wires from the sensor to the PCB container were cut and soldered to the backs of Dsub25 socket connectors (Figure 44). These sockets connected to Dsub25 plugs wired to the pin terminals inside the autoclave. Initial connectors used were 8 micro-inch (0.20 micron) gold plated. This gold plating minimizes corrosion of contacts in connectors with limited usage. These were later replaced with 30 micro-inch (0.76 micron) gold plated Dsub9 connectors (as was done for the Sensor B THB samples) for improved robustness in the harsh temperature and humidity environment within the autoclave. These were later replaced again with an Amphenol Aerospace MIL-DTL-38999 high temperature connector (discussed in the test results of Section 0).

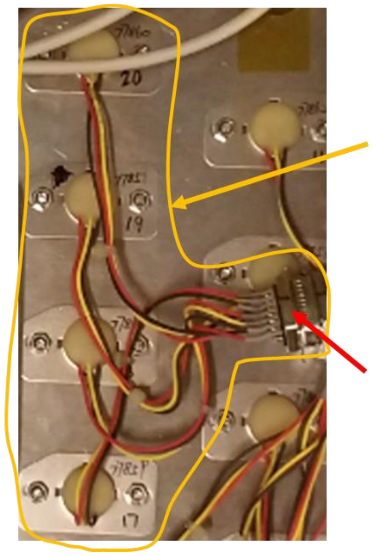


Figure 44: Sensor C THB Sensor Connections

The samples were continuously powered per the requirements in Section 2.9.3 and continuously monitored for input power (voltage and current) and signal output voltage via the datalogger and computer. Separate break-out boards with 10 ohm sense resistors were used for these measurements, allowing determination of the input current by measuring the voltage drop across the known 10 ohm resistance. The wiring diagram for this setup is shown in APPENDIX C: Sensor C TC and THB Wiring Diagram.

3.3 Gas Sensitivity Testing Setup

3.3.1 Sensor A TC and THB Gas Sensitivity Setup

For both TC and THB testing, the environmental chambers were brought to room temperature conditions prior to gas sensitivity testing. For THB testing, the chamber was ramped up and ramped down from test conditions in a manner to reduce chances of condensation (raising temperature first to help acclimate units prior to raising humidity, and lowering humidity first prior to reducing temperature). Ramp up time was 3 hours, and ramp down time after each exposure period between gas sensitivity checks was 2 hours.

Once at room temperature conditions, the sensors were retained there for a minimum of 25 hours before gas sensitivity measurements were made in-situ with tubing through the access port of the environmental chamber (reference Figure 24 and Figure 35 for TC and THB setups, respectively). This allowed for self-calibration to surrounding room temperature conditions under which the devices were tested. The sensors' warm-up time to be operational is within 2 minutes, but since they were continuously powered as they acclimated to room temperature conditions and later tested, no additional warm-up time was needed. After an initial 5 minutes exposure to air, the sensors were exposed to gas flow at each concentration for 10 minutes (reasonably minimal time for stabilized measurements) with 0.2 LPM flowrate (within the 0.25 LPM maximum allowed). A nitrogen purge of 0.2 LPM for 2 minutes was used in between each gas concentration exposure to purge out residual gas in the silicone tubes from the previous tank (going from Tank 2 (T2) to Tank 3 (T3) on a group of 4 daisy-chained sensors, for instance). Sufficient time of greater than 20 minutes in air was used to allow the residual gas to dissipate in the absence of a nitrogen purge (going from Tank 3 (T3) to Tank 4 (T4) on the same group of 4 daisy-chained sensors, for instance).

Figure 45 shows a summary of the general test sequence. The inlet gas from a single flowmeter was connected to a first set of 4 daisy-chained sensors, and then was manually switched over (within the chamber) to the inlet of the second set of 4 daisy-chained sensors. This was an efficient method to test all 8 sensors in TC testing (using one flowmeter) or all 48 sensors in THB testing (using 6 flowmeters) for each of the 5 test gas concentrations (reference Table 16).

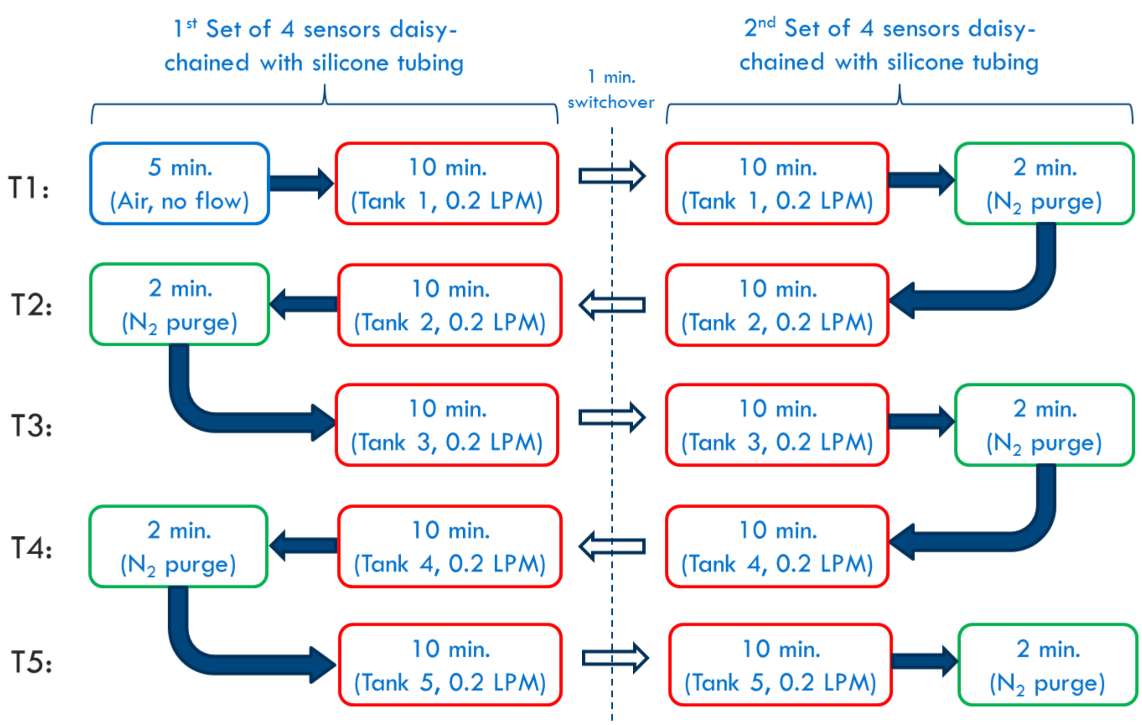


Figure 45: Sensor A Gas Sensitivity Test Sequence

3.3.2 Sensor B TC Gas Sensitivity Setup

The heating element on the 8 Sensor B units was powered to maintain proper operating temperatures at all times for TC testing. Because the sensors remained attached to the custom door, they could be left powered on when the door was transferred to the gas sensitivity vessel for gas sensitivity testing (Figure 46). The vessel was an approximately 0.15 cu-ft volume plastic container with a smooth flat top to seal against the inside of the custom door, encompassing the 8 sensors. This was not an air-tight seal, as the incoming gas needed to displace the existing air in the vessel. The door was positioned with sensor no. 2 closest to the inlet.

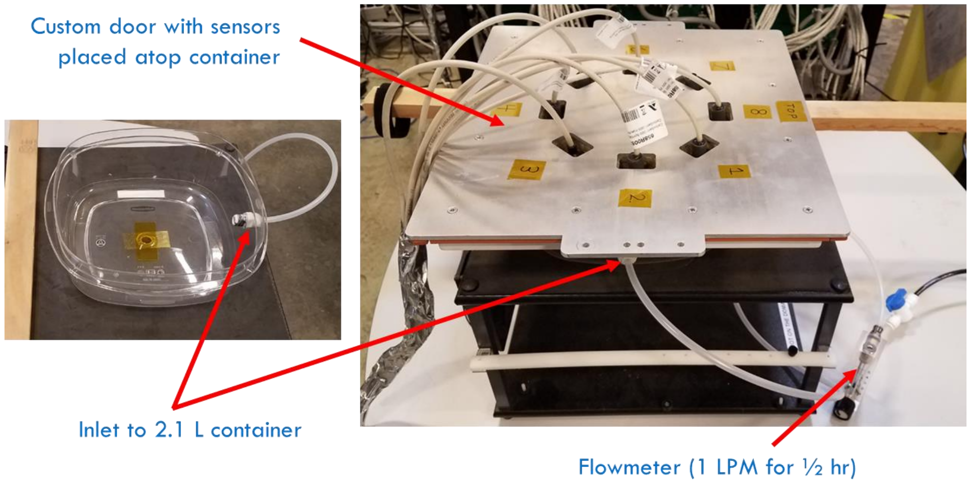


Figure 46: Sensor B TC Gas Sensitivity Setup

Figure 47 shows a summary of the test sequence. The test gas was applied for 30 minutes, allowing for stabilized signal output from the sensors within a reasonable time period. For purging the vessel in between switching to a different tank concentration, the custom door was lifted off of the vessel and set aside for 5 minutes to let the gas dissipate from the container and sensors.

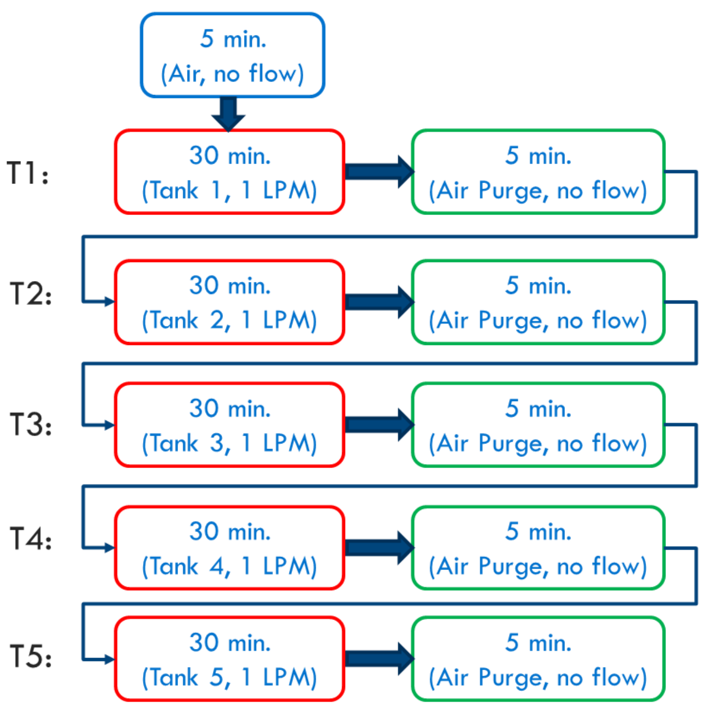


Figure 47: Sensor B TC Gas Sensitivity Test Sequence

3.3.3 Sensor C TC Gas Sensitivity Setup

Similar to Sensor B TC setup, the 48 Sensor C units remained attached to the custom door and powered when transferring from exposure testing in the chamber to gas sensitivity testing. The door was laid down, supported on opposite ends, with the sensor elements facing upwards. The ultra high-temperature rope flange seal and the seal mounting plate were removed from the custom door to accommodate a separate seal during gas sensitivity testing. An acrylic plastic sheet with a closed-cell EPDM ultra-soft adhesive-backed strip aligned along the perimeter was placed over the inside of the door. Standard 1” rail extrusions and plastic vice clamps were used to clamp along the perimeter to affect a seal while administering the test gases (Figure 48).

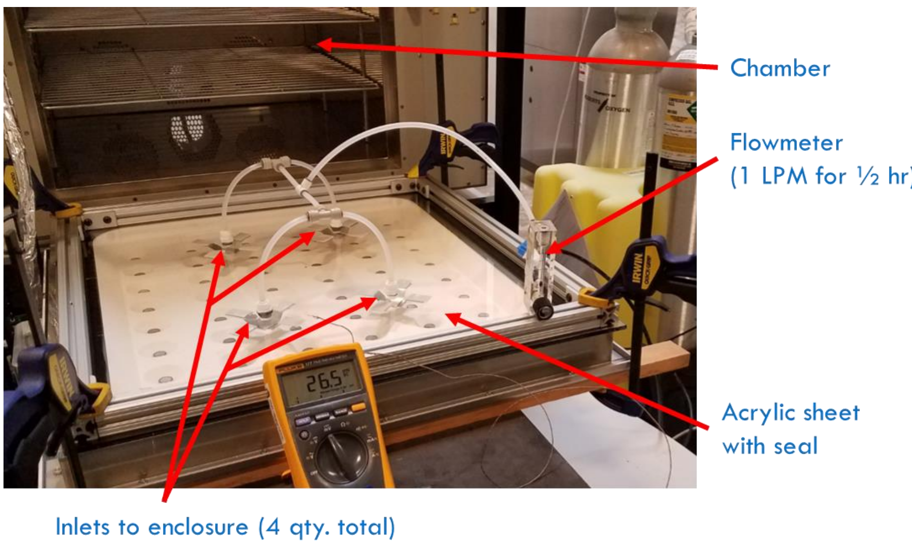


Figure 48: Sensor C TC Gas Sensitivity Setup

The gas lines were run in a symmetric “H” pattern feeding through the acrylic sheet into the enclosure. Custom diffusers were placed at each inlet in order to prevent direct impingement of the gases on the closest sensors, and allow for better distribution within the enclosure (Figure 49).

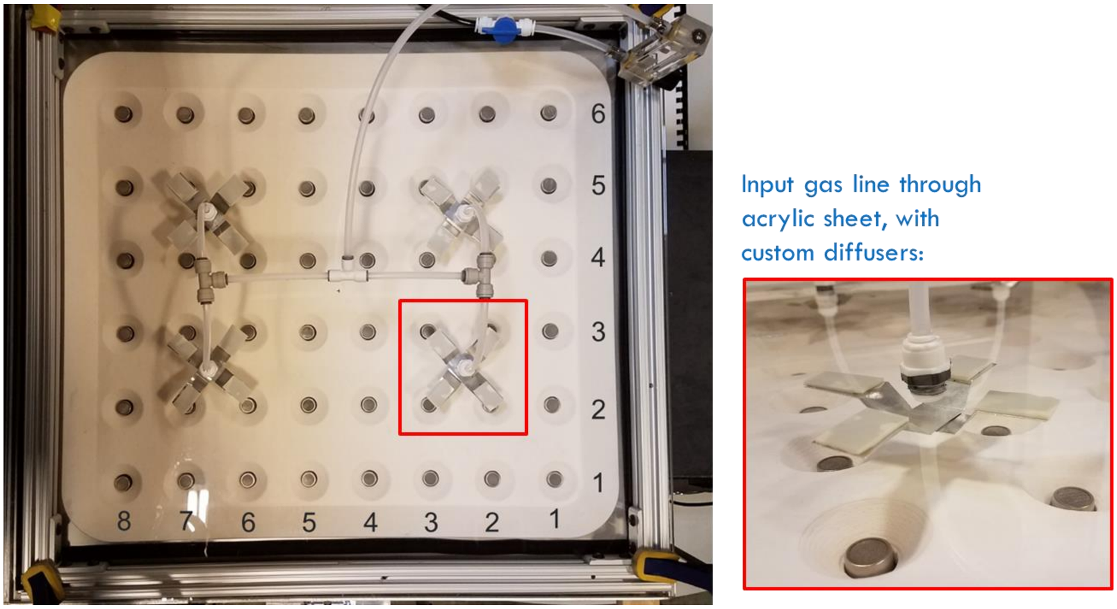


Figure 49: Sensor C TC Gas Sensitivity Enclosure

Pre-testing was performed on the enclosure, and a fairly even distribution of the gas concentration was observed after a 20 minute exposure to 1 LPM gas flow (Figure 50).

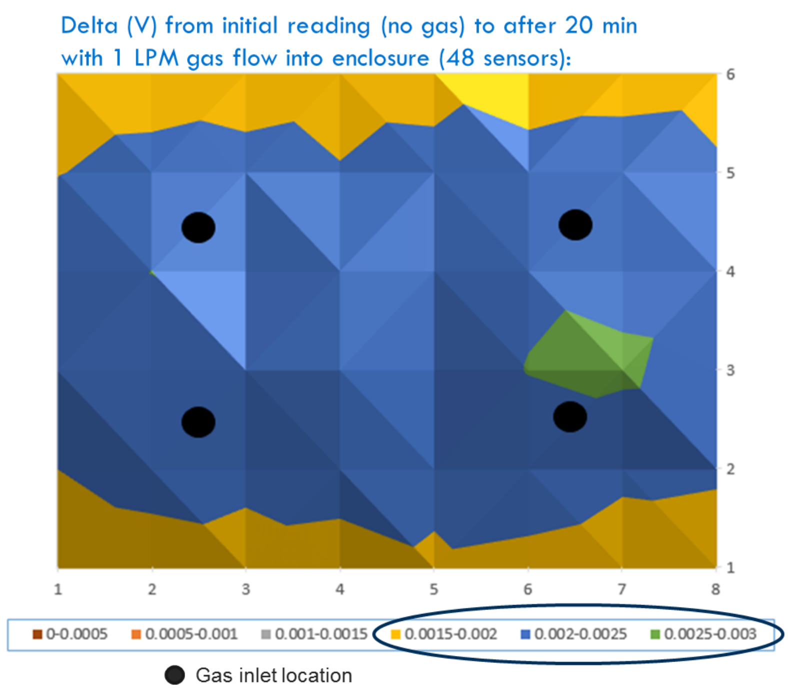


Figure 50: Sensor C TC Gas Concentration Distribution

The test gas was applied for 30 minutes at 1 LPM total, allowing for stabilized signal output from the sensors within a reasonable time period. For purging the enclosure in between switching to a different tank concentration, the custom acrylic sheet was lifted off of the door and set aside for 5 minutes to let the gas dissipate from the sensors. The test sequence was the same as that used for Sensor B TC gas sensitivity tests (Figure 47).

3.3.4 Sensor B and Sensor C THB

For Sensor B and Sensor C THB gas sensitivity testing, power was turned off to remove the sensors from the autoclave. The sockets and plugs inside were disconnected, sensor mounting plates removed from the autoclave with sensors attached, and then connected to mating plugs on the outside (which were connected to the power supplies and data loggers). For the Sensor B units, power was turned back on slowly to bring the heater element to 2.8-3 W (reference Section 2.9.2). These sensors are operational within 60 seconds, but could need 2-3 more minutes for most stable results per the manufacturer. The Sensor B units were exposed to gas concentrations after the proper heater element power was achieved and, like the Sensor C units, after 5 minutes of being exposed to air. The Sensor C units are indicated to stabilize about zero within acceptable limits within 2 minutes normally (even after a long storage period).

A custom gas sensitivity box was made from acrylic sheets (Figure 51). Additional sheets were added along the sides to seal unused volume (using Latex acrylic caulk instead of silicone due to the sensitivity of the Sensor C units to silicone outgassing). Gas flow entered through 4 ports on one side. An aluminum adapter plate with flange closed the top of the box, with the sensor mounting panels resting atop that panel. A closed-cell EPDM ultra-soft adhesive-backed strip was aligned along the top perimeter of the box to affect a seal. The enclosed volume was about 0.34 cu-ft.

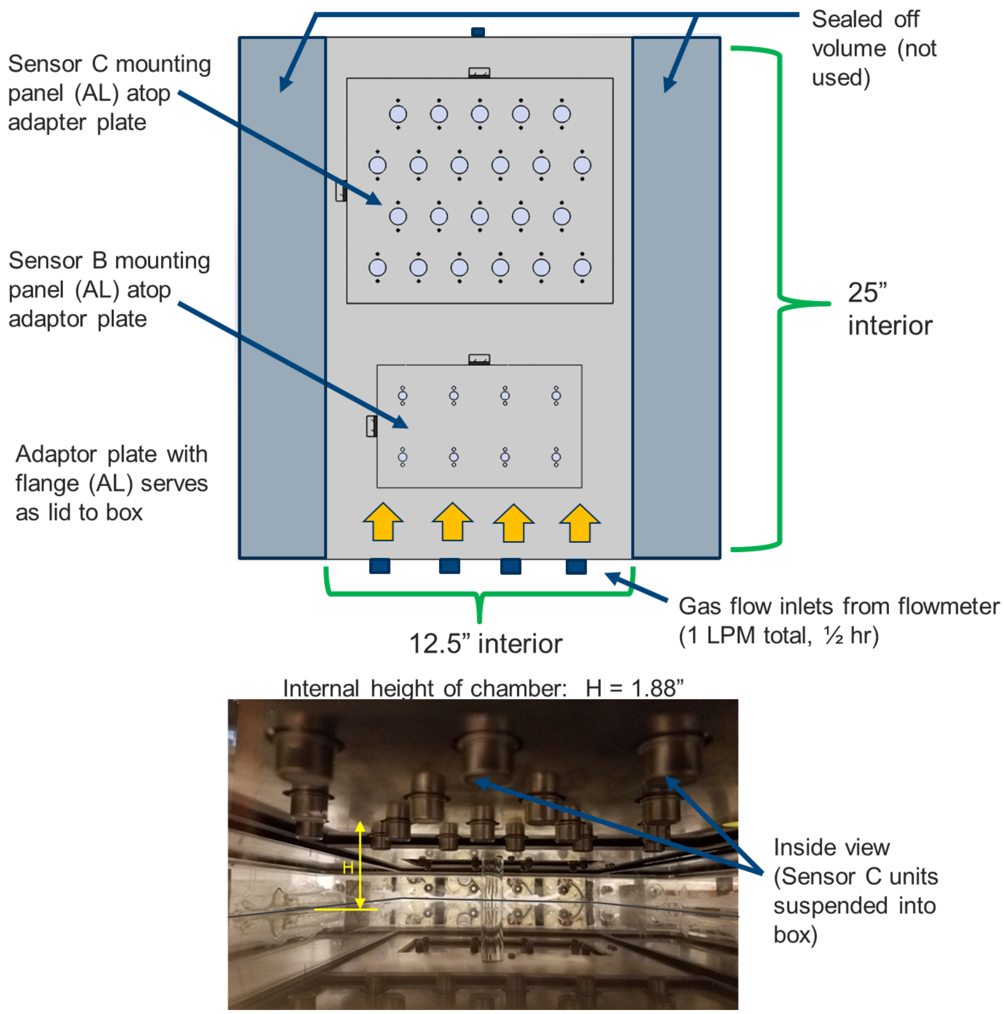


Figure 51: Sensor B and Sensor C Gas Sensitivity Box

The test gas was applied for 30 minutes at 1 LPM total, allowing for reasonably stabilized signal output without extending the test time or gas consumption to unreasonable levels. For purging the enclosure in between switching to a different tank concentration, the adapter plate was lifted up on one end and fans placed on top for forced air to dissipate the gas over a 5 minute period (Figure 52). The test sequence was the same as that used for the Sensor B TC gas sensitivity tests (Figure 47).

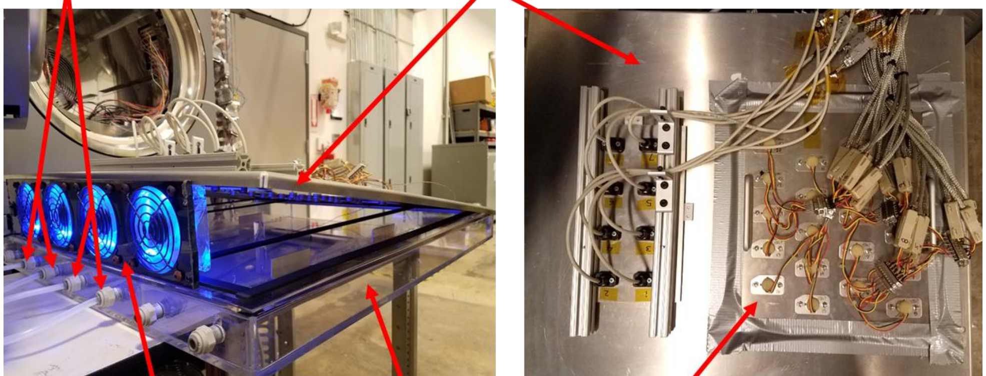


Figure 52: Sensor B & Sensor C Air Purge

3.4 Data Monitoring

DfR Solutions used Agilent 34970A data acquisition systems with the 34908A 40-channel multiplexer cards to monitor power input to the sensors and signal output while in the chambers (Figure 53). For Sensor C, the 3490A 20-channel multiplexer cards were used to monitor the differential signal output. These data acquisition systems can monitor up to 120 single ended channels with reading rates of up to 600 readings per second on a single channel, and scan rates of 250 channels per second. Data was transferred to a host PC through a GPIB (IEEE-488) interface.

Figure 53: Agilent 40 Channel Data Acquisition/Switch System for Monitoring Sensors

3.5 Equipment List

The equipment list for the temperature cycling and THB testing, for all three sensors, is found in APPENDIX D: Equipment List. This list includes the environmental chambers, power supplies, and data loggers. Also included are custom-designed break-out boards and custom-designed fixtures.

4 Test Results

Test results are presented for each sensor type with respect to the two accelerated life tests performed: temperature cycling and temperature humidity bias.

4.1 Sensor A

4.1.1 Temperature Cycling (TC) Results

A baseline gas sensitivity check (GS0) was performed with each of the five tanks (gas concentrations listed in Table 16) prior to exposure testing. All 8 sensors had progressively increased signal output ranging between about 2.5 and 4.0 V for increased tank CO_2 concentrations ranging between 8% and 12% (Figure 54). Sensor voltage output settled and became fairly stable over the initial 5-minute exposure period to each gas concentration. Subsequent gas sensitivity checks were made over 10-minute exposure periods as planned, revealing any additional response delays or other performance degradation during testing.

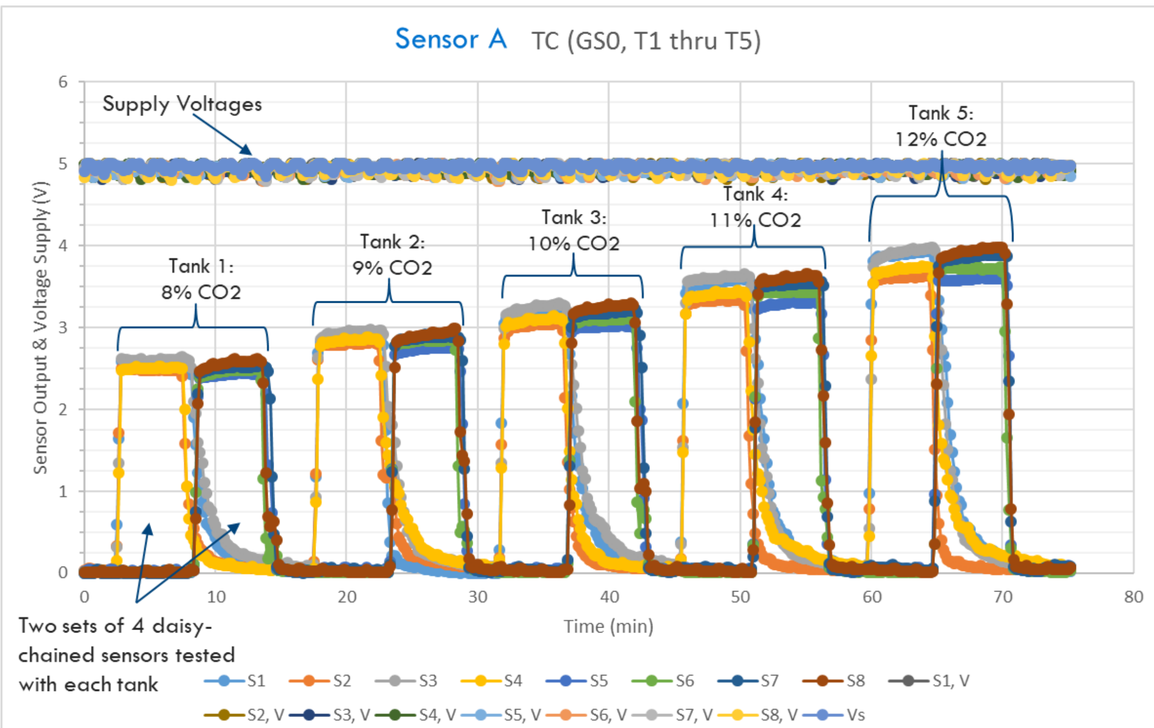


Figure 54: Sensor A TC, Baseline Check (GS0)

Supply voltages were steady and remained on average between 4.891 and 4.959 V throughout all gas sensitivity checks performed. Sensor current drawn was low throughout testing, indicating no short circuiting within the sensor. APPENDIX J: Baseline Electrical Measurements shows the baseline electrical current measurement results, consistent with subsequent results over the course of testing.

Temperature cycling exposure between gas sensitivity checks was indicated by "cycling", followed by the sequential exposure number. Some fluctuation in signal output voltage was evident during exposure to temperature cycling. The self-calibration performed every 24 hours was affected by these temperature swings. Figure 55 shows a typical sensor response throughout exposure cycles, with sensor signal output returning to baseline zero within 25 hours of being brought down to room temperature. An exception was sample S1, showing some fluctuation in output (with data sampling taken every 15 minutes). This occurred after temperature cycling was stopped at 360 cycles for a subsequent gas sensitivity check (where each gas sensitivity check was performed after 120 cycles).

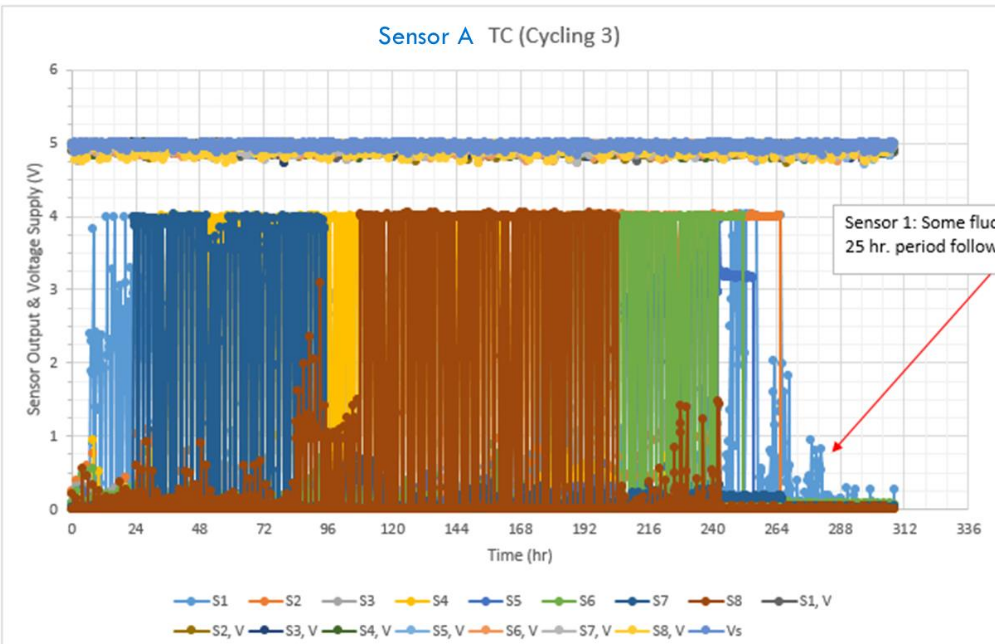


Figure 55: Sensor A TC, Sensor Output during Cycling

During gas sensitivity checks, where sampling rates were every 10 seconds, several sensors exhibited various levels of fluctuation in signal output, as well as going to a maximum 4 V output. Sample S1 exhibited this after 360 temperature cycles (Figure 56). Samle S8 also exhibited similar behavior with the subsequent gas sensitivity check 4 (GS4). Both responded to the test gas concentrations and, while obviously inaccurate from the baseline, were not considered hard failures. Some sensors would respond without fluctuation in later gas sensitivity checks (as both of these did in GS6).

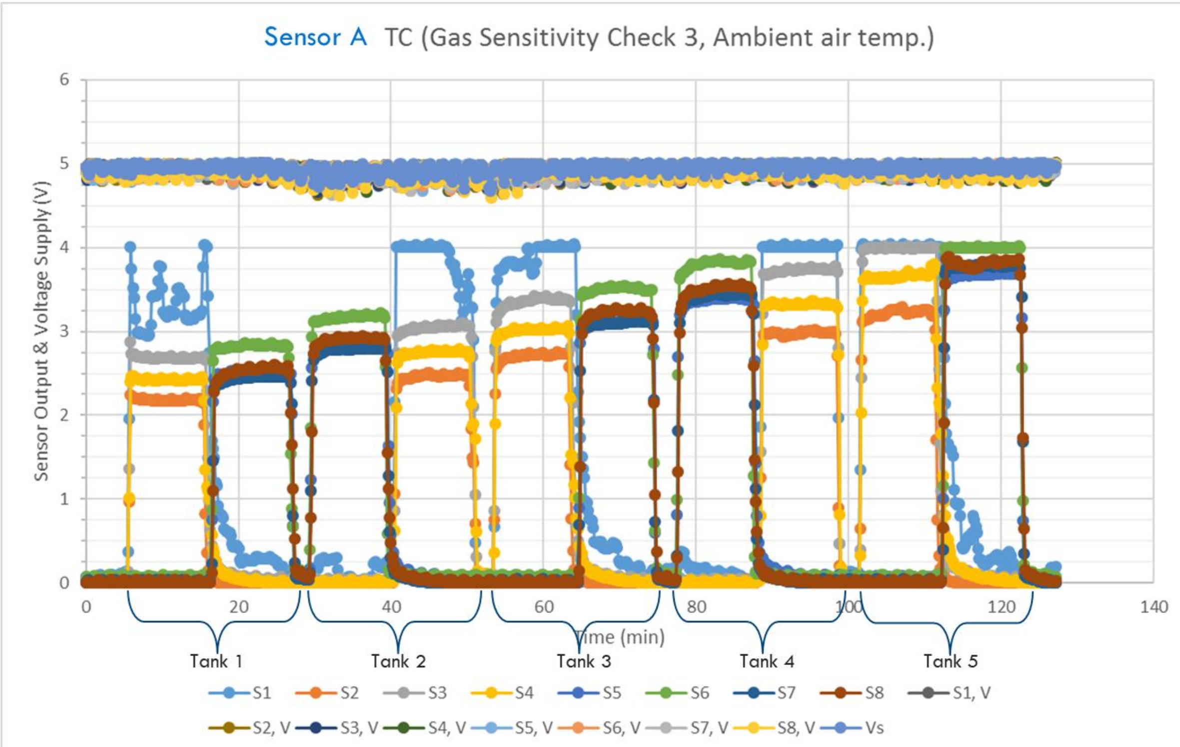


Figure 56: Sensor A TC, Fluctuation in Signal Output

A total of 2 hard failures were noted over the course of testing. These two occurred after 840 temperature cycles during gas sensitivity check 7 (GS7) (Figure 57). Sample S8 had shown signs of erratic response and high output even after 25 hours at room temperature just prior to starting GS7.

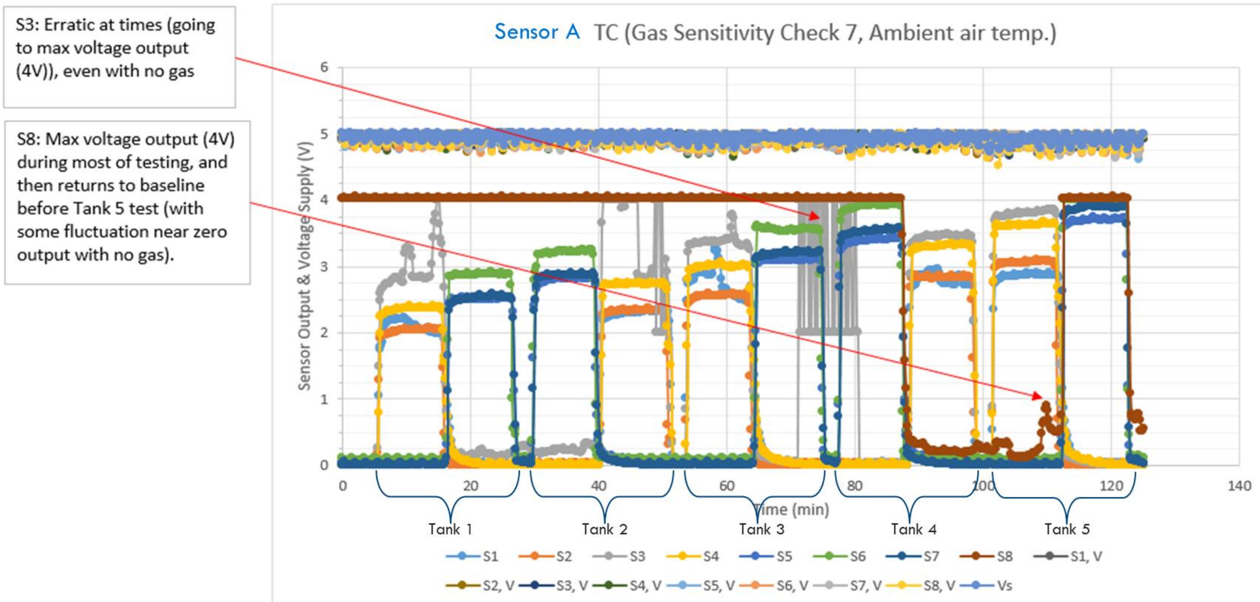


Figure 57: Sensor A TC, Response of Hard Failures

During this gas sensitivity check, sample S3 was erratic (2 V to 4 V output), even with no gas supplied. Sample S8 had a constant maximum voltage output regardless of gas being supplied, and later fluctuated with no gas. Both results are “false positives”, indicating the maximum of its intended target gas range when it should not. These units remained in testing to evaluate for any recovery, and indeed they performed better in subsequent gas sensitivity checks (at times considered a soft failure at most). They were both removed from test after experiencing fluctuating output in later gas sensitivity checks.

The remaining 6 sensors survived through the 1920 temperature cycles required to satisfy the reliability goal with 2 failures allowed. The last gas sensitivity check (GS16) showed some continued fluctuation in output and drift from the baseline results, but all responded to sensing each gas concentration (Figure 58).

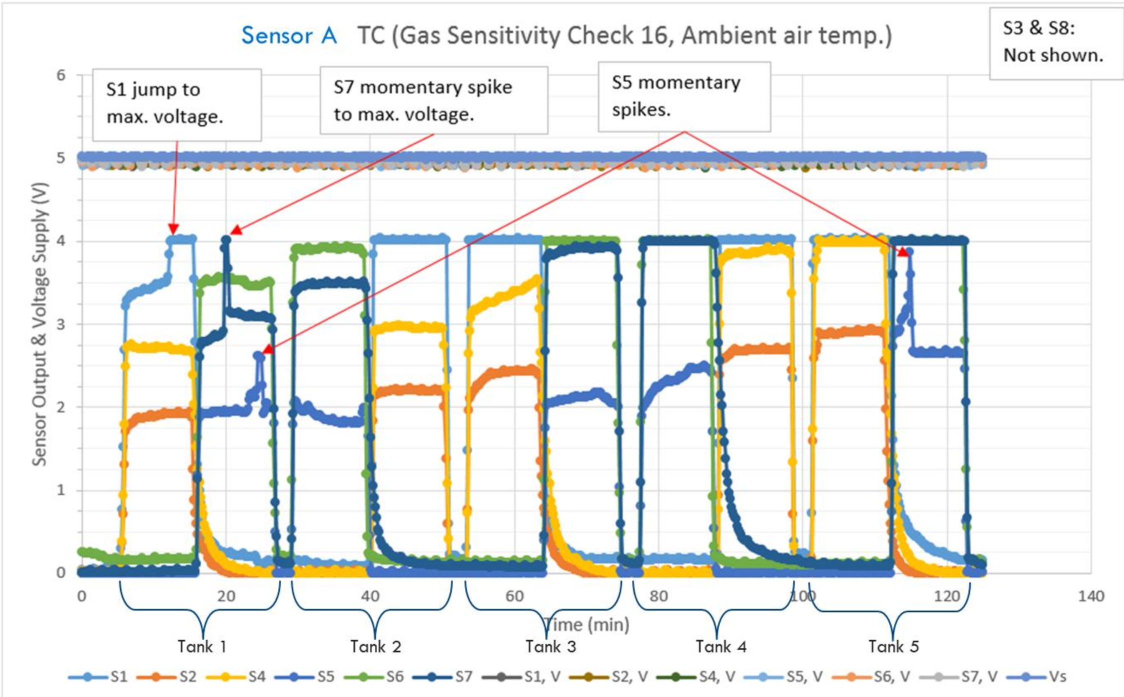


Figure 58: Sensor A TC, Final Gas Sensitivity Check

Performance results for accuracy and stability were also evaluated against the specification (reference Table 17) by using the average output voltage over the 10-minute time period that gas was administered (5 minutes for baseline). This data was averaged for each sensor during each gas concentration administered and each gas sensitivity check performed, starting when the signal output had minimal percent change from the previous measurement (sampling over 10-second intervals). The average across all the sensors being measured simultaneously was taken from this time stamp to 8 minutes later (4 minutes for baseline), covering about 80% of the gas exposure duration without including erroneous data once the gas concentration was removed.

Significant instability in output in ambient air was first noticed with sample S8 during gas sensitivity check 7 (GS7) after 840 cycles, along with sample S3 during GS11after 1320 cycles (Figure 59). As mentioned previously, both of these sensors were considered to be hard failures at these points in the test and were later removed. Sample S1 also had significant offset from zero during gas sensitivity check 14 after 1680 cycles (up to 0.6 V offset over all 5 gas concentrations), but responded to each gas concentration.

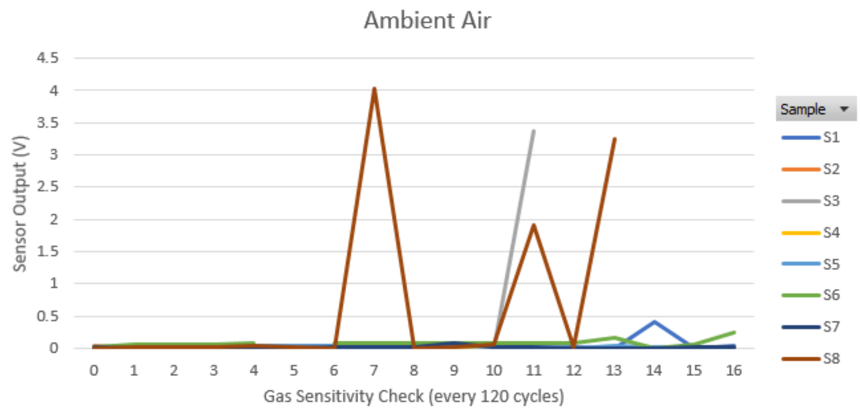


Figure 59: Sensor A TC, Sensor Output with Ambient Air over Time

In general, sensor output variation increased over time (

Figure 60). Higher gas concentrations showed less variation throughout the test due to the output reaching its upper ceiling limit of 4 V. A significant decrease in output was noticed with sample S1, S5, and S8 during gas sensitivity check 12. Two recovered later to some degree, while sample S8 was removed at the subsequent gas sensitivity check. Sample S2 drifted lower in output over time, while sample S6 drifted slightly higher (both during ambient air and gas concentration exposure). The average results for each sensor across all gas concentrations are provided in APPENDIX E: Sensor A TC, Gas Sensitivity Performance.

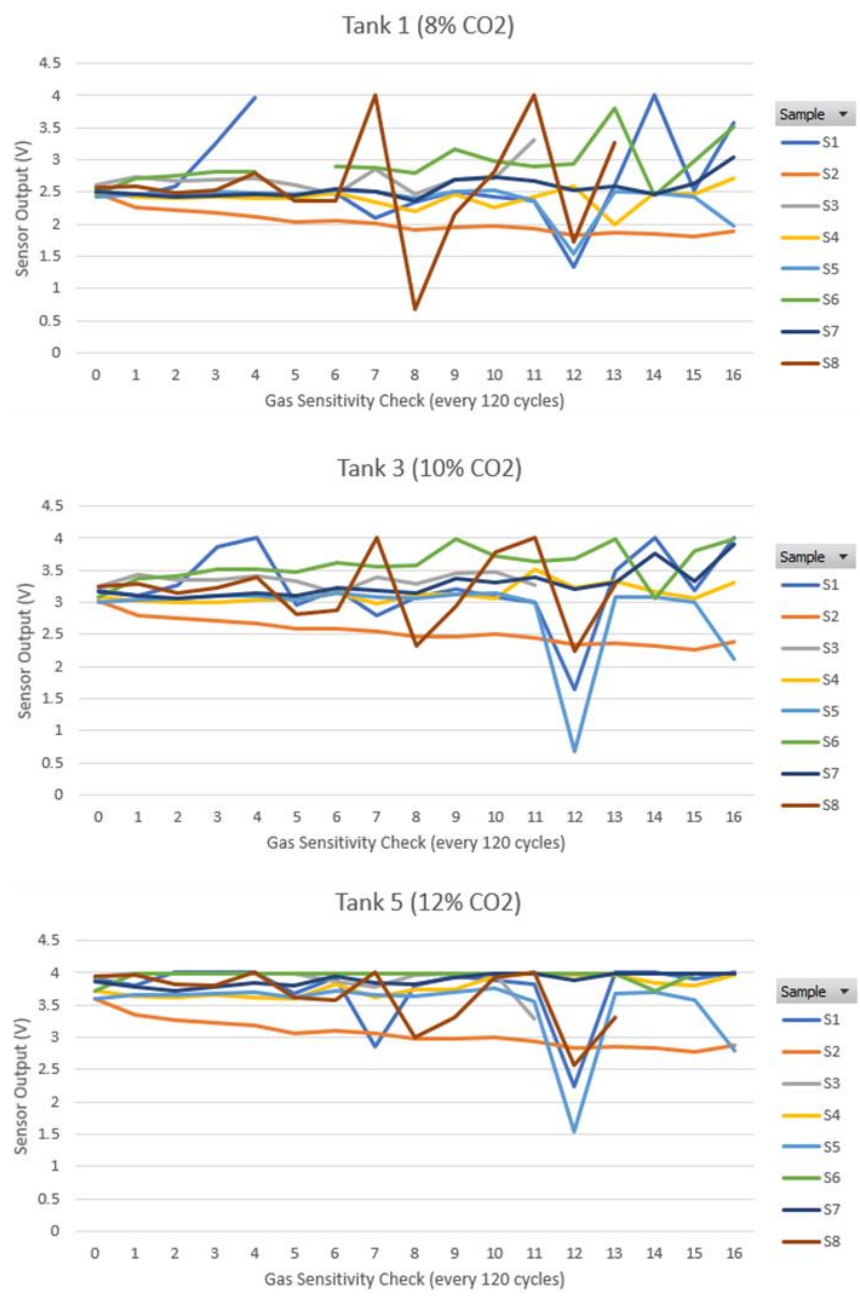


Figure 60: Sensor A TC, Sensor Output with Gas Concentrations over Time

Table 20 shows the summary of soft failures (with respect to accuracy and stability specification in Table 17) and hard failures. During gas sensitivity testing, the temperature remained within 5°C of these baseline checks. Atmospheric pressure was not recorded, but conservatively would likely not have varied by more than 1 inHg (25.4 mmHg). These worst-case temperature and pressure deviations from baseline conditions were used to allow additional tolerance in the specification, and assessments on accuracy and stability take this into consideration. The stability tolerance of

10% per year was additive each year and applied to each gas sensitivity check (representing approximately every 2 years in the field, or about 20% of the stability tolerance).

Table 20: Sensor A TC, Failure Summary (among 8 sensors tested)

GS Check	Cycles Completed	Soft Failures: Accuracy (in Gas Concentrations)	Soft Failures: Stability (in Ambient Air)	Hard Failures (first instance)
1	120	--	--	--
2	240	--	--	--
3	360	S1, S2, S6	--	--
4	480	S1, S2, S6	--	--
5	600	S2, S6, S8	--	--
6	720	S2, S6, S8	--	--
7	840	S1, S2, S3, S6, S8	S8	S3, S8
8	960	S2, S4, S6, S8	--	--
9	1080	S2, S6, S8	--	--
10	1200	S2, S6, S8	--	--
11[1]	1320	S2, S3, S4, S6, S7, S8	S3, S8	--
12	1440	S1, S2, S5, S6, S8	--	--
13[2]	1560	S1, S2, S4, S6, S8	S6, S8	--
14	1680	S1, S2, S7	S1	--
15	1800	S2, S6	--	--
16	1920	S1, S2, S4, S5, S6, S7	S6	--

1. Sample S3 removed from test afterwards.
2. Sample S8 removed from test afterwards.

All sensors went beyond accuracy specification at some point during testing, most notably with the lowest concentration. This was not surprising, given the maximum 4 V output capability that limits variability on the upper end when exposed to the maximum gas concentration. Samples S6, S8, S3, and S1 also exceeded the accuracy tolerance in ambient air beginning with gas sensitivity check 5, 7, 11, and 14, respectively. None of the sensors exceeded the stability tolerance when exposed to the 5 different gas concentrations (only in Air was the stability specification exceeded).

4.1.2 THB Results

A baseline gas sensitivity check (GS0) was performed with each of the five tanks (gas concentrations listed in Table 16) prior to exposure testing. All 48 sensors had progressively increased signal output ranging between about 2.5 and 4.0 V for increased tank CO_2 concentrations ranging between 8% and 12% (Figure 61). Sensor voltage output settled and became fairly stable over the 10-minute exposure period to each gas concentration.

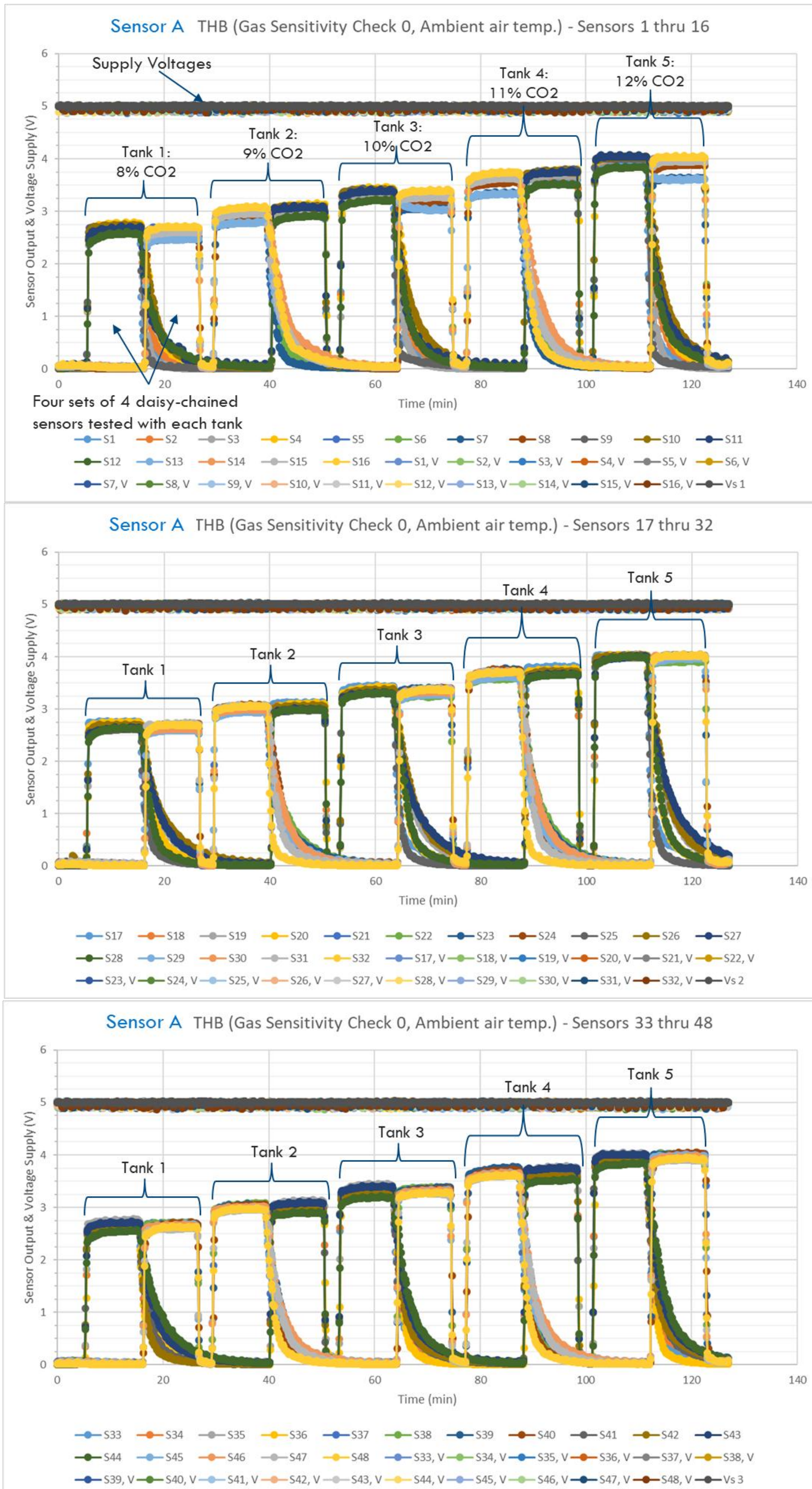


Figure 61: Sensor A THB, Baseline Check (GS0)

Supply voltages were steady and remained on average between 4.977 and 5.005 V throughout all gas sensitivity checks performed. Sensor current drawn was low throughout testing, indicating no short circuiting within the sensor. APPENDIX J: Baseline Electrical Measurements shows the baseline electrical current measurement results, consistent with subsequent results over the course of testing.

Very little fluctuation in output was observed during exposure to temperature-humidity bias testing, with only a few sensors momentarily reading high in output. The self-calibration was performed every 24 hours and could have influenced some of the initial response during ramp-up of temperature and humidity. Figure 62 shows a typical sensor response during THB exposure periods.

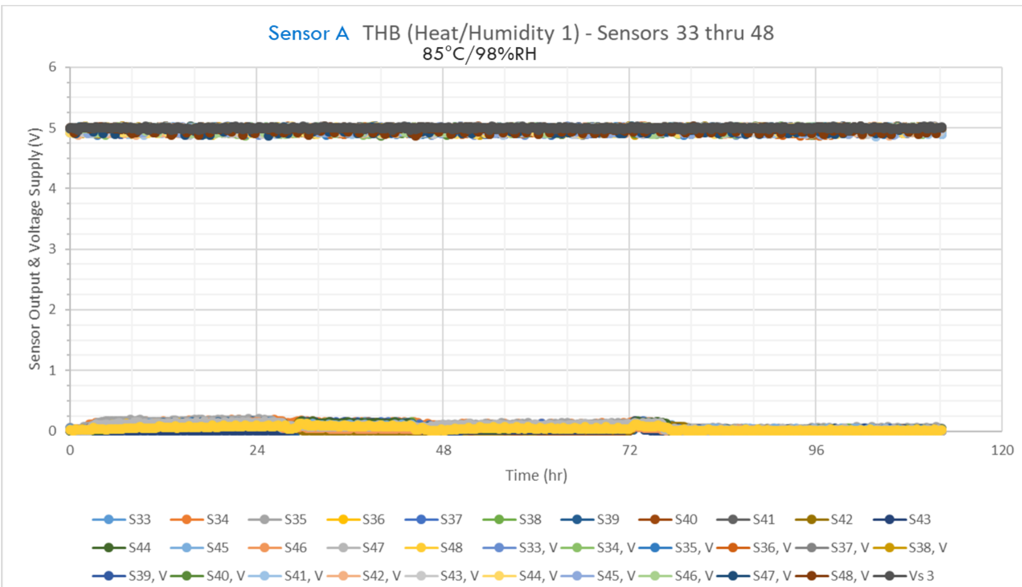


Figure 62: Sensor A THB, Sensor Output during THB Exposure

Sample S48 exhibited fluctuating output (2 to 4 V) in response over the third 48-hour exposure period, with no gas present. This was a "false positive" and was treated as a hard failure at 118 hours total into the exposure period. This response existed during the subsequent gas sensitivity check as well (Figure 63).

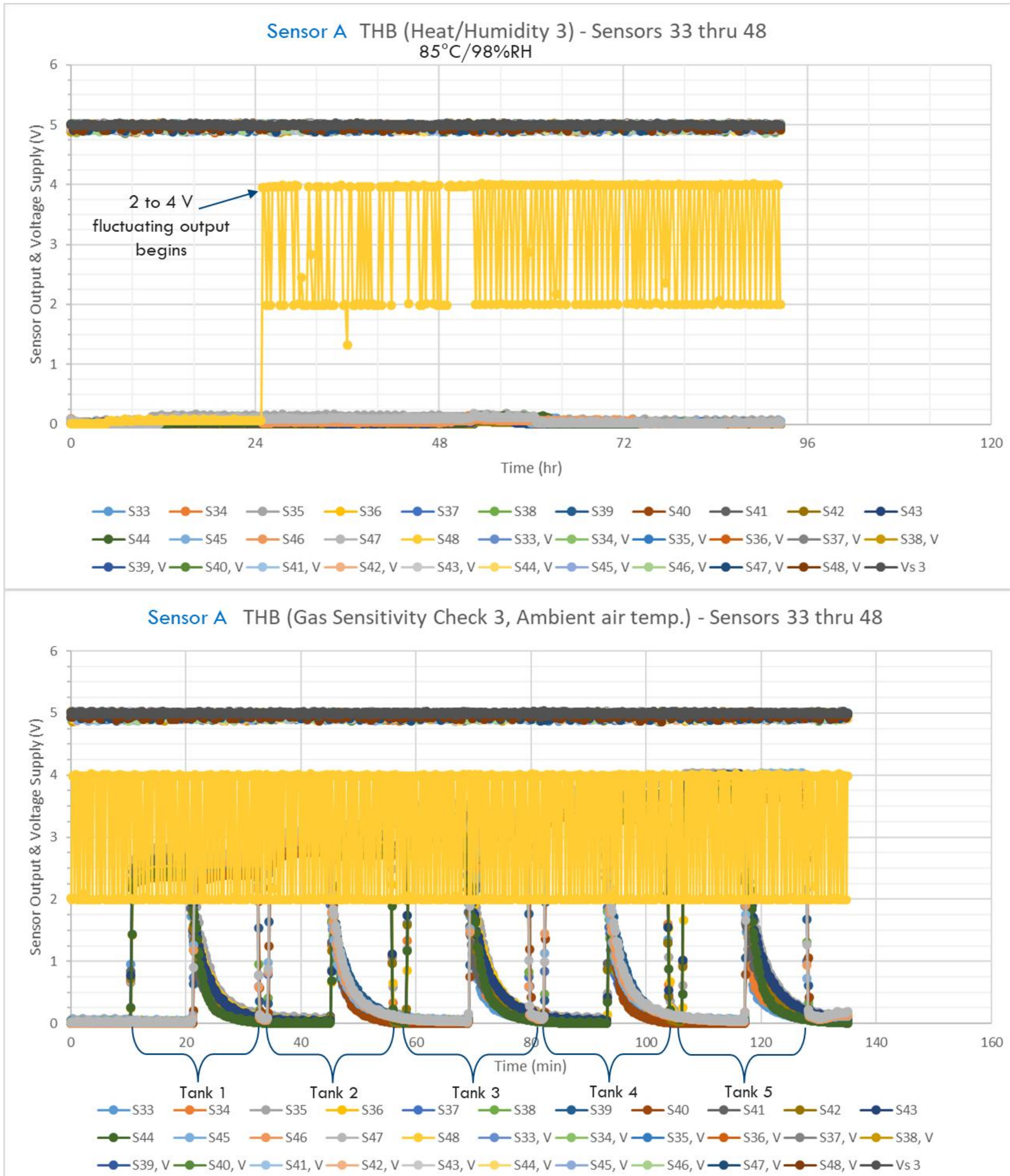


Figure 63: Sensor A THB, S48 Hard Failure

A second hard failure occurred with sample S13 during the seventh 48-hour exposure period with no gas present. The sensor exhibited sporadic output after a total of 317 hours exposure to THB conditions, and subsequently did not respond with output signal when exposed to gas concentrations (Figure 64).

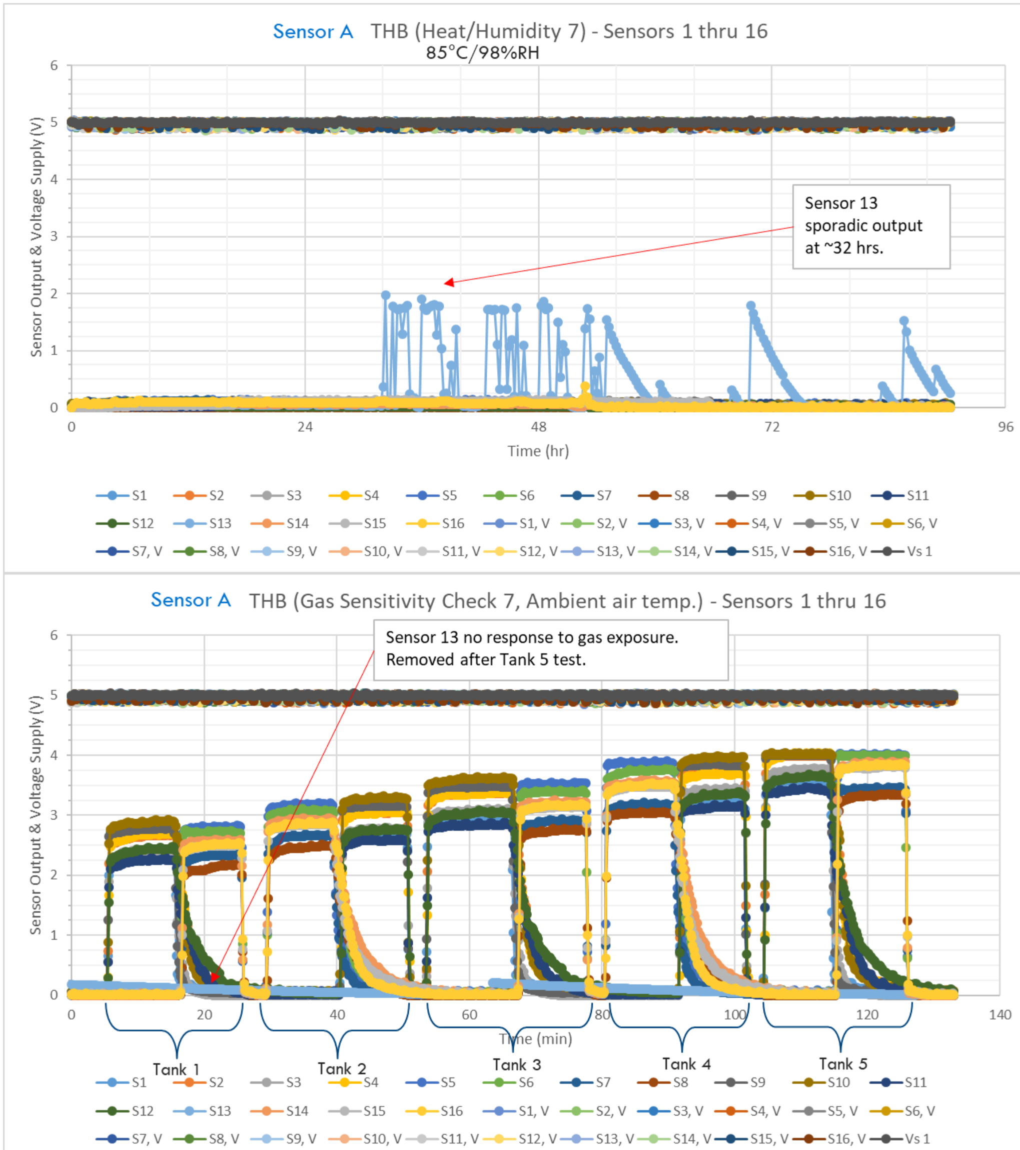


Figure 64: Sensor A THB, S13 Hard Failure

With two hard failures, testing needed to be extended to 539 total hours per the OFF-cycle test parameters (refer to Table 10). After 480 total hours were obtained, a third sensor (S16) experienced a hard failure with varying 2 to 4 V output during THB exposure. Rather than stop the test after exceeding the allowed number of failures, the sensors were left in test for an exposure period of 41 days (984 hours) before performing a final gas sensitivity check. In-situ monitoring of the output signal provided insight into the failure mode and time of additional failures (Figure 65). A total of 20 hard failures occurred during this period. A total of 15 sensors had constant non-zero output voltage, while the remaining 5 had varying output voltage (mainly 2 to 4 V output). The additional sensor output signal results for this THB exposure period and the subsequent ninth gas sensitivity check are shown in APPENDIX F: Sensor A THB, Additional THB Exposure Hard Failure Responses.

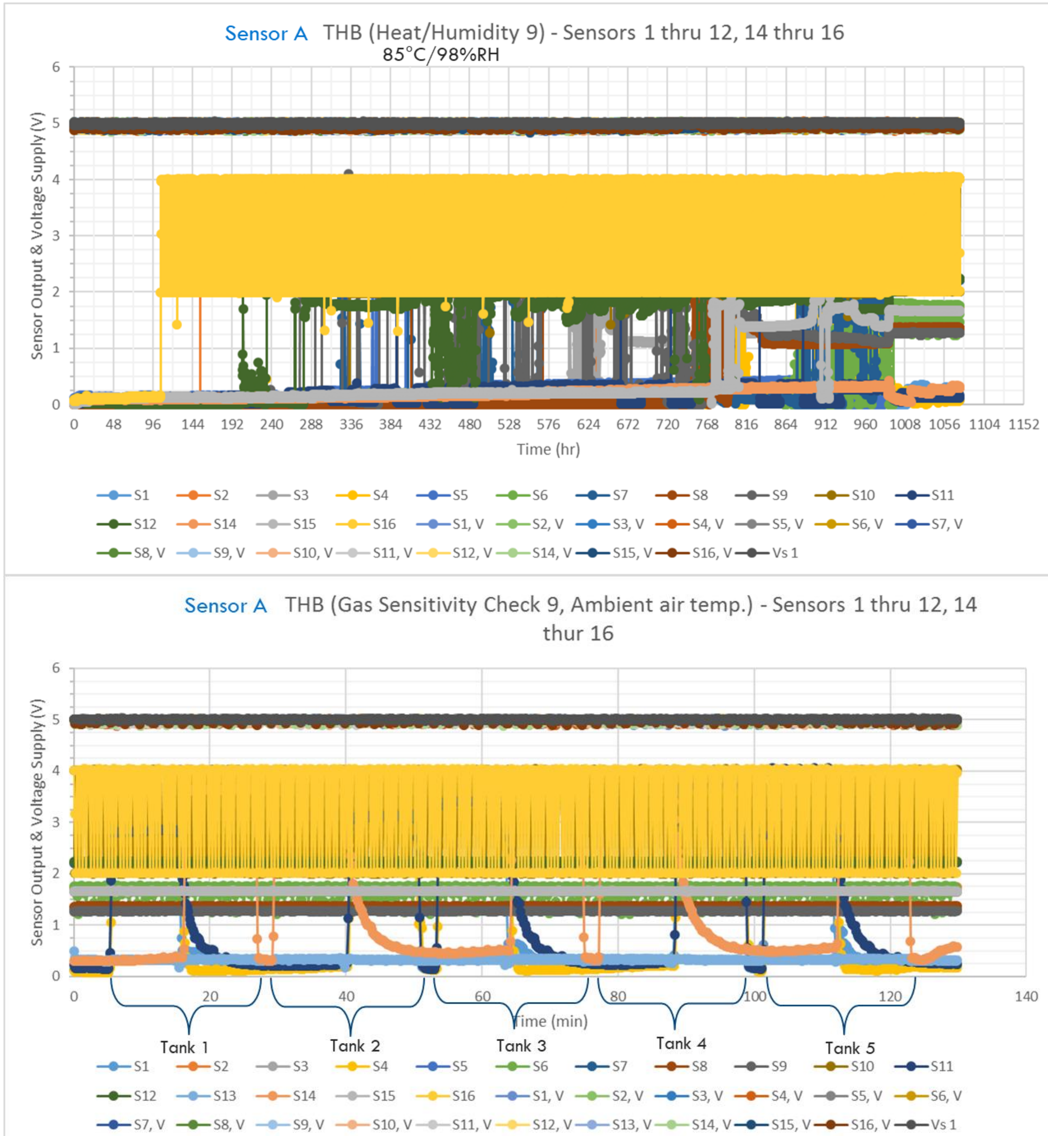


Figure 65: Sensor A THB, Representative Additional Hard Failure Responses

Performance results for accuracy and stability were also evaluated against the specification (reference Table 17) by using the average output voltage over the 10-minute time period that gas was administered. This data was averaged for each sensor during each gas concentration administered and each gas sensitivity check performed, starting when the signal output had minimal percent change from the previous measurement (sampling over 10-second intervals). The average across all the sensors being measured simultaneously was taken from this time stamp to 8 minutes later, covering about 80% of the gas exposure duration without including erroneous data once the gas concentration was removed.

Except for the first two hard failures, sensor signal output was fairly stable in ambient air until after gas sensitivity check 8 (GS8) (Figure 66). Results were within accuracy and stability specifications for all sensors for the first gas sensitivity check (GS1).

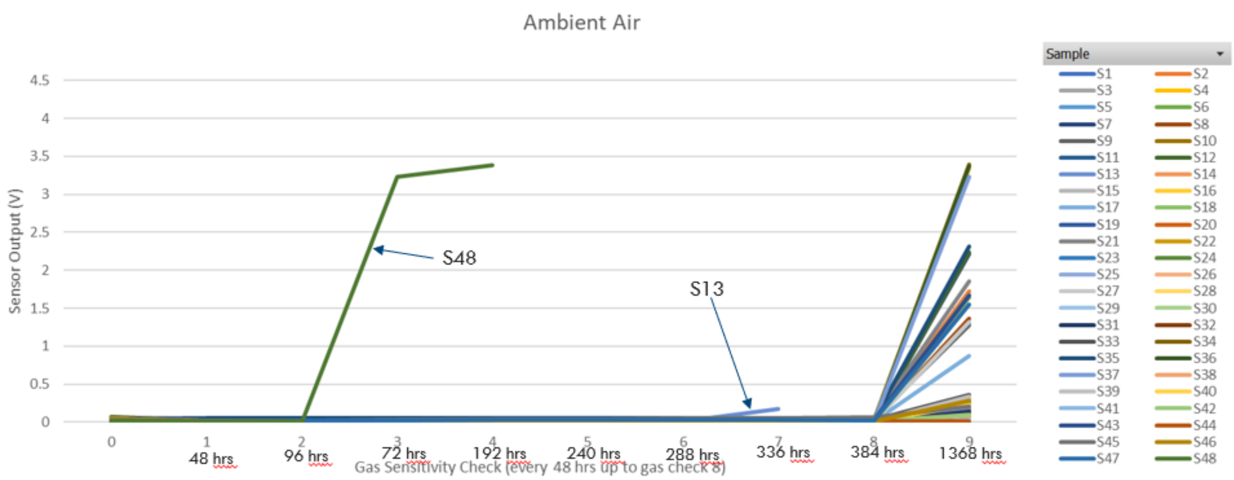


Figure 66: Sensor A THB, Sensor Output with Ambient Air over Time

The average sensor output for all sensors, besides the first two hard failures, was relatively consistent with baseline results through the first 8 gas sensitivity checks (or 384 total hours under THB exposure) (Figure 67). Large deviations from baseline occurred during gas sensitivity check 9 (after 1368 total hours under THB exposure), where many hard failures had occurred during THB exposure following gas sensitivity check 8. The average results for each sensor across all gas concentrations are provided in APPENDIX G: Sensor A THB, Gas Sensitivity Performance.

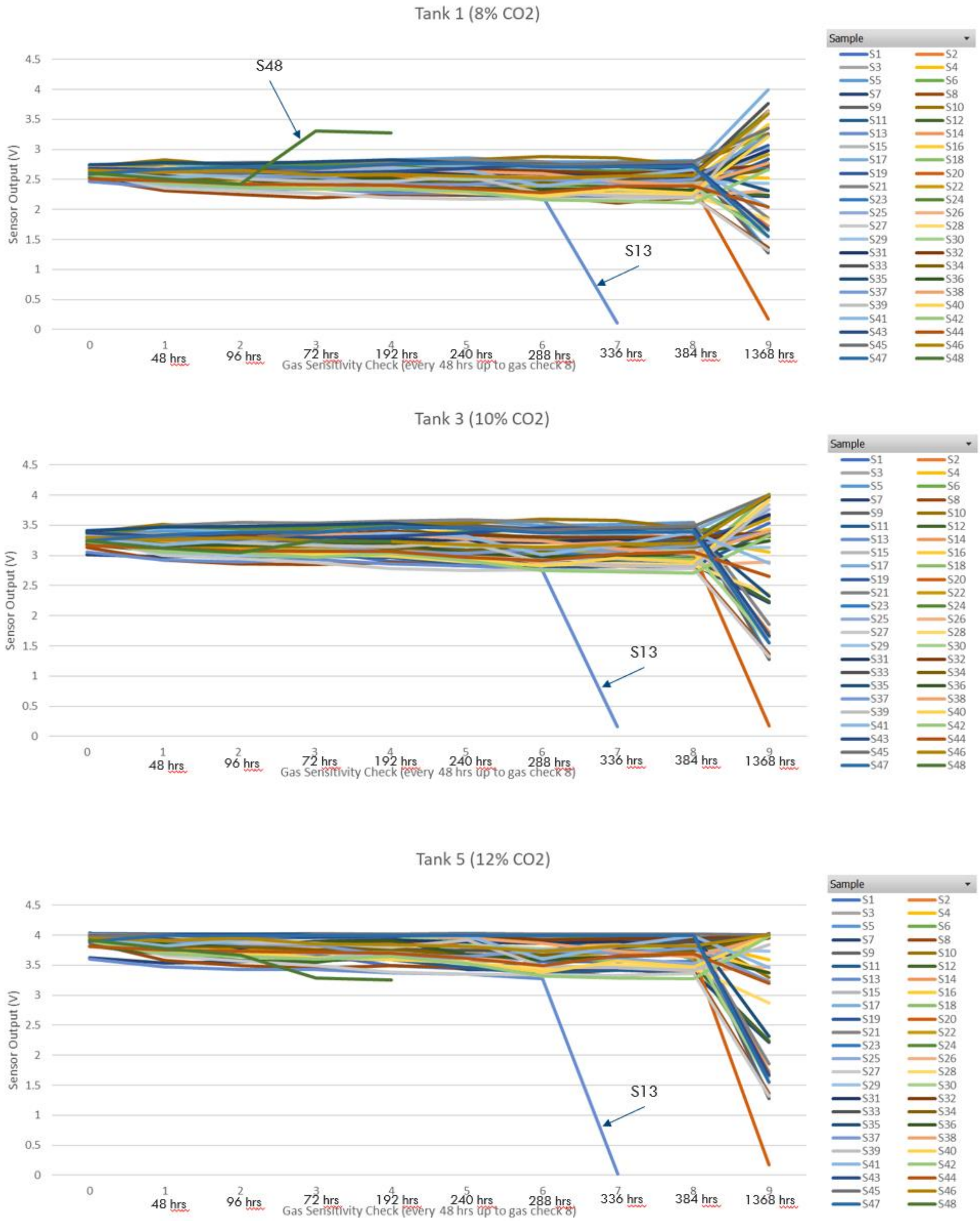


Figure 67: Sensor A THB, Sensor Output with Gas Concentrations over Time

Table 21 shows the summary of soft failures (with respect to accuracy and stability specification in Table 17) and hard failures. During gas sensitivity testing, the temperature remained within 5°C of these baseline checks. Atmospheric pressure was not recorded, but conservatively would likely not have varied by more than 1 inHg (25.4 mmHg). These worst-case temperature and pressure deviations from baseline conditions were used to allow additional tolerance in the specification, and assessments on accuracy and stability take this into consideration. The stability tolerance of 10% per year was additive and applied to each gas sensitivity check (representing about 1 year in the field, or about 10% of the stability tolerance per gas sensitivity check).

Table 21: Sensor A THB, Failure Summary (among 48 sensors tested)

		Soft Failures (in Air and Gas Concentrations)		Hard Failures (first instance)
GS Check	**Hours Completed**	**Accuracy (in Gas Concentrations)**	**Stability (in Ambient Air)**	
1	48	--	--	--
2	96	S23, S27	--	--
3	144	S8, S11, S23, S27, S40, S48	S48	S48 (during THB exposure)
4[1]	192	S1, S11, S27, S40, S48	S48	--
5	240	S1, S8, S11, S23, S25, S27, S28, S40	--	--
6	288	S8, S11, S18, S20, S26, S27, S28, S39, S40, S42	--	--
7[2]	336	S1, S8, S11, S13, S18, S23, S26, S27, S28, S39, S40, S42	--[4]	S13 (during THB exposure)
8	384	S8, S11, S18, S20, S25, S26, S27, S28, S39, S40, S42	--	--
9[3]	1368	S1 - S12, S14 - S22, S24 - S28, S30, S33, S35 - S37, S39 - S48	S1 - S3, S5-S12, S14 - S21, S24, S25, S27, S30, S33, S35 - S37, S39, S40, S43, S45 - S47	S2, S3, S5 - 10, S12, S15, S16, S20, S21, S27, S30, S35 - S37, S43, S47 (all during THB exposure)

1. Sample S48 removed from test afterwards.
2. Sample S13 removed from test afterwards.
3. Gas sensitivity check conducted 41 days (984 hours) after GS8. Samples S1, S11, and S42 exceeded the accuracy tolerance only when exposed to ambient air.
4. Stability tolerance exceeded on sample S13 only when exposed to gas concentrations.

Most sensors went beyond accuracy specification by the last gas sensitivity check. Only sensors 29, 31, 32, 34, and 38 remained within specification. A total of 20 additional sensors were also hard failures by the last gas sensitivity check (GS9).

4.2 Sensor B

4.2.1 Temperature Cycling (TC) Results

Due to a premature failure at the start of test from a compromised strain relief component on the back half of Sensor B S7, the test parameters were determined based on a sample size of 7 instead of 8 sensors. Only the test durations are directly affected (increased) as shown in Table 22.

Table 22: Sensor B Temperature Cycling Test Parameters Revised for 7 Samples

10-Year Equivalent Life Expectancy (124,800 field cycles) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
7	85%	80%	11,914 cycles (337 days)[A]	15,049 cycles (425 days)[A]	n/a
Number of sensitivity readings following baseline check[B]:			10	13	n/a
Test Conditions -					
Min Field Temperature	**Max Field Temperature**	**Min Test Temperature**	**Max Test Temperature**	**Acceleration Factor**	
65.5°C	121°C	-20°C	135°C	11.76	

[A] Test duration in days is based on 0.68 hr cycles (15°C/min ramp rate and 10 min. dwell)
[B] Sensitivity readings are based on 35-day intervals (1.0-yr field equivalency for test duration with 0 failure)

Testing deviated somewhat from the cycle times indicated in Table 22. About 2-hr cycles (10°C/min ramp rate and 44 minute dwells) were used in the thermal chamber program. This was due to use of an older test plan based on longer temperature dwell times for time-dependent property changes, resulting in extended test durations, but not reflective of real-world cycle times. This prevented reaching the required number of cycles within the 1-year test constraint. Additional gas sensitivity checks were also performed at intervals of about every 133 cycles. Every whole number gas check correlated to about 1.1-yr field equivalency for test duration with 0 failure. Test results to 3860 cycles completed total are presented below.

A baseline gas sensitivity check (GS0) was performed with each of the five tanks (gas concentrations listed in Table 16) prior to exposure testing (Figure 68). All 7 sensors had slightly increased signal output ranging between about -0.50 and -0.65 V for increased tank CO/H_2 concentrations ranging between 350/175 ppm and 1500/750 ppm, with exception of sample S3. The signal output from one of its two electrodes (Usen1) had no output throughout this check. This electrode also had exhibited no response during initial trials prior to the start of testing. However, the other electrode (Usen2) did respond normally. In general, sensor voltage output settled and became fairly stable over the 30-minute exposure period to each gas concentration (with data sampling taken every 15 seconds).

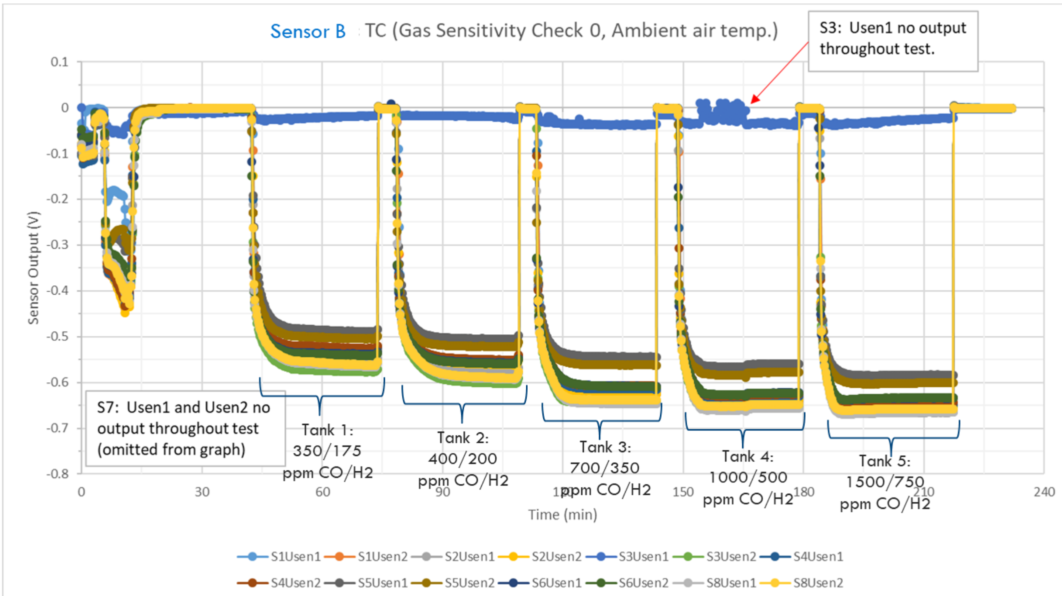


Figure 68: Sensor B TC, Baseline Check (GS0) Signal Output

Heater power was optimal, ranging from 2.72 to 2.92 W across all 7 sensors during GS0 (excluding minor fluctuation between150 and 170 min). Heater current remained between 0.32 to 0.35 A. The calculated heater resistance averaged 25.7 Ohm (ranging between 24.3 to 26.9 Ohm) across all 7 sensors. APPENDIX J: Baseline Electrical Measurements shows the baseline check power, current, and resistance of the sensors.

Temperature cycling exposure between gas sensitivity checks was indicated by "cycling", followed by the sequential exposure number. During the first temperature cycling exposure (no gas present), some fluctuation in signal output was observed (with data sampling taken every 15 minutes) (Figure 69). The temperature swings in test correlated with this fluctuating output.

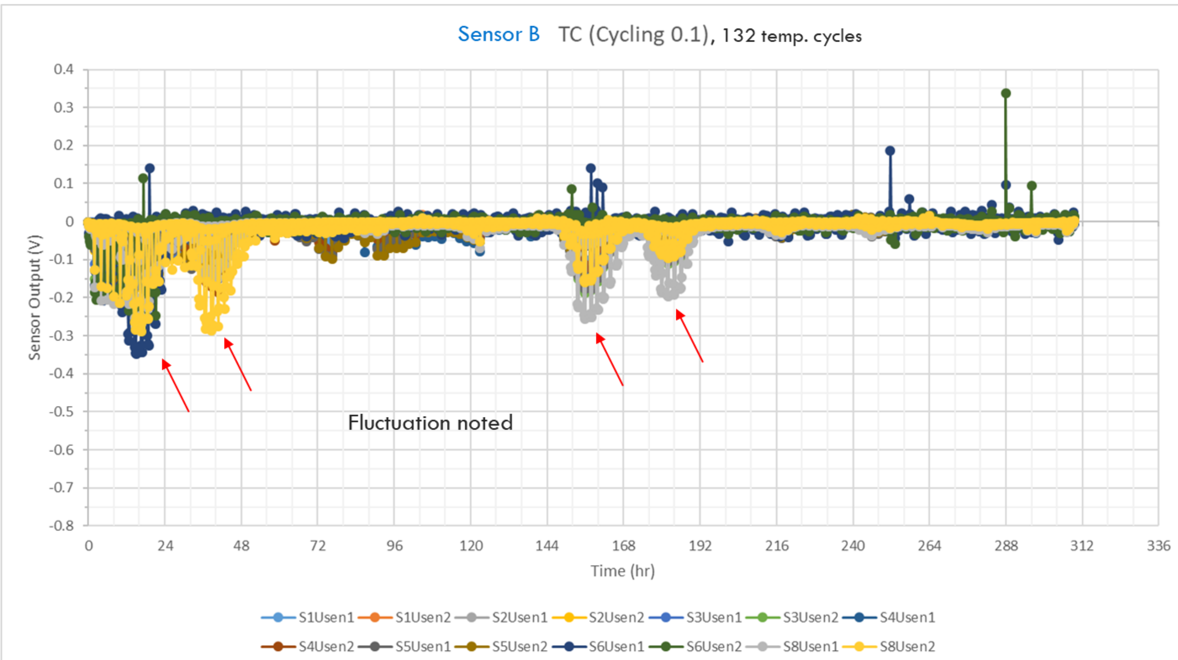


Figure 69: Sensor B TC, Sensor Output during Cycling

Heater power, current, and calculated resistance all correlated in cyclical fashion, with the same response across all three metrics as they are related by equations $V=IR$ and $P=V^2/R$ (where V is voltage, I is current, R is resistance, and P is power). As temperature decreased, heater resistance decreased and therefore heater current and power increased. APPENDIX J: Baseline Electrical Measurements shows this cyclical response, with heater power shown over the entire exposure period, and heater current and resistance over the first 24 hours of cycles.

After 132 temperature cycles were achieved, the first gas sensitivity check (GS0.1) was performed. Sample S6 exhibited no signal output when exposed to the gas concentrations. This was a hard failure, as neither Usen1 nor Usen2 electrodes responded (Figure 70). Heater power, current, and resistance were similar to the baseline results for all 7 sensors (no signs of degradation).

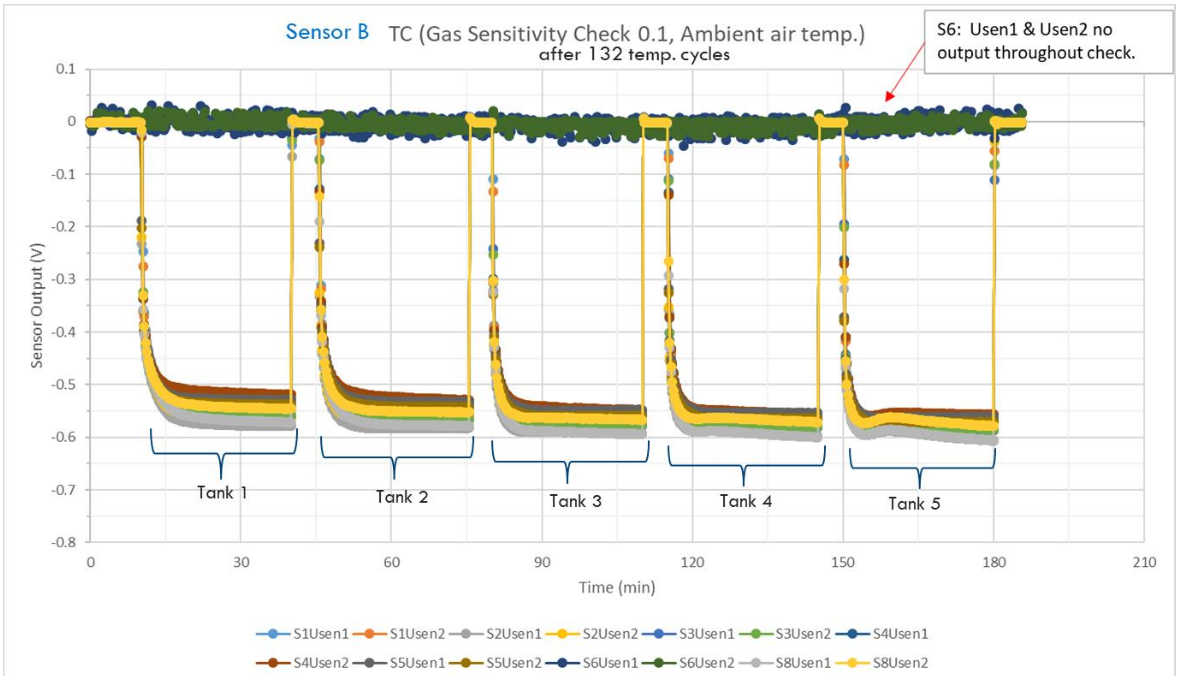


Figure 70: Sensor B TC, Sample S6 Hard Failure

During GS0.4 after 532 cycles, signs of a dip in signal output became more evident, particularly at the higher gas concentrations (Figure 71). This started to occur for all sensors, except for sample S5. Sample S8 with Usen2 electrode decreased in stable output by more than 25% from baseline during exposure to the highest gas concentration (Tank 5 gas concentration listed in Table 16).

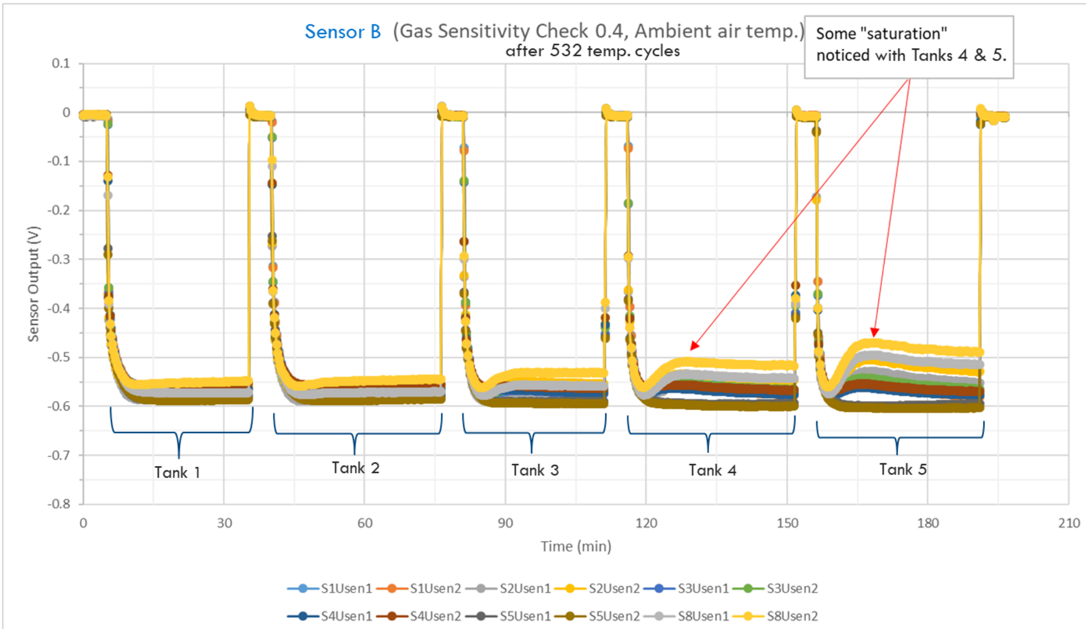


Figure 71: Sensor B TC, First decrease in signal output >25%

By gas sensitivity check GS1, following 1331 cycles, the dip in signal output became more pronounced and pervasive, and started occurring with lower gas concentrations (Figure 72). At this point, except for sample S5, all sensors decreased in stable output by more than 25% from baseline under the highest gas concentration (Tank 5 gas concentration listed in Table 16). A momentary positive voltage output also was more noticeable immediately after the sensors were exposed to ambient air.

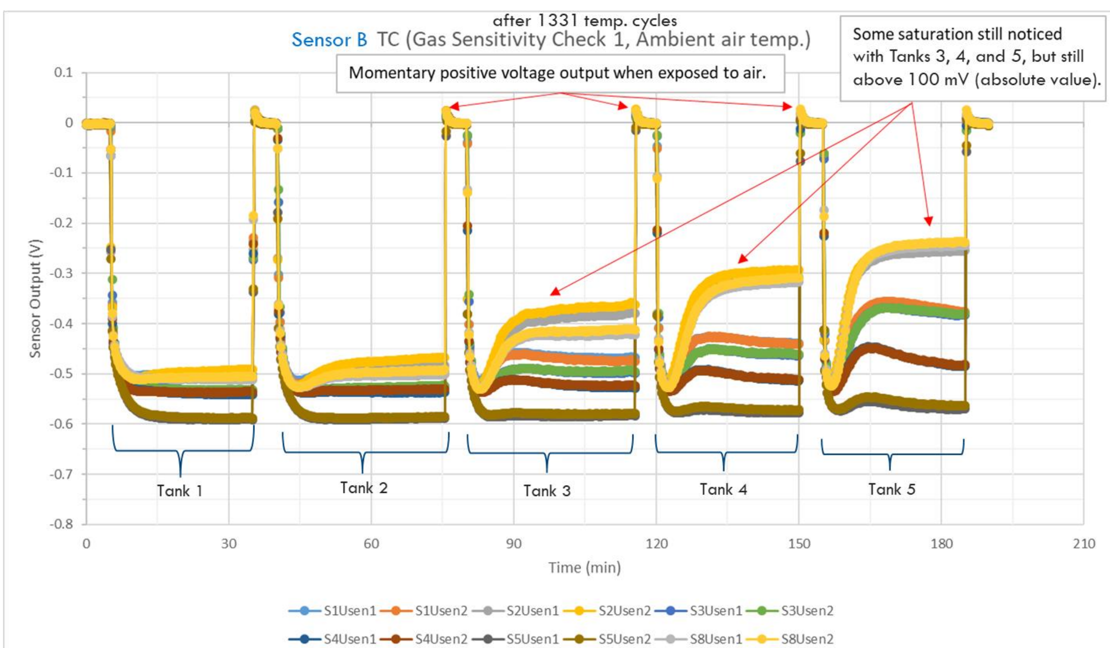


Figure 72: Sensor B TC, further decrease in signal output

Sample S5 had also decreased in stable output by more than 25% by gas sensitivity check GS2 (following 2529 cycles). By gas sensitivity check GS3 (following 3727 cycles), continued decrease in signal output had occurred, most notably at the higher gas concentrations (Figure 73).

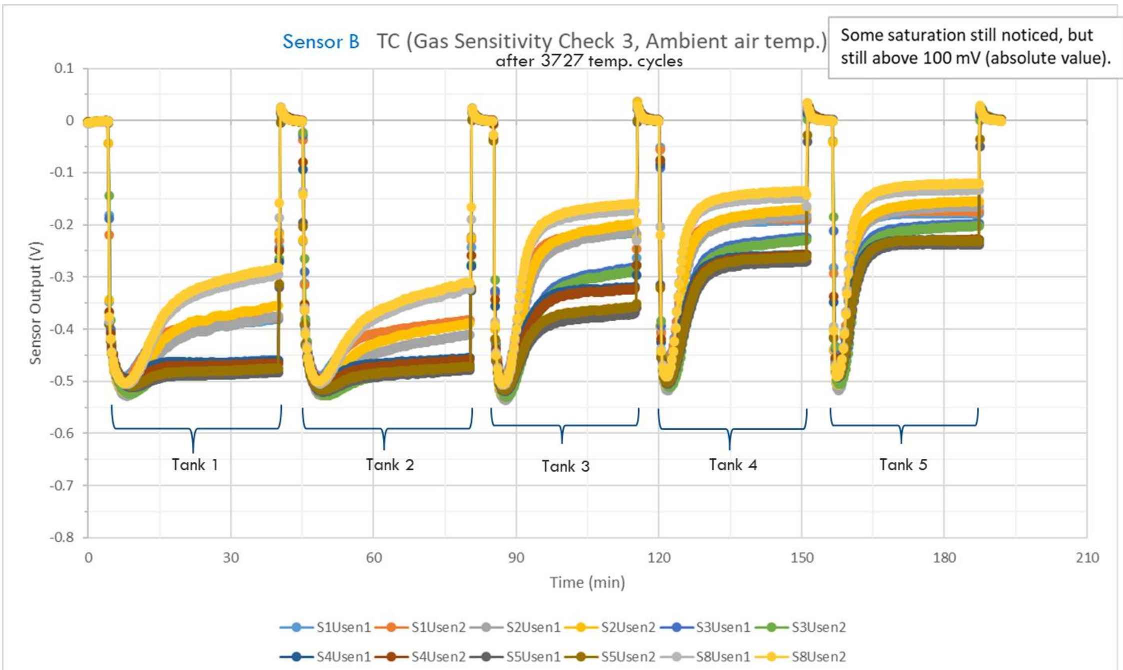


Figure 73: Sensor B TC, GS3 Signal Output

A final gas sensitivity check GS3.1 was performed before stopping cycling exposure testing. The 1-year test duration limit had been reached, with a total of 3860 cycles. Signal output voltage had a slight momentary increase when sensors were exposed to ambient air with two gas concentrations (Figure 74). This had been observed previously at times.

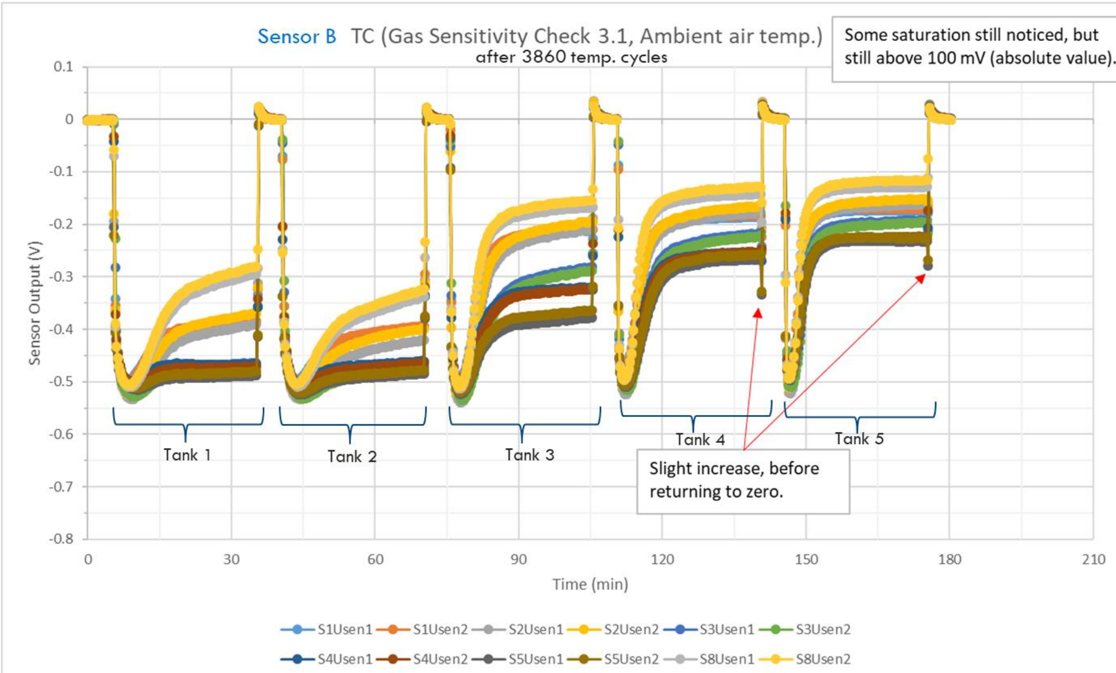


Figure 74: Sensor B TC, GS3.1 Signal Output

Heater power remained optimal, keeping to 2.76 to 2.94 W across the remaining 6 sensors. Heater current remained between 0.32 to 0.35 A. The calculated heater resistance averaged 25.6 Ohm (ranging between 24.4 to 26.8 Ohm). These heater metrics are very consistent with the baseline results.

Table 23 shows the summary of soft failures (with respect to 25% change in output) and hard failures.

Table 23: Sensor B TC, Failure Summary (among 7 sensors tested)

GS Check	Cycles Completed	Soft Failures (in Gas Concentrations)	Hard Failures (first instance)
0	0	S3-Usen1	--
0.1[1]	132	--	S6
0.4	532	S8-Usen2	--
1	1331	S1, S2, S3, S4, S7, S8	--
2	2529	S1, S2, S3, S4, S5, S7, S8	--
3	3727	S1, S2, S3, S4, S5, S7, S8	--
3.1	3860	S1, S2, S3, S4, S5, S7, S8	--

1. Sample S6 removed from test afterwards.

4.2.2 THB Results

A baseline gas sensitivity check (GSOFF0) was performed with each of the five tanks (gas concentrations listed in Table 16) prior to exposure testing under the OFF conditions (Figure 75). All 8 sensors had slightly increased signal output ranging between about -0.40 and -0.60 V for increased tank CO/H_2 concentrations ranging between 350/175 ppm and 1500/750 ppm. In general, sensor voltage output settled and became fairly stable over the 30-minute exposure period to each gas concentration (with data sampling taken about every 10 seconds).

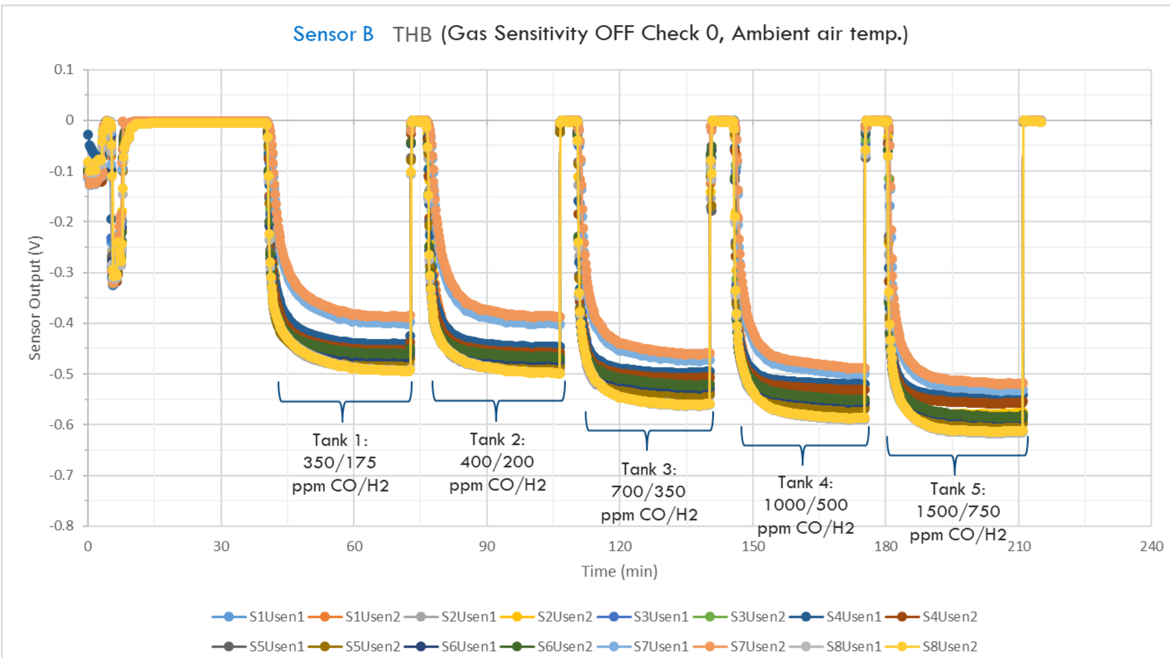


Figure 75: Sensor B THB, Baseline Check (GSOFF0) Signal Output

Heater power was optimal, keeping to 2.69 to 3.06 W across all 8 sensors during GSOFF0 (excluding minor startup fluctuations). Heater current remained between 0.31 to 0.36 A. The calculated heater resistance averaged 25.5 Ohm (ranging between 22.9 to 27.3 Ohm) across all 8 sensors. APPENDIX J: Baseline Electrical Measurements shows the baseline heater power, current, and resistance measurement results.

During THB exposure (no gas present), some shift in signal output was observed (with data sampling taken every 15 minutes) (Figure 76). The signal output reached between about 0.2 and 0.3 V (absolute value), before returning to 0 V output at normal room temperature and humidity for the subsequent gas sensitivity check.

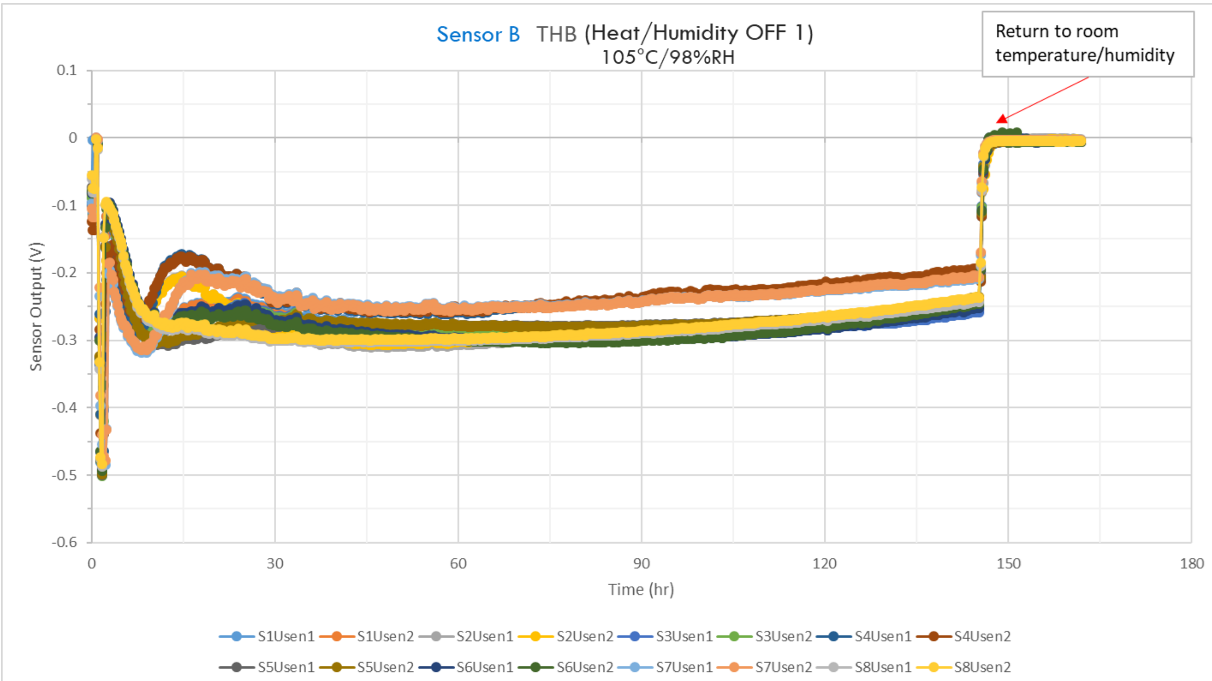


Figure 76: Sensor B THB, Sensor Output during THB Exposure

Heater power, current, and calculated resistance observed during this first exposure (shown in APPENDIX J: Baseline Electrical Measurements) were very similar to that observed during gas sensitivity checks.

After 144 hours of THB exposure, the first gas sensitivity check under the OFF conditions (GSOFF1) was performed. Sensor S2-Usen1 electrode had no output to any of the gas concentrations (Figure 77), while S2-Usen2 electrode was fine. All other sensors had a significant increase in output when exposed to the lowest gas concentration (Tank 1 gas concentration listed in Table 16), greater than 25% change from baseline. All sensors experienced a significant drop in output after Tank 5 gas concentration (the highest gas concentration at 1500/750 ppm CO/H_2) was applied a second time following an air purge, with most changing more than 25% from baseline. None of the sensors reached a stabilized value during this 30-minute exposure to Tank 5.

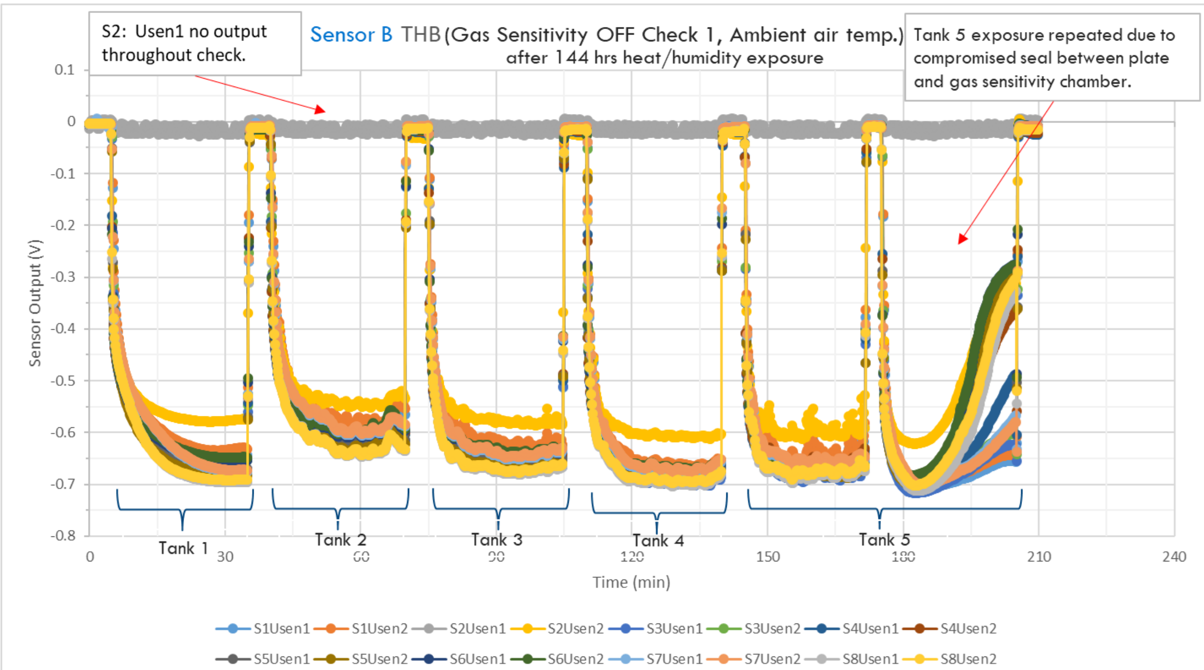


Figure 77: Sensor B THB, Unstable Sensor Output

Deterioration was observed in the white stock cables following 288 hours of THB exposure. The cables were replaced with high temperature silicone cable (as described in Section 3.2.2.2). A significant drop in signal output immediately following initial sensing of the gas concentrations continued across all sensors (response behavior was similar to that before the stock cables were replaced) under the subsequent gas sensitivity check (GSOFF2). This was more prominent at the higher gas concentration exposures (Tanks 3, 4, and 5). Sample S3 had no output throughout this check and was considered a hard failure (Figure 78).

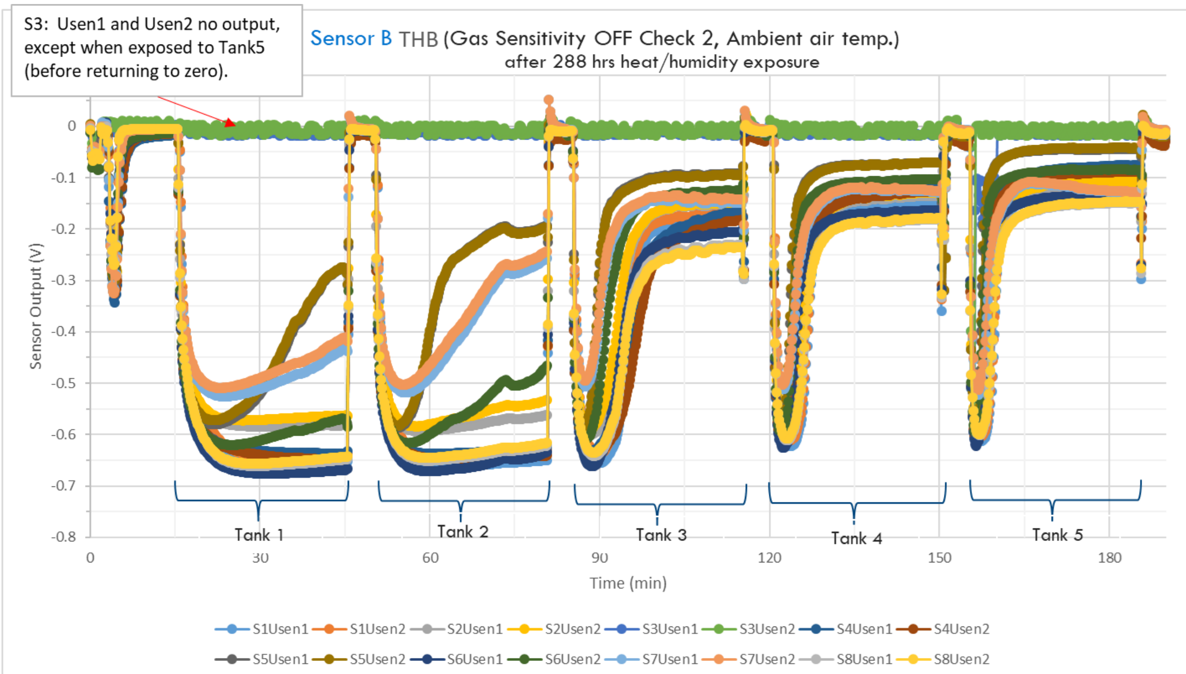


Figure 78: Sensor B THB, Decreased Sensor Output Across All Sensors

Using a small enclosure to isolate the Tank 5 gas concentration to an individual sensor, samples S1 and S3 were checked to confirm results. Sample S1 was initially consistent with results observed during GSON2, but then responded more like the original baseline. Sample S3 consistently did not respond (Figure 79). Tank 1 gas concentration was subsequently supplied to all sensors, and the response was similar to that observed during GSON2. Sample S3 was confirmed a hard failure, but was left in test to determine if recovery would occur, particularly given the connection issues prior.

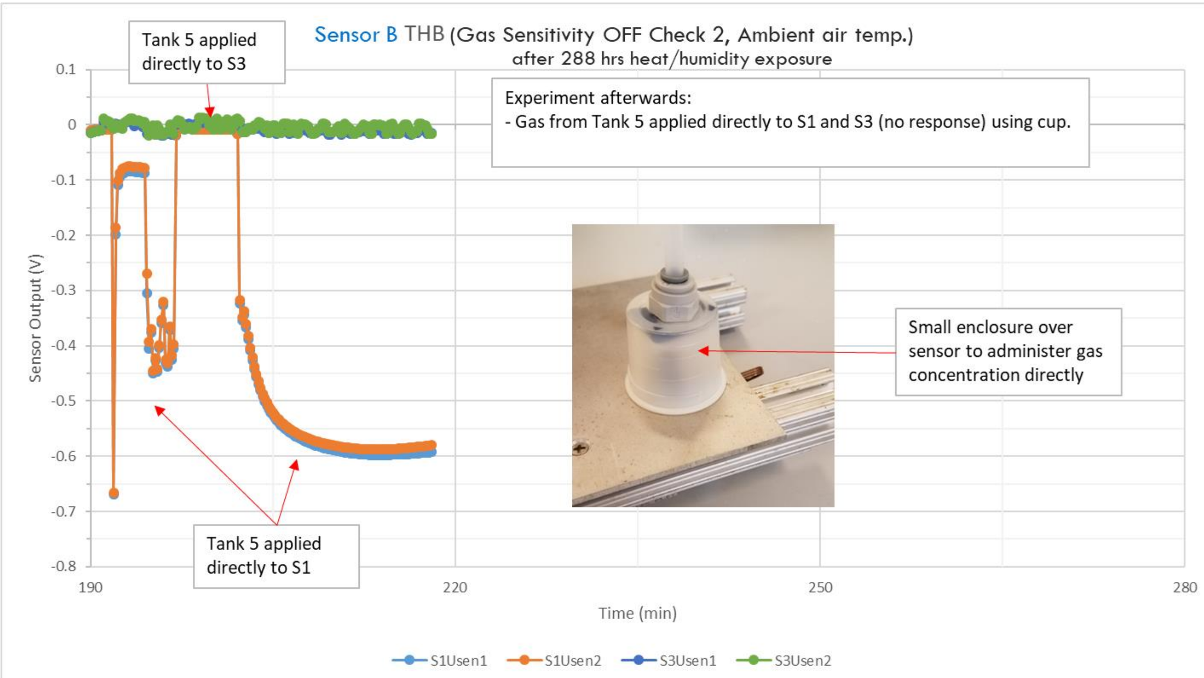


Figure 79: Sensor B THB, Direct Gas Concentration Administered

The subsequent gas sensitivity checks through GSOFF5 were similar to that shown in Figure 80, where all sensors responded initially, and then returned close to “zero” output while gas was being administered. Sample S3 had recovered, and therefore was left in test.

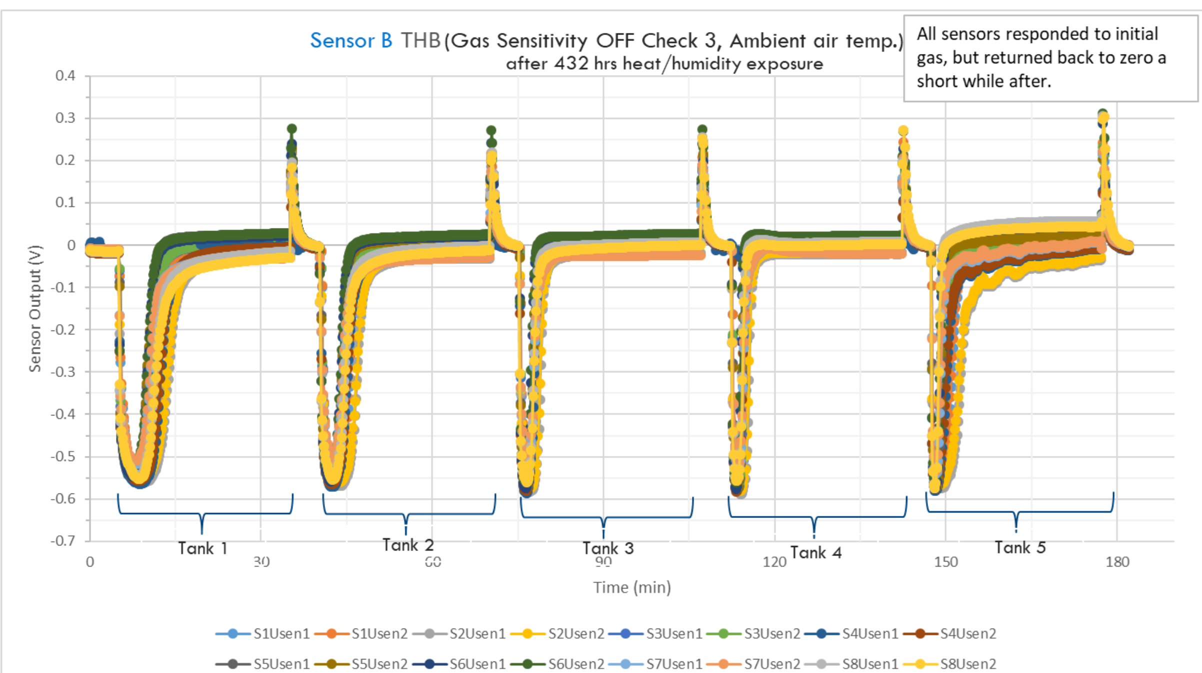


Figure 80: Sensor B THB, Typcial Sensor Output Response from GSOFF3 through GSOFF5

Other anomalous behavior occurred later in testing:

- During the fourth THB exposure period, sample S7-Usen1 went to "zero" output for some time (Figure 81, top graph).
- During gas sensitivity checks GSOFF6 and GSOFF7, sample S8 had no response due to the lack of current through the heating element (and therefore not at proper operating temperature).
- During gas sensitivity checks GSOFF8 and GSOFF9, sample S7-Usen1 had no response to gas concentrations.
- During gas sensitivity check GSOFF10, samples S1-Usen1 and S7-Usen1 had fluctuating response about "zero" (Figure 81, bottom graph).

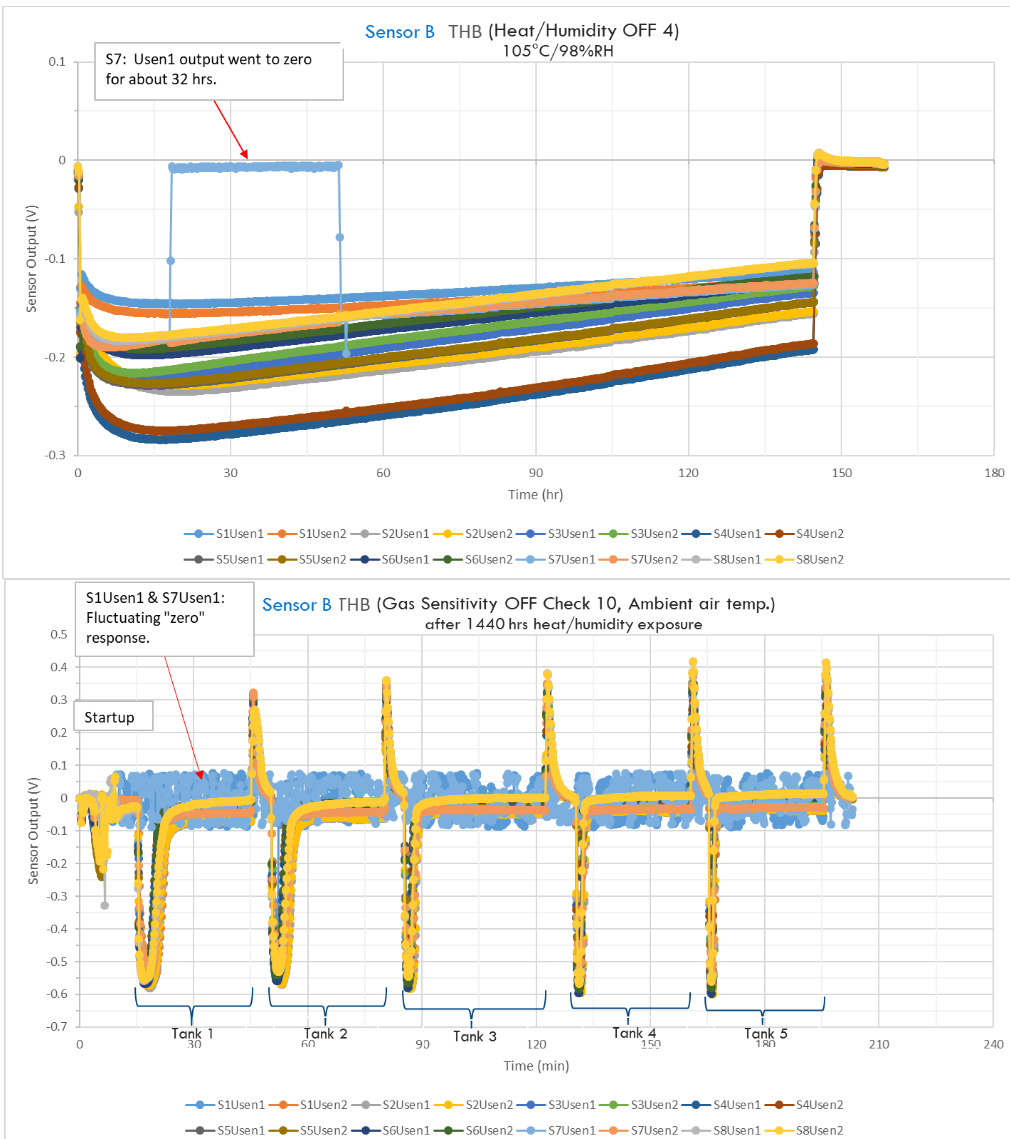


Figure 81: Sensor B THB, Representative Anomalous Sensor Output

Sample S8 had shown intermittent heater power issues leading up to gas sensitivity check GSOFF11 (up to 1584 hours of THB exposure). After this check, it was removed from test due to intermittent current to heater causing fluctuating "zero" response during Tank 5 gas concentration (Figure 82). It was considered a hard failure at this point. Dsub9 sockets inside the chamber for samples S7 and S8 were replaced, but they did not help. At subsequent startup, sample S8 had no current through the heater element.

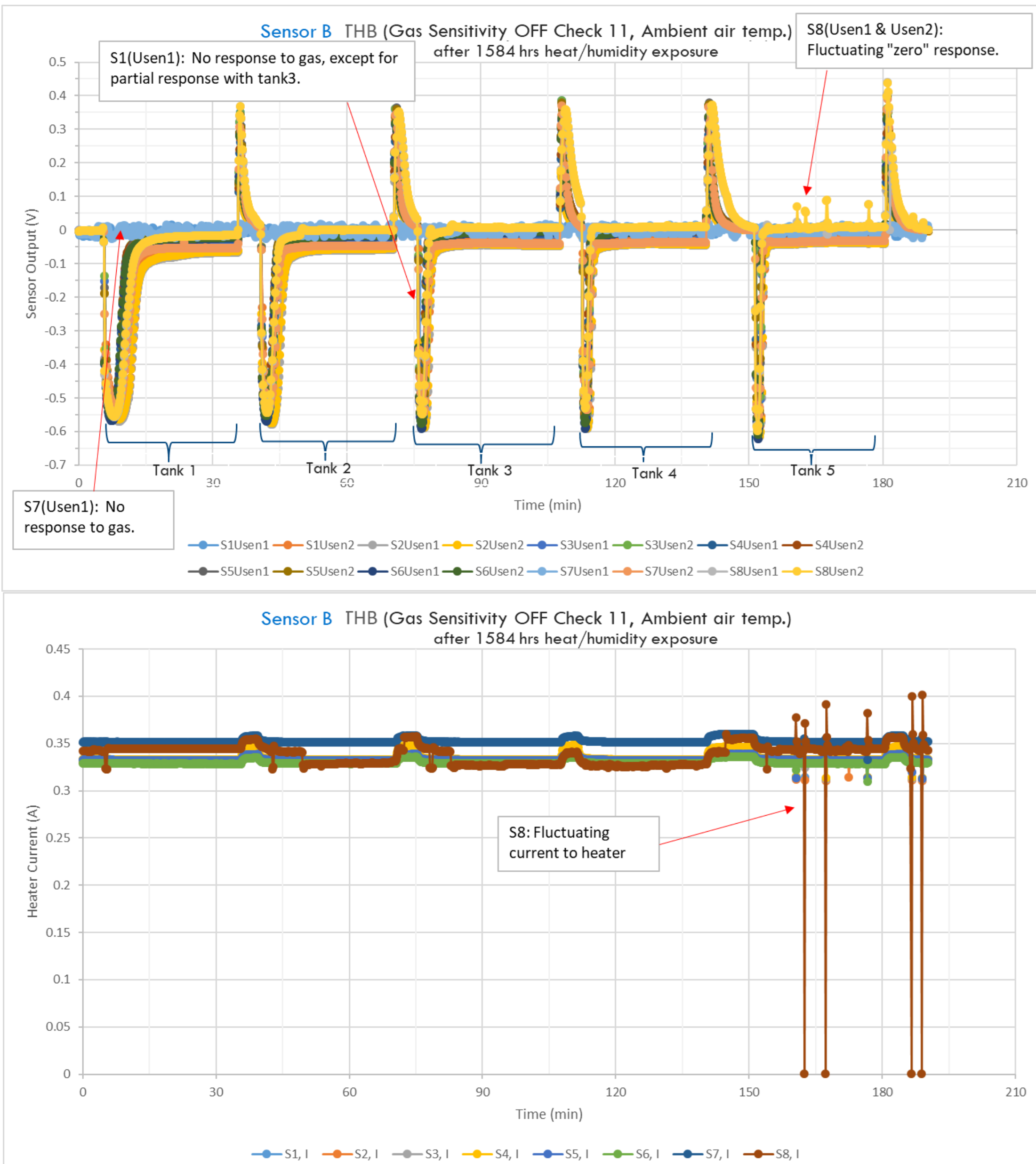


Figure 82: Sensor B THB, Sample S8 Intermittent Sensor Output and Heater Current

In gas sensitivity check GSOFF12, sample S4 had no response under Tank 1 (gas concentration listed in Table 16) initially, and then momentarily responded with -0.1 V. Heater current was normal. A similar no response existed for the last gas sensitivity check in the OFF conditions (GSOFF13). Conducted after 1872 hours of THB exposure, sample S4 had no response when exposed to Tank 1 gas concentration, but did respond on subsequent higher gas concentrations. It also responded with a repeated exposure to Tank 1 about 24 hours later. This was not considered a hard failure, given the response after an extended period of time at ambient room temperature conditions on the back half of the sensor. The remaining 6 sensors responded to the gas concentrations, albeit with higher signal output at the lower gas concentrations compared to baseline. The sensors also responded initially before returning close to “zero” output (Figure 83). Only one of the two electrodes responded on samples S1, S2, and S7.

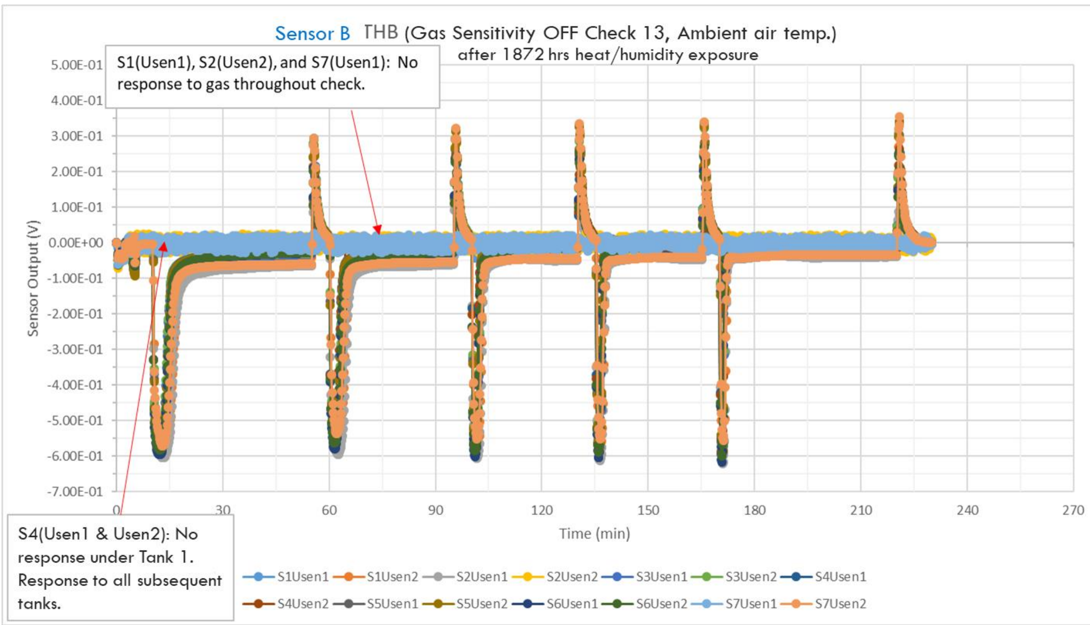


Figure 83: Sensor B THB, Final OFF Conditions Signal Output

Heater power remained optimal, keeping to 2.79 to 3.01 W across the 7 sensors during GSOFF13 (excluding minor startup fluctuations). Heater current remained between 0.33 to 0.36 A. The calculated heater resistance averaged 25.4 Ohm (ranging between 23.2 to 26.1 Ohm). These heater metrics are very consistent with the baseline results.

The subsequent first THB exposure to the ON conditions of 135°C and 98% RH produced anomalous results (Figure 84). Sensor output remained at “zero” for all 7 sensors, unlike previously when under THB exposure (with no gas present). Intermittent current to the heater existed on sensors as well, particularly sample S6.

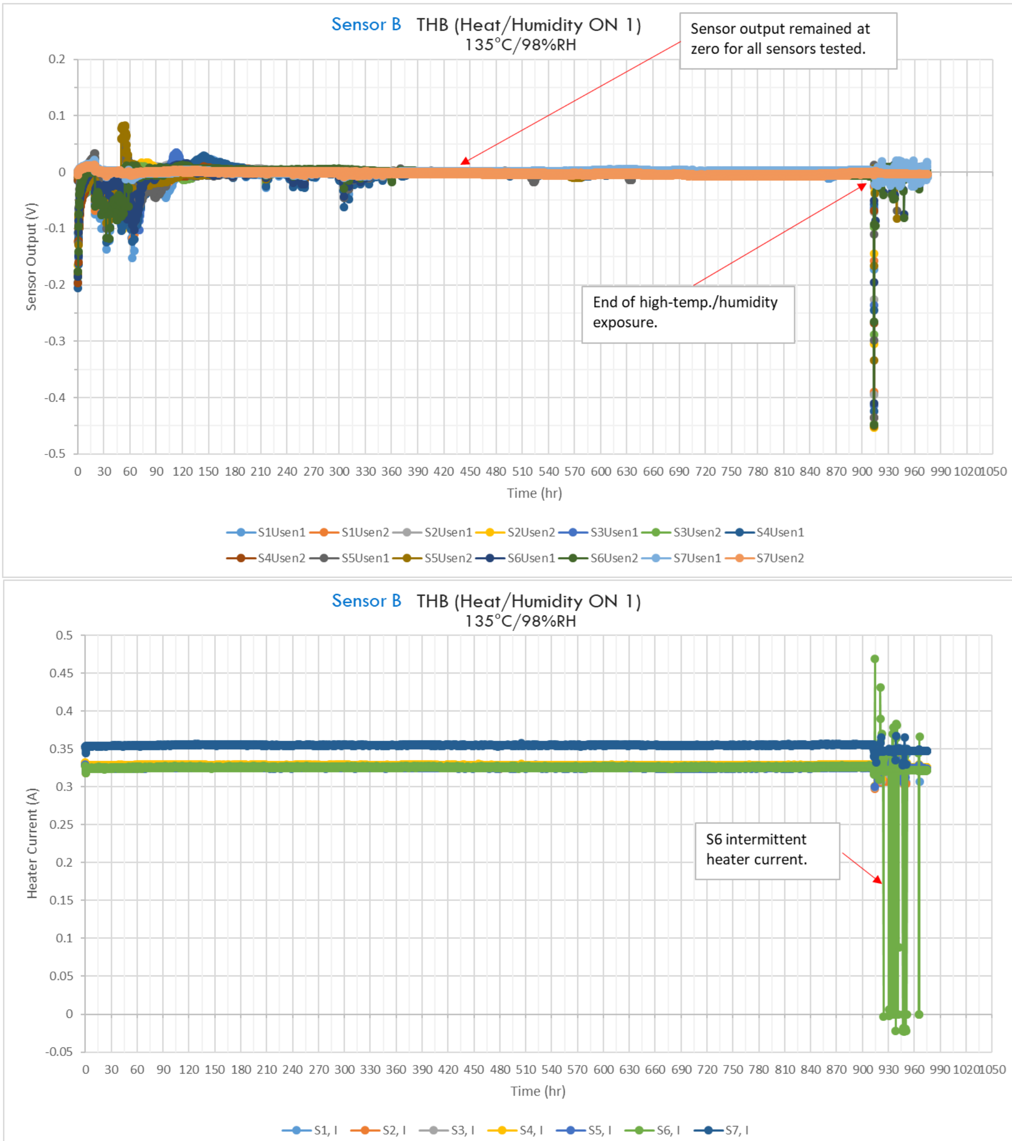


Figure 84: Sensor B THB, First ON Conditions Exposure - Signal Output and Heater Current

After completing the 912 hours of THB exposure (ON conditions), several sensors were confirmed to have connector issues. The Dsub9 connectors (male and female) inside the chamber environment were replaced on all. New connectors with 30 micro-inch (0.76 micron) gold plating were used in place of the existing 8 micro-inch (0.20 micron).

The first gas sensitivity check in the ON conditions (GSON1) was then conducted. Sample S3-Usen2 was the only one to have signal output similar to previous gas sensitivity check GSOFF13. All other sensors had either no signal output (from either electrode) or had intermittent output during gas exposure (Figure 85). The intermittent response corresponded with intermittent current to the heater element. The six sensors were considered hard failures at this point.

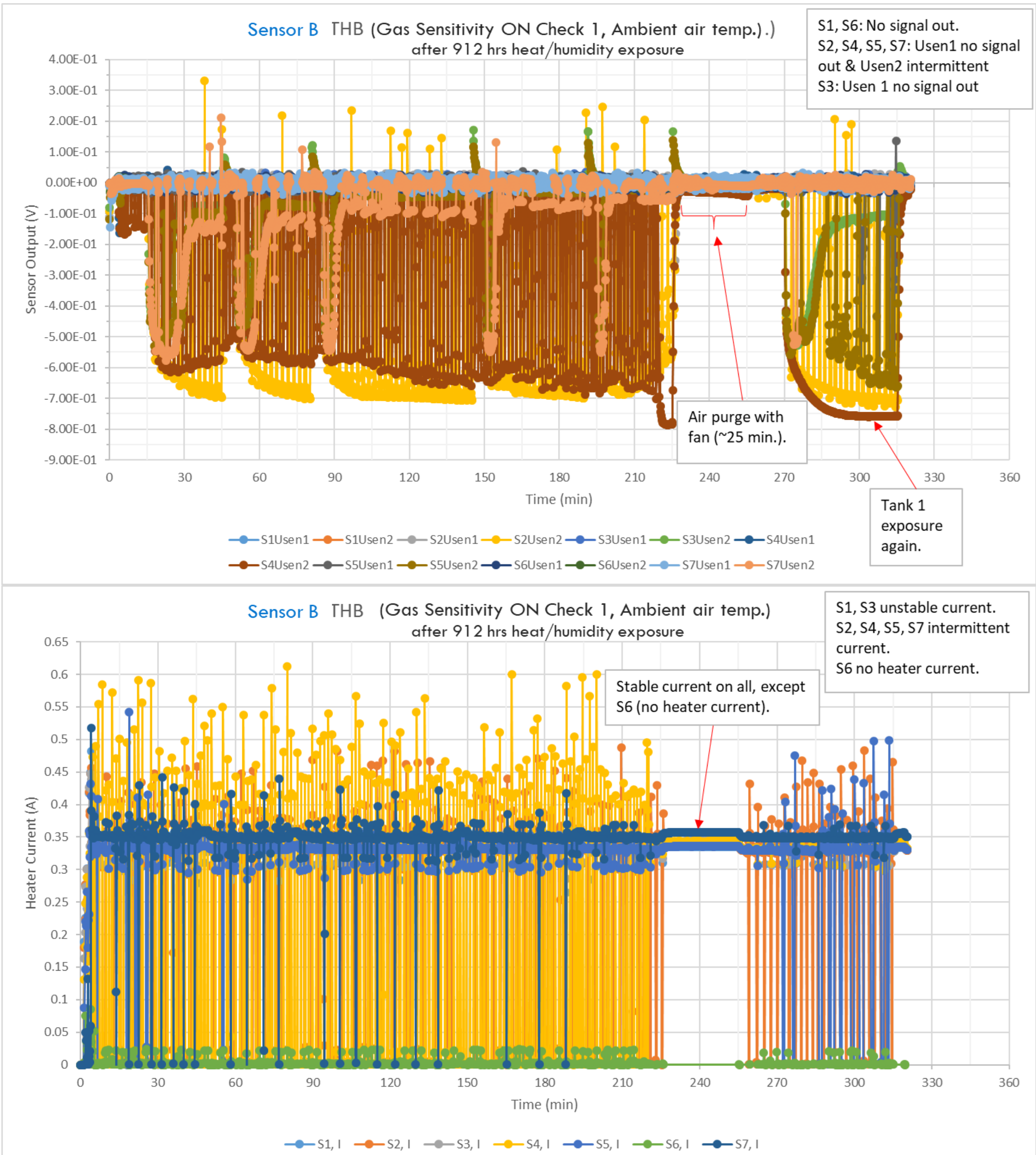


Figure 85: Sensor B THB, GSON1 Check - Signal Output and Heater Current

It is interesting to note that during the forced air purge for an extended period of time (approximately 25 minutes), all sensors exhibited stable current to the heater element, with the exception of sample S6. Also, sample S4-Usen2 no longer had an intermittent response (despite some unstable heater current) when tested afterwards with Tank 1 (gas concentration listed in Table 16).

Given the high number of failures and connection issues experienced, the Sensor B THB testing was stopped. Table 24 shows the summary of soft failures (with respect to 25% change in output) and hard failures.

Table 24: Sensor B THB, Failure Summary (among 8 sensors tested)

Condition	GS Check	Hours Completed	Soft Failures	Hard Failures (first instance)
OFF	1	144	S1, S2, S3, S4, S5, S6, S7, S8	--
	2	288	All 8 sensors	S3[1]
	3	432	All 8 sensors	--
	4	576	All 8 sensors	--
	5	720	All 8 sensors	--
	6	864	All 8 sensors	S8
	7	1008	All 8 sensors	--
	8	1152	All 8 sensors	--
	9	1296	All 8 sensors	--
	10	1440	All 8 sensors	--
	11[2]	1584	All 8 sensors	--
	12	1728	All 8 sensors	S4[3]
	13	1872	All 8 sensors	--
ON	1[4]	912	All 8 sensors	S1, S2, S4, S5, S6, S7

1. Recovered in subsequent gas sensitivity check and remained in test.
2. S8 was removed from test afterwards.
3. S4 had similar response at GSOFF13, but recovered after about 24 hours at ambient room temperature conditions.
4. Dsub9 test connectors replaced inside autoclave with new 30 micro-inch gold-plated connectors

4.3 Sensor C

4.3.1 Temperature Cycling (TC) Results

Testing deviated somewhat from the cycle times planned (refer to Table 9). About 2-hr cycles (10°C/min ramp rate and 31-minute dwells) were used in the thermal chamber program. This was due to use of an older test plan based on longer temperature dwell times for time-dependent property changes, resulting in extended test durations, but not reflective of real-world cycle times. This prevented reaching the required number of cycles within the 1-year test constraint, and the test was stopped pre-maturely. Additional gas sensitivity checks were also performed at intervals of about every 96 cycles. Every whole number gas check correlated to about 1.0-yr field equivalency for test duration with 0 failure. Test results to 1056 cycles completed total are presented below.

A baseline gas sensitivity check in the OFF conditions (GSOFF0) was performed with each of the five tanks (gas concentrations listed in Table 16) prior to exposure testing. All 48 sensors had progressively increased signal output starting with Tank 3, ranging between about 0.5 and 6.5 mV for increased tank CO/H_2 concentrations ranging between 350/175 ppm and 1500/750 ppm (Figure 86). Sensor voltage output did not settle quickly and seemed to just reach close to its peak value towards the end of the 30-minute exposure to each gas concentration. However, to keep the gas consumption and test times within reasonable limits, the 30-min duration was maintained.

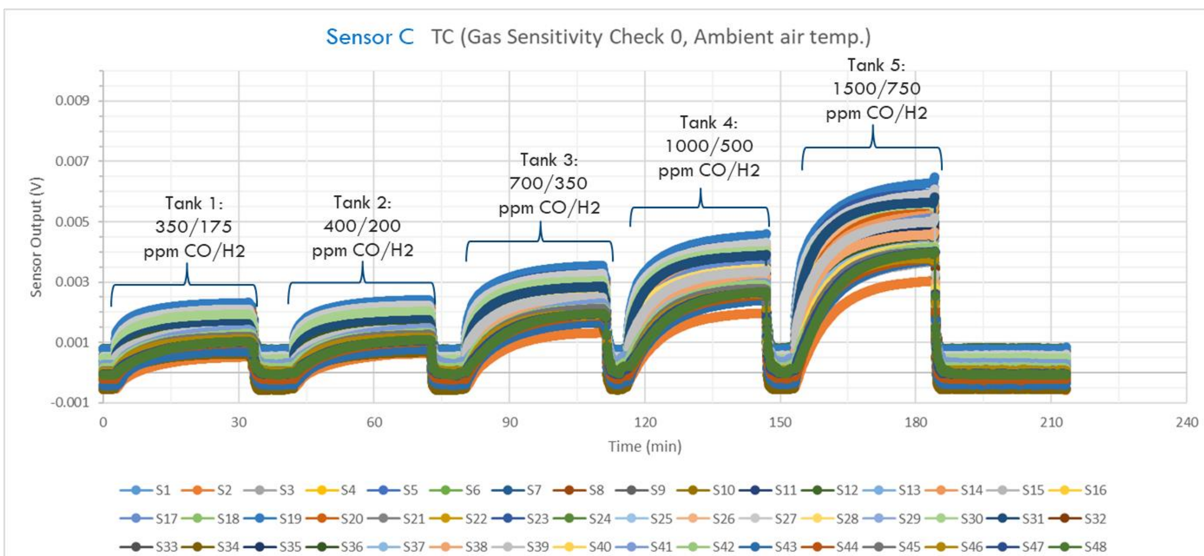


Figure 86: Sensor C TC, Baseline Check (GS0)

Supply voltages were steady and remained on average between 1.928 and 2.053 V throughout all gas sensitivity checks performed. The associated sensor current remained on average between 0.153 and 0.163 A. This was just above the expected current consumption of 0.130-0.150 A, despite applying the proper 2 V nominal voltage. APPENDIX J: Baseline Electrical Measurements shows the baseline voltage applied and current drawn, consistent with subsequent results over the course of testing.

Some fluctuation in signal output voltage was evident during exposure to temperature cycling, with sampling measurements taken every 15 minutes. This seemed to correspond with high and low temperature extremes within each cycle. Figure 87 shows a typical sensor response throughout exposure cycles, with sensor signal output fluctuating and drifting somewhat. This occurred after returning to 25°C with blower motors operating inside the chamber (maintaining set temperature).

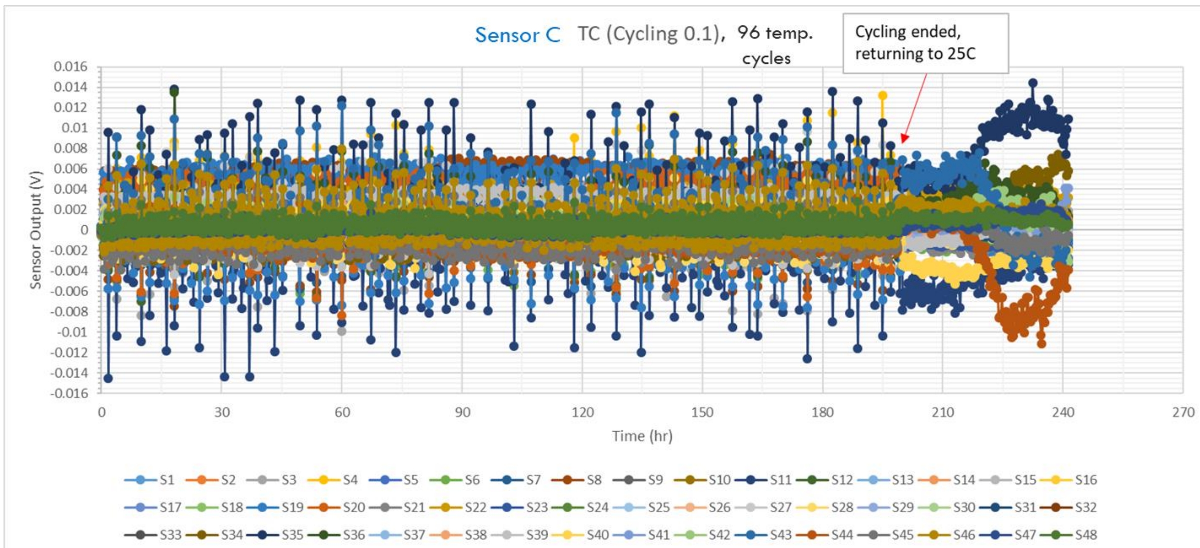


Figure 87: Sensor C TC, Sensor Output during Cycling

Sensor voltage increased slightly and sensor current drawn correspondingly decreased during exposure to cycling. APPENDIX J: Baseline Electrical Measurements shows typical voltage and current measured during cycling (with a minor chamber timeout noted in the first cycling exposure).

A few times during subsequent cycling, a chamber port hole plug had fallen out. Around 135 total cycles, the chamber remained at 230°C to 235°C for about 48 hours (unable to reach 260°C with the plug out). This was temporary and did not impact the results in subsequent cycling and gas sensitivity checks. The plug was restrained to prevent further occurrences.

The sensor signal output remained fairly consistent over the course of gas sensitivity checks performed. Following 96 cycles, the first gas sensitivity check (GS0.1) was performed. The sensors performed with signal output characteristics similar to the baseline. This continued through gas sensitivity check GS1 (after 672 cycles total) and to the final check GS1.6 (after 1056 cycles) (Figure 88). Some additional spread in the “zero” position across the sensors is noted compared to the baseline, but is not surprising with “zero” drift indicated by the manufacturer.

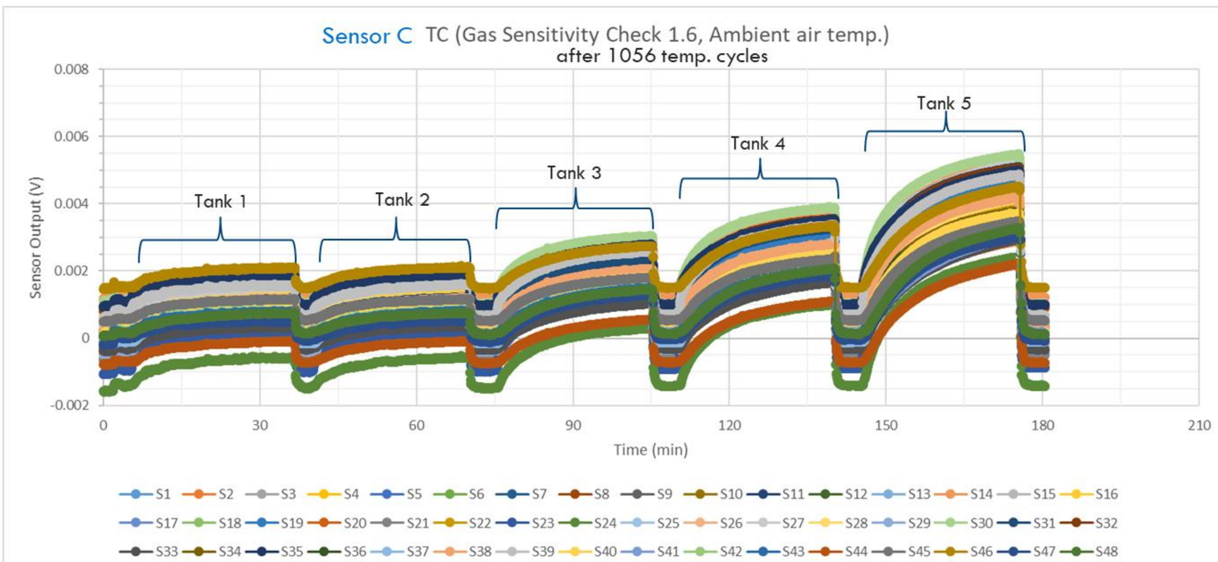


Figure 88: Sensor C TC, Final Gas Sensitivity Check (GS1.6)

Performance results for accuracy and stability were also evaluated against the specification (reference Table 18). Because of the extended time required to approach the sensor’s stable signal output, the reading was taken at the 90% mark of the 30-minute period gas was administered (equating to 27 minutes from the start of gas exposure). This provided consistency in measurements across gas sensitivity checks without averaging over the non-steady-state region of the signal response.

The signal output in Air at the 90% mark in the baseline check varied between -0.54 mV to 0.80 mV across all 48 sensors. By the last gas sensitivity check GS1.6 (after 1056 cycles), the spread about zero had increased to a range of -1.56 mV to 1.48 mV (Figure 89: Sensor C TC, Sensor Output with Ambient Air over Time). However, the change was within the tolerance for stability about “zero” (±2 mV).

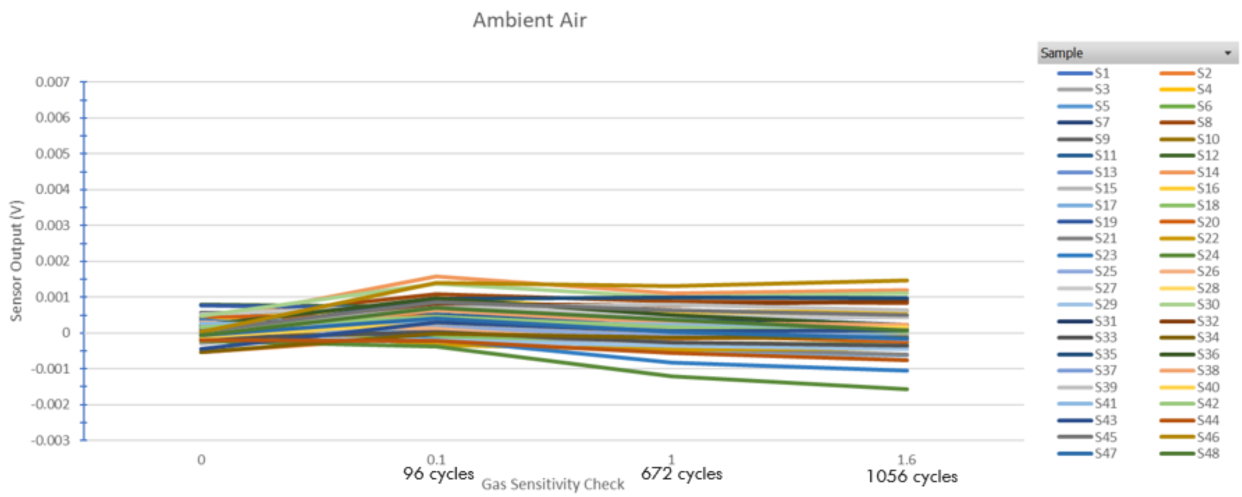


Figure 89: Sensor C TC, Sensor Output with Ambient Air over Time

Over the course of gas sensitivity checks, the signal output generally stayed the same or decreased slightly (Figure 90). The actual signal output with exposure to Tank 4 (1000/500 ppm CO/H_2) was about half the expected value of 6 mV. The exposure time was limited to 30 minutes, and so higher values may have been achieved with longer duration. The results of each sensor across all gas concentrations are provided in APPENDIX H: Sensor C TC, Gas Sensitivity Performance.

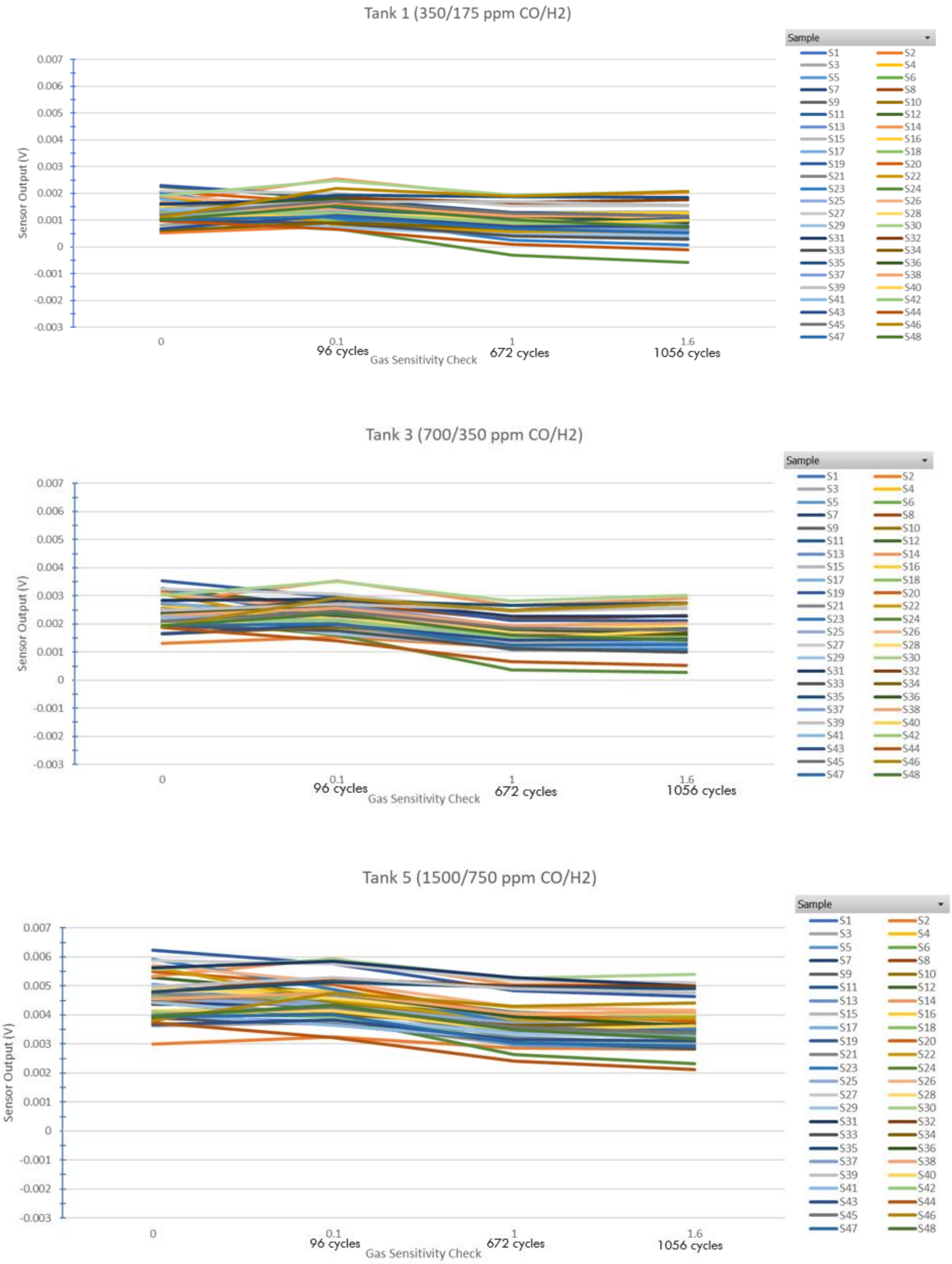


Figure 90: Sensor C TC, Sensor Output with Gas Concentrations over Time

Table 25 shows the summary of soft failures (with respect to accuracy and stability specification in Table 18). There were no hard failures. The stability tolerance of ±2 mV per year for "zero" and ±2 mV per month for gas sensitivity was additive each equivalent year and month, respectively, in testing. At GS1, representing about 1 year in the field, a tolerance of ±2 mV was applied for "zero" (response in Air) and ±24 mV was applied for gas sensitivity (response to gas concentrations). At GS1.6, a total of 36 sensors had exceeded the accuracy tolerance of ±0.5 mV, but there were no stability failures or hard failures. None of the sensors exceeded the stability tolerance when exposed to the 5 different gas concentrations (only in Air was the stability specification exceeded).

Table 25: Sensor C TC, Failure Summary (among 48 sensors tested)

		Soft Failures		Hard Failures (first instance)
GS Check	**Cycles Completed**	**Accuracy (in Gas Concentrations)**	**Stability (in Ambient Air)**	
0.1	96	S4, S12, S14, S17, S19 - S24, S26, S29, S30, S32, S35, S43 - S46, S48	S1 - S4, S6 - S8, S11, S13, S14, S16, S22, S23, S30 - S32, S34 - S40, S42, S43, S45 - S48	--
1	672	S1, S3, S5 - S7, S9 - S13, S15 - S29, S31, S33, S35 - S38, S40 - S44, S46, S47	--	--
1.6	1056	S1, S3, S5 - S7, S9 - S13, S15 - S29, S31, S33, S35 - S37, S41 - S48	--	--

4.3.2 THB Results

The number of gas sensitivity checks was increased from that planned (refer to Table 14). In the OFF-cycle exposure, gas sensitivity checks were performed every 6 days (144 hours) instead of 12 days. Every whole number gas check in the OFF-condition corresponded with 12 days (288 hours) in test, or 0.6-yr field equivalency for test duration with 0 failure.

A baseline gas sensitivity check in the OFF condition (GSOFF0) was performed with each of the five tanks (gas concentrations listed in Table 16) prior to exposure testing. All 20 sensors had progressively increased signal output starting with Tank 3, ranging between about 0.5 and 6.0 mV for increased tank CO/H_2 concentrations ranging between 350/175 ppm and 1500/750 ppm (Figure 91). Sensor voltage output appeared to settle sooner to its peak value than during TC gas sensitivity checks during 30-minute exposure to each gas concentration. The sensors were suspended downwards into a THB gas sensitivity box, a different setup than that used for TC gas sensitivity checks that likely accounted for this response difference. It was noted that sensor output shifted at times on several sensors when the adapter plate lid to the gas sensitivity chamber was placed down.

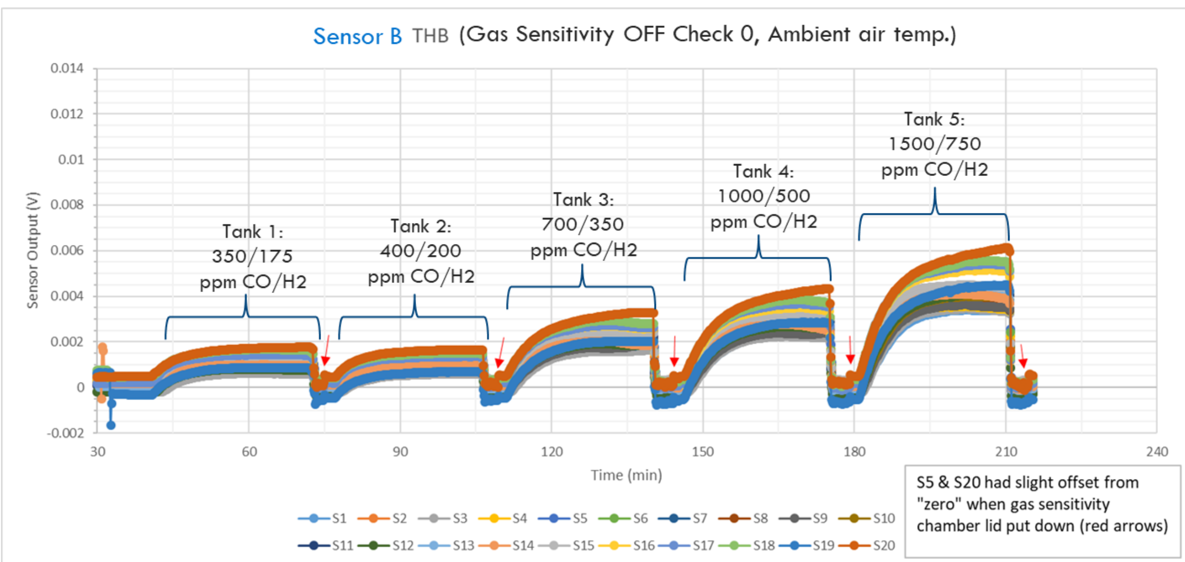


Figure 91: Sensor C THB, Baseline Check (GSOFF0)

After initial adjustment, supply voltages were steady and remained on average between 1.928 and 2.053 V throughout all gas sensitivity checks performed. The associated sensor current remained on average between 0.153 and 0.163 A. This was just above the expected current consumption of 0.130-0.150 A, but the same as the samples used for TC testing. APPENDIX J: Baseline Electrical Measurements shows the baseline voltage applied and current drawn, consistent with the initial subsequent results in testing.

Signal output voltage was elevated but stable inside the autoclave when voltage was supplied during THB exposure. Figure 92 shows a typical sensor response during initial THB exposures.

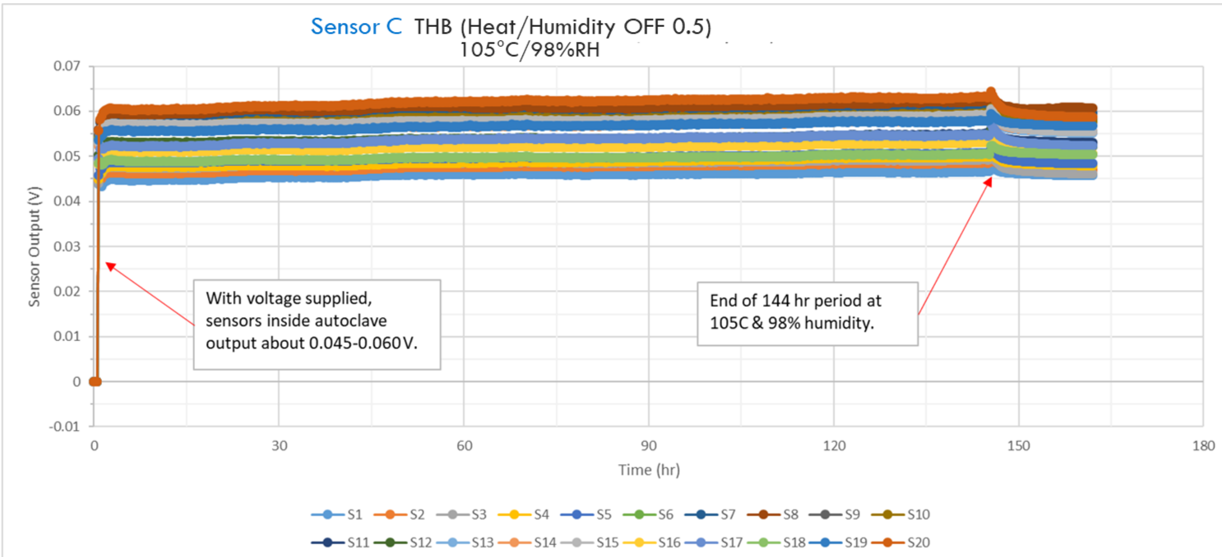


Figure 92: Sensor C THB, Sensor Output during THB Exposure

Sensor voltage increased slightly and sensor current drawn correspondingly decreased during THB exposure. APPENDIX J: Baseline Electrical Measurements shows typical voltage and current measured during exposure.

After 288 total hours of THB exposure under the OFF conditions, samples S6 through S10 exhibited higher output than initially (Figure 93). These sensors were grouped to a common ground through the HAST terminal pins. This response continued up to 110 mV output at the end of 576 total hours of THB exposure (total time under the OFF conditions).

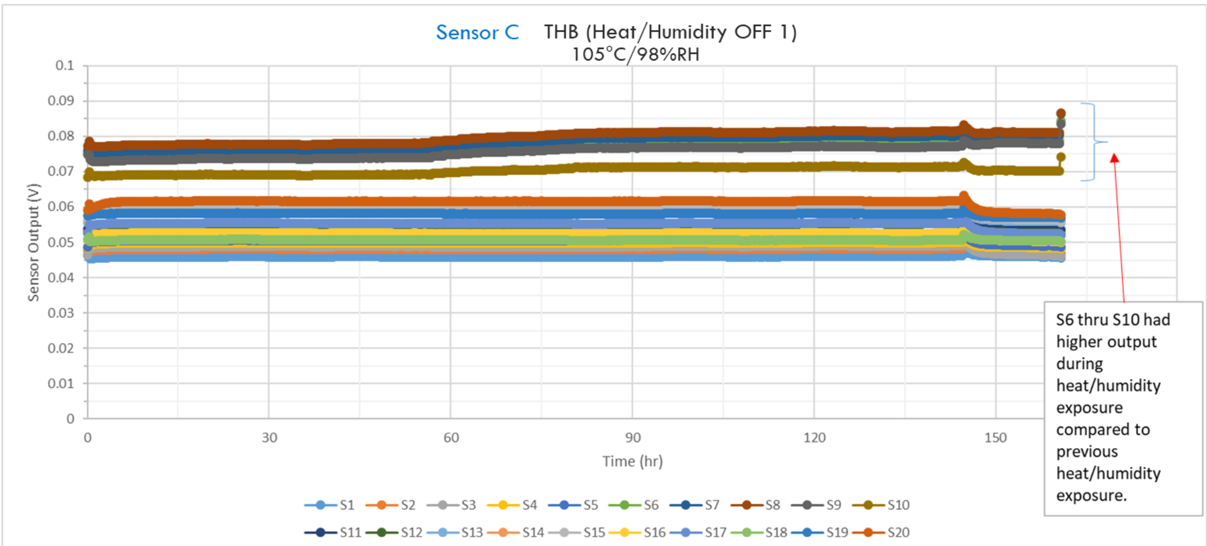


Figure 93: Sensor C THB, Sensor Output Increase under THB Exposure

Anomalous behavior began during gas sensitivity check GSOFF2 following 576 total hours of THB exposure. Sample S14 had shifted in offset and had spikes in output during gas sensitivity testing (Figure 94).

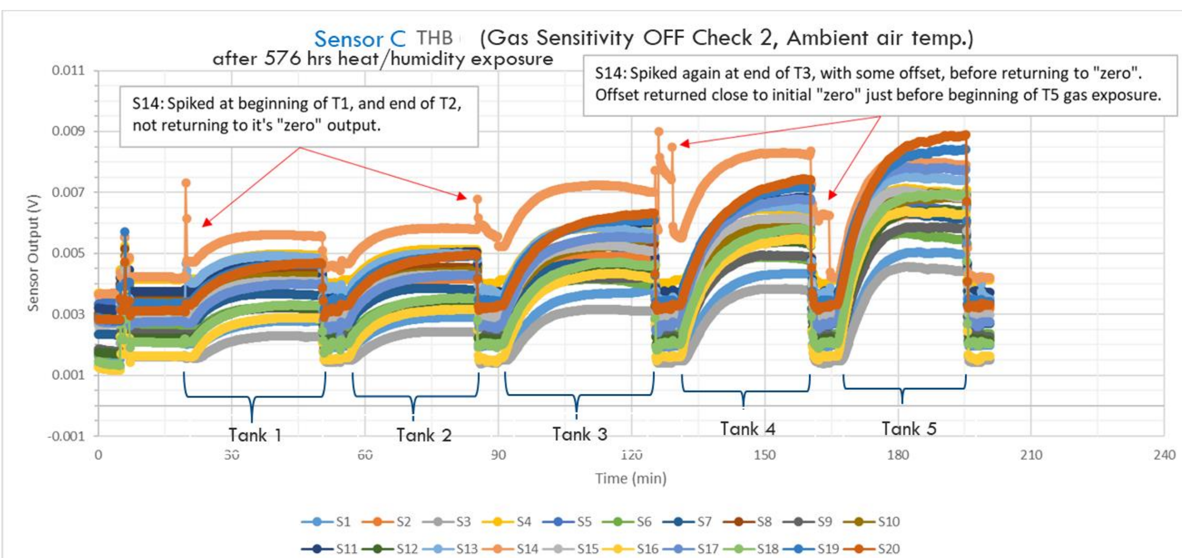


Figure 94: Sensor C THB, Sensor Output Anomalous Behavior (GSOFF2)

Other sensors exhibited shifts and spikes in output during later gas sensitivity checks up to 1152 total hours of THB exposure (Figure 95).

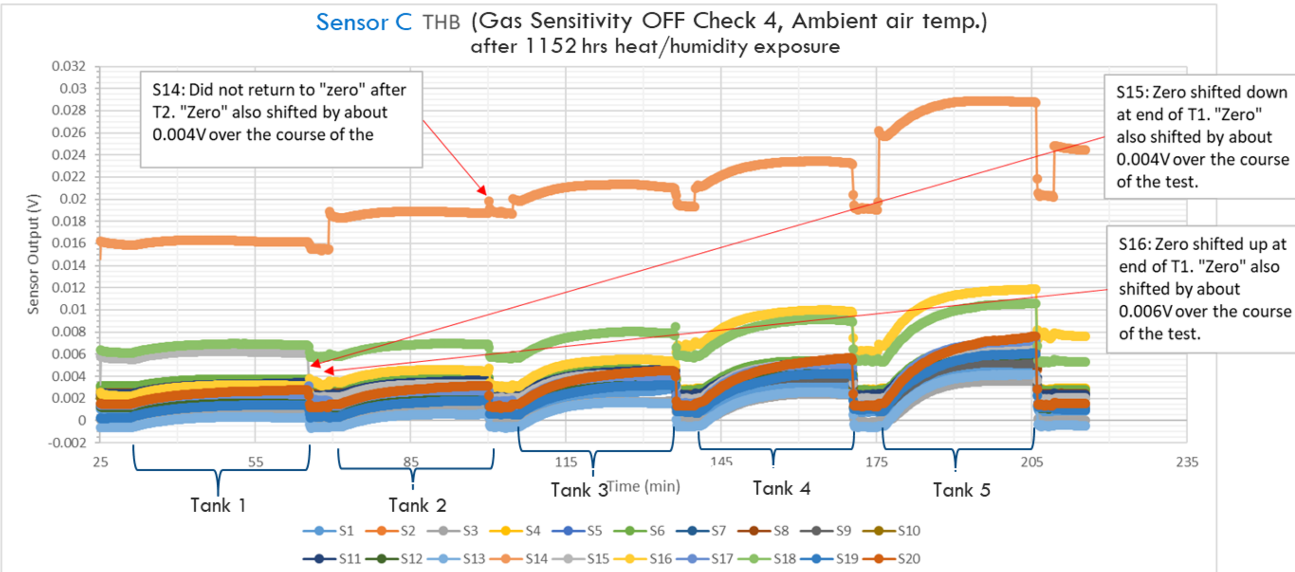


Figure 95: Sensor C THB, Sensor Output Anomalous Behavior (GSOFF4)

Some sensors had drifting sensor output and current draw during THB exposure. Figure 96 shows an example of varying output in samples S5 and S6 through S10 during exposure up to 1008 total hours (between the third and fourth gas sensitivity checks). Corresponding current draw variation is shown in Figure 97. The performance variances observed were indicative of connector issues.

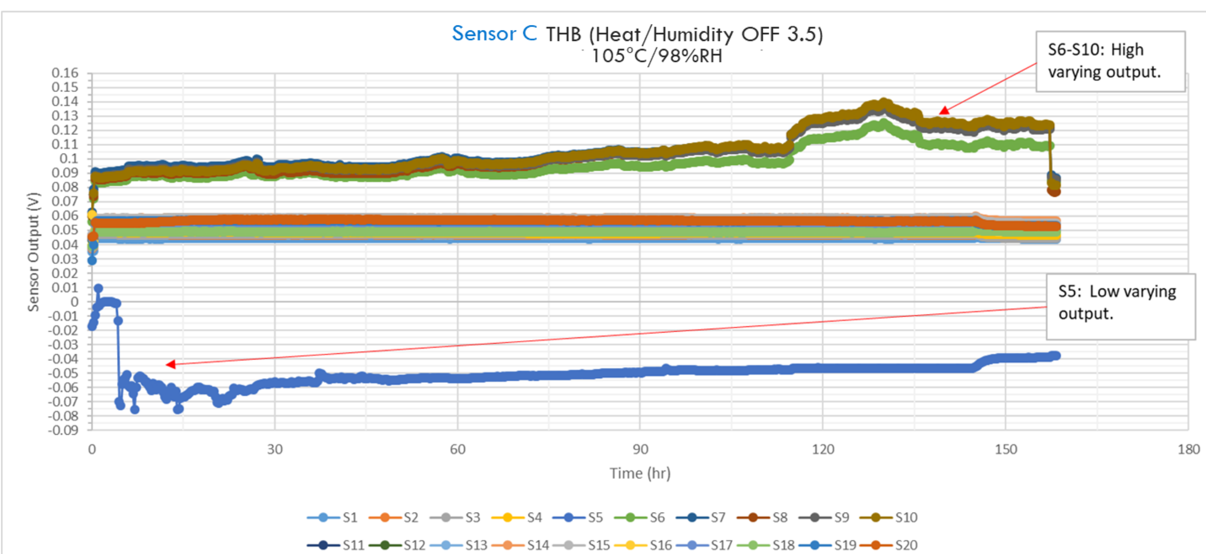


Figure 96: Sensor C THB, Sensor Output Variances during THB Exposure

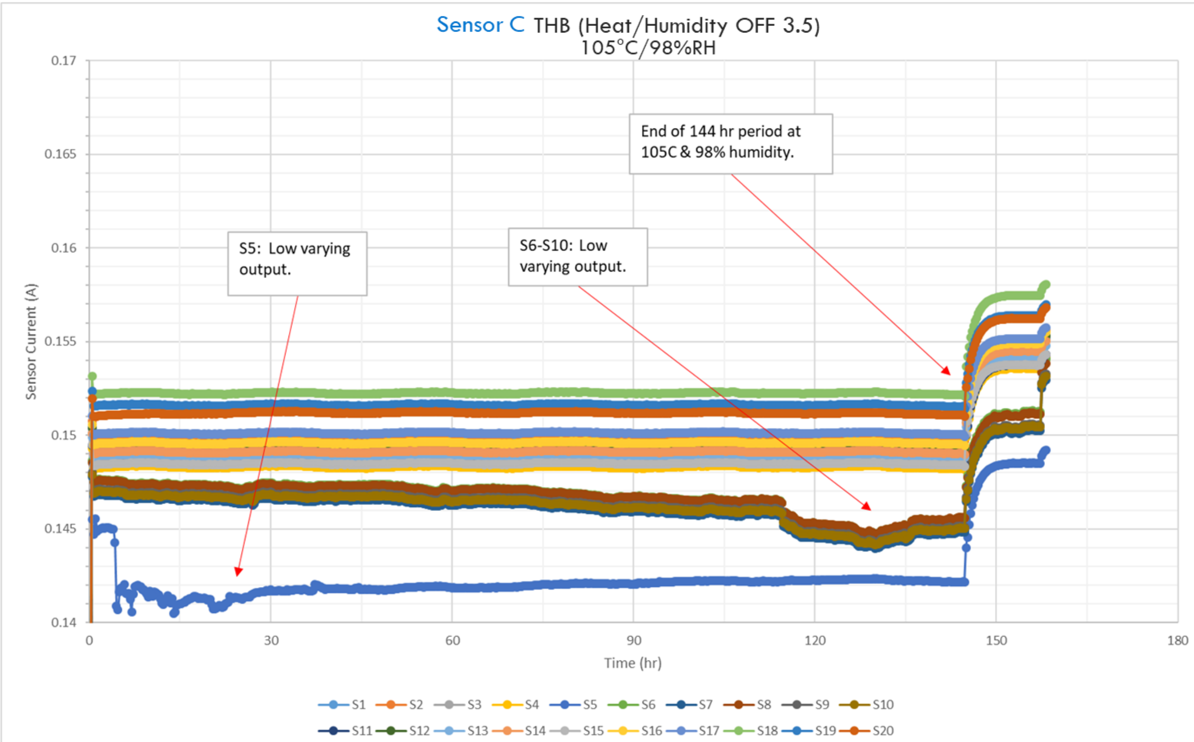


Figure 97: Sensor C THB, Sensor Current Variances during THB Exposure

A total of 1152 hours of THB exposure had been completed without hard failures. Rather than continue in the OFF-conditions further, the samples were removed from the chamber. They were set aside for about 1.5 months in a controlled room-temperature environment until the Sensor B samples had completed their OFF-conditions testing in the same autoclave. The Sensor C samples were then placed back into the autoclave to begin ON-condition testing.

Some variation in sensor output existed during THB exposure, but results were similar to the initial THB exposure period measurements. Voltage supply and current were also similar. But upon startup of the first gas sensitivity check following the ON-condition exposure, significant sensor output variation existed in ambient air (no gas concentration applied), along with voltage supply and sensor current drawn. The connectors inside and outside of the autoclave were then replaced with new Dsub9 connectors containing 30 micro-inch gold plating. Voltage supply and current drawn were as expected afterwards (in line with baseline results).

Figure 98 shows the first gas sensitivity check (GSON1) results following the ON-conditions THB exposure for 912 hours. Response occurs with exposure to each of the five tanks (gas concentrations listed in Table 16), with significant drift from “zero” (similar in magnitude as before). Average voltage supply across the 20 sensors was tighter, ranging between 1.936 to 2.012 V.

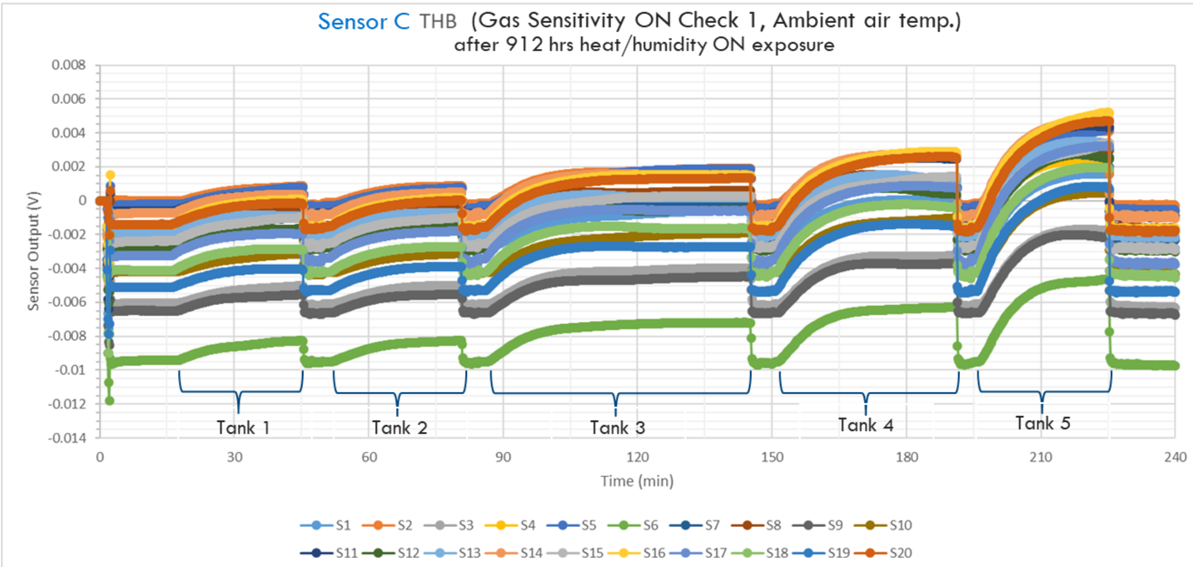


Figure 98: Sensor C THB, Sensor Output after new Dsub9 Connectors installed (GSON1)

However, fluctuation in sensor output with corresponding current draw occurred again with several sensors during the subsequent exposure to THB (Figure 100 and Figure 100). The first occurred with sample S20 after about 112 hours in this second ON-conditions exposure period. These were signs of connector degradation due to the harsh temperature and humidity environment within the autoclave. A robust connector solution was needed before further testing continued, and these were later replaced again with an Amphenol Aerospace MIL-DTL-38999 high temperature connector (discussed in next section).

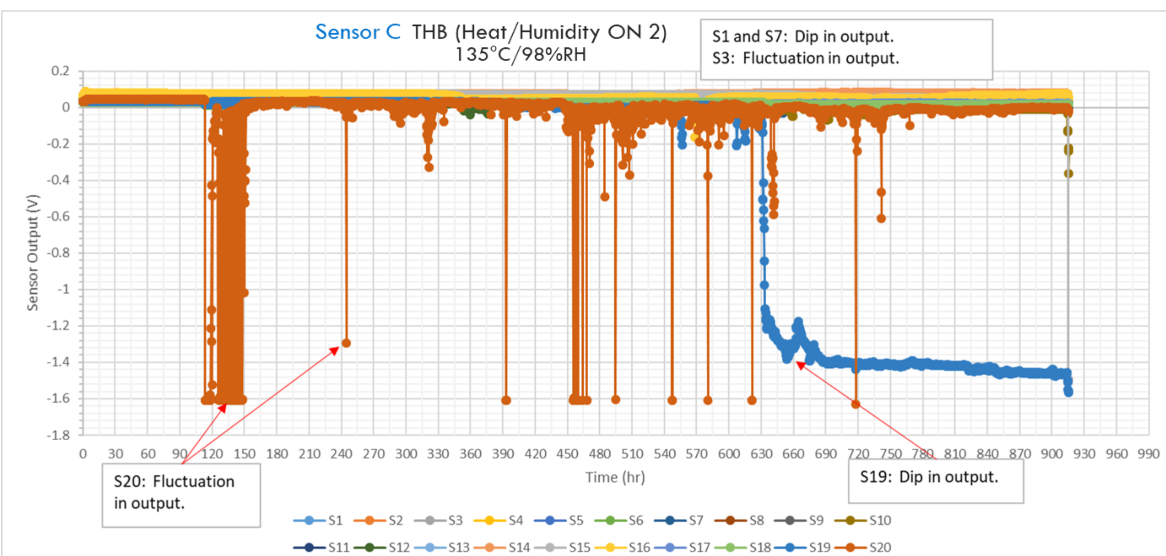


Figure 99: Sensor C THB, Sensor Output Variances during THB Exposure with New Dsub9 Connectors

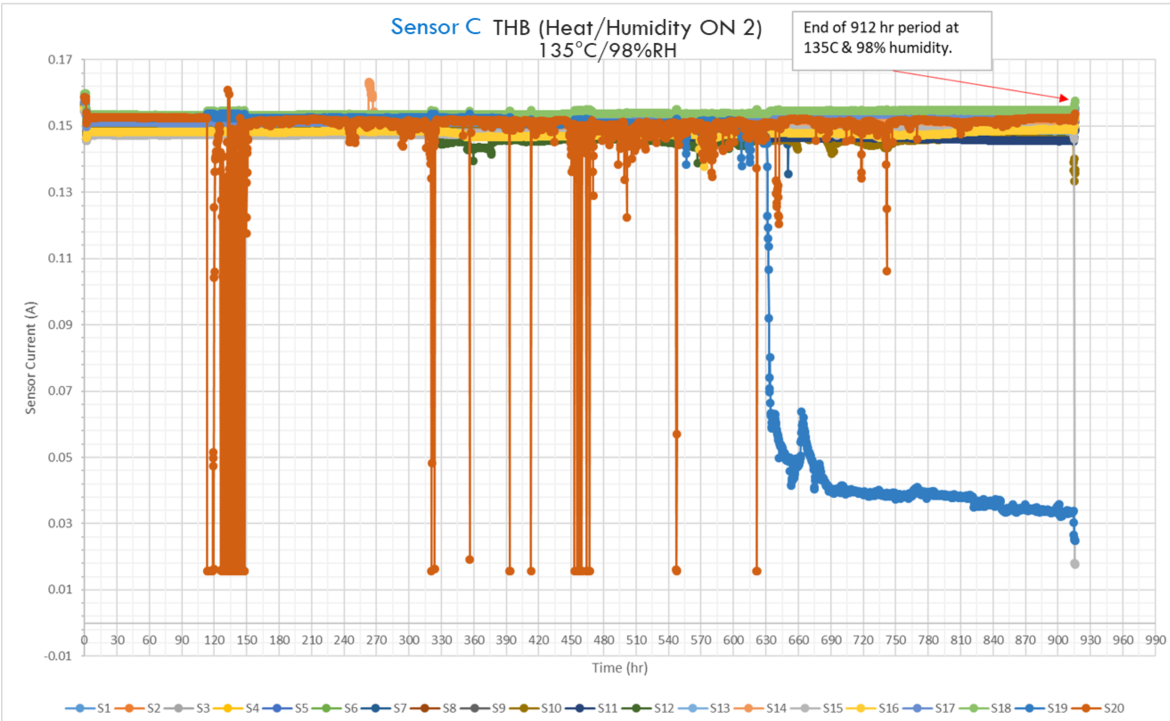


Figure 100: Sensor C THB, Sensor Current Variances during THB Exposure with New Dsub9 Connectors

4.3.2.1 High Temperature MIL-Standard Connector and Silicone Wire Installed

The Dsub9 connectors inside the autoclave were replaced with an Amphenol Aerospace MIL-DTL-38999 Series III TV connector containing 41 contacts (Figure 101). The connector is designed for surviving the harsh temperature and humidity environment:

- Temperature rated -65°C to 175°C
- 50 micro-inch gold plated crimp-style pins
- Sealed connector meets MIL-DTL-38999 Series III requirements for electrolytic erosion resistance
- Cadmium plated aluminum housings
- 500-hr salt spray rated

Figure 101: Amphenol Aerospace MIL-DTL-38999 Series III TV Connector

The wire inside the chamber was replaced with high temperature silicone wire (22 AWG) (Figure 102).

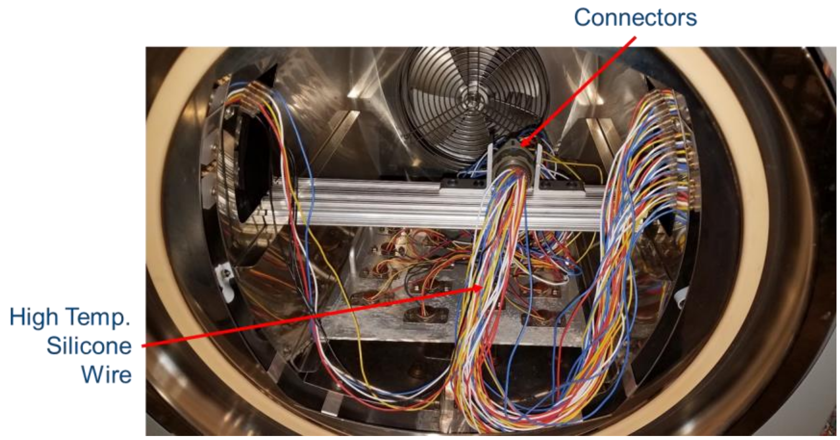


Figure 102: High Temperature Silicone Wire with Amphenol Aerospace Connector

4.3.2.2 Results with High Temperature MIL-Standard Connector

After the new MIL-standard connector was installed with silicone wire, all sensors behaved as expected (with good voltage supply and sensor output). Average voltage supply across the 20 sensors ranged between 1.976 to 2.050 V. Average current draw ranged between 0.157 to 0.161 A. All sensors were re-zeroed to within 0 mV to 0.8 mV. A significant amount of adjustment to decrease the sensor output was needed due to the amount of drift that had occurred over the course of testing and handling (Table 26). This was accomplished through rotation of the variable resistor in the PCB container.

Table 26: Sensor C THB, Re-zero of Sensors

Sensor	Decrease to "Zero" (mV)	Sensor	Decrease to "Zero" (mV)
S1	34.6	S11	38.2
S2	38.7	S12	38.7
S3	34.4	S13	38.3
S4	37.3	S14	38.5
S5	40.6	S15	36.6
S6	29.2	S16	38.2
S7	37.5	S17	36.6
S8	37.7	S18	35.1
S9	31.9	S19	29.7
S10	32.3	S20	38.1
		Avg.:	36.1
		Max.:	40.6
		Min.:	29.2

Figure 103 shows the gas sensitivity check (GSON2) results to each of the five tanks (gas concentrations listed in Table 16) following replacement of the connectors. Results were very similar to the baseline results for sensor output, voltage supply, and sensor current.

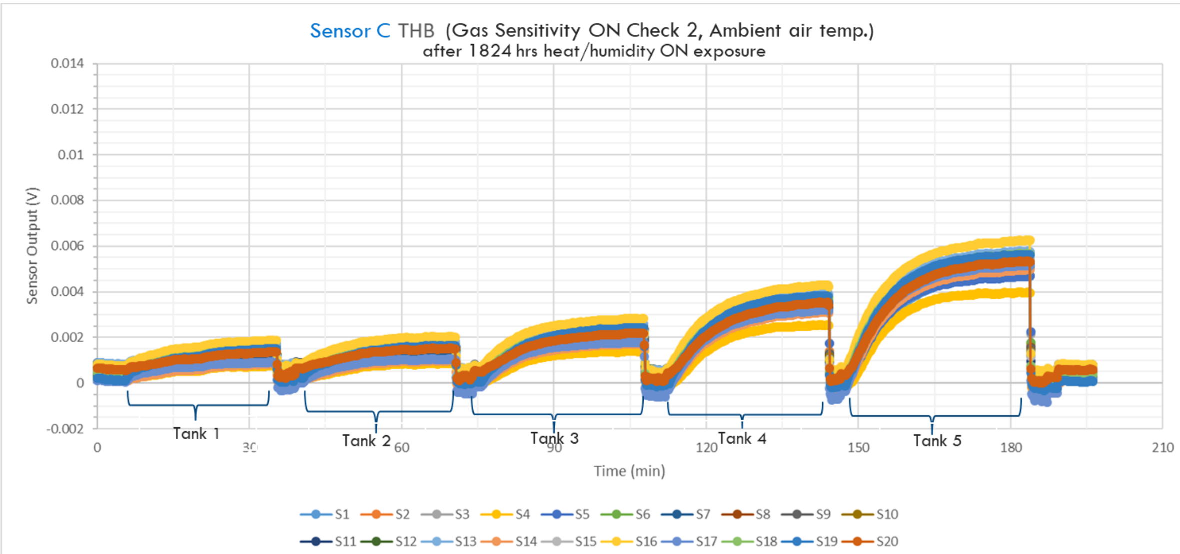


Figure 103: Sensor C THB, Sensor Output after MIL-Std Connector installed (GSON2)

During the subsequent third 912-hr THB exposure period, sensor output was elevated a bit more than previously prior to the connector change (Figure 104). However, the output was stable. Current draw was somewhat less with the same nominal 2.1 V voltage supply at high temperature (Figure 105).

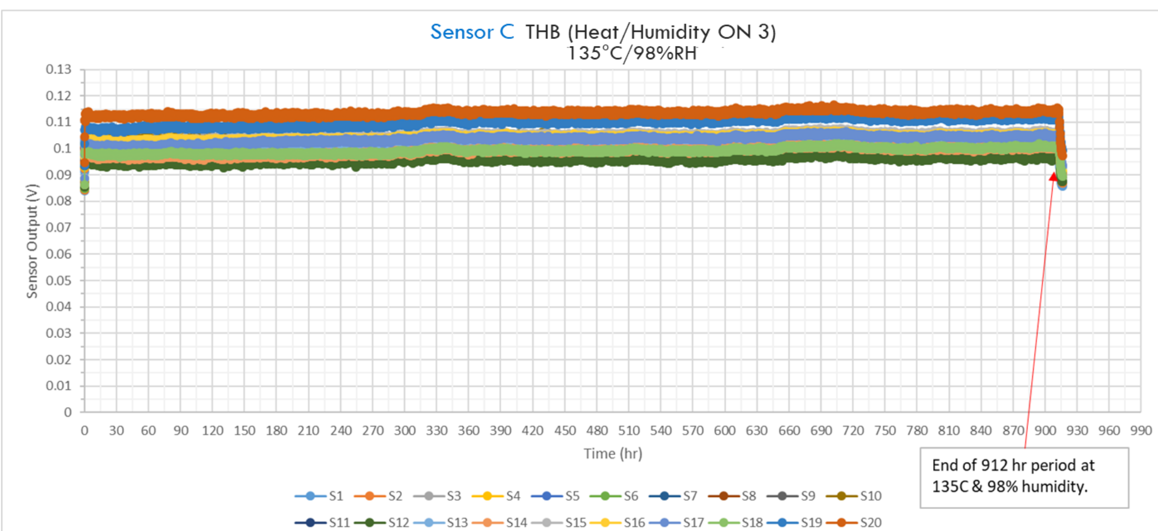


Figure 104: Sensor C THB, Sensor Output during third ON-Conditions THB Exposure

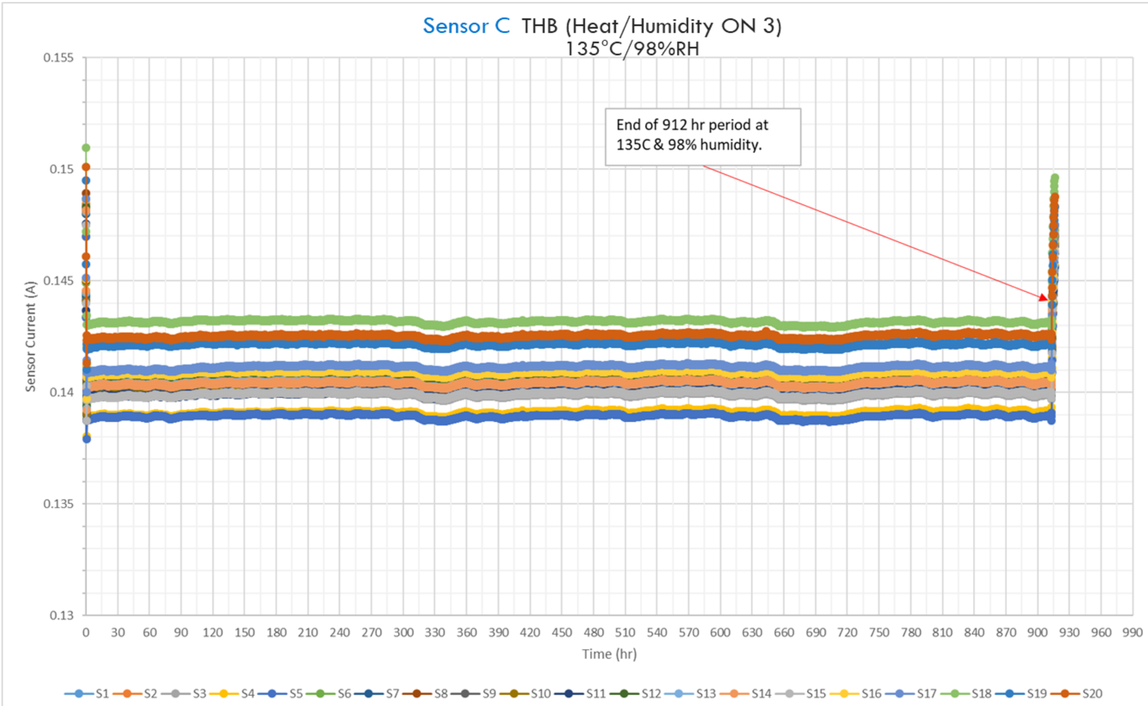


Figure 105: Sensor C THB, Sensor Current during third ON-Conditions THB Exposure

The next gas sensitivity check (GSON3) was conducted after a total of 2736 hours exposure to the ON-conditions. Supply voltage and sensor current were good, ranging from 1.928 to 1.999 V and 0.153 to 0.157 A, respectively. However, there was no real response to the gas concentrations when administered. Significant drift from “zero” occurred on many sensors. All 20 sensors were considered hard failures due to a lack of signal output under the presence of the gas concentrations. The gas sensitivity test was repeated 24 hours later (after having been left at room temperature conditions), with similar absence of any real signal output (Figure 106).

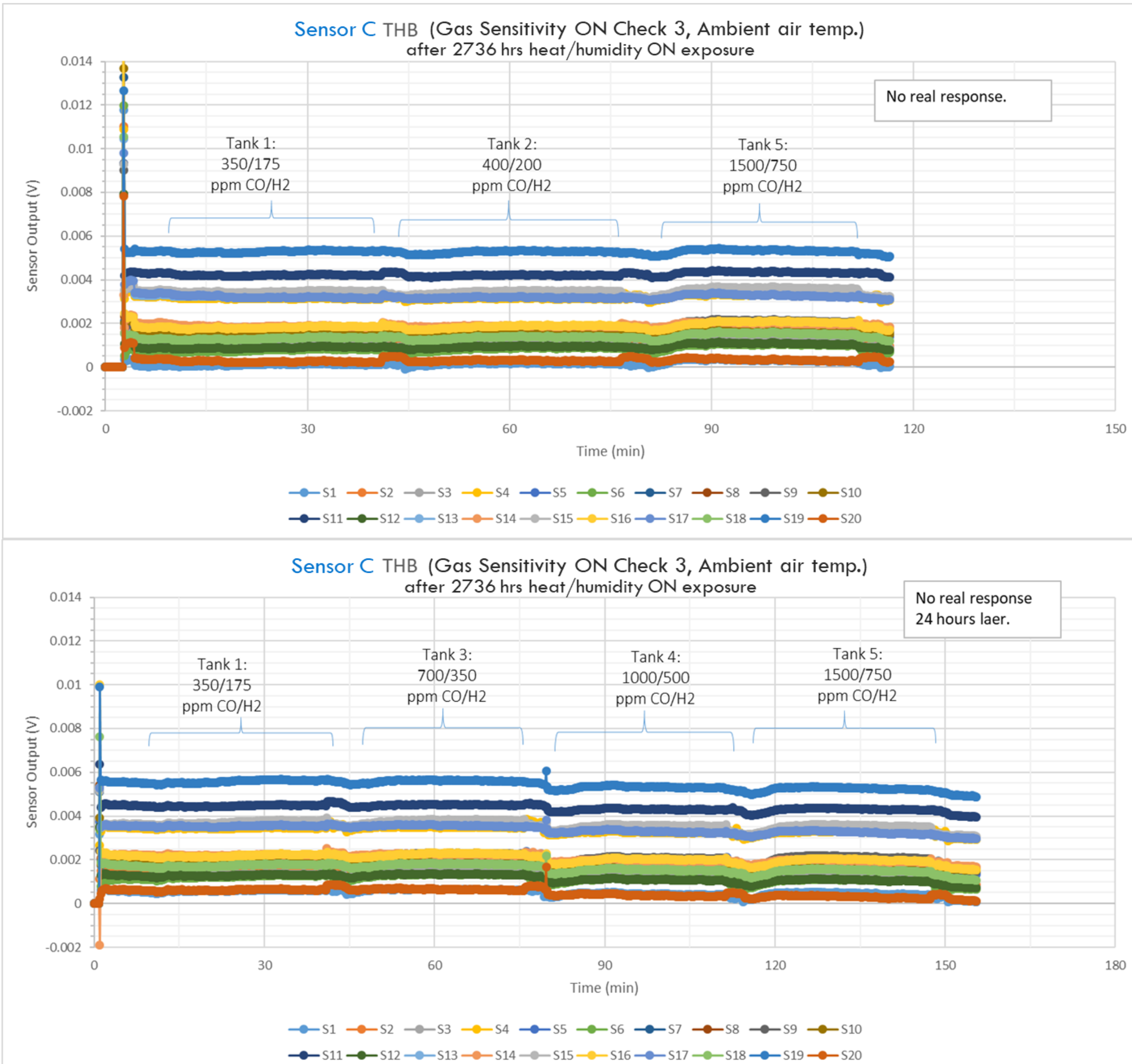


Figure 106: Sensor C THB, Absence of Sensor Output (GSON3)

Performance results for accuracy and stability were also evaluated against the specification (reference Table 18). Consistent with the Sensor C TC gas sensitivity checks, the readings were taken at the 90% mark of the 30-minute period gas was administered (equating to 27 minutes from the start of gas exposure).

The signal output in Air at the 90% mark in the baseline check varied between -0.32 mV to 0.47 mV across all 20 sensors. By gas sensitivity check GSON1 (after 1152 hours in OFF-conditions and 912 hours in ON-conditions, and prior to replacement with the MIL-Std high temperature connectors and re-zeroing of all sensors), the spread about zero had increased to a range of -9.43 mV to -0.03 mV (Figure 107). The stability tolerance about “zero” (±2 mV per year), assuming just over 2 years equivalent in the OFF-conditions and just under 1 year in the ON-conditions, was exceeded on samples S6 and S9.

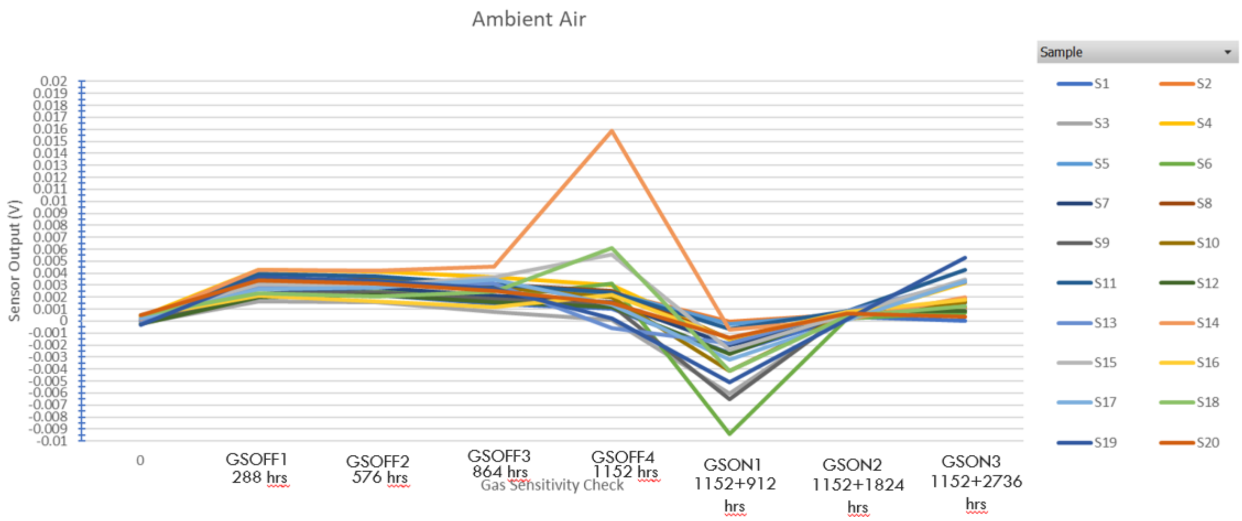


Figure 107: Sensor C THB, Sensor Output with Ambient Air over Time

Over the initial course of gas sensitivity checks, the signal output increased generally in line with the drift in “zero” (Figure 108). This output was consistent across all gas concentrations. The last gas sensitivity check (GSON3, after 1152 hours in OFF-conditions and 2736 hours in ON-conditions) was tested with Tanks 1, 2, and 5, with no real response change. The results of each sensor across all gas concentrations are provided in APPENDIX I: Sensor C THB, Gas Sensitivity Performance.

Figure 108: Sensor C THB, Sensor Output with Gas Concentrations over Time

Table 27 shows the summary of soft failures (with respect to accuracy and stability specification in Table 18) and hard failures. For soft failures, the stability tolerance of ±2 mV per year for "zero" and ±2 mV per month for gas sensitivity was additive to each equivalent year and month, respectively, in testing. For example, at GSOFF2, representing about 1.2 years in the field for the OFF-conditions, a stability tolerance of ±2.4 mV was applied for "zero" (response in Air). A stability tolerance of ±28.3 mV was applied for gas sensitivity (response to gas concentrations). None of the sensors exceeded the stability tolerance when exposed to the 5 different gas concentrations (only in Air was the stability specification exceeded).

Table 27: Sensor C THB, Failure Summary (among 20 sensors tested)

			Soft Failures		**Hard Failures (first instance)**
Condition	**GS Check**	**Hours Completed**	**Accuracy (in Gas Concentrations)**	**Stability (in Ambient Air)**	
OFF	1	288	S1 - S20	S1 - S20	--
	2	576	S1 - S20	S2, S4, S5, S7, S8, S10 - S15, S17, S19, S20	--
	3	864	S1 - S20	S14	--
	4	1152	S1, S2, S4 - S20	S14, S15, S18	--
ON	1 [1]	912	S1 - S20	S6, S9	--
	2 [2]	1824	S1 - S20	--	--
	3	2736	S1 - S20	--	S1 - S20

1. Connectors replaced with new 30 micro-inch gold Dsub9 connectors.
2. Connectors replaced with MIL-Std high temp. connector and silicone wires. Sensors re-zeroed.

5 Failure Analysis

A failure analysis was conducted for the failed groups of sensors within each test to better understand the failure site and mechanism for the failure mode(s) observed.

5.1 Sensor A

5.1.1 TC Failure Analysis

Among the hard failures in temperature cycling, two main failure modes were observed:

- Varying sensor output of 2-4 V (no gas present)
- Maximum sensor output of 4 V (no gas present)

Sample S3 experienced the former. Sample S8 experienced the latter initially, with some fluctuation, before later exhibiting varying 2-4V output (with no gas administered). Signs of some cracking of the conformal coat and discoloration of the flux residues trapped underneath are evident near the soldered connections (similar on both samples, as well as on a good sample S7) (Figure 109). Coefficient of thermal expansion (CTE) mismatch between the flux residues and conformal coating can cause this type of deterioration.

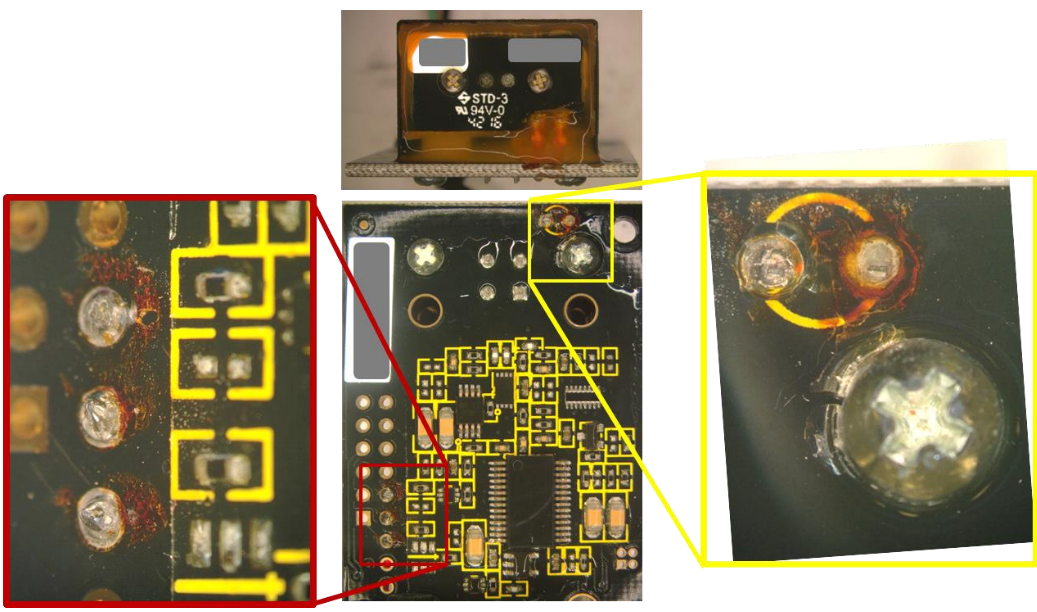


Figure 109: Sensor A TC, Sample S3 External after TC Exposure

The units were electrically characterized. Output from the microprocessor (U4) appeared normal on startup for both, but within 1 minute this output went to <1% duty cycle. Resistance measurements across the 3 wire pins on the bottom were similar for both sample S8 and the good sample S7 (about 275 kOhm across pins 1 and 2, about 299 kOhm across pins 2 and 3, and about 570 kOhm across pins 1 and 3).

Two units were sent to the manufacturer for further evaluation:

- Sample S8: Hard failure
- Sample S7: Good sample (had momentary spike to 4 V during testing, but was not a hard failure)

The manufacturer evaluated sample S8 and observed oscillating output between 2 and 4 V, suggesting continual reboot. Sensor internal ADC measurements of temperature were correct based on sensor communication with the UART interface. The ADC measurement indicated low detector signal for CO_2 channel and low signal for the reference channel (out of bounds of diagnostic limits, resulting in reboot). No issue was found with any component in the detector-to-amplifier circuit.

The detector pin connections appeared to lead to the failure. The manufacturer reported that after solder was reflowed on the detector pins, the CO_2 signal and reference signal measured within expected range. The failure was confirmed, but root cause is not known.

5.1.2 THB Failure Analysis

The two hard failure modes experienced in THB testing were very similar to TC testing. Of the two below, the second was much more prevalent:

- Varying sensor output of 2-4 V in general (no gas present); one sensor varied between 1.25-1.75 V
- Constant non-zero sensor output (no gas present)

Some corrosion and flux residues were noticeable on the bottom side of the board (Figure 110). Some corrosion/contamination existed between the ground and signal output leads on sample S10 (similar to sample S16). These are cause for concern because they can lead to electrical shorting, but not necessarily problematic since the failures were not found to be indicative of electrical shorts.

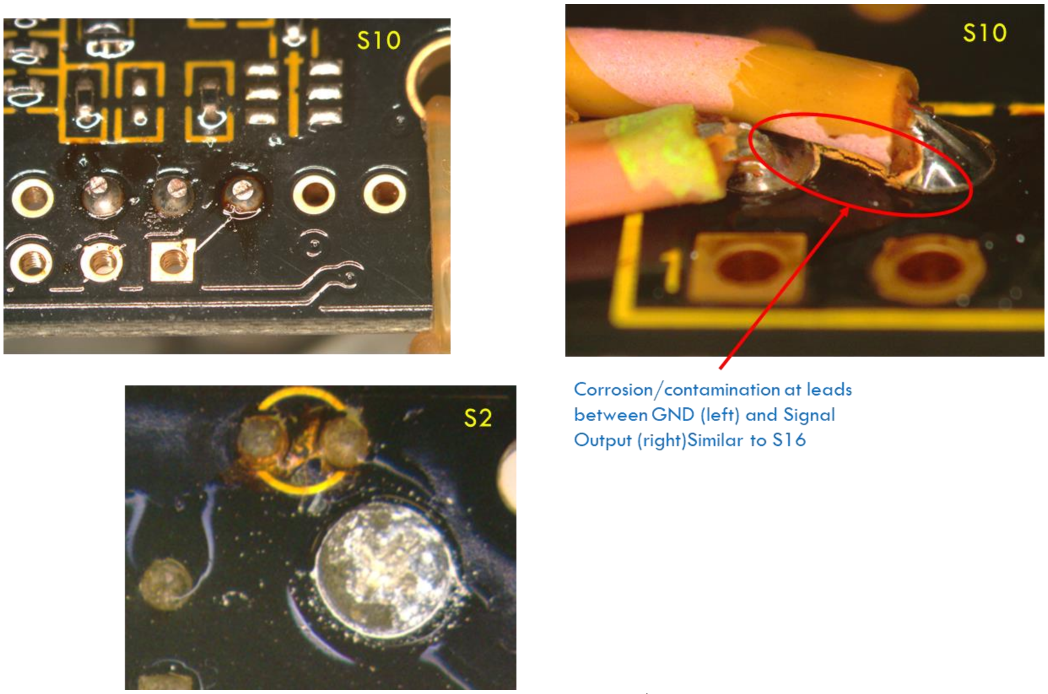


Figure 110: Sensor A THB, Corrosion/Contamination

A total of 6 sensors representative of the hard failures were sent to the manufacturer for evaluation (Table 28). The varying sensor output failure mode was due to an infrared detector failure associated with high resistance failure of the thermistor element and, in some cases, the thermopile element. This failure mode was somewhat intermittent, as sample S37 later responded with sensor output when exposed to low and high gas concentrations. The two constant non-zero sensor output failure mode samples had capacitor failure, causing the infrared lamp to not work. The manufacturer reported these two sensors being functional after replacing the capacitor, but not within the accuracy specifications.

Table 28: Sensor A THB, Summary of FA Findings

Sensor	Failure Mode	Findings
S10	Varying 2-4 V Output	Infrared detector failure (high resistance failure of thermistor element *and* thermopile element no. 2)
S16	Varying 2-4 V Output	Infrared detector failure (high resistance failure of thermistor element *and* thermopile element no's. 1 and 2)
S36	Varying 2-4 V Output	Infrared detector failure (high resistance failure of thermistor element)
S37	Varying 2-4 V Output	Infrared detector failure (high resistance failure of thermistor element)
S2	Constant ~1.75 V Output	Infrared lamp was out. Capacitor had failed (low resistance)
S12	Constant ~2.25 V Output	Infrared lamp was out. Capacitor had failed (low resistance)

The bypass capacitor (Figure 111) works with the linear voltage regulator. Its failure caused the regulator to output a low voltage to the infrared lamp.

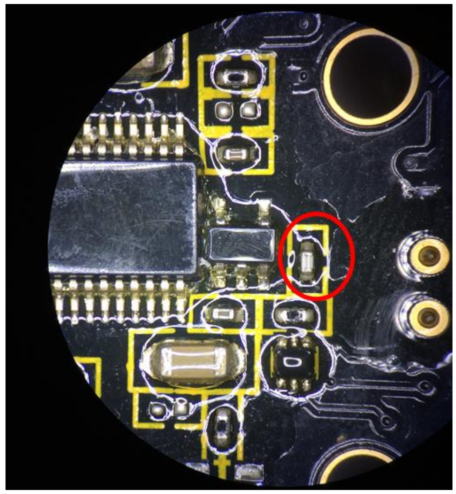


Figure 111: Sensor A THB, Bypass Capacitor Failure (Low Resistance)

5.2 Sensor B

5.2.1 TC Failure Analysis

Two main failure modes were experienced during TC testing:

- Soft Failure: Decay in signal output (following initial sensing of gas concentration)
- Hard Failure: No signal output (both electrodes)

Decay in signal output is discussed in section 5.2.2, as the sensors that underwent THB exposure testing exhibited more of a pronounced decay in signal output.

Sample S6 was the one sensor characterized as a hard failure during testing. No response from either electrode existed when exposed to gas concentrations. Heater resistance was good at about 26 Ohms during testing, and likewise with heater power. The contacts on the front and back half of the sensor also looked fine, with no indication of a compromised electrical connection (Figure 112).

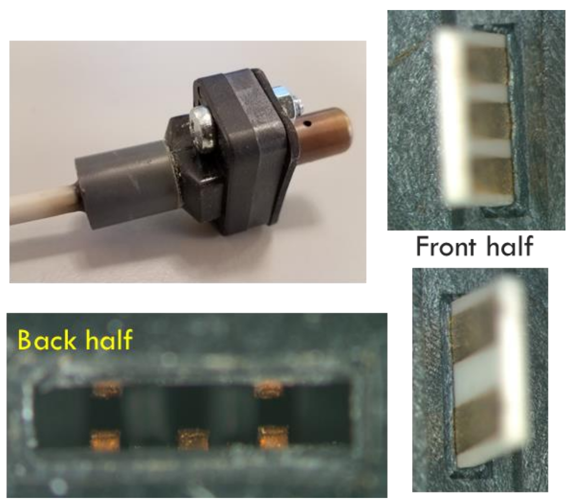


Figure 112: Sensor B TC, Sample S6

Sample S6 was sent to the manufacturer for evaluation. Initial observations by the manufacturer were similar. The root cause of the lack of signal output is not known.

Other sensors were noted for some degradation and melting of the back half of the sensor's elastomeric strain relief, but none of these were hard failures (Figure 113). Only sample S3 had loss of sensor output on one electrode, but recovered after the baseline check.

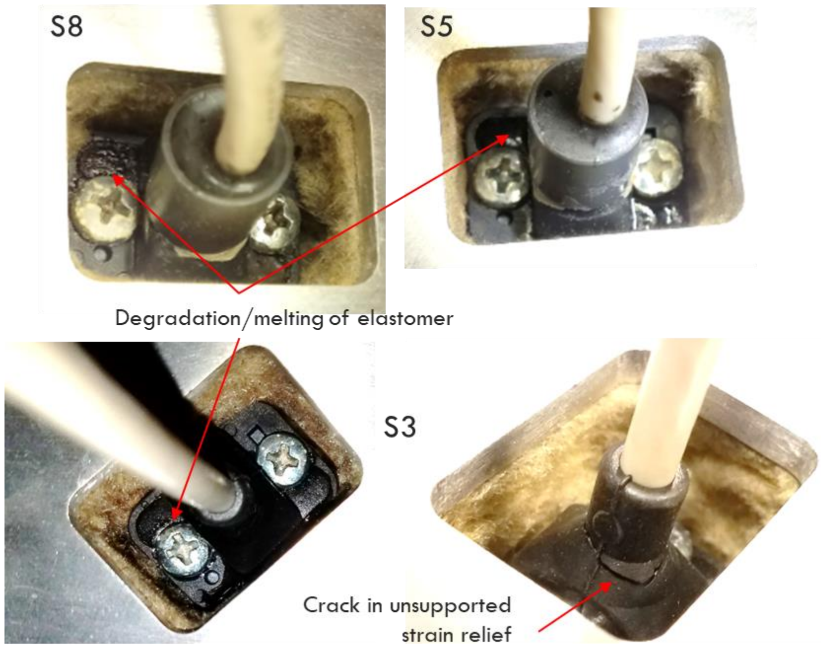


Figure 113: Sensor B TC, Degradation of Strain Relief

5.2.2 THB Failure Analysis

Three main failure modes were experienced during THB testing:

- Soft Failure: Decay in signal output (following initial sensing of gas concentration)
- Soft Failure: Fluctuating signal output about zero (one electrode)
- Hard Failure: No signal output (both electrodes)

5.2.2.1 Signal Output Decay

Decay in sensor signal output can occur when there is too high a concentration of CO and/or H_2 with low O_2. The sensor catalyst converts H_2 to H_2O and CO to CO_2 at high temperature with sufficient oxygen. When under less than stochiometric conditions for the catalyst reaction, signal output can be lost. However, the gas concentrations administered in test contain 3% O_2, well above the required 0.5% to 1% to maintain the reaction at the electrodes.

The manufacturer reported that the sensor is designed to be used near the wall of the exhaust duct. Airflow in this region is slightly less than at the tip of the sensor, and therefore the pressure is slightly higher. This is supposed to facilitate entry of air through the side holes and out the top center hole. The manufacturer has demonstrated that if the sensor is constricted to a small volume with no air-flow, the sensor signal output reduces close to zero within a few seconds.

DfR Solutions conducted additional testing of sample S3 to better understand the degrading signal output. This sensor was the only one not characterized as a hard failure in the last gas sensitivity check (GSON1), in which electrode Usen1 produced no output to gas concentrations while the second electrode Usen2 did. The sensor was placed in a small chamber supplied by the manufacturer to reduce the volume surrounding the sensing element. Electrode Usen2 responded initially with 0.4 LPM flowrate (400 sccm) from Tank 1 gas concentration (350/175 ppm CO/H_2) applied, and then decayed. The response mimicked that observed during the GSON1 check. However, it did not respond subsequently, even with varying flowrates from 0.1 to 1 LPM (Figure 114).

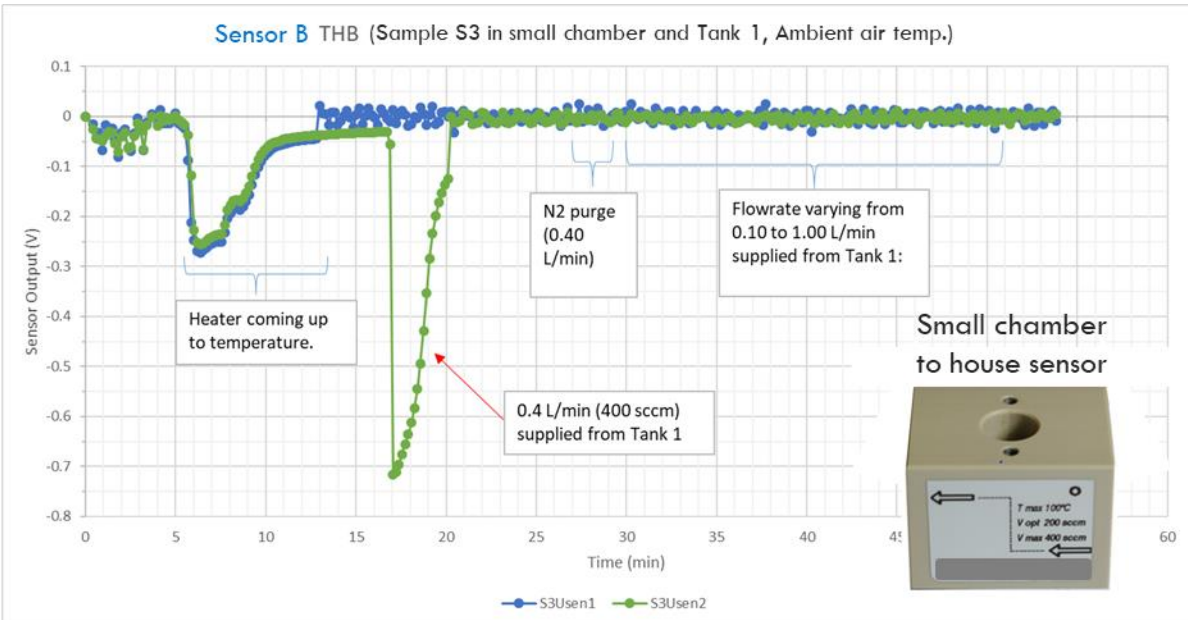


Figure 114: Sensor B THB, Sample S3 Initial Response Inside Small Chamber

Later, it was removed from the small chamber and subjected to the Tank 1 gas concentration administered near the sensor capsule while it was on a table top in ambient air. Both electrodes responded, although intermittently at one point for Usen1. When placed back in the small chamber, only Usen2 responded before decaying again.

The decay in signal output occurs even at a relatively high flowrate in a small volume. This indicates that the sensor consumption of H_2 and CO does not outpace the supply of oxygen (at 3% concentration in the administered gas). However, the decaying signal output is not clearly understood. If the electrodes degrade over time, the ability to support the reaction could be reduced, thereby decreasing the signal output.

5.2.2.2 Fluctuating or No Signal Output

The 8 sensors were electrically characterized to identify the areas of failure. Resistance was checked between the electrical pads in area 2 (Figure 115) or just beyond at the replaced Dsub9 connector. This confirmed no short circuits existed on the electrode side of the sensor. Voltage drop was also measured to help characterize the heater. In addition, a separate manufacturer's controller (designed for controlling the heater power in the field and performing diagnostics) was used to determine any error codes.

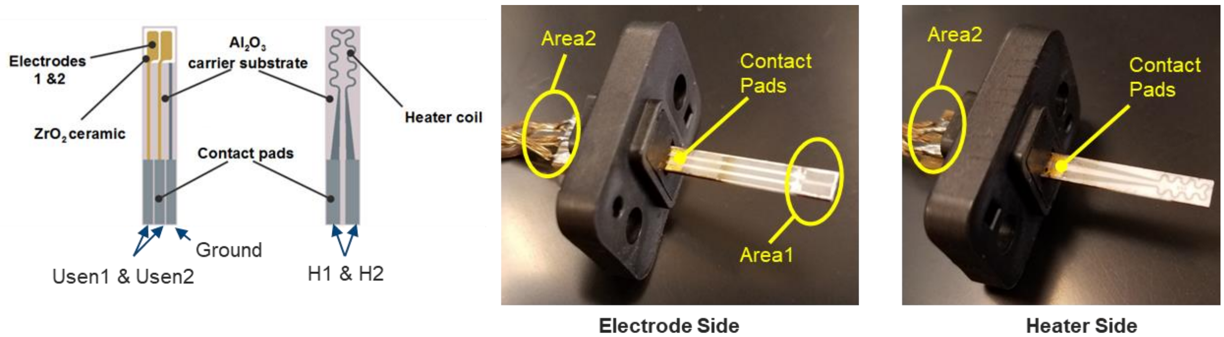


Figure 115: Sensor B THB, Electrical Characterization Designators

From the results of gas sensitivity check GSON1, sample S2 had intermittent heater power and only intermittent Usen2 response, sample S3 had only response from Usen2, and sample S6 had no signal output response at all. Sample S8 was previously pulled from test due to fluctuation response about "zero" with no gas, and intermittent heater power.

Table 29 summarizes the heater issues found with several units. Open or variable connections to the heater element were observed.

Table 29: Sensor B THB, Heater Issues

Sensor	Short Circuit [1]	Voltage Drop (V) across Heater [2]	Manufacturer's Controller Output [3]
S1	NONE	8.2-8.3	**X001 Heater Damaged**
S2	NONE	**8.3-10.1**	No error code
S3	NONE	8.4	No error code
S4	NONE	8.3	No error code
S5	NONE	**8.3-10.2**	No error code
S6	NONE	**10.0-10.3**	**X001 Heater Damaged**
S7	NONE	**8.1-10.3**	No error code
S8	NONE	Not tested	Not tested

1. Measured across Usen1 and Usen2, Usen1 and Ground, and Usen2 and Ground, no power supplied.
2. 10.1 V_{ac} supplied to the breakout boards (which supply the sensors)
3. Controller powered by 24 V_{dc}, connected to H1 and H2 only

The four sensors shown in Table 30 were taken apart and measured to isolate where the issues were occurring internally. The problem was isolated between the front half and back half of the sensor, likely at the internal contacts between the two.

Table 30: Sensor B THB, Isolation of Issues with Internal Contacts

	Resistance (Ohm)			
	Electrode Side (Area 1 to Area 2 Leads)			Heater Side (Area 2 Leads)
Sensor	**Usen1**	**Usen2**	**Ground**	**Heater**
S2	3.1	3.6	2.2	9.9
S3	3.2	3.5	2.5	9.7
S6	3.2	3.2	**OPEN** [1]	**OPEN** [2]
S8	Not tested	Not tested	Not tested	**OPEN** [3]

1. 2.4 Ohm measured between Area 1 to contact pads on ceramic substrate
2. 9.9 Ohm measured between contact pads on ceramic substrate
3. 9.3 Ohm measured between contact pads on ceramic substrate

Sample S6 showed signs of hydrolytic degradation, where the Vectra plastic material became brittle and cracked easily when removing from test fixture with tools (Figure 116). Cracking was evident on the elastomeric pad also. However, this did not appear to be a direct cause of any signal output failure.

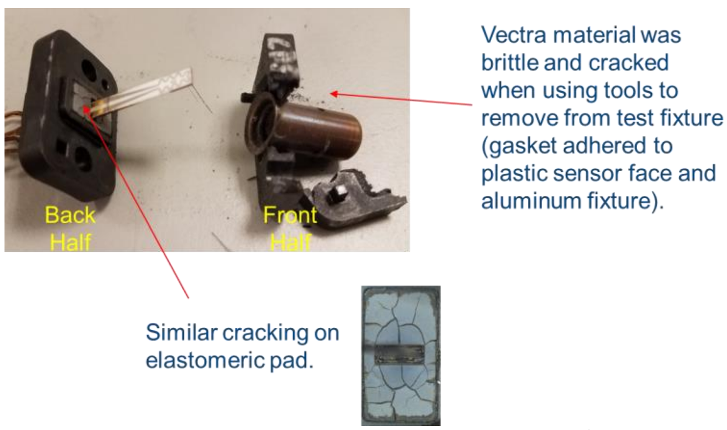


Figure 116: Sensor B THB, Degradation of Plastic/Elastomer

Black resin-like material was observed around the contact pads, and likely played a role in the ceramic substrate adhering to the back half of the sensor when the front half was removed. The spring leads in the back half were also recessed (Figure 117). This prevented good contact (if any) to the contact pads on the ceramic substrate (leading to the open electrical connection observed).

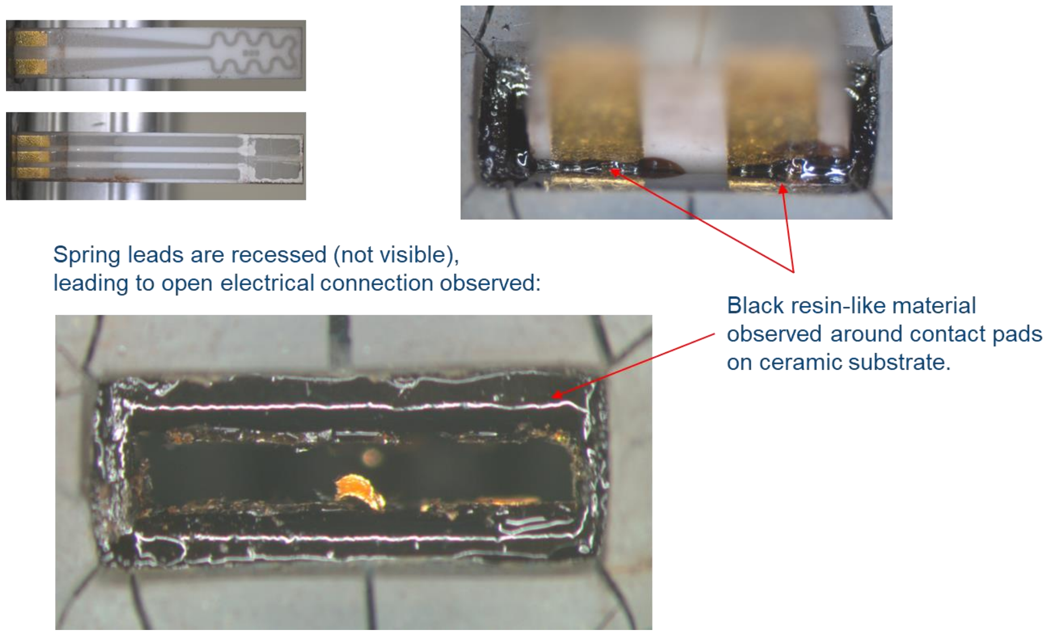


Figure 117: Sensor B THB, Internal Contacts Recessed

The black resin-like material made its way onto the contact pads. When the ceramic substrate was removed, the gold plating had delaminated and stuck to the spring leads (Figure 118). Similar observations were made on the other 3 sensors taken apart as well (samples S2, S3, and S8).

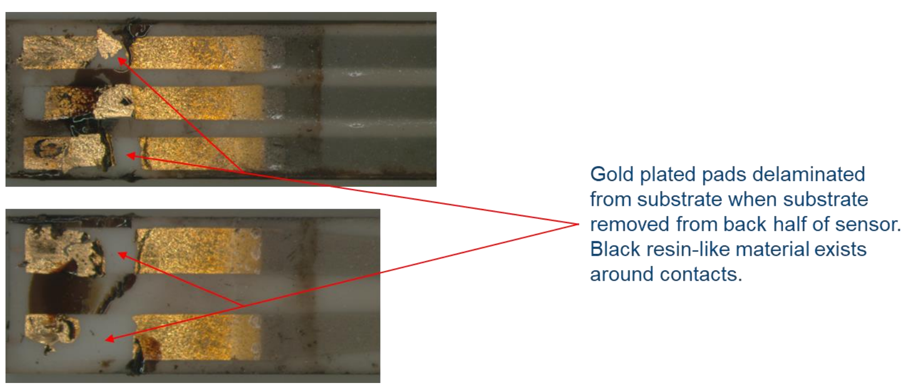


Figure 118: Sensor B THB, Contact Pads with Black Resin-like Substance

The black material was compared to the rubber strain relief material and the epoxy material found on the back half of the sensor using Fourier Transform Infrared Spectroscopy (FTIR). The resin appears to be from the rubber strain relief (not the epoxy).

The internal connection between the front half and back half of the sensor appears to have been compromised. The spring leads had relaxed and recessed away from the contact pads, leading to intermittent heater power. The non-conductive black resin melting onto the contact pads can exacerbate the compromised electrical connection between the spring leads and pads. Furthermore, as the heater element temperature increases, the contacts can shift away from the pads due to their coefficient of thermal expansion, and then retract when they cool down and make contact again. Results are consistent with some improved performance observed when cooler ambient air flow and extended air purges were applied to some sensors. This can explain many of the intermittent power results observed, and therefore fluctuating or no response in signal output (proper temperature for the catalyst reaction cannot be achieved without proper heater power).

5.3 Sensor C, THB Failure Analysis

Two main failure modes were experienced during THB testing:

- Soft Failure: Drift in “zero”
- Hard Failure: No signal response

The sensors had some signs of corrosion on the bottom metal mesh screen. The corrosion was consistently to the same side on all sensors. The very slight angle of the shelving in the autoclave, on which the fixtured sensors sat, corresponded with the observation (Figure 119). This indicated some condensing of moisture that pooled to one side due to gravity. The sensors were hung vertically to prevent condensation from pooling inside of the sensor, and it is unlikely this would affect the results.

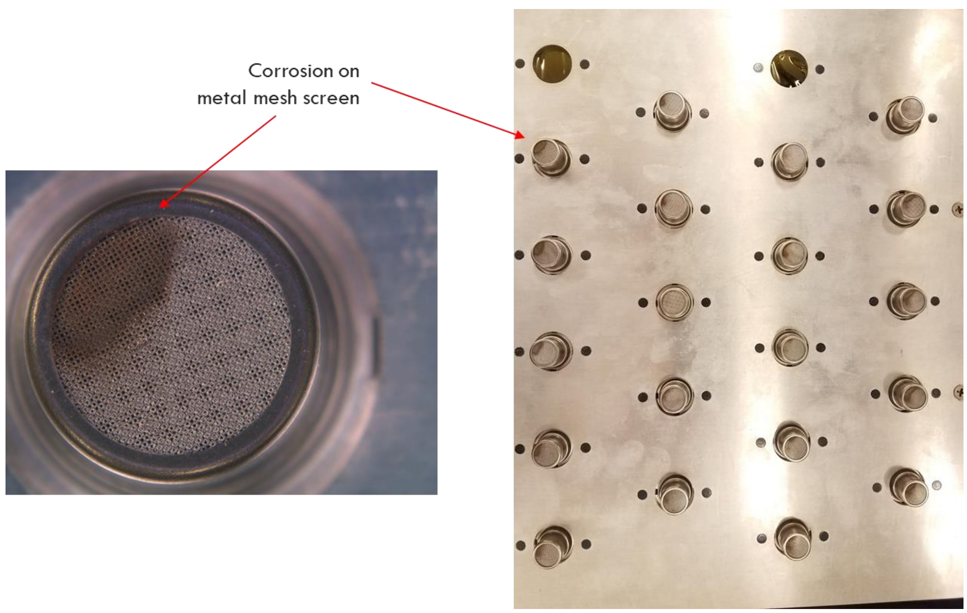


Figure 119: Sensor C THB, Corrosion on Metal Mesh Screen

After the last gas sensitivity check GSON3, all 20 Sensor C samples were left at ambient room temperature conditions. After about a month, another gas sensitivity check was performed to determine if there was any recovery in the sensors. Only a muted response at best was observed with the highest gas concentration Tank 5 (about 1 mV instead of closer to 5 mV originally) (Figure 120). Sample S20 had no response. None of sensors had a response to the lowest gas concentration Tank 1.

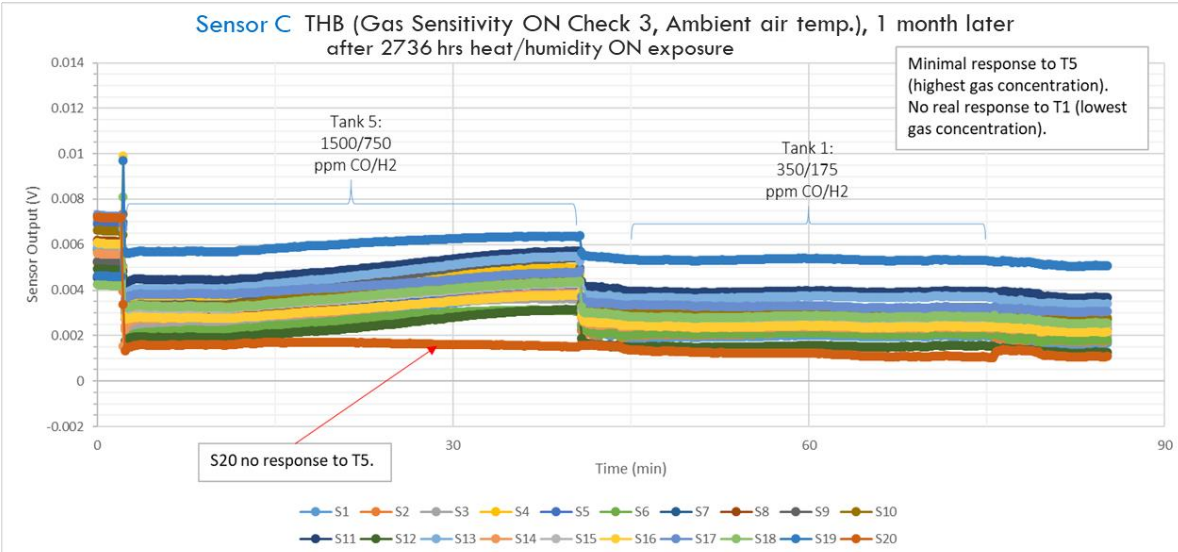


Figure 120: Sensor C THB, Re-check for Recovery

Samples S7, S17, and S20 were isolated with 1 LPM gas administered to each sensor individually. Samples S7 and S17 responded with approximately 1 mV signal output to Tank 1 gas concentration, and approximately 5 mV signal output to Tank 5 gas concentration. These were similar to baseline results in the gas sensitivity chamber. Sample S20 had no response under Tank 1 gas concentration, and only a muted response of about 1 mV under Tank 5 gas concentration. The sensors did have some recovery in general, but still significant degradation with little to no signal response when exposed to their target gas concentrations.

On sample S20, the sensor itself was replaced with a new unused sensor, but connected to the existing sensor's PCB container. Response was restored, indicating failure was due to the detector (and not the PCB).

Optical microscopy was performed on the failed sample S20 (Figure 121). The detector element appeared lighter optically compared to an unused one, and had traces of blue speckles. The compensator element appeared slightly lighter also compared to the unused one.

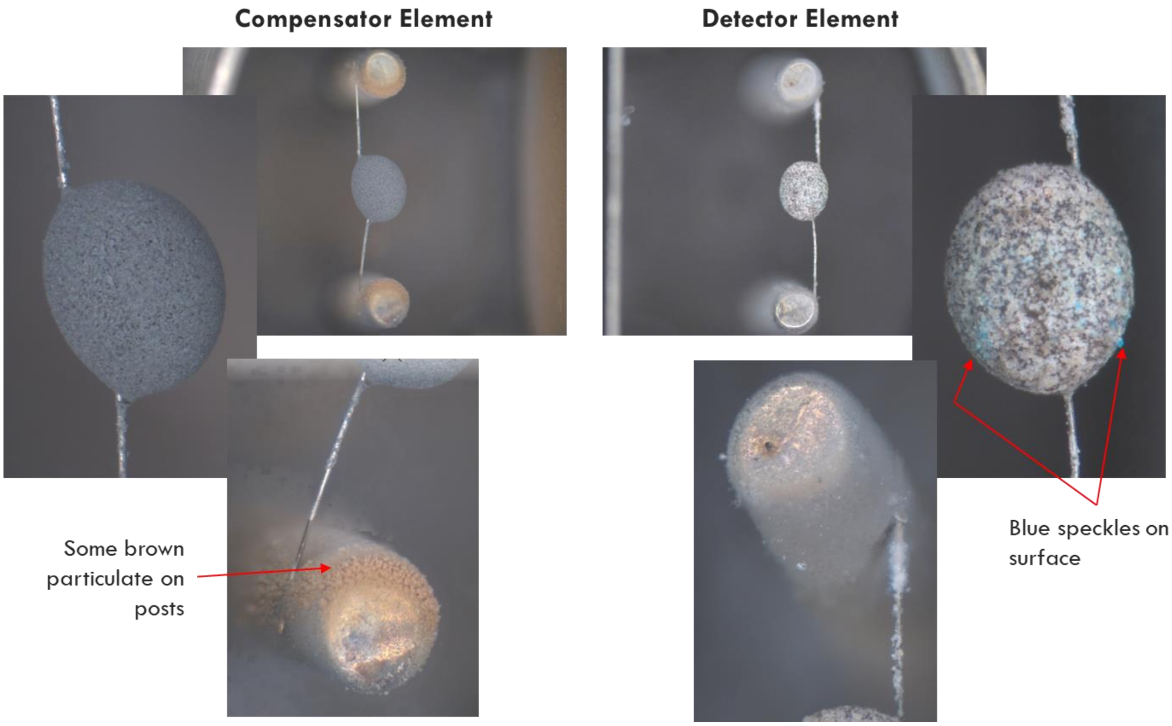


Figure 121: Sensor C THB, Sample S20 Compensator and Detector Elements

Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS) was performed on the detector element. The elemental constituents in the material were determined for the failed samples S20 and S7 (Figure 122). One main composition difference between the failed sensors and the unused sensor was the amount of Tin (Sn) detected on the surface. The non-responsive sample S20 had no presence of Sn, followed by sample S7 with only 23% tin (by weight percentage). This is significantly less than the unused sample of 37% Sn, indicating some depletion had occurred during testing. Another composition difference was the amount of Silicon (Si) (Table 31).

Detector Element

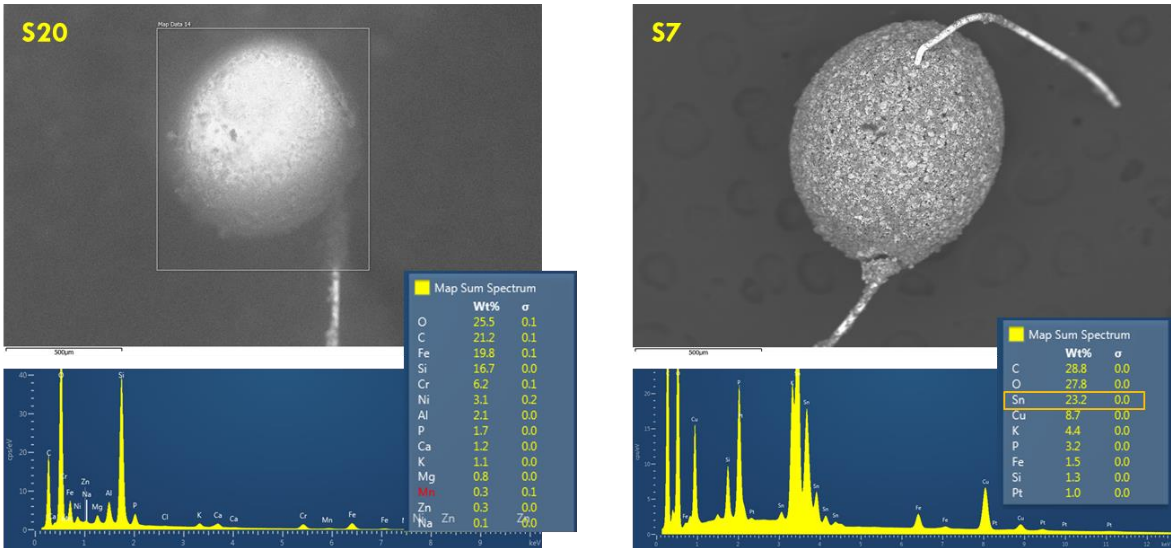


Figure 122: Sample C THB, Detector Elemental Constituents

Table 31: Sample C THB, Tin (Sn) and Silicon (Si) % Weight

Sensor	Characterization	Sn (% Wt)	Si (% Wt)
S20	Non-responsive	Not registered	16.7%
S7	Degraded to non-responsive	23.2%	1.3%
Unused	Normal	37.0%	5.0%

The degraded or non-response of the sensor to gas concentrations corresponds to the depletion of surface Sn during the THB exposure and/or during gas sensitivity checks. This could affect the catalyst reaction and therefore signal output response, but the exact mechanism is not known. Sample S20 did have significantly more silicon on the surface, but sample S7 was also a non-responsive sensor and had less silicon than the unused sensor. Silicone (comprised of the element Silicon) can cause poisoning of the pellistor, in which compounds decompose on the catalyst and form a dense barrier. The only addition of silicone just prior to the failures was from the high temperature silicone cable used with the MIL-Standard test connector. While the silicone and connector are rated for use in higher temperatures than used in test, it is not clear if there was any correlation between the silicone introduction and the subsequent failures after subsequent THB exposure.

6 Discussion

DfR Solutions analyzed the test results to provide CPSC with overall performance predictions and life expectancy for each sensor model.

6.1 Sensor A Reliability Analysis

6.1.1 TC Analysis

Of the 8 sensors tested, there were 2 hard failures. Table 32 summarizes the failures and suspensions in test. The “state” refers to whether the unit failed (in this case, whether the unit was a hard failure) or was suspended (did not meet the failure criteria and therefore survived). The time at which the unit was observed as failed is recorded as the “state end time”. The unit could have failed somewhere in between the previous inspection point and the state end time, and so the last inspection point in cycles is recorded. This is known as interval data, since the exact point in time of failure is not known (but it is known to have occurred somewhere within the interval).

Table 32: Sensor A TC Hard Failures and Suspensions (out of 8 samples tested)

Number of Units in State	Last Inspected (cycles)	State (Failed (F) or Suspended (S))	State End Time (cycles)
2	720	F	840
6	1920	S	1920

The remaining samples survived 1920 cycles, with only soft failures observed over the course of testing. These sensors still responded to their target gas concentrations.

Per the test plan parameters (refer to Table 7), a total of 1261 cycles were needed to demonstrate a 20-yr field equivalent. Instead, 1920 cycles were achieved in test. The equivalent field life is simply the 20 years multiplied by the ratio of actual test cycles to that required. In this case, the equivalent field life is determined to be 30.4 years.

Because the minimum test durations required were achieved, no additional analysis is represented with cycles-to-failure data and ReliaSoft Weibull++ software. The additional data in Table 32 is not used. In fact, because there were only two failures and they occurred in the same interval, not enough failure data exists to perform a correct rank regression analysis estimation in Weibull++. The original test plan metrics for allowable failures are used instead.

The testing demonstrated beyond 20-year field life equivalent for thermo-mechanical failure mechanisms associated with temperature cycling. While accuracy, and to some extent stability, may drift over the expected lifetime of the sensor, sensors are expected to function over that period by responding to their target gas concentrations.

6.1.2 THB Analysis

Of the 48 sensors tested, there were 22 total hard failures. Testing was stopped because the 2 allowable number of failures per the test plan parameters had been exceeded. Table 33 summarizes the failures and suspensions in test. In this case, there is no interval data, as the point in time of failure is known from the in-situ data taken during THB exposure.

Table 33: Sensor A THB Hard Failures and Suspensions (out of 48 samples tested)

Number of Units in State	State (Failed (F) or Suspended (S))	State End Time (hr)
1	F	118
1	F	317
1	F	480
3	F	528
1	F	576
1	F	648
1	F	720
1	F	792
1	F	864
1	F	984
2	F	1056
1	F	1104
1	F	1128
1	F	1152
1	F	1176
1	F	1248
1	F	1272
1	F	1320
1	F	1368
26	S	1368

Analysis on the failures was performed using ReliaSoft Weibull++. The life data was evaluated using the following analysis settings:

- Analysis Method: Maximum Likelihood Estimation (MLE). This is good when heavy censoring is present (in this case, a relatively large number of suspensions). Unbiasing of parameters is utilized (uses a correction factor for the biased estimate of the Weibull beta parameter due to MLE sampling error for both censored and non-censored data).
- Rank Method: Median Ranks (MED) with standard ranking method (SRM)
- Confidence Bounds Method: Fisher Matrix

Figure 123 shows the plot of Unreliability (F(t)) versus time (t). Unreliability is equal to 1 – R(t), where R(t) is Reliability. For instance, 15% unreliability is equivalent to 85% reliability. The expected time in test for 85% reliability is the corresponding time where the probability line intersects with the 15% unreliability line. This value is determined to be 659.07 hours in test. To determine the equivalent field life in hours, this value must be multiplied by the equivalent acceleration factor.

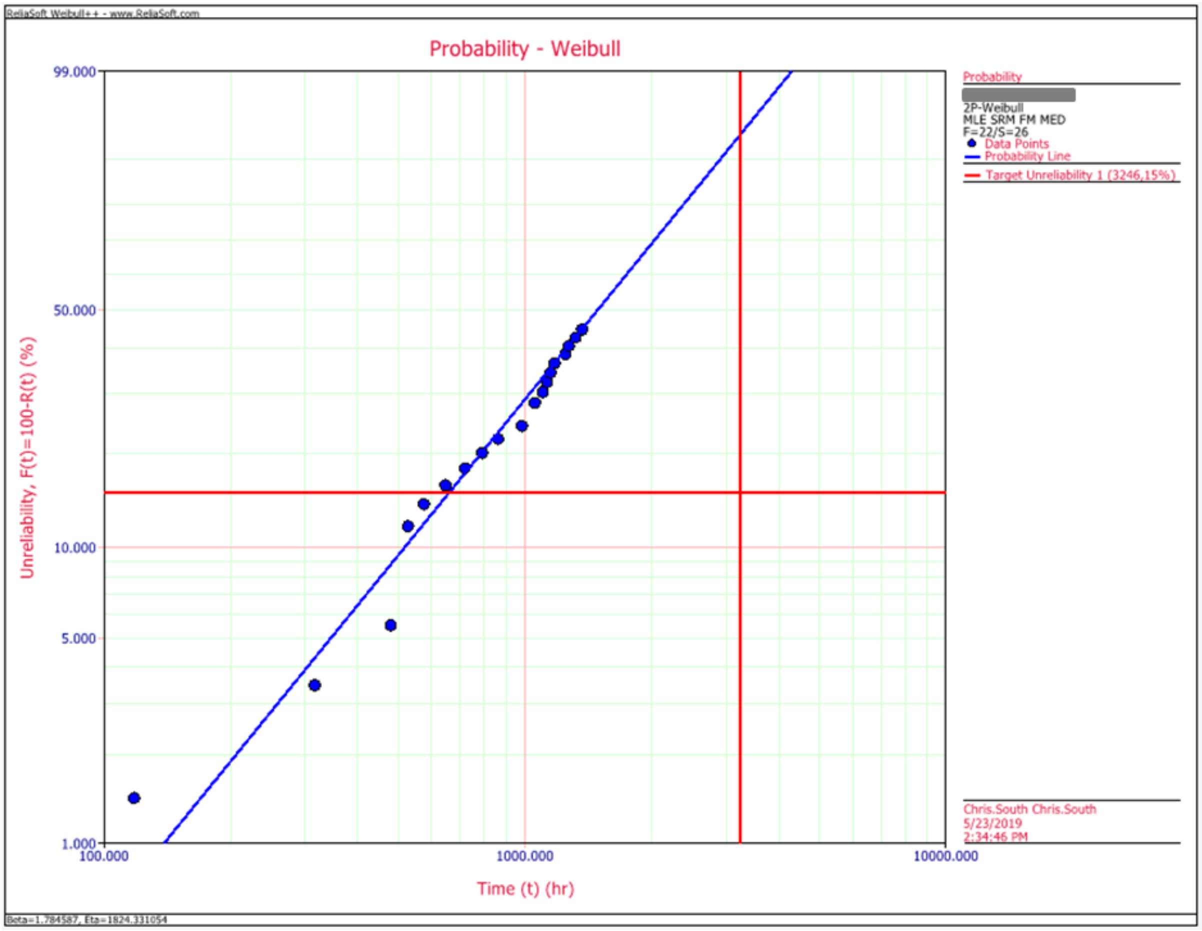


Figure 123: Sensor A THB, Weibull Probability Plot

The equivalent acceleration factor is equal to just the acceleration factor if the field stress and test stress are held constant. In this case, the field stress is comprised of both OFF-cycle and ON-cycle conditions. The test stress (consisting of exposure to 85°C and 85% RH) is held constant. The equivalent stress therefore needs to be calculated from the following equations [16]:

$$AF_e = \frac{T_{field}}{T_t} \qquad (1)$$

where AF_e = Acceleration factor, equivalent
T_{field} = Time in field
T_t = Time in test, which can be made up of T_{t1}, T_{t2}, T_{t3}, etc. for each set of test stress conditions

[16] Reliability Hot Wire, 144, Feb. 2013. https://www.weibull.com/hotwire/issue144/hottopics144.htm

$$T_t = \frac{T_{field}}{AF_e} = \sum_i \left(\frac{P_i T_{field}}{AF_i}\right) = T_{field} \sum_i \left(\frac{P_i}{AF_i}\right)$$

$$T_{field} = \frac{T_t}{\sum_i \left(\frac{P_i}{AF_i}\right)} = \frac{T_{t1}}{\sum_i \left(\frac{P_i}{AF_i}\right)} + \frac{T_{t2}}{\sum_i \left(\frac{P_i}{AF_i}\right)} + \frac{T_{t2}}{\sum_i \left(\frac{P_i}{AF_i}\right)} + \ldots \quad (2)$$

where P_i = Probability of time in field under the i^{th} field conditions
AF_i = Acceleration factor under the i^{th} field conditions

Table 34 shows the values used in the above equations and the calculated equivalent acceleration factor. Values for P_i are based on the assumed 10 min ON and 10 min OFF cycles of the furnace in the field.

Table 34: Sensor A THB, Calculated Equivalent AF

	i^{th} Field Conditions	
Values	**OFF-cycle**	**ON-cycle**
Inputs:		
P_i	0.5	0.5
AF_i for T_{t1}	63.64	16.05
AF_i for T_{t2}	63.64	16.05
T_{t1}	384 hrs	
T_{t2}	984 hrs	
Results:		
T_{field}	35,069 hrs	
AF_e	25.63	

The equivalent field life at 85% reliability is then the reliability in test (from the Weibull++ analysis) multiplied by the equivalent acceleration factor (AF_e). This is converted to years in the field based on the heating season of 4160 hours per year.

$$Equivalent\ Field\ Life = \frac{(659.07\ hrs)(25.63)}{4160\ hrs/yr} = \frac{16{,}895\ hrs}{4160\ hrs/yr} = 4.1\ yrs$$

The two-sided confidence level of 80% can be applied to determine the upper and lower bounds of the equivalent field life. Weibull++ is used to determine the times in test that encompass 80% of units expected to survive with 85% reliability (Figure 124). The equivalent acceleration factor and heating season hours are then used to calculate the upper (90%) and lower (10%) bounds of equivalent field life.

Figure 124: Sensor A THB, Confidence Level Results

Table 35 summarizes expected field life results for THB-induced failure mechanisms. Accuracy is not expected to be maintained over this time, but the sensors are expected to function by responding to their target gas concentrations.

Table 35: Sensor A THB, Expected Field Reliability Summary

		Expected Field Life Equivalent
Reliability of 85%		4.1 years
w/ Confidence Level of 80%	Upper Bound (90%)	5.1 years
	Lower Bound (10%)	3.2 years

The reliability results fell significantly short of the desired life of 20 years. Recommendations for sensor improvement based on these results and the failure analysis are discussed in Section 7.1.

6.2 Sensor B Data Analysis

6.2.1 TC Analysis

Of the 7 sensors tested, there was 1 hard failure. This occurred between the start of testing and gas sensitivity check GS1 after 132 thermal cycles. Per the revised test plan parameters (refer to Table 22), a total of 15,049 cycles were needed to demonstrate a 10-yr field equivalent. Instead, only 3860 cycles were achieved in test due to extended dwell times. These dwell times were chosen to allow more than adequate time for creep mechanisms to occur, but also surpassed real-world cycle durations so much that the number of cycles required within 1-year test time was not obtainable. The equivalent field life is simply the 10 years multiplied by the ratio of actual test cycles to that required. In this case, the equivalent field life to which the sensors were tested was 2.6 years. This is not their expected equivalent field life.

Changes greater than 25% in signal output can be expected, but the sensors responded to their target gas concentrations, maintaining above 100 mV output. Recommendations for continued testing with new sensors are made in Section 7.2. If followed, these recommendations should allow demonstration out to 15 years field life equivalent.

6.2.2 THB Analysis

Of the 8 sensors tested, there were 7 total hard failures. Testing was stopped because the 2 allowable number of failures per the test plan parameters had been exceeded. Only sample S3 was characterized as a hard failure up to the last gas sensitivity check GSON1, due to previous test connector issues prior to replacement and later response of samples S3 and S4. Table 36 summarizes the failures and suspensions in test. All the failures are considered interval data since they were discovered at a gas sensitivity check point, but could have occurred between that checkpoint and the previous one.

Table 36: Sensor B THB Hard Failures and Suspensions (out of 8 samples tested)

Number of Units in State	Last Inspected (hr)	State (Failed (F) or Suspended (S))	State End Time (hr)
1	720	F	864
6	1872	F	2784
1	2784	S	2784

Analysis on the failures was performed using ReliaSoft Weibull++. The life data was evaluated using the following analysis settings:

- Analysis Method: Maximum Likelihood Estimation (MLE). This is good when a high proportion of interval data points are present. Unbiasing of parameters is utilized (uses a correction factor for the biased estimate of the Weibull beta parameter due to MLE sampling error for both censored and non-censored data).
- Rank Method: Median Ranks (MED) with ReliaSoft ranking method (RRM) (for interval and left censored data)
- Confidence Bounds Method: Fisher Matrix

Figure 125 shows the plot of Unreliability (F(t)) versus time (t). The expected time in test for 85% reliability is the corresponding time where the probability line intersects with the 15% unreliability line. This value is determined to be 1400.59 hours in test. To determine the equivalent field life in hours, this value must be multiplied by the equivalent acceleration factor. The equivalent acceleration factor is determined by equations (1) and (2) in Section 6.1.2. In this case, both the field stress and the test stress conditions were varied between the OFF-cycle and ON-cycle.

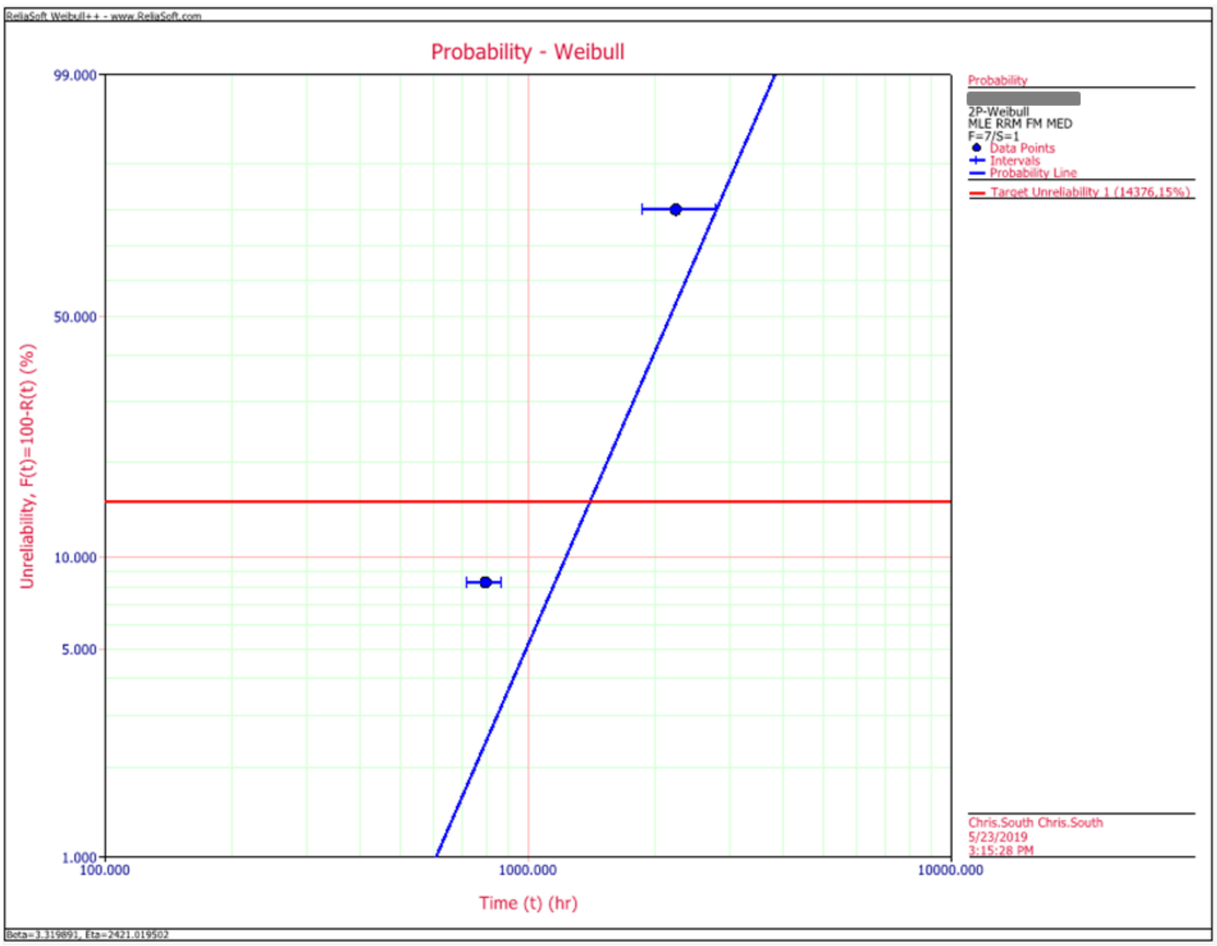


Figure 125: Sensor B THB, Weibull Probability Plot

Table 37 shows the values used in equations (1) and (2) and the calculated equivalent acceleration factor. Values for P_i are based on the assumed 10 min ON and 10 min OFF cycles of the furnace in the field.

Table 37: Sensor B THB, Calculated Equivalent AF

	i^{th} Field Conditions	
Values	**OFF-cycle**	**ON-cycle**
Inputs:		
P_i	0.5	0.5
AF_i for T_{t1}	24.94	0.52
AF_i for T_{t2}	120.87	2.54
T_{t1}	1872 hrs	
T_{t2}	912 hrs	
Results:		
T_{field}	6445 hrs	
AF_e	2.31	

The equivalent field life at 85% reliability is then the reliability in test (from the Weibull++ analysis) multiplied by the equivalent acceleration factor (AF_e). This is converted to years in the field based on the heating season of 4160 hours per year.

$$Equivalent\ Field\ Life = \frac{(1400.59\ hrs)(2.31)}{4160\ hrs/yr} = \frac{3242\ hrs}{4160\ hrs/yr} = 0.8\ yrs$$

The two-sided confidence level of 80% can be applied to determine the upper and lower bounds of the equivalent field life. Weibull++ is used to determine the times in test that encompass 80% of units expected to survive with 85% reliability (Figure 126). The equivalent acceleration factor and heating season hours are then used to calculate the upper (90%) and lower (10%) bounds of equivalent field life.

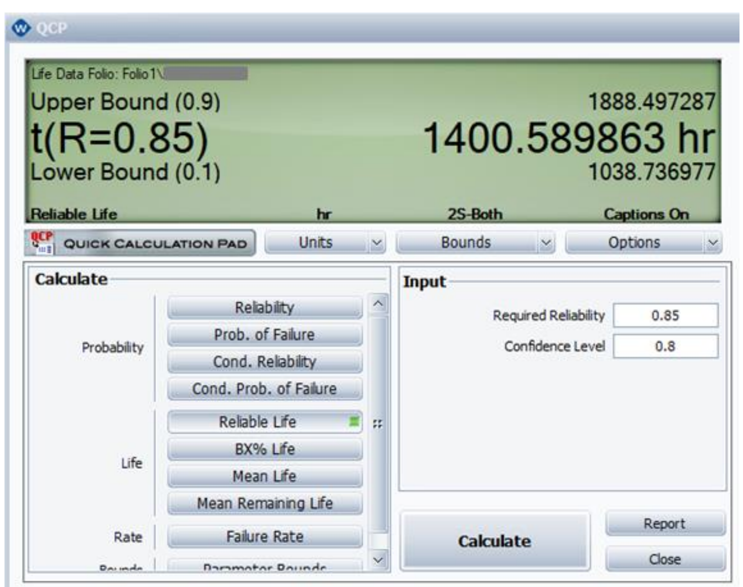


Figure 126: Sensor B THB, Confidence Level Results

Table 38 summarizes expected field life results for THB-induced failure mechanisms. Changes greater than 25% in signal output can be expected based on results dropping below 100 mV after initial signal output. However, the sensors still responded to their target gas concentrations.

Table 38: Sensor B THB, Expected Field Reliability Summary

		Expected Field Life Equivalent
Reliability of 85%		0.8 years
w/ Confidence Level of 80%	Upper Bound (90%)	1.1 years
	Lower Bound (10%)	0.6 years

The reliability results fell significantly short of the planned demonstrated life of 8 years. This is due in large part to the significant stressors placed on the back half of the sensor. The use of the autoclave, needed to obtain the acceleration factors in test, precluded separation of the front half of the sensor from the back half. The test conditions inside the autoclave were too extreme for the back half of the sensor at the start of testing. Their integrity was already compromised when the back half connections were later replaced. The back half of the sensor was never designed for exposure to the conditions needed to accelerate the THB-induced failure mechanisms. Recommendations for improvement with the test approach and sensors, based on these results and the failure analysis, are discussed in Section 7.2.

6.3 Sensor C Data Analysis

6.3.1 TC Analysis

There were no hard failures among the 48 sensors tested. Per the test plan parameters (refer to Table 9), a total of 6698 cycles were needed to demonstrate a 10-yr field equivalent. Instead, only 1056 cycles were achieved in test due to extended dwell times. These dwell times were chosen to allow more than adequate time for creep mechanisms to occur, but also surpassed real-world cycle durations so much that the number of cycles required within 1-year test time was not obtainable. The equivalent field life is simply the 10 years multiplied by the ratio of actual test cycles to that required. In this case, the equivalent field life to which the sensors were tested was 1.6 years.

Based on the test results, accuracy (and to some extent stability at "zero") are likely to drift without auto calibration methods utilized. The relatively high number of sensors exceeding the accuracy (repeatability) tolerance could be less if allowed to reach a final stable value in test. Test gas concentrations and test time was limited and prevented allowing additional time for sensors to fully plateau (stabilize) in their response. Stability in the field may be better without the movement associated with handling and testing. The sensors are expected to function by responding to their target gas concentrations. Recommendations for continued testing with these same sensors are made in Section 7.3. If followed, these recommendation should allow demonstration out to 10 years field life equivalent.

6.3.2 THB Analysis

All 20 samples were hard failures at gas sensitivity check GSON3 after a total of 1152 hours exposure in the OFF-cycle conditions and 2736 hours in the ON-cycle conditions. Because all the failures were observed at the gas check point (and therefore in the same interval), there were no suspensions (Table 39). This restricts analysis to only a 1-parameter Weibull with maximum likelihood (MLE) analysis method. This requires estimating a Beta factor for the actual data results.

Table 39: Sensor C THB Hard Failures and No Suspensions (out of 20 samples tested)

Number of Units in State	Last Inspected (hr)	State (Failed (F) or Suspended (S))	State End Time (hr)
20	2976	F	3888

An alternative approach is to first determine the equivalent acceleration factor from the test plan parameters (refer to Table 14 and Table 15) and actual test durations achieved in the OFF- and ON-cycle conditions. Because the failures could have occurred between the last two gas sensitivity checks, the median of this time interval is chosen as the failure point in time. Table 40 shows the values used with equations (1) and (2) in Section 6.1.2 and the calculated equivalent acceleration factor.

Table 40: Sensor C THB, Calculated Equivalent AF

	i^{th} Field Conditions	
Values	**OFF-cycle**	**ON-cycle**
Inputs:		
P_i	0.5	0.5
AF_i for T_{t1}	6.73	0.52
AF_i for T_{t2}	32.62	2.46
T_{t1}	1152 hrs	
T_{t2}	2280 hrs	
Results:		
T_{field}	11,543 hrs	
AF_e	3.36	

A new test design can then be run in Weibull++ using a total 8-yr life expectancy (or 33,280 hours) and the equivalent acceleration factor determined above, keeping all other test design parameters the same. A total of 7836 hours are required to demonstrate an 8-yr field equivalent (Figure 127). A total of 3432 hours was achieved to the assumed failure point. The equivalent field life is simply the 8 years multiplied by the ratio of achieved test cycles to that required. In this case, the equivalent field life is determined to be 3.5 years.

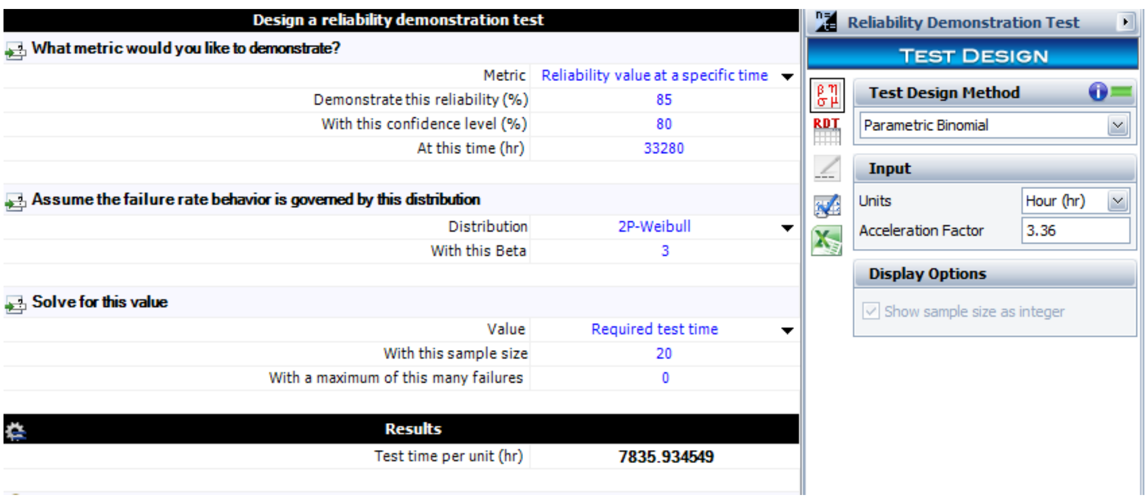


Figure 127: Sensor C THB, Reliability Demonstration with Equivalent AF

The reliability results fell significantly short of the planned demonstrated life of 8 years. This may be due to the significant stressors placed on the back half of the sensor. Despite the test conditions being within the allowable test temperature range for the back half of the sensor, the humidity conditions are well above what it would normally experience in the field. Unfortunately, an alternative approach was not feasible for this testing. Feedback from results shared with the manufacturer is pending as of the submission of this report.

Based on the test results and similar to the Sensor C samples tested in thermal cycling, accuracy (and to some extent stability at “zero”) are likely to drift without auto calibration methods utilized. The relatively high number of sensors exceeding the accuracy (repeatability) tolerance could be less if allowed to reach a final stable value in test. Test gas concentrations and test time was limited and prevented allowing additional time for sensors to fully plateau (stabilize) in their response. While the variable resistor in the PCB container is very sensitive, stability in the field may be better without the movement associated with handling and testing. The sensors are expected to function by responding to their target gas concentrations.

6.4 General

The periodic gas sensitivity checks provide an assessment on the performance of the sensor and any degradation that may have occurred in its function. It also exposes it to elements of combustion gases it could see in the field. The amount used in test is not expected to exceed what the sensors could see in the field. For the 5 different gas concentrations, each applied for half an hour and for the maximum number of gas sensitivity checks of 30 in test, the concentration hours of exposure is just under 60,000 ppm-hrs. The maximum allowable air-free flue gas sample of CO is 400 ppm in gas furnaces and boilers per the governing standards ANSI Z21.47, ANSI Z21.86, and ANSI Z21.13. With a heating season of 2080 hours assumed, this equates to 832,000 ppm-hrs in a year. There is no concern that the amount of combustion gas concentrations to which the sensors were exposed in test was excessive.

7 Recommendations

7.1 Sensor A

Due to the extensive failures experienced in THB testing, it is recommended that the Sensor A samples be re-tested with modifications to the design:

- Minimize the impact of humidity ingress into the sensor area. This could be achieved with a change in the design/material of the seal barrier.
- Consider sourcing a more robust bypass capacitor. Automotive grade components can withstand higher temperatures and longer exposure periods to heat and humidity than standard commercial grade components.

The manufacturer reports that the capacitor is rated at the temperature of the application. However, if not properly de-rated, it could present a higher risk for failure. The supplier makes infrared detectors. Hundreds of thousands are used each year for this sensor, and so there is a proven history in the design. Conformal coating doesn't seem to be an issue, but the sensor is recommended to test again with any revised design.

The extent of the change will dictate if TC testing is also repeated. This would be conducted to confirm that the change does not negatively impact the reliability and performance thermal cycling induced failure mechanisms.

7.2 Sensor B

The connection between the front and back halves of the Sensor B sample was susceptible to heat degradation and strain from the cable when not properly strain relieved. The heat from the heater element is conducted through the spring leads and surrounding housing to the sensor's back half. The following is recommended for consideration from a design standpoint:

- Consider improving the high temperature strength and heat resistance of the elastomeric strain relief. Proper geometry can improve stiffness, and materials like high temperature silicone could be utilized.
- The spring leads in the back half of the sensor could be constrained to prevent recessing away from the contact pads. This would help prevent intermittent heater power supply issues and signal output loss.

The test approach with the use of a highly accelerated stress test (HAST) autoclave was too extreme of a stressor on the back half of the sensor. A new set of sensors is recommended for re-testing with a different test setup:

- Isolate the front half of the sensor for reliability testing and applying HAST conditions only to that half of the sensor.
- Apply lower temperature-humidity stress conditions to the entire sensor to address the reliability of the back half of the sensor (closer to the more benign indoor ambient temperature and humidity environment).

New sensors should also be tested in thermal cycling to complete the test duration required to demonstrate up to 15 years field life equivalent. Power-cycling can be employed to artificially raise and lower the sensor temperature to impart thermo-mechanical stresses relatively quickly and inexpensively. High temperature deltas can be achieved in relatively short cycle times with this method, and allow for completion of the test durations required within a reasonable 6 to 9 months.

7.3 Sensor C

The sensitivity to physical movement seemed to lead to drift or shifts in output. A more robust potentiometer, with less sensitivity to positional change, could help lessen this. It is less of a concern in the field, where the sensor is unlikely to get moved and handled after install.

Unfortunately, the front and back half of the sensor cannot be separated to isolate just the front half to the HAST conditions. Creating a hermetically sealed container to place inside the autoclave that: a.) isolates the sensor back side from the humidity within the autoclave, b.) allows for electrical passages to the sensors, and c.) allows for pressure equilibrium, is challenging in execution if not infeasible for this type of testing. Testing longer than a year under THB exposure could be performed at lower stress conditions on the entire sensor to satisfy the 8-year field life demonstration in test, and not be concerned with excessive overstress on the back half of the sensor.

The existing Sensor C samples should continue to be tested in thermal cycling to complete the test duration required to demonstrate up to 10 years field life equivalent. Ramp rates of 15C/min and 10 min dwell times will reduce the cycle times to about 1 hour, allowing for completion of testing within 10 months (with up to 1 failure allowed).

7.4 General

Manufacturers could develop algorithms to respond appropriately to sensor output and allow for self-calibration and zeroing, mitigating effects of fluctuation, spikes, or drift. In the case of Sensor B, an initial spike peaks in signal before attenuating to a lower output, despite gas concentration still being administered. This would have to be resolved in order to reliably use a time-weighted average algorithm and not indicate a false negative.

8 Sensor Modifications and Test Approach

8.1 Sensor A

The manufacturer of Sensor A has modified the design of their sensor to encapsulate the infrared detector and provided initial samples for further testing. In the original design as tested, the optical filters were in direct contact with the air flow stream through the sensor (Figure 128). A small seal existed between the optical filters and the top of the metal can.

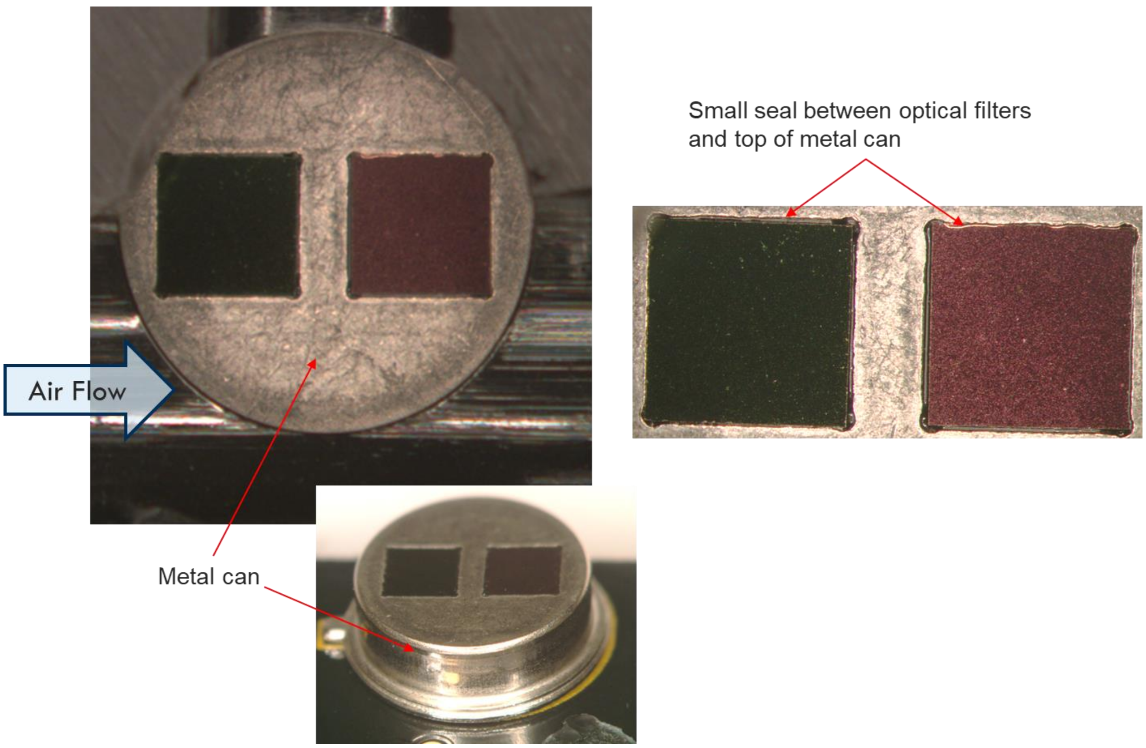


Figure 128: Sensor A Original Design, Infrared Detector

The new design has a larger canister that encapsulates the optical filters (protecting them from the air flow stream) while allowing the light from the infrared lamp to pass through. The optical filters have a much larger seal with the metal plate also.

8.2 Sensor B

The manufacturer of Sensor B has redesigned the back half of the sensor and provided initial sensors for further testing (Figure 129). The rubber strain relief material has changed and is thicker and stiffer than the original design. It is not known if there is an improvement in retention of the spring leads internally that connect to the contact pads for the electrodes and heater element.

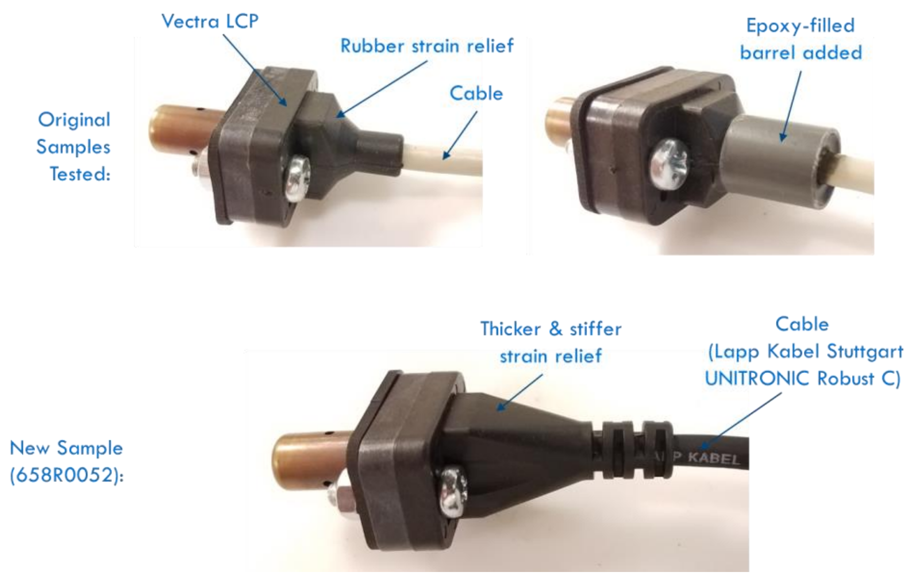


Figure 129: Sensor B New Design, Back Half

The new cable is a stranded and shielded Unitronic Robust C with a temperature range of -50°C to 90°C. This is a slight improvement in temperature rating over the original white cable (rated from -30°C to 80°C nominal).

In addition, the manufacturer has provided a clamp solution for testing purposes. This isolates just the front half of the sensor to the HAST conditions, and still provides a robust connection for power and sensor monitoring during testing. Samples of Sensor B front half come with a high-temperature material clamp adapter on the back half (Figure 130). Samples had been 100% function tested at the manufacturer and are ready to use for testing with connection to the flying leads.

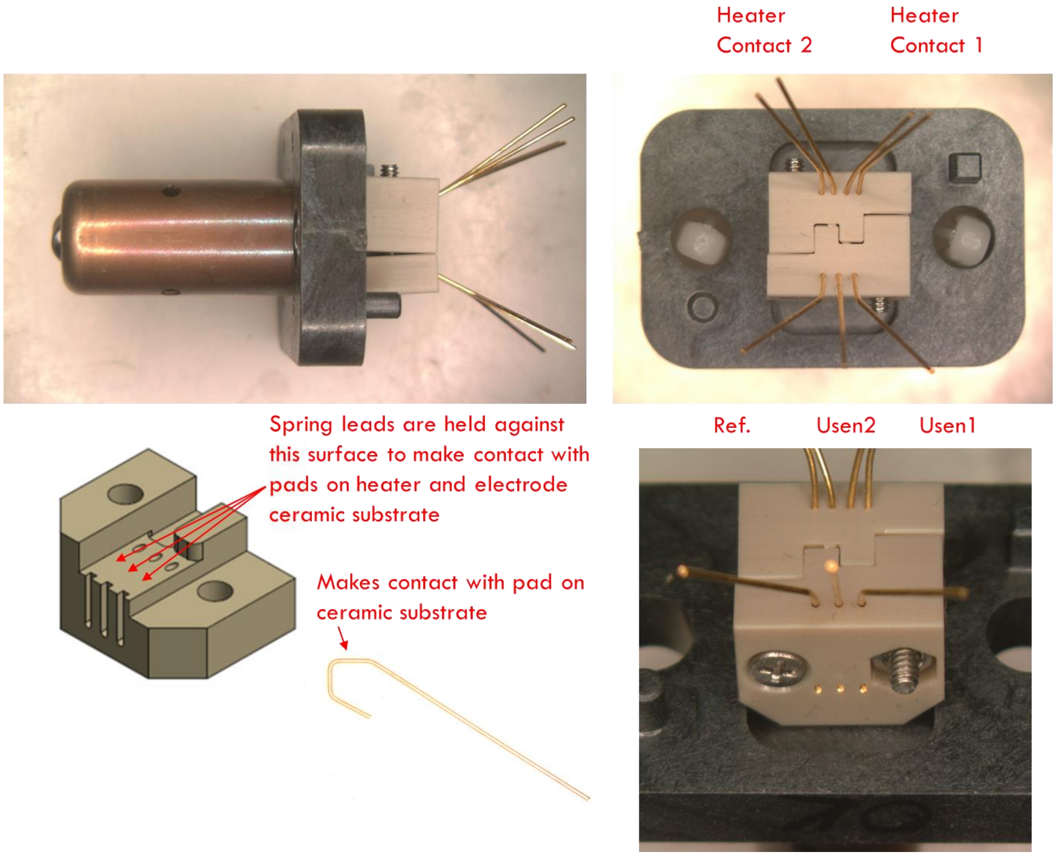


Figure 130: Sensor B Clamp Solution for Testing HAST Conditions on Front Half of Sensor

9 Conclusions

9.1 Sensor A

Sensor A performed well in the thermal cycling. It is expected to survive the thermo-mechanical induced failure mechanisms for 30 years based on 85% reliability demonstrated in test with 80% confidence level. This applies for application in the less severe conditions found in the vent pipe area in residential gas furnaces or boilers. Some functional failures can be anticipated but should not be expected to exceed the reliability metrics indicated. While accuracy and stability may drift over the expected lifetime of the sensor, sensors are expected to function over that period by responding to their target gas concentrations. The manufacturer recognizes the need for calibration by incorporating programming that allows the sensor to periodically self-calibrate..

Under THB testing, the significant number of hard failures experienced correlated to an expected field life equivalent of 4 years. Because failures were experienced, upper and lower bounds about the predicted reliability could be determined. At 80% confidence level, the range for 85% reliability is about 3 to 5 years. This is significantly shorter than the life desired for residential gas furnaces and boilers.

A good approach to prevent reliability issues in the field is through design modifications aimed at improving the robustness in this environment. Several recommendations were noted in Section 7.1, and the manufacturer has redesigned the area that encapsulates the infrared detector. This is intended to improve the seal barrier between the detector and the flow of high temperature humid air across it. Samples provided by the manufacturer are intended to undergo ALT with THB exposure again. To confirm no detrimental effect on reliability and performance under thermo-mechanical induced failure mechanisms, thermal cycling will be performed again also. Both tests are intended to be covered under a separate project and report.

9.2 Sensor B

Sensor B functionally performed well throughout the temperature cycling tests but experienced a degradation in signal output relatively early in testing. The signal output tended to saturate just above 100 mV, starting with the higher gas concentrations before being experienced across all gas concentrations. This degradation was worse in THB testing, peaking upon initial exposure to the various gas concentrations before returning close to “zero” signal output within minutes. Further investigation and discussions were held with the manufacturer, but the decaying signal output is still not clearly understood. The brief response to the targeted gas concentration would have to be resolved in order to reliably use a time-weighted average algorithm and not indicate a false negative.

Because test durations were not achieved in temperature cycling to demonstrate the reliability metrics beyond 3 years, additional thermal cycling testing will be performed to demonstrate up to 15 years equivalent field life. This will be done on a new set of sensors. The alternative approach of power cycling will be used, with test durations of 6 to 9 months.

Under THB testing, the back half of the sensor was compromised due to the highly accelerated stress test (HAST) conditions in the autoclave. This led to early and intermittent failures mainly attributed to degradation in the internal connection between the back half and front half of the sensor. The expected equivalent field life equivalent of just under a year is not reflective of actual expected field life.

An alternative test approach with new samples was recommended in Section 7.2. The proposed test will be performed under one set of test conditions for the front half of the sensor for both the OFF- and ON-cycle field conditions. The back half of the sensor will be tested as a complete assembly under different test conditions in a conventional humidity chamber. These tests are intended to be covered under a separate project and report.

9.3 Sensor C

Sensor C functionally performed well under the number of temperature cycles achieved in test. Due to the limited number of cycles tested within the 1-year test time constraint, the sensor performance was not demonstrated out to beyond 2 years equivalent field life. Not enough cycles are present to extrapolate beyond this. Accuracy to various gas concentrations may be improved if sufficient time is allowed to reach stabilized values, but that was not the case for the higher gas concentrations in test and is not reflective of real-world cycle times. Variability from one gas sensitivity check to another when measuring at a single point in time from the start of exposure can add to the deviation observed. Performance needs to be monitored over many more temperature cycles to determine if any significant trends in signal output develop.

Additional thermal cycling will be performed to demonstrate up to 10 years equivalent field life. This will be done on the same set of sensors to the remaining number of cycles needed, allowing for completion of testing within 10 months.

Under THB testing, sensor signal output was disrupted by test connector issues. The use of high temperature MIL-standard connectors resolved this. Significant drift had occurred at the time the connector issue was identified (roughly the 3-yr field equivalent mark). This amount of drift would not necessarily be expected in the field, since the sensor would not likely experience movement and handling once it is installed and “zeroed”. The manufacturer claims the sensors survived harmonic vibration tests of 10 Hz, 5mm amplitude, in all three axes for 20 minutes.

The expected equivalent field life of 3.5 years in THB is likely not reflective of actual expected field life. Per the manufacturer’s data sheet and technical manual, Sensor C utilizes the most widely used method of detecting flammable gases in industry with the catalytic pelletized resistor (“pellistor”) invented over 40 years ago. The “pellistor” has been used in the combustion chambers of instantaneous gas water heaters in Japan since about 2001. The manufacturer rates the sensor to over 10 years expected life.

Similar for both thermal cycling and THB exposure, while accuracy and stability at “zero” may drift, the sensors are still expected to function over their expected life time by responding to their target gas concentrations. Accuracy and sensitivity to physical movement seemed to lead to drift or shifts in the signal output. The manufacturer of this sensor indicates that this drift can easily be compensated for by the appliance’s software carrying out a routine zero correction calibration just before the burner is ignited.

Potential for excessive overstress existed on the back half of the sensor in THB exposure. The humidity conditions in test were well above what it would normally experience in the field. A common concern in using HAST systems is the potential to increases stresses beyond the limitation of the device materials and induce failure mechanisms that are not seen or relevant in the field. In this case, the test conditions remained within the material limitations.

Poisoning is a common risk where compounds begin to decompose on the catalyst to form a dense barrier. Silicone and organic lead are common poisons. Silicone wire was used with the new high-temperature MIL-standard test connector. While the silicone and connector are rated for use in higher temperatures than used in test, it is not clear if there was any correlation between the silicone introduction and the subsequent failures after subsequent THB exposure. The results of the THB testing are not conclusive. The manufacturer reports that the failure is not something they have seen. They have tested sensors exposed to 10 ppm Hexamethyledisiloxane (HMDS), a commonly encountered silicone known to poison noble metal catalysts, with acceptable span and sensitivity results. Results were shared with them, and feedback is pending as of the submission of this report.

APPENDIX A: Sensor A TC and THB wiring diagram

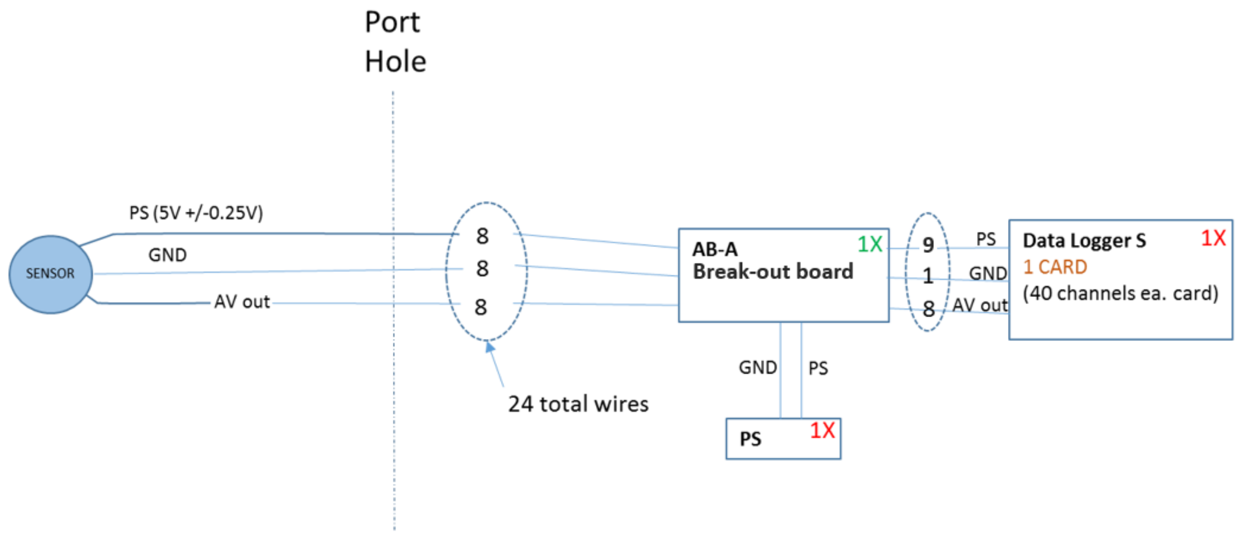


Figure 131: Sensor A TC wiring diagram

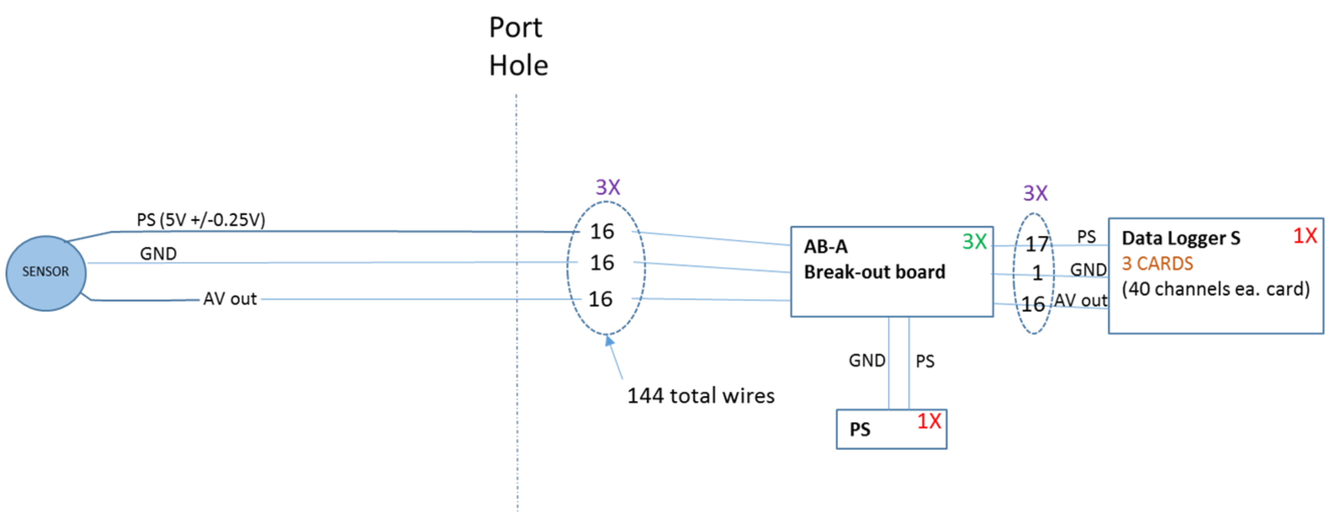


Figure 132: Sensor A THB wiring diagram

APPENDIX B: Sensor B TC and THB Wiring Diagram

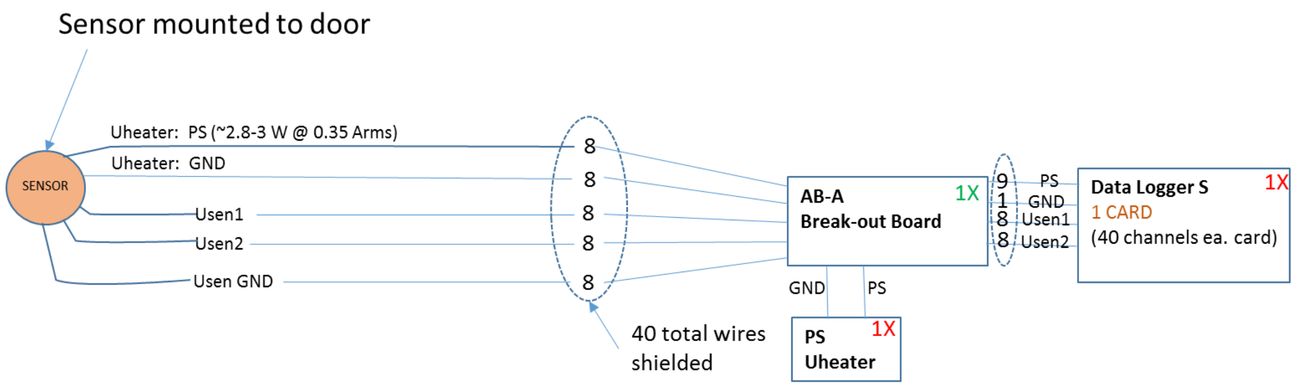


Figure 133: Sensor B TC Wiring Diagram

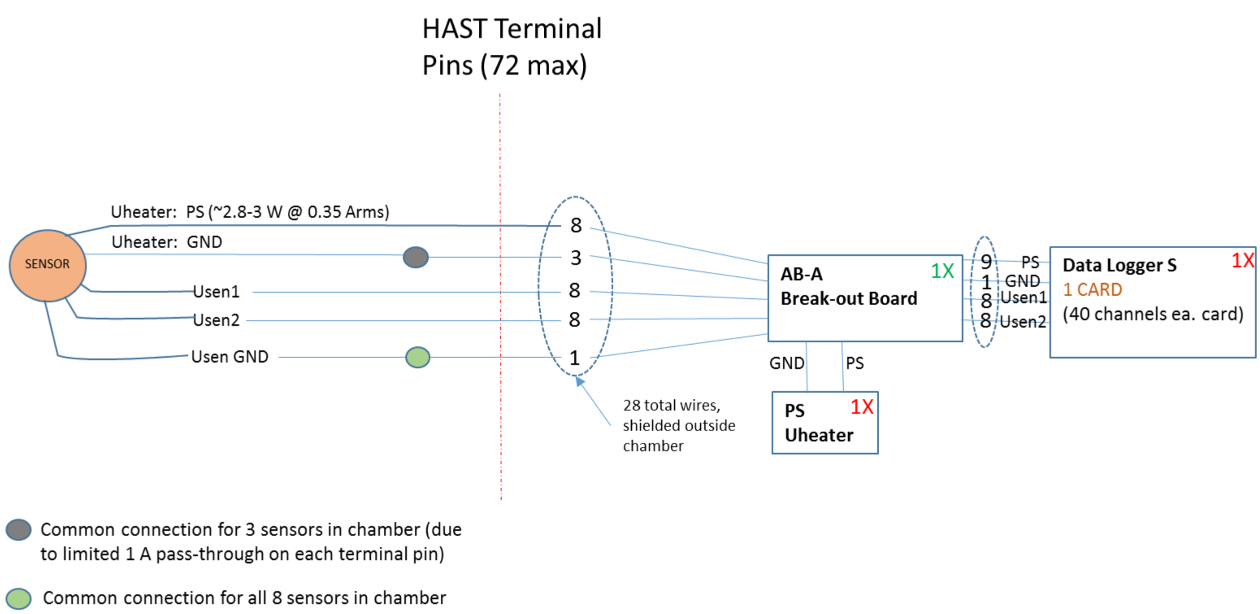


Figure 134: Sensor B THB Wiring Diagram

APPENDIX C: Sensor C TC and THB Wiring Diagram

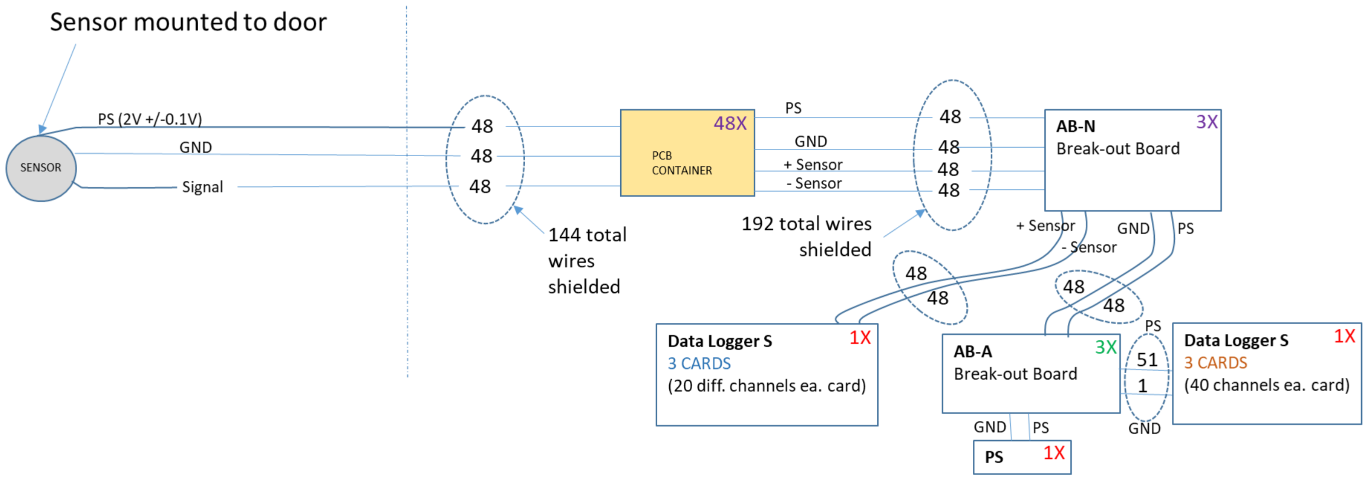


Figure 135: Sensor C TC Wiring Diagram

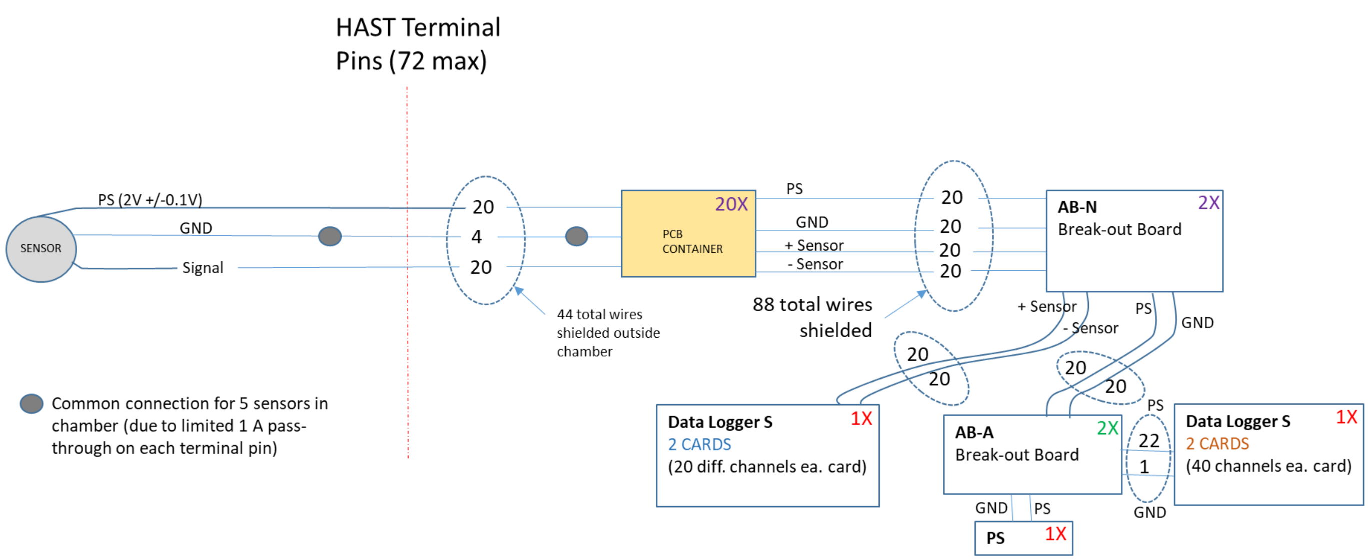


Figure 136: Sensor C THB Wiring Diagram

APPENDIX D: Equipment List

Table 41: Chamber, Data Acquisition, Power Supply Equipment

Sensor	Test	Environmental Chamber	Data Logger	Card	Power Supply
A	TC	Asset 1218 Sun Systems EC10 rev.G	Asset 1315 Agilent 34970A Cal. 3/22/17, Due 3/31/19	Agilent/HP 34908A	BK Precision 1788 (0-32V/0-6A)
	THB	Asset 1508 ESPEC EPL-3H Cal. 4/5/17, Due 4/5/19	Asset 1382 Agilent 34970A Cal. 3/22/17, Due 3/31/19	Agilent/HP 34908A	Asset 1564 BK Precision 1788 (0-32V/0-6A)
B	TC	Asset 1368 Sun Systems EC10 rev.G	Asset 1219[A] Agilent 34970A Cal. 3/22/17, Due 3/31/19	Agilent/HP 34908A	Asset 1361 Behlman Power Passport (60Hz AC Power)
	THB	Asset 1560 ESPEC EHS-221M HAST System[B]	Asset 1176 Agilent 34970A Cal. 3/22/17, Due 3/31/19	Agilent/HP 34908A	Asset 1570 Behlman AC Power Source w/ Oscillator
C	TC	Asset 1535 Sun Systems EC16HA rev.G2	Asset 1299 Agilent 34970A Cal. 3/22/17, Due 3/31/19	Agilent/HP 34908A	Asset 1201 Xantrex XFR 60-46 (0-60V,0-46A)
	THB	Asset 1560 ESPEC EHS-221M HAST System[B]	Asset 1143 Agilent 34970A Cal. 3/22/17, Due 3/31/19; Asset 1256 Agilent 34970A Cal. 3/22/17, Due 3/31/19	Agilent/HP 34908A; Agilent/HP 34901A	Asset 1524 BK Precision 1900B (1-16Vac,60A)

NOTES:

A.) Later replaced with Asset 1315 (after Sensor A TC testing completed)

B.) Test and Inspection Report provided by ESPEC (passed 4/19/17)

Table 42: Break-out Board, Custom Fixtures Equipment

Sensor	Test	Break-out Board	Misc. Custom Fixtures
A	TC	DFR16-0694-ADP1_R1	n/a
	THB	DFR16-0694-ADP1_R1	n/a
B	TC	DFR16-0694-ADP1_R1	Door: DFR16-0694-7 thru -8, Rev.1
	THB	DFR16-0694-ADP1_R1	Mounting Panel: DFR16-0694-THB-3_REV1 Adapter Plate: DFR16-0694-THB-4_REV1 Sensitivity Box: Shallow Box_Rev3
C	TC	DFR16-0694-ADP1_R1, DFR16-0694_[redacted]_ADP_R1	Door: DFR16-0694-1 thru -6, Rev.1
	THB	DFR16-0694-ADP1_R1, DFR16-0694_[redacted]_ADP_R1	Mounting Panel: DFR16-0694-THB-1_REV1 Adapter Plate: DFR16-0694-THB-4_REV1 Sensitivity Box: Shallow Box_Rev3

APPENDIX E: Sensor A TC, Gas Sensitivity Performance

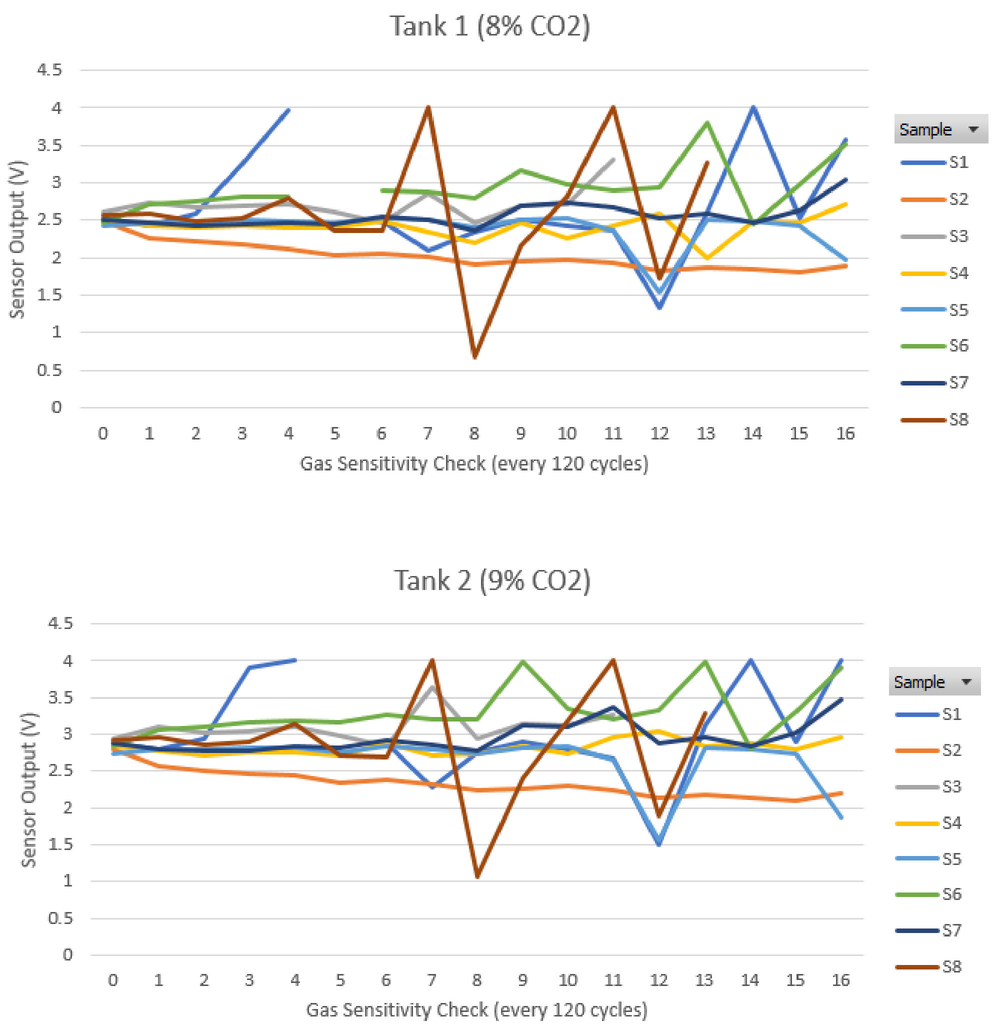


Figure 137: Sensor A TC, Sensor Output (T1 to T2)

Sensor A S1 and S6 appear to have undergone self-calibration after measurements were started (just within 25 hours of cycling ending) during GS5. This data is disregarded from the average results during exposure to Tank 1 and Tank 2 gas concentrations.

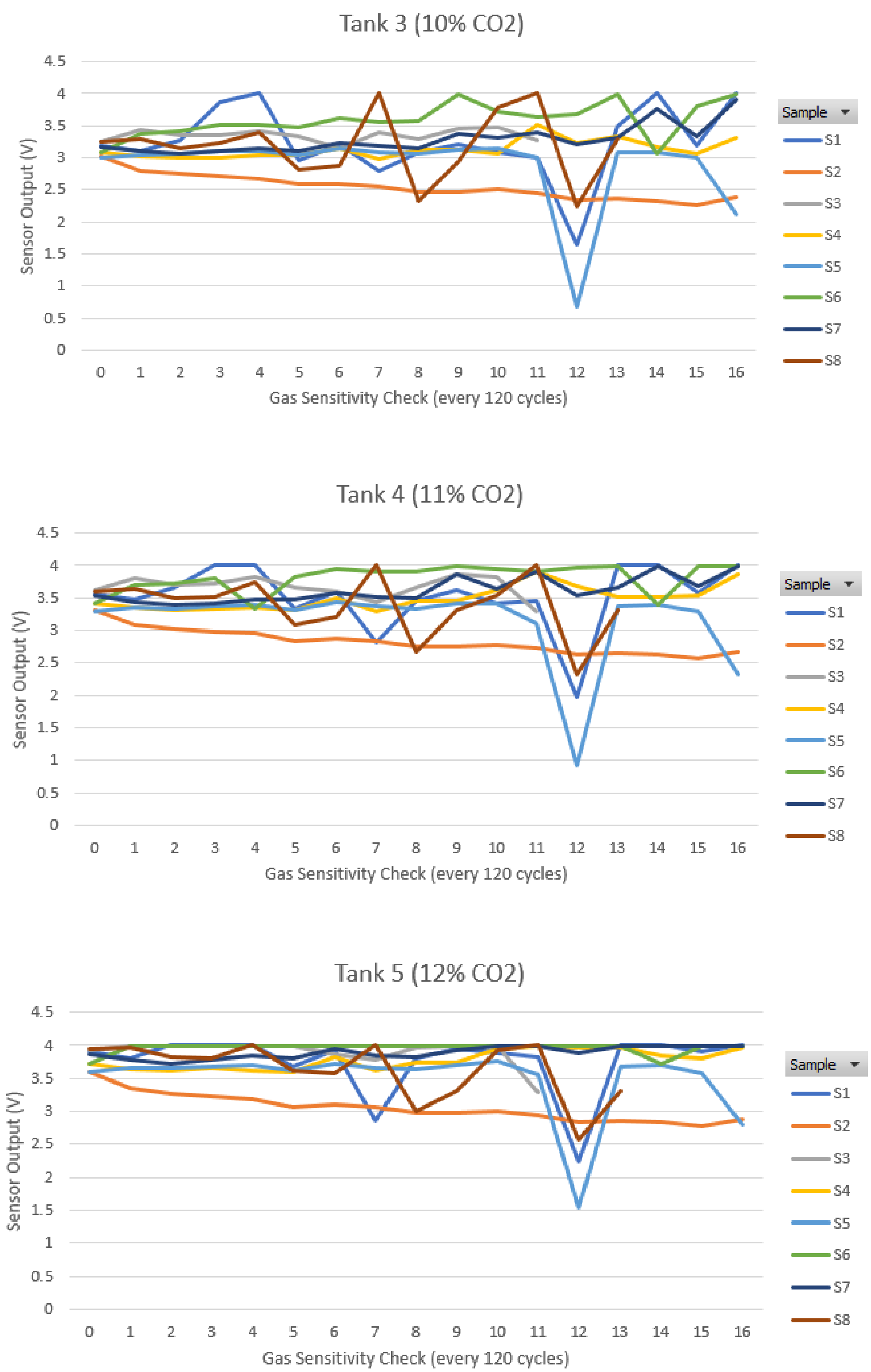


Figure 138: Sensor A TC, Sensor Output (T3 to T5)

APPENDIX F: Sensor A THB, Additional THB Exposure Hard Failure Responses

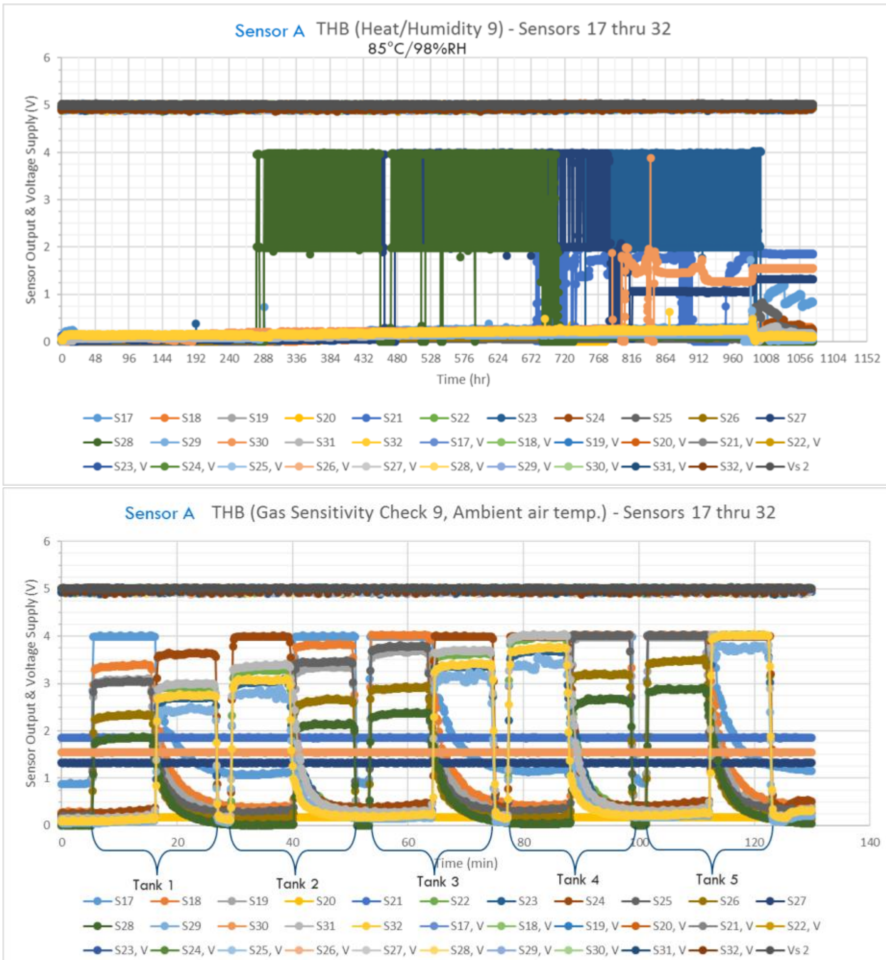


Figure 139: Sensor A THB, Additional Hard Failure Responses

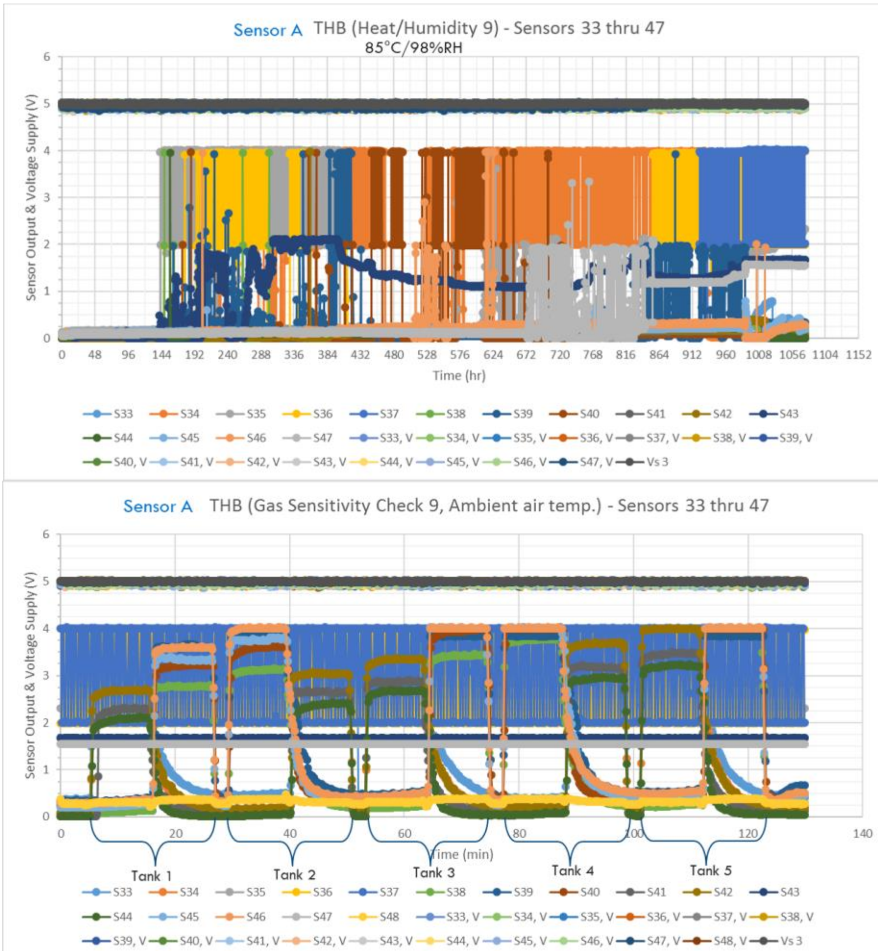


Figure 140: Sensor A THB, Additional Hard Failure Responses

APPENDIX G: Sensor A THB, Gas Sensitivity Performance

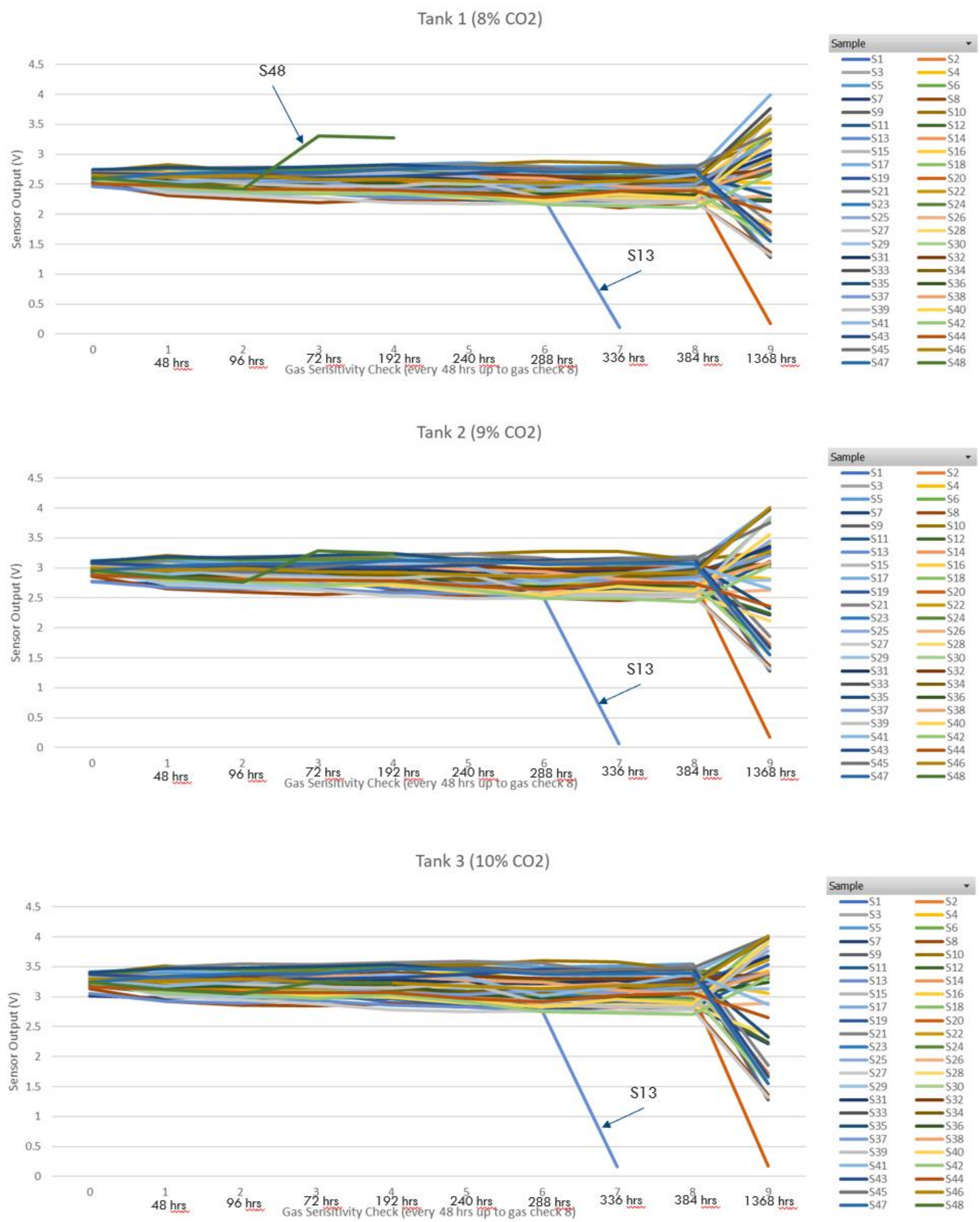
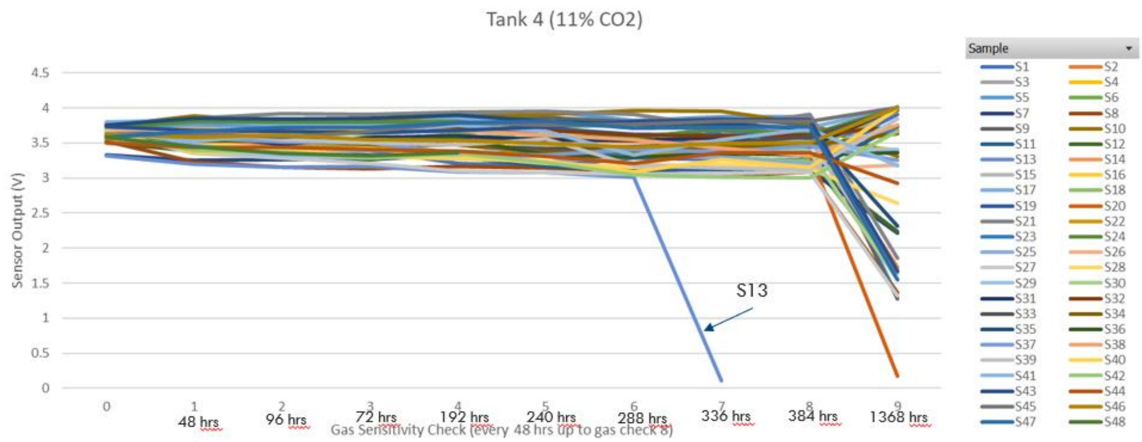


Figure 141: Sensor A THB, Sensor Output (T1 to T3)



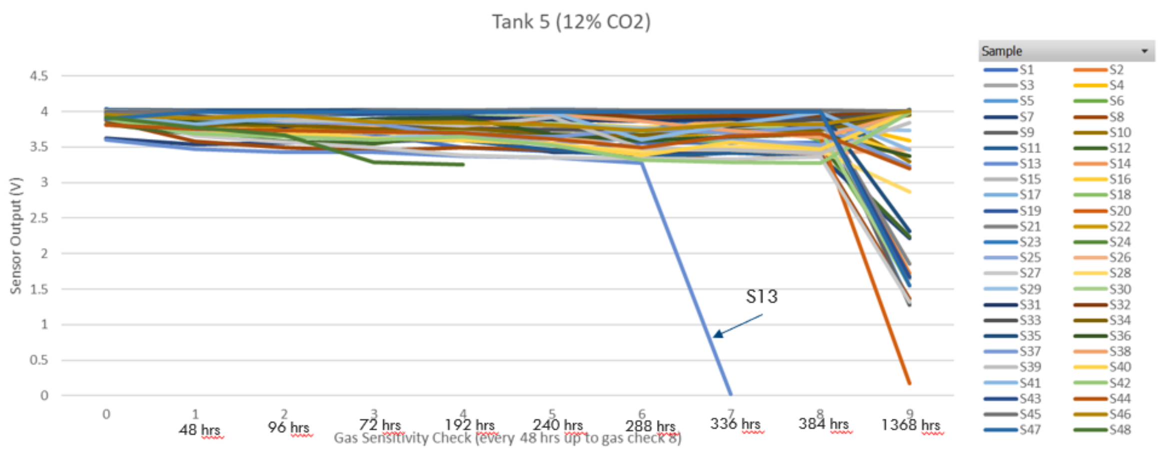


Figure 142: Sensor A THB, Sensor Output (T4 to T5)

APPENDIX H: Sensor C TC, Gas Sensitivity Performance

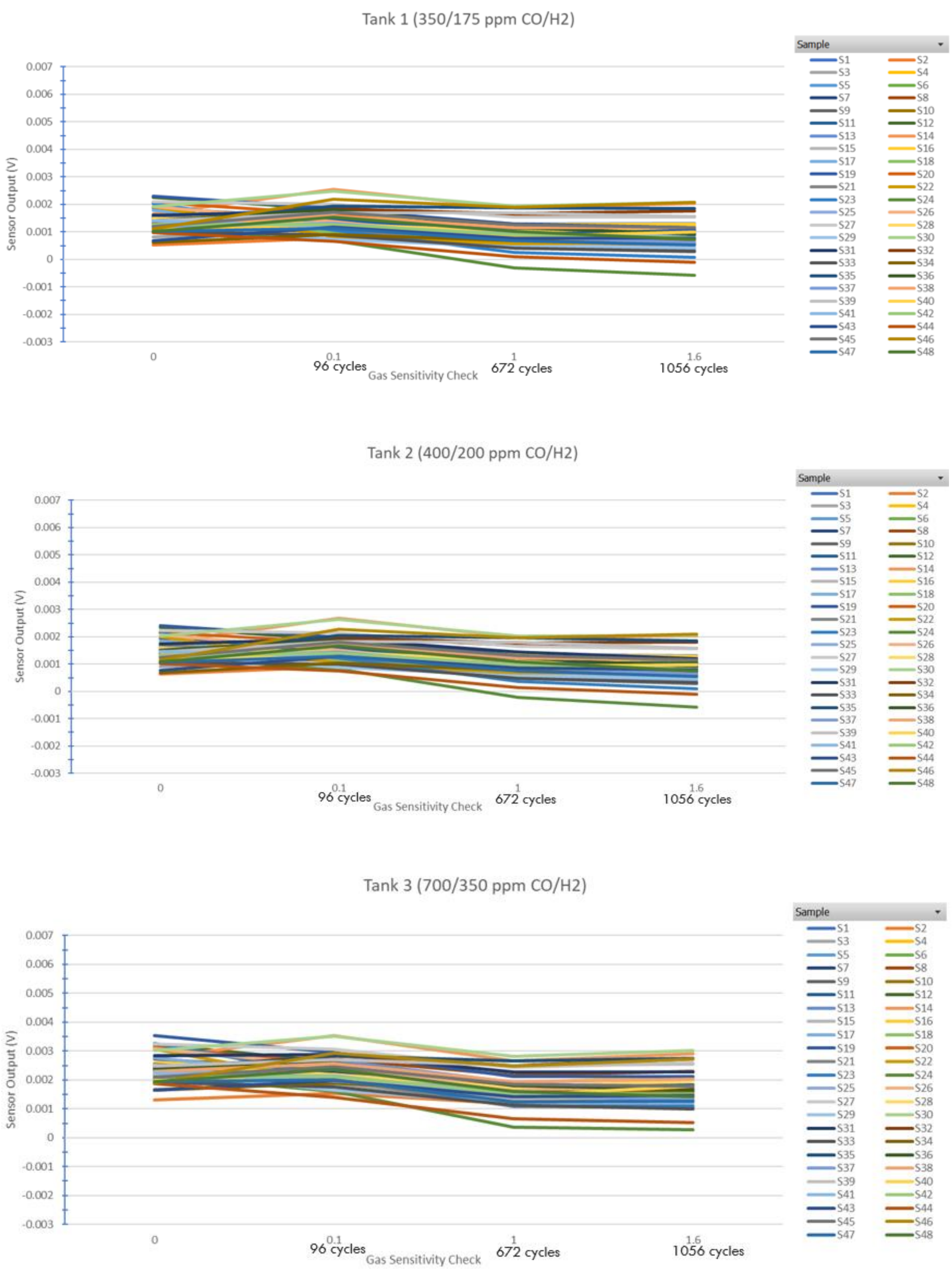
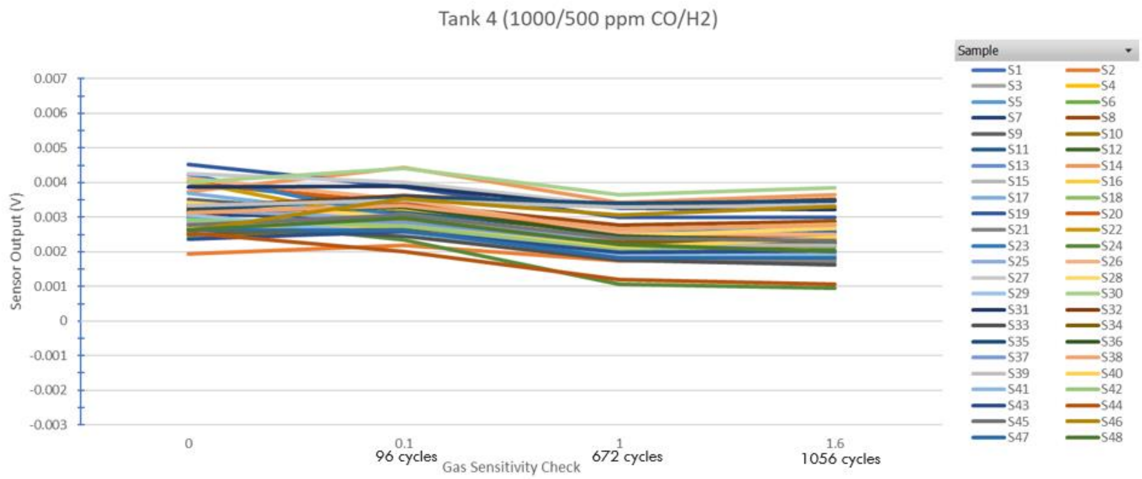


Figure 143: Sensor C TC, Sensor Output (T1 to T3)



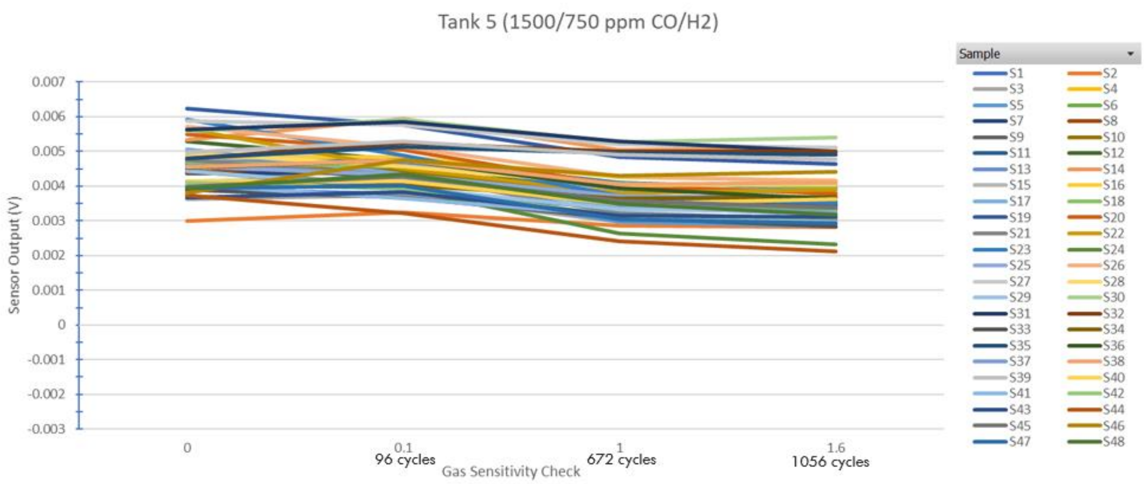


Figure 144: Sensor C TC, Sensor Output (T4 to T5)

APPENDIX I: Sensor C THB, Gas Sensitivity Performance

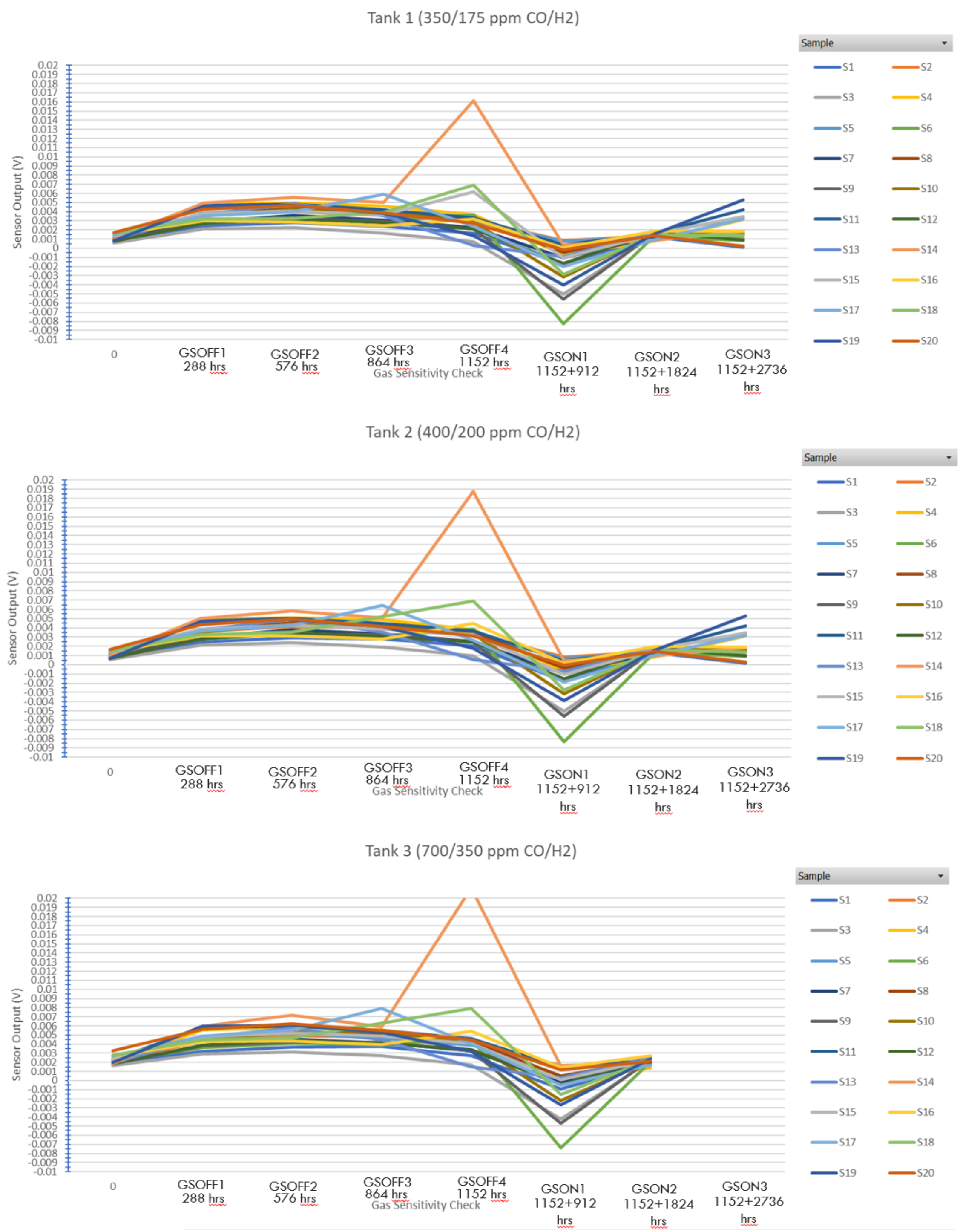


Figure 145: Sensor C THB, Sensor Output (T1 to T3)

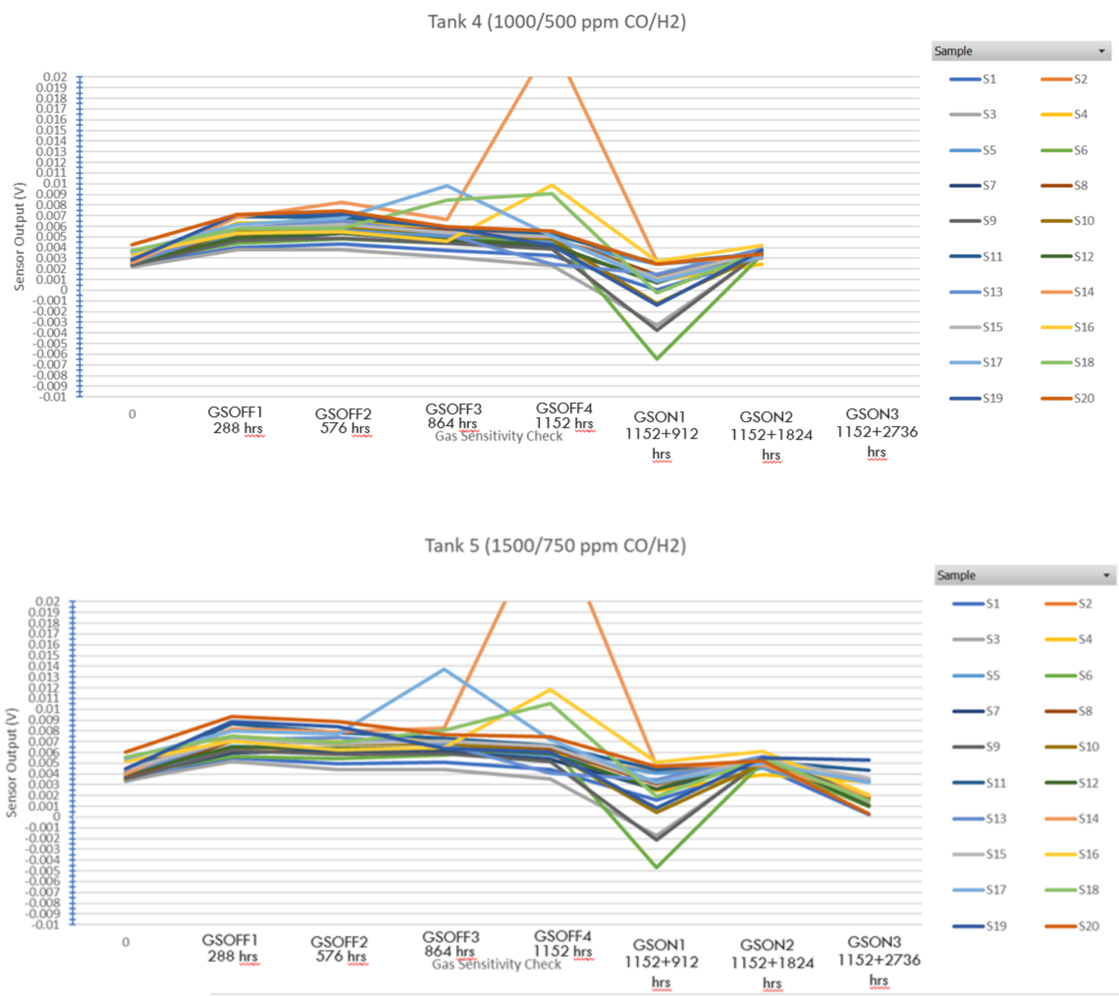


Figure 146: Sensor C THB, Sensor Output (T4 to T5)

APPENDIX J: Baseline Electrical Measurements

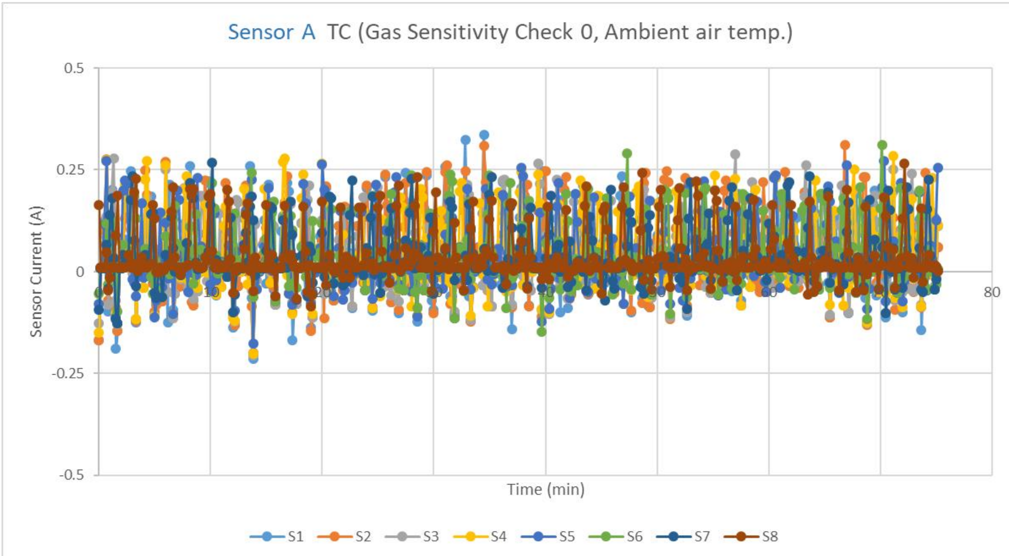


Figure 147: Sensor A TC, Baseline Check (GS0) of Current

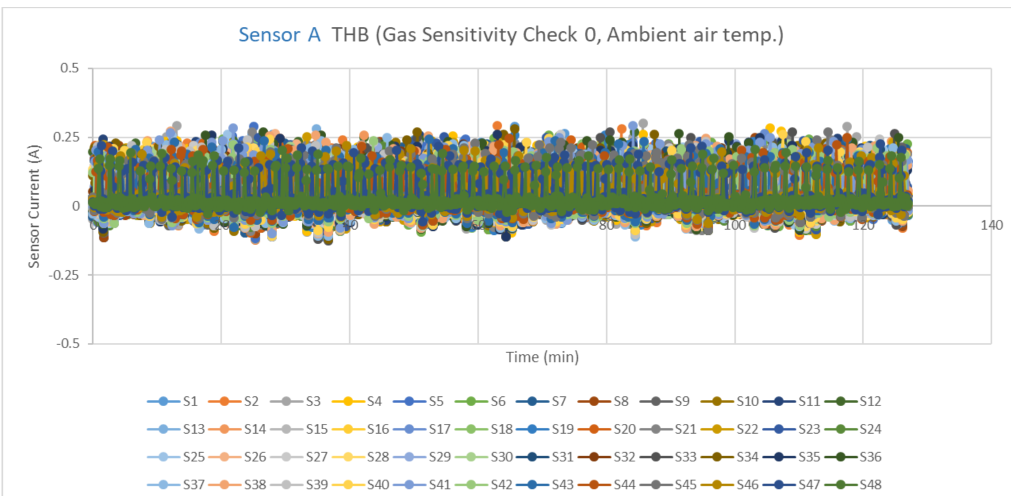


Figure 148: Sensor A THB, Baseline Check (GS0) of Current

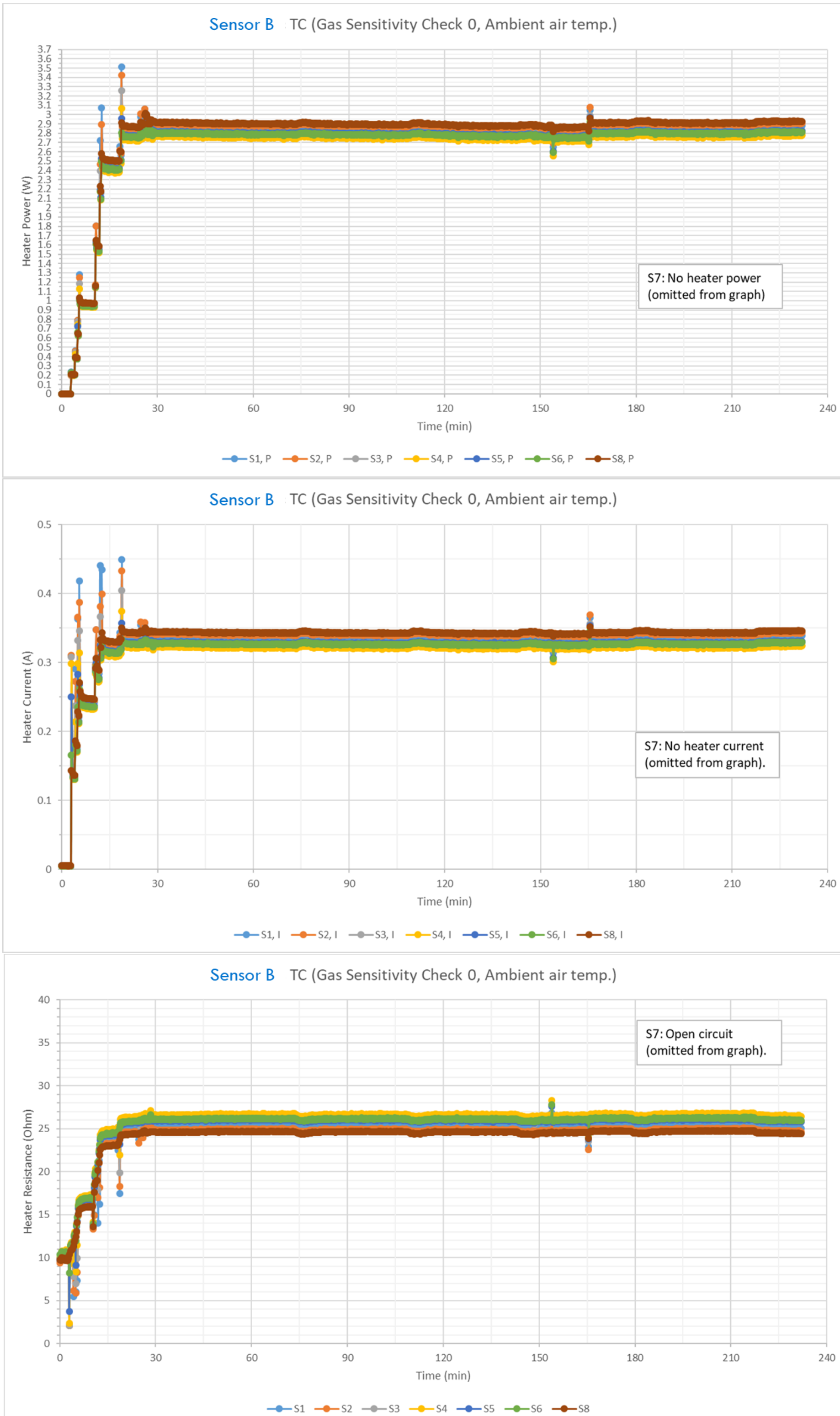


Figure 149: Sensor B TC, Baseline Check (GS0) Power/Current/Resistance

Figure 150: Sensor B TC, Power/Current/Resistance during Cycling

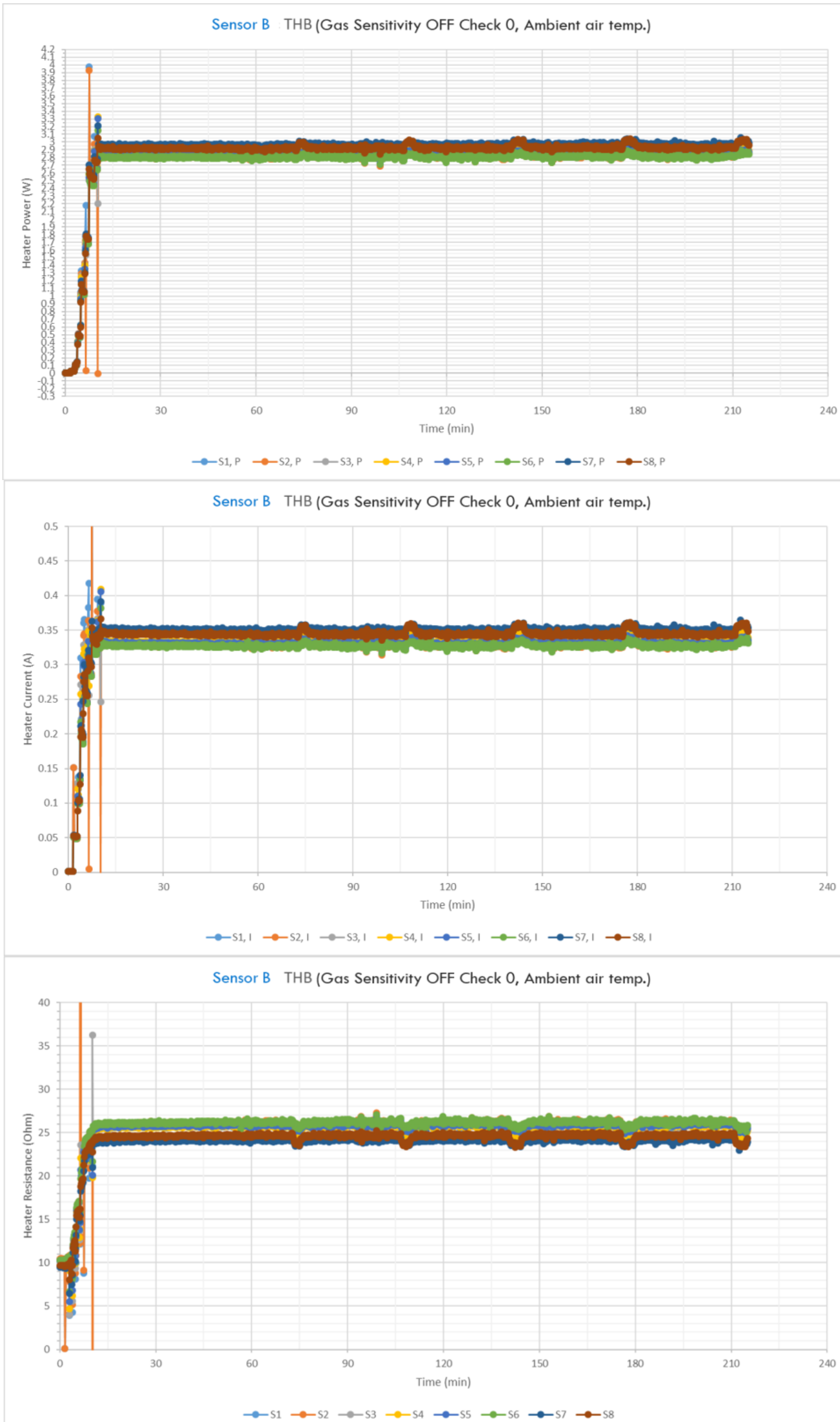
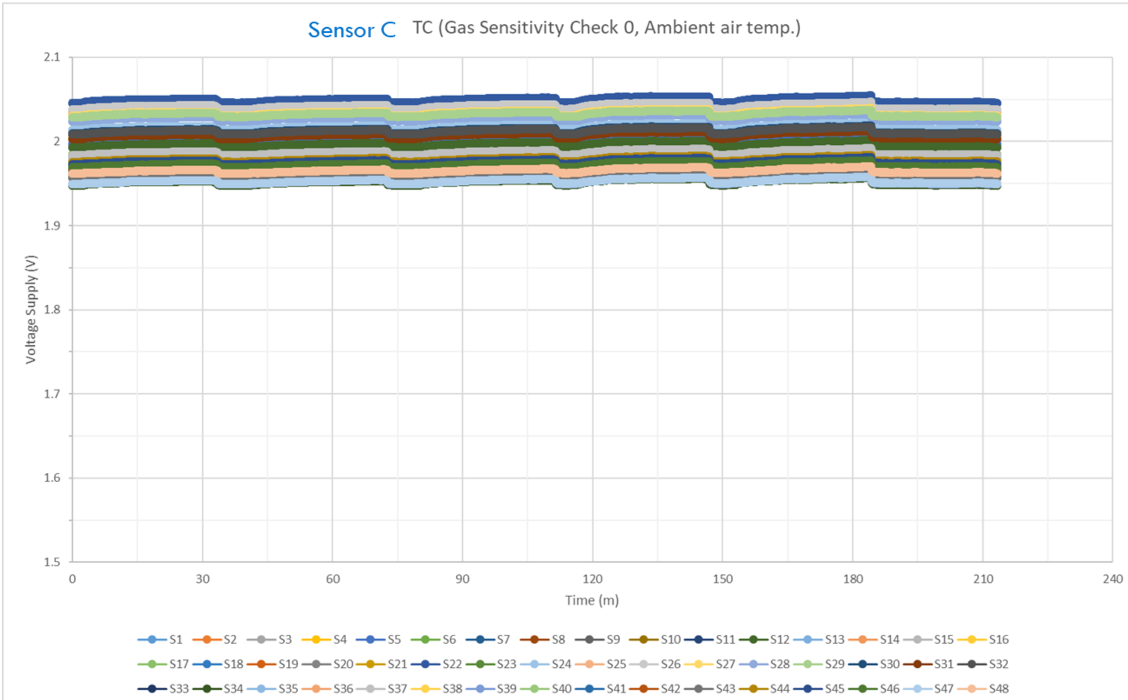


Figure 151: Sensor B THB, Baseline Check (GS0) Power/Current/Resistance

Figure 152: Sensor B THB, Power/Current/Resistance during first THB Exposure



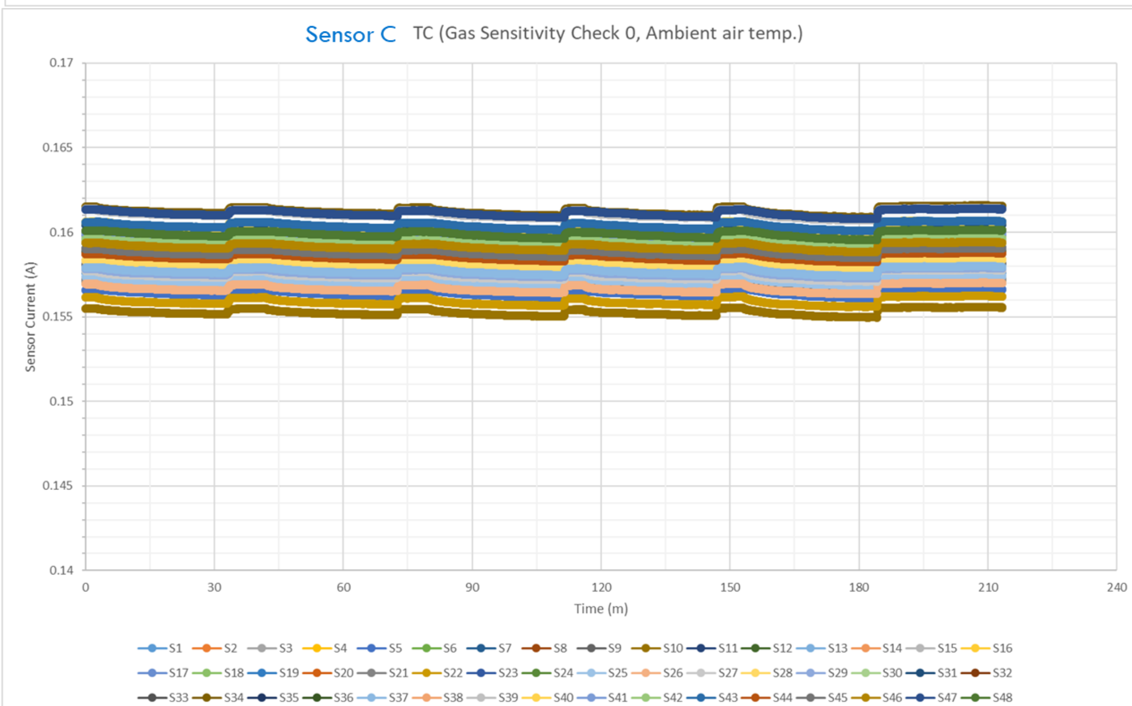


Figure 153: Sensor C TC, Baseline Check (GS0) of Voltage and Current

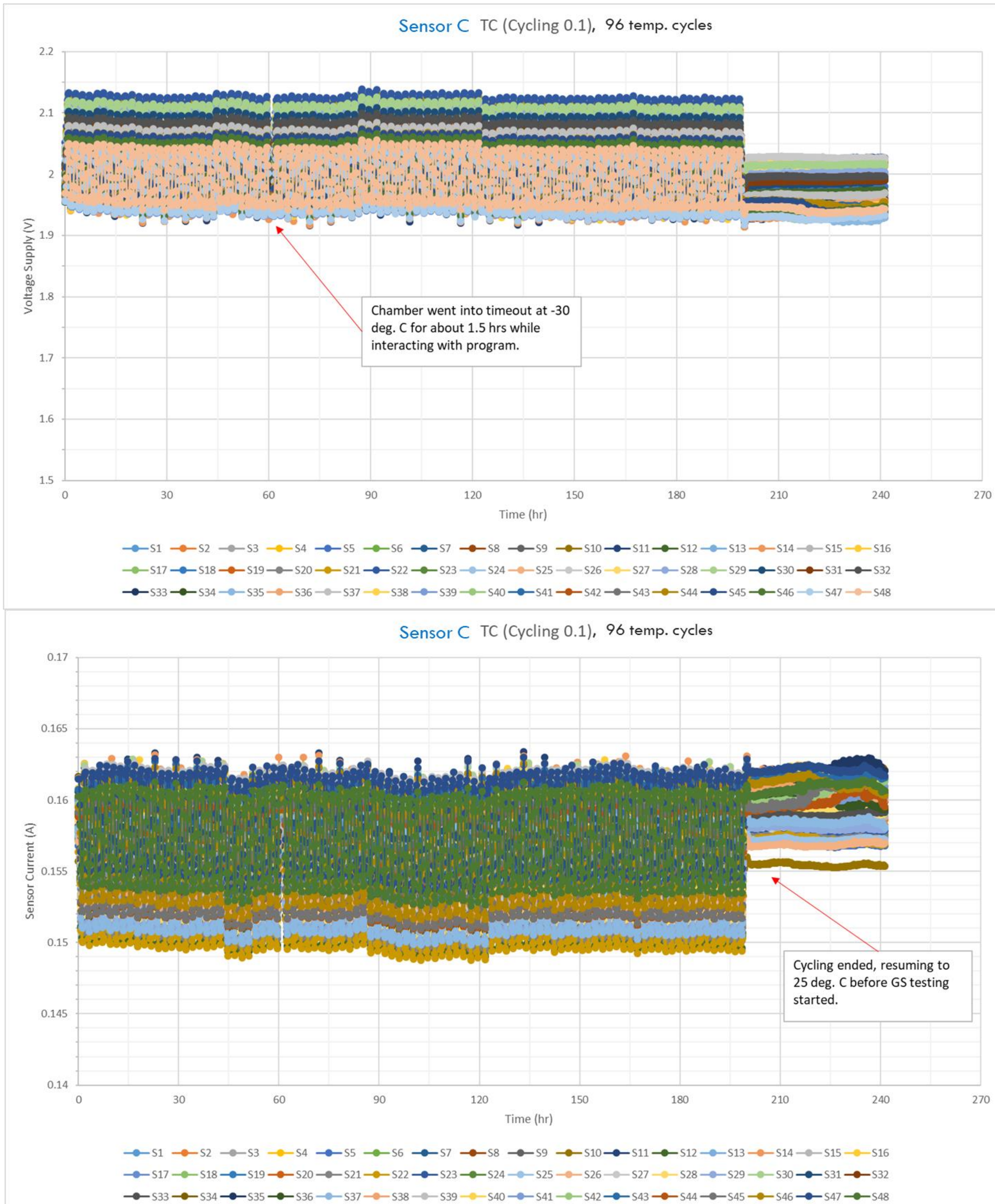


Figure 154: Sensor C TC, Voltage and Current during Cycling

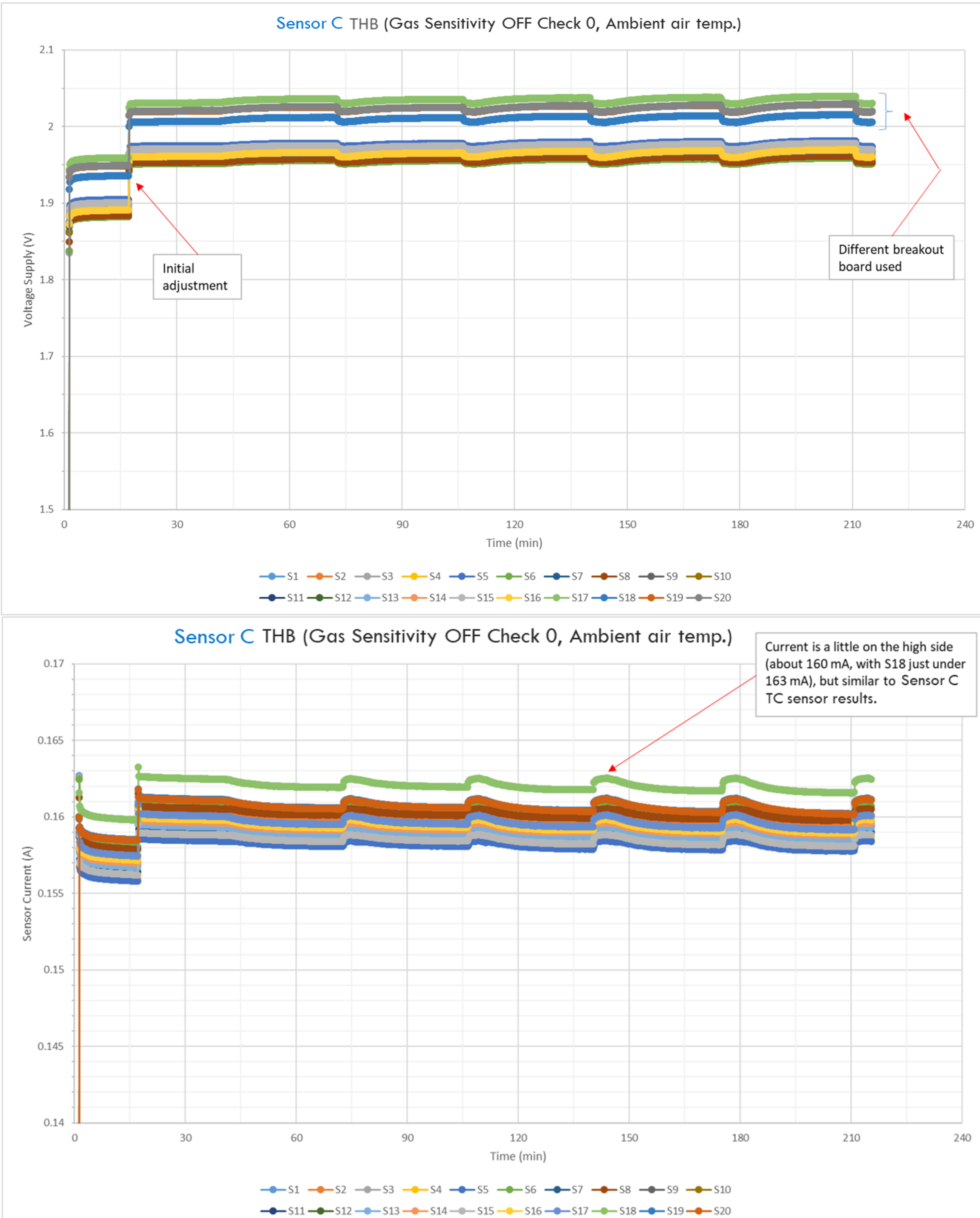
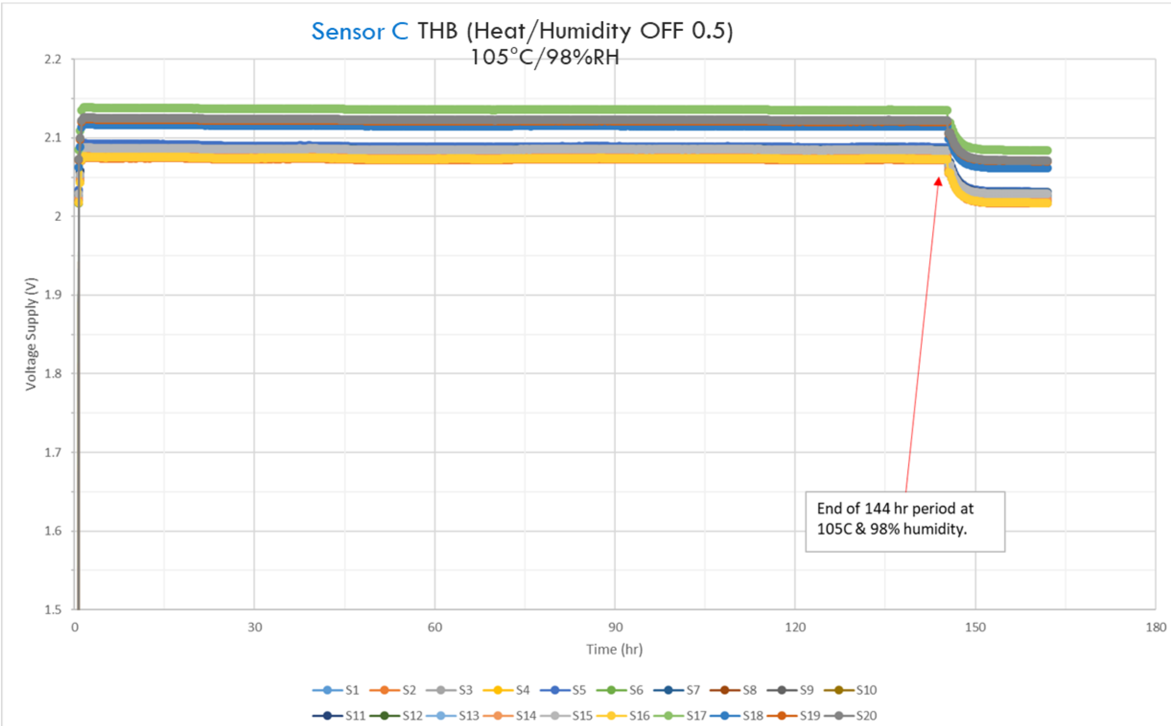


Figure 155: Sensor C THB, Baseline Check (GSOFF0) of Voltage and Current



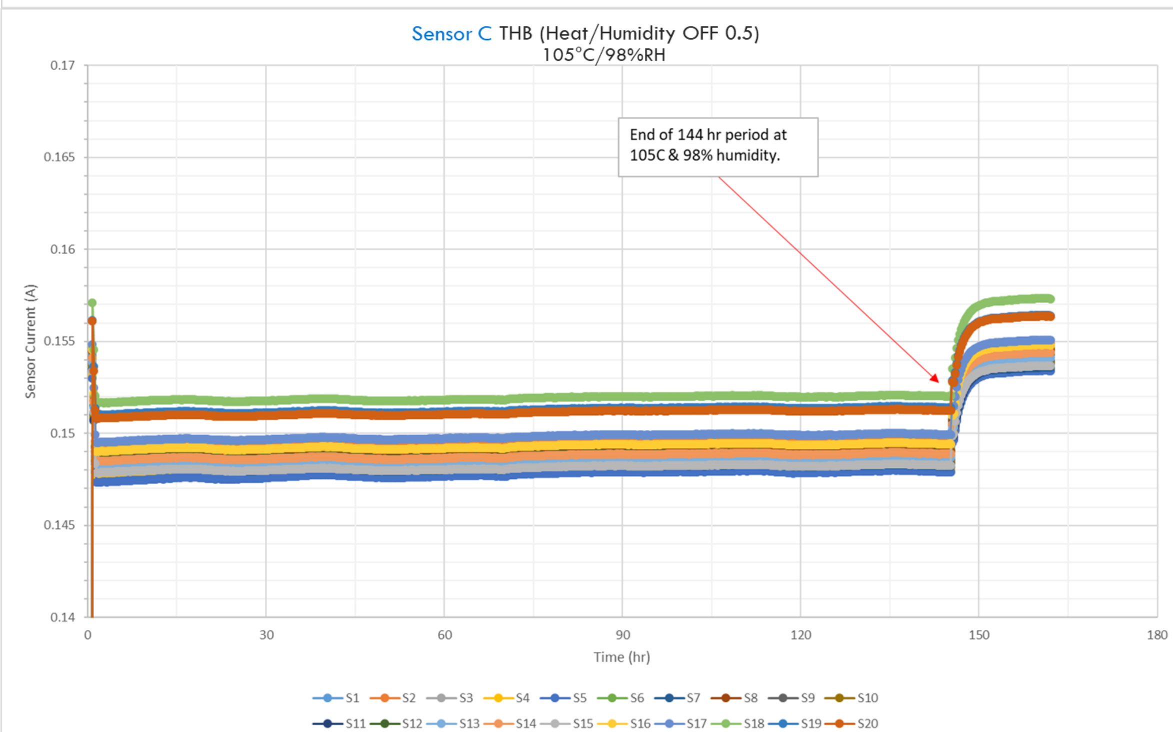


Figure 156: Sensor C THB, Voltage and Current during THB Exposure

Revision History

Version	Description of Change	Date	Author
1	Initial release.	5/28/2019	CS
2 DRAFT	Editorial updates, clarifications, and comments from CPSC addressed. Not released.	10/16/2019	CS
3 DRAFT	Editorial updates, clarifications, and comments from CPSC addressed. Not released.	1/31/2020	CS
4	Approval of revisions by CPSC. Editorial updates, including with Sample Disposition, Disclaimer, and Confidentiality/Indemnification. Revision History page added. Report template updated to Ansys/DfR.	10/19/2022	CS

Sample Disposition

If you would like your samples returned, please provide:

- Shipping account number
- Shipment type (FedEx 2-day or overnight, UPS, DHL, etc.)
- Complete shipping address
- Recipient's name, phone number, and email address
- Insured value (if any)
- Customer information (when returning to overseas location)

If no disposition instructions are received, samples will be retained for 6 months before being recycled and destroyed.

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From all of us at ANSYS, we would like to thank you for choosing us as your partner in quality and reliability assurance.

ATTACHMENT 3

Ansys / DfR

Project Number: DfR18-0542 **Date**: 9/16/2022, v5

Performance and Accelerated Life Testing of Redesigned Carbon Monoxide and Combustion Gas Sensors

For Submission to

Consumer Product Safety Commission (CPSC)

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Table of Contents

Executive Summary

Accelerated life testing (ALT) was conducted on two commercially available combustion gas sensing technologies, Sensor A and Sensor B, that were redesigned for improving reliability based on previous ALT. The goal was to obtain an assessment of the performance and reliability of the sensors in two common application areas of a residential gas furnace. The operating and environmental conditions for these application areas were based on the U.S. Consumer Product Safety Commission's Performance Work Statement to Ansys and common duty cycle rates derived from the Federal Test Procedures for Residential Furnaces and Boilers[1].

From the application field conditions and the sensor design and material limitations, two main tests were performed to induce the expected failure mechanisms:

- Temperature Cycling (TC)
- Temperature Humidity Bias Testing (THB)

The tests were conducted to demonstrate 85% reliability with an 80% confidence level. Industry standard reliability acceleration models were used for determining acceleration factors from field and test conditions. Test sample quantity and test durations were part of test parameter development using ReliaSoft Weibull++ software. Results in test were correlated back to equivalent field life based on meeting or exceeding the prescribed test parameters.

Hard failures were defined as a severely degraded or absent sensor signal output, in which the sensor is unable to detect some level of its intended target gas range. In the case where the number of hard failures exceeded that allowed for the demonstration test, a life data analysis was performed in Weibull++. Acceleration factors were used to determine the expected equivalent field life from the Weibull++ analysis results in test.

<u>Sensor A</u>

For Sensor A, all 8 samples undergoing thermal cycling survived through 2292 thermal cycles without any hard failures. A 20-year equivalent field life expectancy was demonstrated for the vent pipe application area.

In THB testing for 10-year equivalent life expectancy, the demonstration test requirement of up to 7957 hrs with 2 hard failures was not met. Based on 14 hard failures out of 48 samples in test, a Weibull++ analysis shows a 6.4-year expected field life equivalent for THB-induced failure mechanisms for the vent pipe application area, with a lower bound of 5.9 years and upper bound of 6.9 years for 80% confidence level.

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[1] DOE, Energy Conservation Program for Consumer Products: Test Procedures for Residential Furnaces and Boilers; Final Rule. Federal Register, Vol. 81, No. 10, Part V, January 15, 2016.

Sensor A is expected to have a lower life prediction under THB-induced failure mechanisms compared to thermo-mechanical failure mechanisms. The predominant failure mechanism is likely humidity-based given the relatively benign temperatures compared to humidity levels experienced in the vent pipe application. Based on this, the conservative approach was to take the 6.4-year expected field life from THB testing as the overall life prediction.

Accuracy and stability performance in both TC and THB testing exceeded the manufacturer's published specification limits, but ramp and settling time are not defined by the manufacturer. Regardless, functionality with response to target gas concentrations was maintained.

Sensor B

For Sensor B, six (6) of eight (8) samples undergoing thermal cycling survived through 12,113 thermal cycles (via power cycling) without hard failures. A 15-year equivalent field life expectancy was demonstrated for the secondary heat exchanger application area.

THB testing for the front half of the sensor was conducted separately from the back half due to the environment and material limitations for accelerated life testing.

- For the front half, all 10 samples undergoing THB testing survived through 8465 hrs exposure under temperature/humidity and bias without hard failures. There were 4 samples that exhibited soft failure, in which signal output degraded significantly (<100 mV) with one or more of the target gas concentrations, but still responded initially. A 10-year equivalent field life expectancy was demonstrated for the secondary heat exchanger application area.
- For the back half, all 8 samples undergoing THB testing survived through 4110 hrs of temperature/humidity and bias without any failures, exceeding the 2534 hrs requirement and demonstrating beyond a 10-year equivalent life expectancy.

Sensor B was limited to a 10-year equivalent field life demonstration for THB-induced failure mechanisms due to the test time and sample size constraints in test. This was less than the 15-year equivalent field life demonstrated for thermo-mechanical-induced failure mechanisms. The predominant failure mechanism appears to be from thermal cycling given the application and failures observed in test. However, without additional testing under THB, the conservative approach was to take the 10-year expected field life as a minimum overall life prediction for the given reliability metrics.

As noted in the prior report (DfR report v3 from project DfR16-0694) from previous testing, the manufacturer of Sensor C opted to not provide the requested feedback on results or the recommended design changes. As a result, Sensor C was not included in this round of testing.

1 Introduction

The U.S. Consumer Product Safety Commission ("CPSC") staff contracted the services of Ansys-DfR Solutions to conduct performance and quantitative accelerated life testing (ALT) of re-designed carbon monoxide (CO) and combustion sensors in accordance with generally accepted practices established within the field of Reliability Engineering.

The purpose of this test program is to accelerate the aging of the two (2) different CO/combustion gas sensing technologies under examination in order to estimate their life span within the operating environment of a residential gas furnace or boiler. Previous sensing technology designs were tested for reliability under a separate contract, and improvements were made by each manufacturer based on the performance results.

1.1 Background

Residential gas furnaces and boilers are among the leading causes of annual, non-fire related CO poisoning deaths among all consumer products in the United States. Currently, the governing voluntary standards for these appliances do not require protection against many of the failure modes known to cause or contribute to the leakage of unsafe levels of CO into the living space of a residential structure.[2] CPSC staff has demonstrated the concept of using CO or other combustion gas sensors in the heat exchangers, flue passageways, and vent pipes of gas furnaces to detect unsafe levels of CO in these areas of the appliance and cause the shutdown of the appliance in response.[3,4,5] The gas appliance voluntary standards community has expressed concern about sensors having the durability and longevity to operate within the operating environments of these appliances for the lifespan of the appliance (estimated to range from 15-20 years).[6,7,8,9]

In Japan, incomplete combustion devices have been required by the Japanese Industrial Standards (JIS) in residential gas water heaters to protect against CO poisoning since approximately 2001.[10] In Europe, the Committee for European Standardization (CEN) published a standard for combustion product sensing devices (CPSD) for usage within residential gas boilers to help maintain the proper air-fuel ratio of these appliances.[11] The United States does

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[2] ANSI Z21.47, *Standard for Gas-Fired Central Furnaces*; ANSI Z21.13, *Standard for Gas-Fired Low Pressure Steam and Hot Water Boilers*; and ANSI Z21.86, *Standard for Vented Gas-Fired Space Heating Appliances*.
[3] *Furnace Combustion Sensor Test Results*, R. Jordan, U.S. Consumer Product Safety Commission (2001).
[4] *Combustion Sensor Test Results*, R. Jordan, U.S. Consumer Product Safety Commission (2004).
[5] *Evaluation of the Durability and Longevity of Chemical Sensors Used In-Situ for Carbon Monoxide Safety Shutdown of Gas Furnaces,* R. Jordan, R. Butturini, U.S. Consumer Product Safety Commission (2012).
[6] *Minutes of the Z21/83 Committee, September 22, 2005 Meeting, Item 2.*
[7] *Letter from GAMA to CPSC, dated September 5, 2005.*
[8] *Final Report from Cross-Functional Working Group (WG) on Carbon Monoxide Detector Sensors in Gas Appliances to the Z21/83 Technical Committee, June 2019.*
[9] *Minutes of the Z21/83 Technical Committee, October 29, 2019, Action A.22-e.*
[10] JIS-S-2109, *Japanese Industrial Standard for Gas burning water heaters for domestic use*
[11] EN 16340, *Safety and control devices for burners and appliances burning gaseous or liquid fuels—Combustion product sensing devices.*

not presently require CO or combustion gas sensors to be installed in residential heating appliances.

1.2 Accelerated Life Testing (ALT)

Accelerated life testing (ALT) is a method of test that accelerates failures in devices in order to quantify life characteristics in normal use conditions, known as the field environment. Acceleration of damage accumulation (failures) typically requires the application of stresses above that which the device will see in a typical field environment.

ALT requires the application of an acceleration factor, which is the ratio of time in field to time in test for an event (i.e., failure). Higher acceleration factors equate to shorter test times. However, increasing these stresses beyond the limitations of the device materials will induce failure mechanisms that are not seen or relevant in the field. Therefore, these material limitations serve as constraints on the amount that any test can be accelerated.

The stresses used in test (e.g., temperature, humidity) are chosen to accelerate the failure modes of interest in the field environment. Higher stresses equate to higher rates of damage accumulation in test, resulting in test times shorter than the anticipated life of the devices under test:

Total Test Time = Field Life / Acceleration Factor

Additional parameters that impact the life expectancy of a device, in addition to the stresses applied during test, include:

- Environmental duty cycle for the devices
- Reliability factor that the test will strive to demonstrate (essentially, the percentage of sensors expected to perform their intended function for the anticipated life expectancy)
- Confidence level factor that describes how accurate the predicted reliability is (defining the range of certainty around the predicted reliability)

ALT can be run to demonstrate a particular field life based on the test parameters. If a sufficient number of samples pass in test, an equivalent field life is demonstrated for the device. If the number of allowable failures is exceeded, time-to-failure data can be analyzed to extrapolate to field conditions, thereby providing a prediction of life expectancy.

2 Test Plan

The test plan identifies the ALT conditions prescribed for each of the chosen CO/combustion gas sensors, including environmental conditions and electrical requirements. Also, a strategy for monitoring and measuring sensor degradation within the environment, through in-situ testing and periodic removal and characterization to gas sensitivity, is described.

The approach taken first identifies the operating and environmental conditions for the sensors and their application requirements. A construction and design evaluation, including design changes made, was performed under the previous testing. This is shown in this test plan and is used to assess the device's specifications and capability against the requirements and help identify critical areas that would impact the reliability. Failure mechanisms were previously determined and appropriate failure acceleration models utilized to develop the final test parameters.

2.1 Operating and Environmental Conditions

Representative conditions found in typical use (field) environments for residential gas furnaces are shown in Table 1[12].

Table 1: Normal (Typical) Operating Ranges of a Residential Gas Furnace

Area of Furnace	Temperature On-Cycle	Humidity On-Cycle	Temperature Off-Cycle	Humidity Off-Cycle
Primary Heat Exchanger	149-260°C	0-50% RH	65.5-121°C	50-75% RH
Secondary Heat Exchanger	60-121°C	90-100% RH	37.8-65.5°C	75-90% RH
Vent Pipe	32.2-48.8°C	90-100% RH	23.8-37.8°C	75-90% RH

Based on the assumptions in the Federal Test Procedures for Residential Furnaces and Boilers[13], the duty cycle rates are shown in Table 2.

Table 2: Duty Cycle Rates

		ON (min)	OFF (min)
Gas Furnace	Single-stage	3.87	13.3
	Multi-stage	10	10
Gas Boiler	Single-stage	9.68	33.26
	Multi-stage	15	15

[12] U.S. Consumer Product Safety Commission, Performance Work Statement, "Performance and Accelerated Life Testing of Carbon Monoxide and Combustion Sensors," p. 11, October 3, 2016

[13] DOE, Energy Conservation Program for Consumer Products: Test Procedures for Residential Furnaces and Boilers; Final Rule. Federal Register, Vol. 81, No. 10, Part V, January 15, 2016.

The following additional parameters impacting life expectancy are defined, with reliability and confidence levels reasonable for the application and industry:

- Field life: Up to 20 years desired for combustion gas sensors (test duration constraints limited to 12 months can decrease the field target life attainable to less than 20 years)
- Heating load hours: 2080 hours based on the national average per year[14] (furnace burn time, or ON time)
- Heating season: 4160 hours (about 5.7 months) based on a ratio of 2 for the average length of the heating season to the average heating load hours[14]
- Reliability factor: 85% or better
- Confidence level factor: 80% or better

The number of thermal cycles experienced in the field was based upon the heating season indicated above and the duty cycle of a multi-stage gas furnace. While they may not be as commonly used as single-stage furnaces, multi-stage furnaces are typically more efficient and would be expected to increase in usage for the future with lower overall energy costs. A multi-stage furnace's total cycle time is a little more than that for a single stage furnace, as it has a significantly longer ON time. This equates to slightly fewer thermal cycles per year than for single stage furnaces, but significantly more cycles than that experienced with gas boilers.

For a multi-stage gas furnace, a total of 12,480 cycles per year was determined for a heating season of 4160 hours and the duty cycle indicated in Table 2.

2.2 Construction/Design Evaluation

Two different types of CO/combustion gas sensors were evaluated to undergo ALT. Reference to the manufacturer and model of these sensors are omitted in the text and graphics (via greyed-out boxes) for anonymity reasons:

- Sensor A: CO_2 Sensor Module
- Sensor B: Combustion Gas Sensor Module

The sensors tested had undergone a redesign to overcome the failures experienced in previous testing. An evaluation of each sensor design (both the original and re-design) was conducted to assess the limitations of the materials used to construct each sensor. The results are repeated below, with additional evaluation of the re-design.

[14] DOE, Energy Conservation Program for Consumer Products: Test Procedures for Residential Furnaces and Boilers; Final Rule. Federal Register, Vol. 81, No. 10, Part V, p. 2653, January 15, 2016.

2.2.1 Sensor A

Sensor A (Figure 1) is a dual-channel CO_2 module. Per the manufacturer's specifications, it is designed for high concentration measuring applications and uses a dual-channel non-dispersive infrared (NDIR) optics technology for diffusion or flow-through sampling.

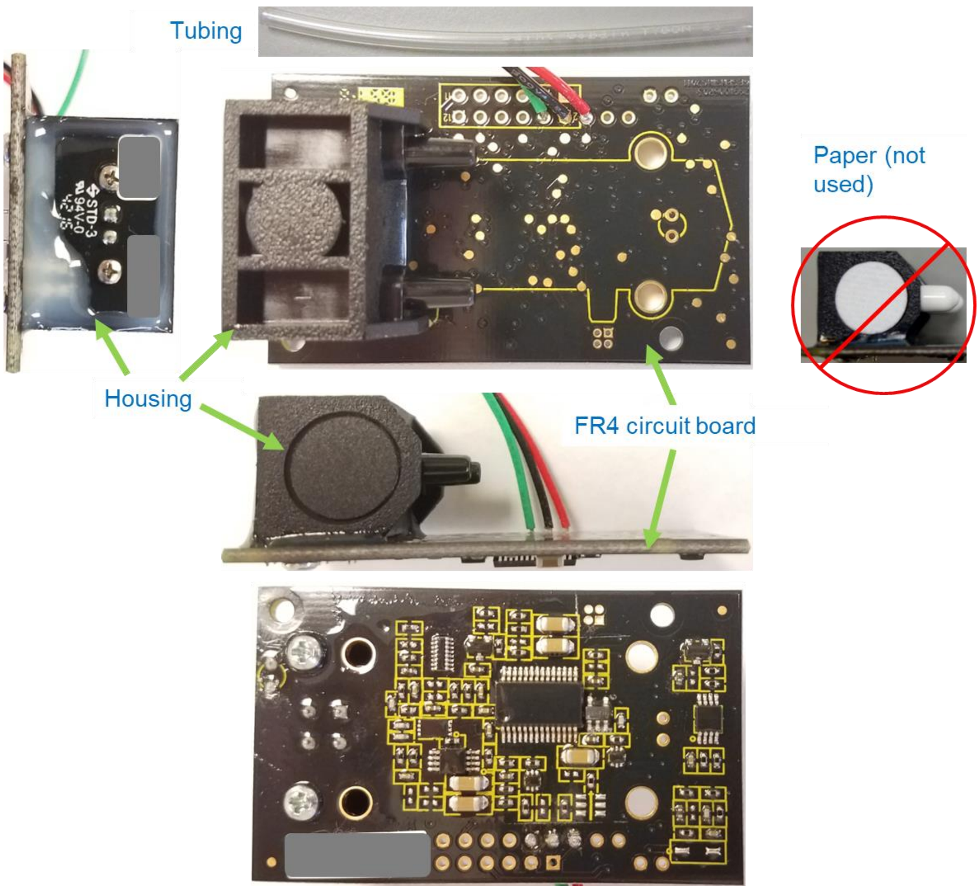

Figure 1: Sensor A

The IR lamp modulates on and off, and the filtered IR detector below monitors the intensity depending upon how much IR is absorbed by the measured gas (Figure 2). One channel measures CO_2 gas concentrations, and the other serves as a reference channel for the sensor signal intensity. The sensor has a 0 to 4 V output corresponding to a measurement range of 0 to 12% CO_2. Operating conditions are indicated at 0°C to 50°C and 0 to 95% RH (non-condensing), and the device operates off of 5 V_{dc} power supply. Storage conditions are indicated as -40°C to 60°C.

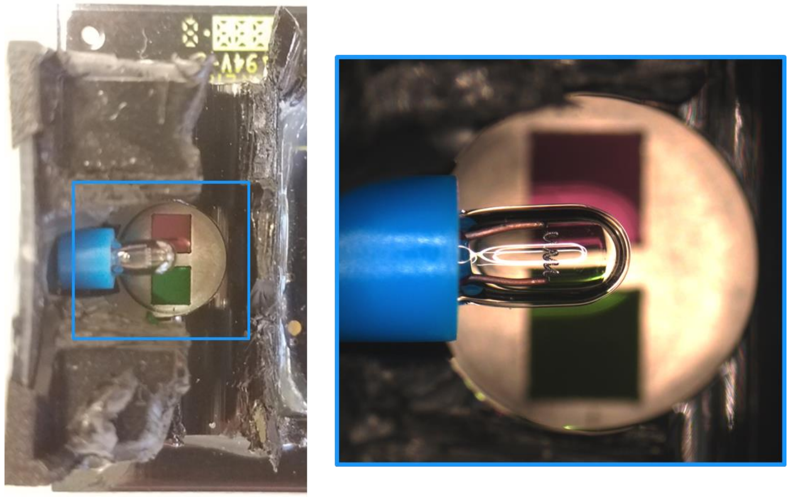

Figure 2: Sensor A, IR Source Lamp (Original Design)

In the original design previously tested, the optical filters were in direct contact with the air flow stream through the sensor (Figure 3). A small bead of epoxy seal existed between the optical filters and the top of the metal can. As indicated by the manufacturer, the epoxy seal is water permeable. This can lead to moisture ingress where the thermopiles are located.

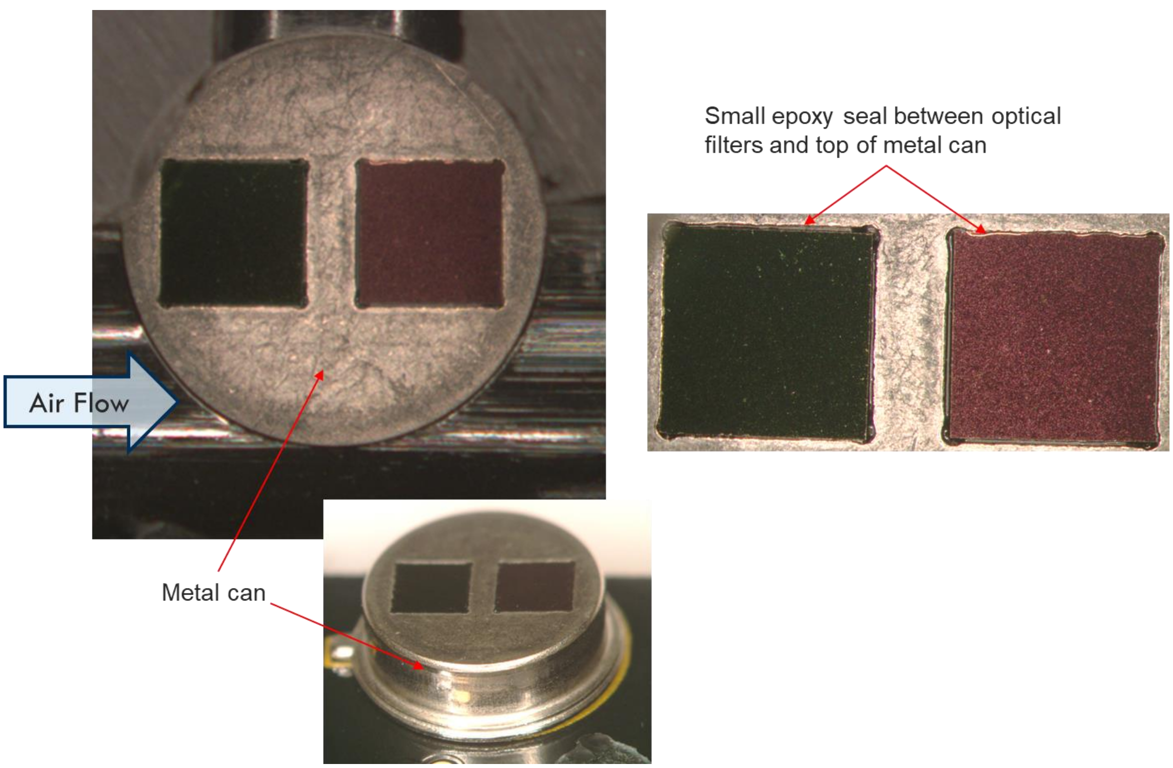

Figure 3: Sensor A, Infrared Detector (Original Design)

In the redesigned sensor, the infrared detector is encapsulated. A larger metal can with a glass window atop is used (Figure 4). This covers the optical filters (protecting them from the air flow stream) while allowing the light from the infrared lamp to pass through. The optical filters are sealed to the metal plate inside with a much larger epoxy seal.

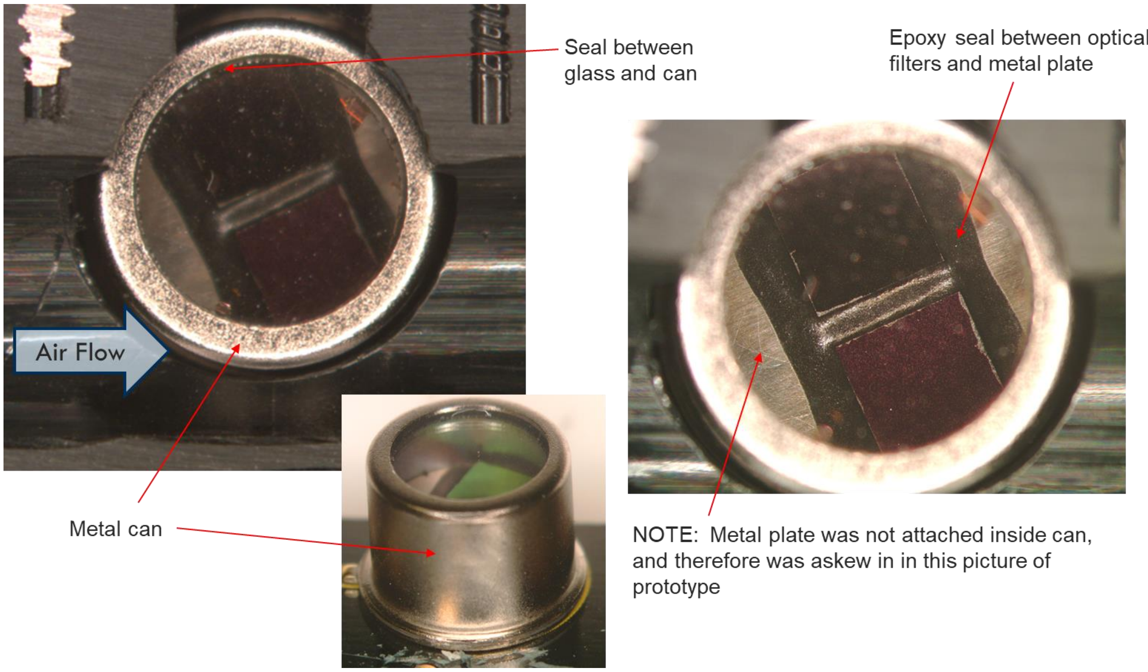

Figure 4: Sensor A, Infrared Detector (New Design)

The new design is a hermetically sealed package. Both the original and new design appear to have the metal can adhered to the detector board with solder. The main board to which the detector is soldered contains the same infrared detector component in wide use.

The manufacturer provided initial prototypes of the modified design. The black plastic housing was relieved in order to physically accommodate the larger metal can of the new design. The same assembly was used as on the original design, with epoxy glue added around the housing base to the main board (for retention, not a hermetic seal).

As before, the normal operating environment for Sensor A is in the vent pipe temperature range identified in Table 1. The sensor is designed to be installed entirely inside the field environment (diffusion sampling) or with only tubing into the field environment (flow-through sampling). Flow through rate is 250 mL/min maximum through the ports in the housing.

The thermal stability of the materials in this sensor were evaluated through the destructive analysis and manufacturer-provided specifications in relation to the vent pipe application temperature range (Table 1). The thermal stability range of temperatures has not changed from before.

Materials exposed to the environment: Thermal stability range

- Tubing, polyvinyl chloride (PVC) (Tygon): maximum 74°C
- Housing, polycarbonate (PC): maximum 170°C
- FR4 circuit board: maximum 140°C
- Paper: maximum 200°C (*Note – Actual units tested had cover with 3M 200MP adhesive (rated at 149°C) in place of paper (for use as flow-through sampling instead of diffusion sampling)).*
- Integrated circuits: maximum 125°C
- Infrared source lamp: -40°C to 105°C
- Infrared detector: -20°C to 120°C

Allowable test temperature range based on the above:

- Minimum temperature: -20°C
- Maximum temperature: Adhesives may be limited to the maximum storage temperature of 60°C (otherwise, 105°C can be used when substituting silicone tubing for PVC tubing for higher temperature capability in test)

2.2.2 Sensor B

Sensor B (Figure 5) is a mixed potentiometric chemical sensor module. Per the manufacturer's specification, it can detect multiple oxidizable gaseous substances (COe), like CO and H_2, in the measured gas (up to 3000 ppm CO/H_2, with ideal resolution up to 1000 ppm).

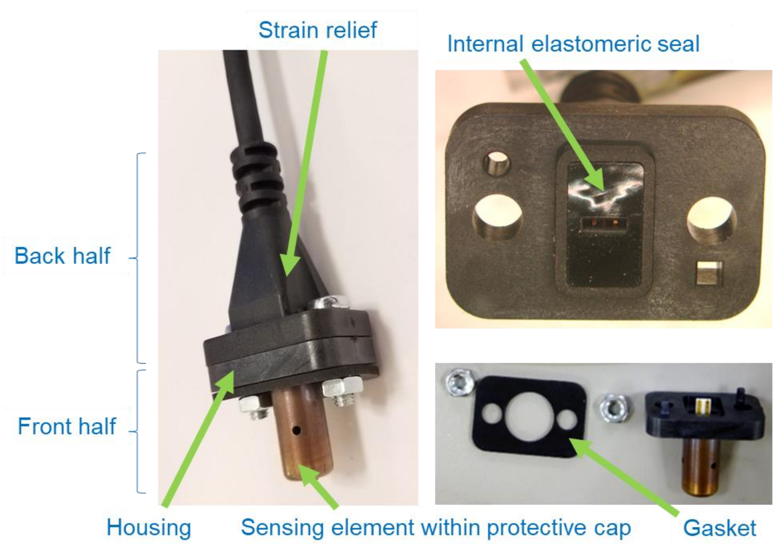

Figure 5: Sensor B

The sensor element (Figure 6) consists of: ZrO_2 ceramic (electrode substrate), Al_2O_2 ceramic (carrier substrate), and noble metals (sensing electrode material). A heating element exists on the back side of the substrate, as the sensor voltage output is very temperature dependent. The sensor element requires operation around 650°C (between 450°C to 700°C possible operating range), in addition to requiring a minimum level of oxygen of about 0.5% to 1% to maintain the chemical reaction of the electrodes. Power is supplied to the heater element only. A separate power supply controller box keeps the resistance of the heater at a constant value in the field (equal to the value that consumes 2.8 W to 3 W power in air with no airflow).

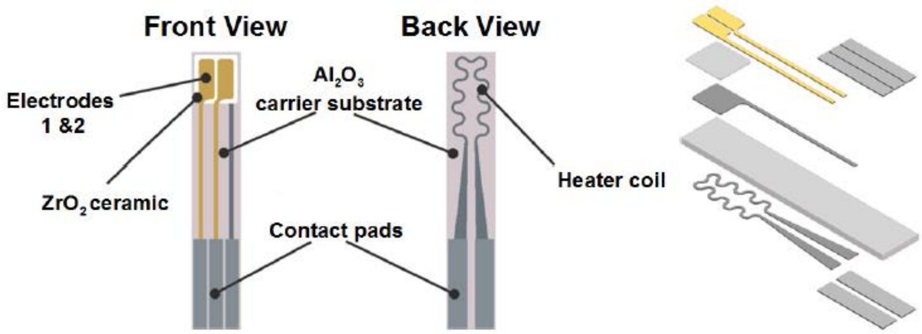

Figure 6: Sensor B Element Design (from manufacturer's specification)

The contact pads make electrical connection with the back half of the sensor through leads (interconnect) that deflect upon insertion of the pads (Figure 7).

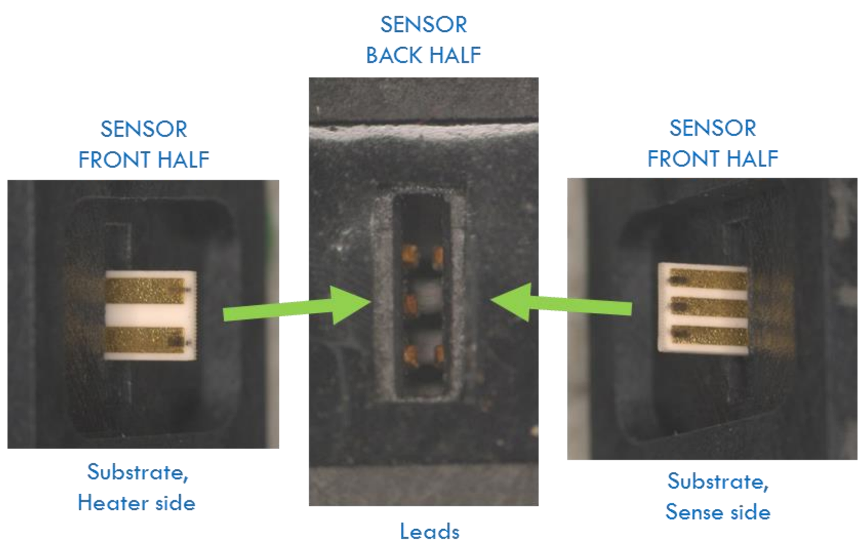

Figure 7: Sensor B Interconnect

The redesigned sensor has a new back half (design and materials) (Figure 8). The rubber strain relief material has changed and is thicker and stiffer than the original design. According to the data sheet, it maintains >75% tensile strength and elongation with hot air aging at 136°C/168 hr (DIN 53504). This is an improvement in temperature rating and structural design for the cable strain relief.

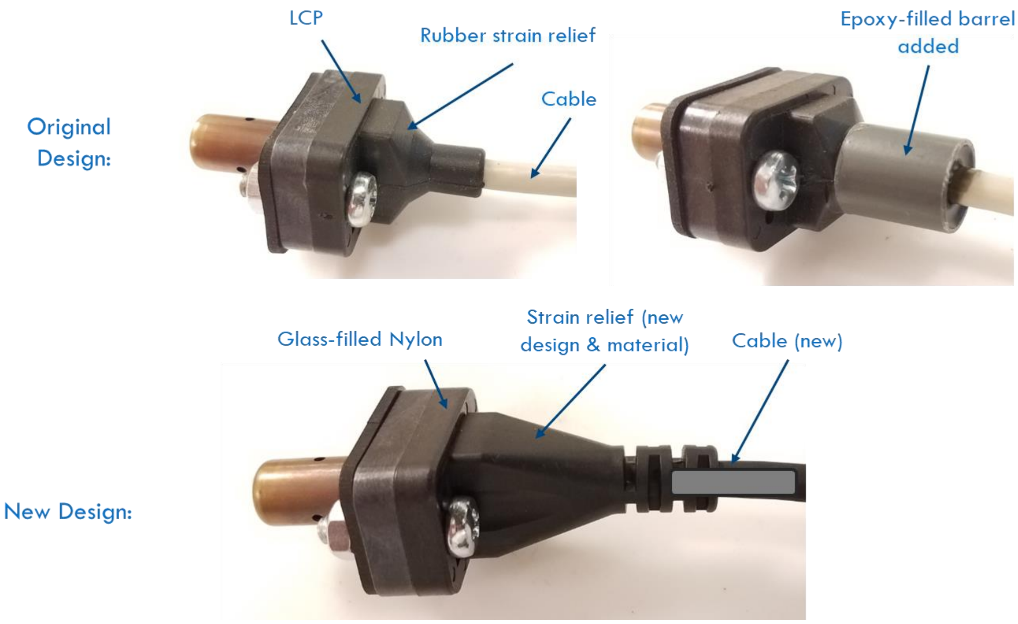

Figure 8: Sensor B, Changes to Back Half

Internal to the housing is a low density polyethylene (LDPE) material (Figure 9). This material typically is limited down to 70°C. The leads are connected to a board in the back half and, based on FTIR analysis, encapsulated in a polyamide potting, which is typically used in environments up to 120°C. It is not known if there is an improvement in retention of the spring leads internally that connect to the contact pads for the electrodes and heater element.

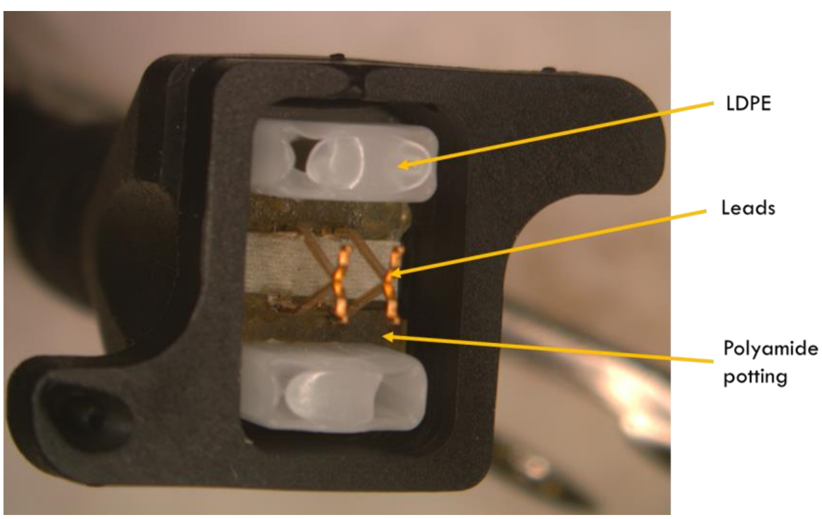

Figure 9: Sensor B, Strain Relief Connection (new design)

The back half housing material is a glass-filled nylon. It’s thermal index for 5000 hr is 163°C (IEC 60216), and it has a heat deflection temperature of 290°C (ISO 75 -1/-2). It is heat stabilized and is rated to maintain many of its mechanical properties at high temperature up to 220°C. This is a good material and is similarly good for high-heat applications as the original LCP material.

The new cable is a stranded and shielded, with a temperature range of -50°C to 90°C. This is a slight improvement in temperature rating over the original white cable (rated from -30°C to 80°C nominal).

As before, the normal operating environment for this device is in the secondary heat exchanger temperature range identified in (Table 1). The device has a rated temperature range of -20°C to 150°C (with short peaks up to 200°C). It is considered immune to condensing humidity and is suitable for condensing boilers and the exhaust of fuel cells. The sensor is designed to be installed with only the sensor element exposed to the field environment.

The thermal stability of the materials comprising Sensor B were evaluated through the destructive analysis and manufacturer-provided specifications in relation to the secondary heat exchanger application temperature range (Table 1). The thermal stability range of temperatures has changed somewhat from before.

Material exposed to the environment: Thermal stability range

- Sensing element (ceramic ZrO_2): melting point of 2700°C
- Cap, stainless steel: 930°C or higher

Materials not exposed to the environment: Thermal stability range

- Gasket, Viton elastomer: maximum 200°C
- Housing, front main body, liquid crystal polymer (LCP): -40°C to 216°C
- Connector gasket, back main body, silicone: -60°C to 200°C
- Housing, back main body, GF nylon: max. 220°C
- LDPE, internal: about 70°C continuous
- Polyamide potting: max. 120°C typically
- Strain relief, TPE 85A: max. 136°C
- Cable: -50°C to 90°C

Allowable test temperature range based on the above:

- Minimum temperature: -20°C
- Maximum temperature: Operating temperature limit of 150°C when heater element is powered (front half), 70°C (external back half)

Heat generated from the roughly 650°C operating temperature of the heater element, combined with the high temperatures in the operating secondary heat exchanger environment, is conducted to the back half of the sensor. This is where lower temperature-limited materials are used, and so the rated maximum operating temperature of 150°C should not be exceeded.

2.3 Failure Mechanisms

The CO and combustion sensors under test, if used in residential gas furnaces and boilers in the U.S., would experience a combination of high temperatures and high humidity in use. With a duty cycle of 50%, these environmental extremes are cyclical in nature. The stress conditions could also include power cycling stresses if they powered on and off with the furnace (e.g. 10 minutes on and 10 minutes off cycles) and possible corrosion caused by a typical residential gas furnace. However, these sensors are intended to remain powered ON during the heating season, and therefore power cycling stresses would not be expected.

Based on the material characteristics of each sensor, temperature cycling can drive mechanical fatigue due to thermo-mechanical loading. Any time two different materials are connected to one another in electronic assemblies, there is a potential for a coefficient of thermal expansion (CTE) mismatch to occur. Some of these CTE mismatch interactions can be quite complicated due to the different mechanical properties of materials, complex geometries, and competing material behaviors. Solder durability/fatigue and material fatigue (e.g. component packaging, interconnections) become of concern for overall reliability. This type of failure mechanism is often replicated through temperature cycling, and is typically applied to induce cracking in permanent interconnects (solder joints, wire bonds, vias, die attach, etc.) and fretting in separable connectors (as between the front and back half of Sensor B devices).

Humidity exposure can induce corrosion, metal migration, oxidation of exposed metal surfaces, or hydrolysis of polymers. For these sensors, electrical parameter shifts, absorption or adsorption of materials, and potential shorting are all potential failure mechanisms typically associated with a temperature humidity bias (THB) stress, where the bias is the power source. Corrosion from external gases and humidity are also a potential failure mechanism that could affect these types of sensors given their typical use environments.

2.4 Acceleration Models for Testing

Accelerated life tests were devised to expose the sensors to stressors associated with their field use, compressing the time for testing through overstress acceleration. Acceleration factors were determined for each ALT test based on the failure mechanisms identified (brought on by temperature cycling and THB exposure) and the associated models for acceleration.

2.4.1 Temperature Cycling Model

In temperature cycling, sensors are subjected to high and low temperature extremes. The intent is to create cyclic stresses due to thermal expansion and contraction of the various materials comprising the sensors. For ductile metals (such as solder), the most common approach is to use the Coffin-Manson equation. The assumption is that the failures will be due to fatigue from cyclic strain dependent upon the number of applied temperature cycles. This strain is in the inelastic and creep regions for soldered interconnects on Sensor A, as well as the back half of Sensor B. The spring-loaded leads in Sensor B can also experience stress relaxation. The equation shown in Figure 10 illustrates this computation.[15]

[15] "Design for Reliability-Concepts in Accelerated Testing," http://www.dfrsoft.com/DfRSoft%20Accel%20Testing.pdf, January 8, 2017

$$A_{TC} = \frac{N_{Use}}{N_{Stress}} = \left(\frac{\Delta T_{Stress}}{\Delta T_{Use}}\right)^{K}$$

$$Ln(N_f) = C - K \ Ln(\Delta T)$$

Notation

A_{TC}	=Temperature cycle acceleration factor
N_{Stress}	=Number of cycles tested
N_{Use}	=Equivalent number of field cycles
ΔT_{Stress}	=Temperature cycle test range
ΔT_{Use}	=Nominal daily temperature change in the field
K	=Temperature cycle exponent
N_f	=Number of cycles to failure
C	=Constant

Figure 10: Temperature Cycle Acceleration Linearized Cycles to Failure Model

Acceleration factors are very sensitive to the value of the K exponent. Values between 2 and 4 for this exponent have been used in the industry. A value of 2.4 is applied based on the soft ductile material used in lead-free solder interconnects[16].

The temperature delta in the field is a driving factor in the temperature cycling acceleration model. This temperature delta is taken as the difference between the maximum field temperature in the ON-cycle and the maximum field temperature in the OFF-cycle. It is considered less likely for a temperature delta to occur between the maximum and minimum extremes of the ON- and OFF-cycles, respectively. The temperature delta between the maximum ON- and OFF-cycle temperatures is also larger than that between the minimum ON- and OFF-cycle temperatures, and therefore is more conservative in applying real-world field conditions.

2.4.2 Temperature-Humidity Bias Model

In THB testing, sensors are placed at elevated temperatures and humidity for an extended period of time. The model includes a relationship between life and temperature (Arrhenius Model) and life and humidity (Peck's Law Model).[17] The product of these two separate models generates an overall acceleration factor that must be greater than 1 for the model to be valid. Figure 11 delineates the equations used for this model[18].

[16] Blish R, Temperature Cycling and Thermal Shock Failure Rate Modeling, 1997 IEEE International Reliability Physics Symposium Proceedings. 35th, April 8-10, 1997

[17] Peck, D. Stewart, A Comprehensive Model for Humidity Testing Correlation, 1986

[18] "Design for Reliability-Concepts in Accelerated Testing," http://www.dfrsoft.com/DfRSoft%20Accel%20Testing.pdf, January 8, 2017

$$A_T = Exp\left\{\frac{E_a}{K_B}\left[\frac{1}{T_{Use}} - \frac{1}{T_{Stress}}\right]\right\}$$

$$A_H = \left(\frac{R_{Stress}}{R_{Use}}\right)^m$$

$$A_{TH} = A_T A_H$$

$$Ln(t_f) = C + \frac{E_a}{K_B T} - m \ Ln(R)$$

Notation

A_H = Humidity acceleration Factor
A_T = Temperature acceleration factor
A_{TH} = Temperature-Humidity acceleration factor
RH_{stress} = Relative humidity of test
RH_{use} = Nominal use relative humidity
T_{stress} = Test temperature
T_{use} = Nominal use temperature
m = Humidity constant
E_a = Activation energy
t_f = Time to Fail
C = Constant

Figure 11: THB Model Equations

The failure mechanism's activation energy, E_a, is assumed to be 0.7 eV (an industry standard for conservatively estimating test times)[19] for the sensors based on the materials and composition. Boltzmann's constant, K_B, is given as 8.617×10^{-5} eV/K. A humidity constant, m, of 2.66 is also assumed (typical industry value).

For THB exposure, the low percent relative humidity values are taken at the ON- and OFF-cycle maximum temperatures (reference Table 1). While this provides a slightly higher acceleration factor, it represents a more realistic field condition for the acceleration model (it is less likely for the highest humidity conditions to occur during the highest temperature conditions in the field).

2.5 Test Parameter Development

With the acceleration factors determined from the appropriate acceleration models associated with the failure mechanisms identified, the test durations and sample sizes can then be developed. This was done for each ALT performed on each sensor type. The field life (time or number of cycles), reliability factor, and confidence level factor are already defined in Section 2.1. The following additional general parameters were needed:

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[19] Bayle, Franck; Mettas, Adamantios; Temperature Acceleration Models in Reliability Predictions: Justification and Improvements, 2010, IEEE RAMS Conference

- Assumed reliability distribution (including the Beta, β, parameter for the commonly used parametric binomial Weibull distribution)
- Number of test samples desired – OR – Test duration desired

The acceleration factor was used in ReliaSoft Weibull++ software to determine test duration with *"n"* test samples. The number of test samples/duration times can be adjusted to achieve the field target life with the prescribed percent reliability and confidence level.

The Beta, β, value is known as the shape parameter, and represents the slope of the unreliability curve vs. time. It can be determined based on failure history (calculated based on a time- or cycles-to-failure plot if known) or expected failure along the typical reliability bathtub curve of failure rate vs. time (Figure 12). Along this curve, β<1 for early-life failures, β=1 for constant failure rate (random failures), and β>1 for wear-out failures.

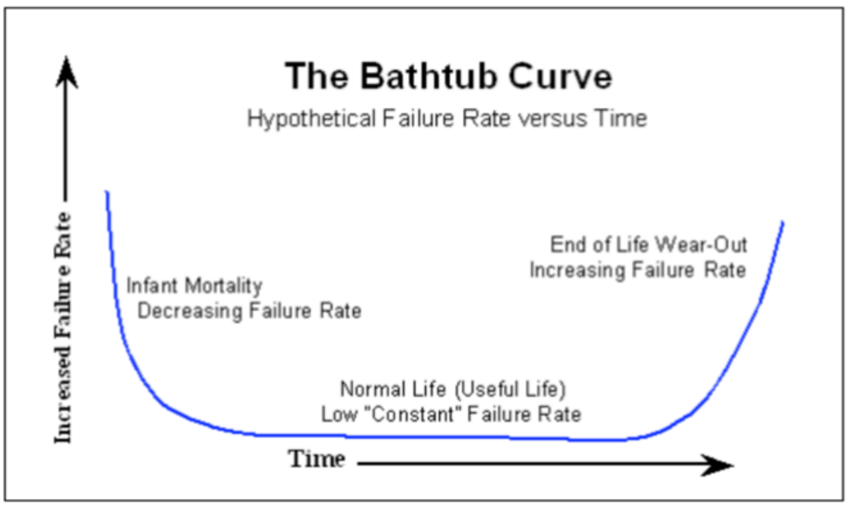


Figure 12: Reliability Bathtub Curve

A Beta value of 3 was chosen. This is reasonable for wear-out failure mechanisms, and is just beyond the influence of random latent defects (where β<2.5).

The reliability and confidence level factors, the number of failures permitted, and the sample size can all be varied to define the appropriate test structure. As reliability and confidence level factors increase, so do the number of test samples required to demonstrate those increased factors in the same amount of test time. Addition of failures allowed in test also requires an increase in test duration to achieve the same reliability and confidence level goals.
Increasing the sample size will decrease the width of the confidence interval because it reduces the standard error involved. Thus, the larger the sample size, the higher the confidence in the results.

2.6 Test Approach

Temperature cycling and THB testing were the two ALT's assigned to accelerate the failure mechanisms identified previously. The final test parameters were developed for these two tests, taking the following parameters into account:

- Available number of samples
- Material limitations
- Budget and timeline constraints

Acceleration of damage accumulation typically requires the application of stresses in excess of what the product would see in the use environment. However, increasing these stresses beyond the limitations of the sensor materials would induce failure mechanisms that are not relevant in the field (i.e., would not normally have occurred). Due to these constraints, Ansys-DfR Solutions developed test conditions to accelerate the tests as much as possible without causing unrepresentative damage.

2.6.1 Sensor A

Extensive failures were experienced in previous THB testing with the original design. Humidity ingress into the sensor area was determined to be the significant cause of failure. The Beta value from those failures is not applicable to the new design, and therefore the assumed Beta value of 3 is used.

Temperature cycling was conducted to determine the reliability and performance of the redesigned sensors given the previous thermal-cycling-induced failure mechanisms.

2.6.2 Sensor B

In previous testing of the original design, the connection between the front and back halves of Sensor B was susceptible to heat degradation and strain from the cable when not properly strain relieved. The heat from the heater element is conducted through the spring leads and surrounding housing to the sensor's back half. The test approach with the use of a highly accelerated stress test (HAST) autoclave was too extreme of a stressor on the back half of the sensor. Partial sensor placement inside the test environment was not feasible due to limitations of the autoclave when pressurized for high temperature and humidity conditions (i.e., no physical pass-through capability existed for the front and back half of the sensor).

For the re-designed sensors, a different test setup was planned:

- Isolate the front half of the sensor for reliability testing and applying HAST conditions only to that half of the sensor.
- Apply lower temperature-humidity stress conditions to the entire sensor to address the reliability of the back half of the sensor (closer to the more benign indoor ambient temperature and humidity environment experienced in the field).

Sensor B samples were provided with a clamp solution in order to isolate just the front half of the sensor to the HAST conditions, and still provide a robust connection for power and sensor monitoring during testing. The clamp is a PEEK material adapter on the back half (Figure 13). Samples had been 100% function tested by the manufacturer to be ready for use in test with connection to the flying leads.

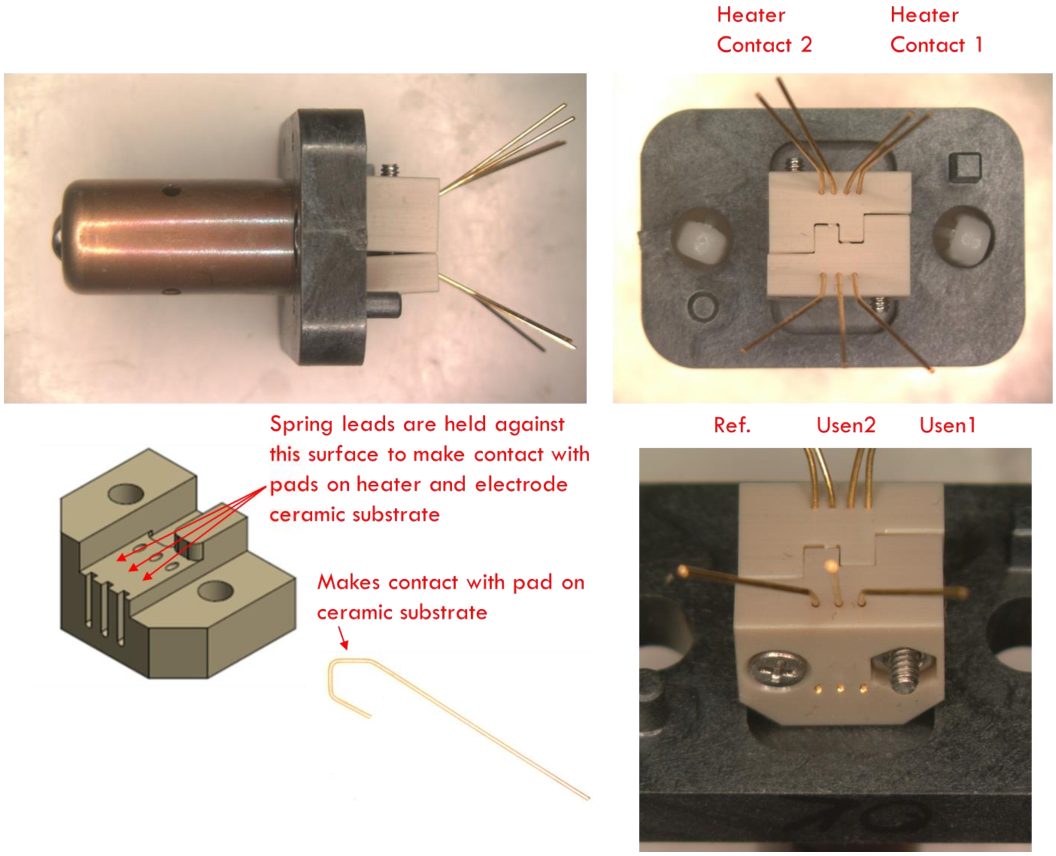


Figure 13: Sensor B Solution for HAST Conditions on Front Half of Sensor

Temperature cycling was conducted to determine the impact of thermal- cycling-induced failure mechanisms on the reliability and performance of the redesign and material changes on the back half of Sensor B. In order to achieve the temperature deltas for each cycle in test without exceeding the ambient operating temperature limit of 150°C, power-cycling can be employed to artificially raise and lower the sensor temperature (within the operating range of 450°C to 700°C predominately provided by the heater element) to impart thermo-mechanical stresses. High temperature deltas can be achieved in relatively short cycle times with this method, and allow for completion of the test durations required within the 1-year test time constraint.

2.6.3 General Test Conditions

The test conditions were unique for each of the two sensing technologies, and included environmental conditions, electrical requirements, recommended sample size, and periodic gas sensitivity checks. The frequency of performing gas sensitivity tests correlate to about every 1 to 2 years equivalent in the field. Failures observed during those tests can then be correlated back to an expected point in time in the field.

If no failures are observed during testing, then the prescribed reliability and confidence level factors will have been demonstrated for the sensors with respect to the associated failure mechanisms discussed. If failures are observed before the planned test duration was achieved, there are two scenarios that can occur:

1.) The test is continued the additional number of cycles (for temperature cycling testing) or additional time (for THB testing) per the planned number of failures allowed.
2.) The test is stopped if the number of failures exceeds that allowed, and the cycles- or time-to-failure data is plotted and fit to the 2-parameter binomial Weibull distribution, using the measured Beta value from the test population, with Weibull++ software.

With sufficient failures in test, a plot of unreliability versus time can be determined with Weibull++ software. The original reliability and confidence level factors can be applied to determine the expected life in test. With the equivalent acceleration factor known, the expected lifespan in the field can then be determined.

Based on the test parameter development and test plan approach presented, Ansys-DfR Solutions recommended the number of CO/combustion gas sensor test samples as shown in Table 3 for temperature cycling and THB testing. A Beta value of 3 was used in the reliability calculations for test durations and sample sizes. The number of failures allowed for each test was 2, with exception of the Sensor B front half THB test. This approach is reasonable for the sample sizes and the additional time required to demonstrate the 85% reliability and 80% confidence level goals within 1-year test timeframe.

Table 3: Sample Size Per Test

Sensor	# for Temperature Cycling Test	# for THB Test	Total # Sensors Required
A	8	48	56
B	8	18 *	26

* 10 qty. for the front half test and 8 qty. for the remainder of sensor test

2.7 Temperature Cycling Conditions

The temperature cycling test conditions were based on the environmental conditions found in Table 1, the duty cycle for a multi-stage furnace in Table 2, and the allowable test temperature ranges determined. Sensor A samples were tested within the lower temperature ranges found in the vent pipe. Sensor B samples were tested within the mid temperature ranges typically found in the secondary heat exchanger.

The minimum and maximum test temperatures were selected based on a calculated acceleration factor and corresponding reasonable test duration (number of days given an achievable cycle rate in test) for the sample sizes shown in Table 3. The test conditions were a balance between not creating an excessively over-stressed environment based on the thermal properties of the sensor materials, while still achieving an economical and timely approach to test completion.

2.7.1 Sensor A Temperature Cycling

Ansys-DfR Solutions followed the test parameters outlined in Table 4 to meet the desired reliability, confidence, and life expectancy goals for Sensor A. Although the sensor had an operating temperature rating of 0-50°C, the sensor's determined allowable temperature range based on the design evaluation was not exceeded. The entire device was subjected to the environmental conditions for temperature cycling stress testing.

Table 4: Sensor A Temperature Cycling Test Parameters

20-Year Equivalent Life Expectancy (249,600 field cycles) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
8	85%	80%	2292 cycles (49 days)[A]	2884 cycles (62 days)[A]	3335 cycles (72 days)[A]
Number of sensitivity readings following baseline check[B]:			12	16	18
Test Conditions -					
Min Field Temperature	**Max Field Temperature**	**Min Test Temperature**	**Max Test Temperature**	**Acceleration Factor**	
37.8°C	48.8°C	-20°C	60°C	116.97	

[A] Test duration in days is based on 0.51 hr cycles (15°C/min ramp rate and 10 min dwell)
[B] Sensitivity readings are based on 4-day intervals (1.6-yr field equivalency for test duration with no failures)

2.7.2 Sensor B Temperature Cycling

Ansys-DfR Solutions followed the test parameters outlined in Table 5 to meet the desired reliability and confidence goals, with 15-year life expectancy (to keep within the 1-year test time constraint given longer test durations required due to the lower acceleration factor), for Sensor B. Only the sensing portion (front half) of the device was subjected to the environmental conditions for temperature cycling stress testing.

A temperature range of 210°C in test provided the needed acceleration factor to demonstrate 15-year equivalent life. With a minimum test temperature of -20°C, the maximum test temperature of 190°C required would exceed the design and material limitations of the sensor due to excessive heat conduction to the back half of the sensor. Therefore, the method of power cycling was used to achieve the 210°C temperature deltas required. Resistance of the heater element can be correlated to its temperature based on resistance measurements taken at several equilibrium temperatures with units unpowered. With the use of a programmable power supply, voltage was varied to achieve an upper and lower temperature (based on resistance measurements) for each cycle.

Sensitivity intervals were closer to 1 year since no power supply for signal output was used on this type of sensor to continuously monitor in situ (although the passive sensor output was continuously monitored).

Table 5: Sensor B Temperature Cycling Test Parameters

15-Year Equivalent Life Expectancy (187,200 field cycles) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
8	85%	80%	8245 cycles (172 days)[A]	10,376 cycles (217 days)[A]	11,998 cycles (250 days)[A]
Number of sensitivity readings following baseline check[B]:			13	16	18
Test Conditions -					
Min Field Temperature	**Max Field Temperature**	**Test Temperature Range**		**Acceleration Factor**	
65.5°C	121°C	210°C		24.38	

[A] Test duration in days is based on 0.50 hr cycles (42°C/min ramp rate (5 min ramp) and 10 min dwell)
[B] Sensitivity readings are based on 14-day intervals (1.2-yr field equivalency for test duration with 0 failure)

2.8 Temperature-Humidity Bias (THB) Conditions

Conventional humidity chambers have a maximum operating temperature of 85°C and a maximum humidity level of 98%, which became a limiting factor with respect to Sensor B. To be able to complete the test for this sensor within the available test time, test temperatures up to 135°C were needed with the use of an autoclave type chamber.

2.8.1 THB Combined ON-OFF Methodology

With respect to the THB testing, Ansys-DfR Solutions applied the same test conditions over both the OFF-cycle and ON-cycle field conditions. While the acceleration factors were different due to the two different field conditions, the test durations were combined. Due to the 50% duty cycle for multi-stage gas furnaces (Table 2), half of the desired total field life to be demonstrated was under the OFF-cycle conditions and half was under the ON-cycle conditions. The total test duration was simply the sum of each the OFF-cycle and ON-cycle test durations.

2.8.2 Sensor A THB

Sensor A testing was conducted in a traditional THB chamber. Ansys-DfR Solutions applied the test parameters outlined in Table 6 and Table 7 to meet the desired reliability and confidence goals, with 10-year life expectancy (to keep within the 1-year test time constraint). The test conditions for 5-year life for each the OFF-cycle and the ON-cycle were applied. The combined test duration summary is shown in Table 8.

Although the sensor has an operating temperature rating of 0-50°C, the sensor's determined allowable temperature range based on the design evaluation was not exceeded. The 95% RH non-condensing test condition was within the maximum operating rating. The entire device was subjected to the environmental conditions for THB stress testing.

Table 6: Sensor A THB OFF-Cycle Test Parameters

OFF-cycle, 5-Year Equivalent Life Expectancy (20,800 hrs) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
48	85%	80%	1150 hrs (48 days)	1419 hrs (60 days)	1605 hrs (67 days)
Test Conditions -					
Field Temperature	**Field Humidity**	**Test Temperature**	**Test Humidity**	**Acceleration Factor**	
37.8°C	75%	60°C	95%	10.69	

Table 7: Sensor A THB ON-Cycle Test Parameters

ON-cycle, 5-Year Equivalent Life Expectancy (20,800 hrs) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
48	85%	80%	4553 hrs (190 days)	5619 hrs (235 days)	6352 hrs (265 days)
Test Conditions -					
Field Temperature	**Field Humidity**	**Test Temperature**	**Test Humidity**	**Acceleration Factor**	
48.8°C	90%	60°C	95%	2.70	

Table 8: Sensor A THB Combined OFF- and ON-Cycle Test Duration Summary

10-Year Equivalent Life Expectancy (41,600 hrs) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
48	85%	80%	5703 hrs (238 days)	7038 hrs (294 days)	7957 hrs (332 days)
Number of sensitivity readings following baseline check[A]:			7	9	10
Test Conditions - 60°C and 95% RH					

[A] Sensitivity readings based on 35-day intervals (1.5-yr field equivalency for test duration with 0 failure)

2.8.3 Sensor B THB – Front Half of Sensor

During the ON-cycle, field temperatures up to 121°C (and associated humidity levels at that extreme) limited the acceleration factor achievable with the allowable test conditions. This prevented getting test duration times below one year with even just 1 failure and using 10 qty. test samples. Ansys-DfR Solutions tested the front half of Sensor B using the test parameters outlined in Table 9 and Table 10 to meet the desired reliability and confidence goals, with 10-year life expectancy (5 years OFF, 5 years ON). The combined test duration summary is shown in Table 11. Test durations for 1 or more failures are not indicated since the 1-year test duration constraint is well exceeded under those conditions.

Table 9: Sensor B (Front Half) THB OFF-Cycle Test Parameters

OFF-cycle, 5-Year Equivalent Life Expectancy (20,800 hrs) -			Test Duration		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
10	85%	80%	172 hrs (8 days)	215 hrs (9 days)	247 hrs (11 days)
Test Conditions -					
Field Temperature	**Field Humidity**	**Test Temperature**	**Test Humidity**	**Acceleration Factor**	
65.5°C	75%	135°C	98%	120.87	

Table 10: Sensor B (Front Half) THB ON-Cycle Test Parameters

ON-cycle, 5-Year Equivalent Life Expectancy (20,800 hrs) -			Test Duration		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
10	85%	80%	8163 hrs (341 days)	10,222 hrs (426 days)	11,746 hrs (490 days)
Test Conditions -					
Field Temperature	**Field Humidity**	**Test Temperature**	**Test Humidity**	**Acceleration Factor**	
121°C	90%	135°C	98%	2.54	

Table 11: Sensor B (Front Half) THB Combined OFF- and ON-Cycle Test Duration Summary

10-Year Equivalent Life Expectancy (41,600 hrs) -			Test Duration		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
10	85%	80%	8335 hrs (348 days)	n/a	n/a
Number of sensitivity readings following baseline check[A]:			10	n/a	n/a
Test Conditions - 135°C and 98% RH					

[A] Sensitivity readings based on 35-day intervals (1.0-yr field equivalency for test duration with 0 failure)

2.8.4 Sensor B THB – Back Half of Sensor

To test the back half of the sensor (absent in the front half of sensor testing in Section 2.8.3), the full sensor was exposed to a set of conditions existing during the ON- and OFF-cycles in a given boiler room environment, with allowable field temperatures described as 5-40°C and 80% RH maximum.[20] Given a residential application in the United States, Ansys-DfR Solutions estimated a realistic worst case of 30C and 80%RH. Ansys-DfR Solutions tested the remainder of the sensor using the test parameters outlined in Table 12 to meet the desired reliability and confidence goals, with 10-year life expectancy.

The performance of the front half of the sensor with 1-year resolution was accounted for in the front half of sensor testing, and continuous monitoring during remainder of sensor testing provided similar resolution for the remaining device. In order to capture additional data and ensure continued operation of the whole device, gas sensitivity checks were performed every 35 days test time (5-year life equivalent).

Table 12: Sensor B (Back Half) Test Parameters

10-Year Equivalent Life Expectancy (41,600 hrs) -			**Test Duration**		
Sample Size	**Reliability**	**Confidence**	**0 Fail**	**1 Fail**	**2 Fail**
8	85%	80%	2534 hrs (106 days)	3189 hrs (133 days)	3687 hrs (154 days)
Number of sensitivity readings following baseline check[A]:			3	4	5
Test Conditions -					
Field Temperature	**Field Humidity**	**Test Temperature**	**Test Humidity**	**Acceleration Factor**	
30°C	80%	60°C	95%	17.63	

[A] Sensitivity readings based on 35-day intervals (3.3-yr field equivalency for test duration with 0 failure)

[20] LOOS Bosch Group "Requirements for Boiler Installation Rooms", Technical Informations (sic) (TI024), Version 9 (03/12)

2.9 Sensor Power Conditions

Both sensor types were powered during temperature cycling and THB testing (Sensor B signal output is passive, but its heater element was powered for proper operation). Input voltage and current to the sensor was continuously monitored and recorded, as was output voltage from the detector. This allows for capture of degradation and time of occurrence.

2.9.1 Sensor A

Sensor A requires 5 V_{dc} (±5%) applied to pin C and ground connected to pin 2 during testing (Figure 14). Power consumption is rated at 0.165 W average and 0.90 W peak (using 33 mA average and 180 mA peak). In THB testing, this power provided the bias necessary for electrochemical migration, if it were to occur.

Connector Pinout	Function
A	TX (UART)
B	RX (UART)
C	V+ (5 VDC)
1	V+ (5 VDC)
2	GND
3	GND
4	AV OUT (0 to 4 VDC)
5	I2C SCL
6	No Connect
7	I2C SDA
8	No Connect
9	No Connect
10	TX (UART)
11	RX (UART)
12	GND

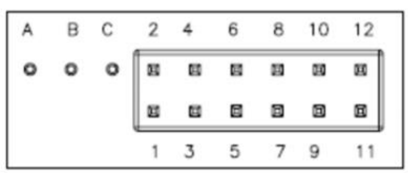


Figure 14: Sensor A Pin Designations (per manufacturer's specification)

2.9.2 Sensor B

For Sensor B, only the heating element was powered (the sensor element is passive by design, and therefore not supplied with a voltage bias in the field). The sensor element can output up to about 700 mV signal passively depending upon the CO/H_2 gas concentrations to which it is exposed. This self-generated voltage could be simulated in test during the aging process, but small voltages of even 100mV would continuously force O2- ions to cross any electrolyte and simulate an amperometric oxygen sensor, potentially changing the electrode and its nominal behavior over time. Going to a duty cycle for this type of bias is less of a concern for this issue, but it would not be significant for promoting electro-chemical migration (ECM). Therefore, no voltage bias was applied to the sensor element in test.

In the field, Sensor B comes with an external power control box that provides 10-12 V_{dc} that is pulse width modulated (PWM) at 50 Hz (and at about a 33% duty cycle) (Figure 15). The stock power control box keeps the resistance of the heater at a constant value (equal to that which provides 2.8-3 W heating power in air with no airflow) by regulating the power supplied to the heater element, and therefore maintaining its temperature. However, this power control box was cost prohibitive to utilize for each of the 24 quantity Sensor B samples designated for TC and THB testing, and did not allow easy manipulation of voltage supplied for TC testing.

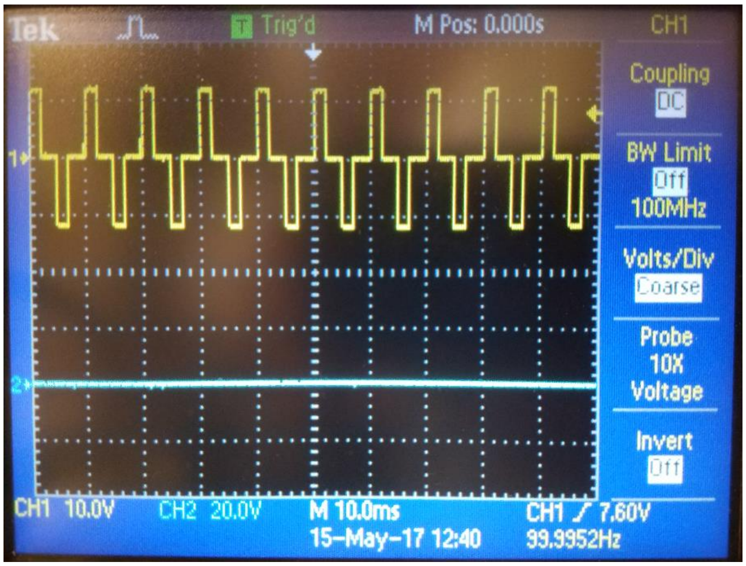


Figure 15: Sensor B Stock Power Supply Trace (Voltage vs. Time)

An alternative approach was used instead to power the heater elements with a single power source for each test. For THB testing, a variable AC power supply at 60 Hz was set to a voltage that would achieve about 2.8-3 W power across the heater element in ambient air with no airflow (Figure 16). The root mean squared (rms) voltage and current across the heater element was determined by measuring the voltage drop across a 5 Ohm sense resistor added to an external breakout board. From a cold startup, voltage had to be slowly increased so that the current is less than 0.5 A (starting at 1 W and increasing slowly to 3 W within minimum 30 sec), and so that the heater power did not exceed 6 W per the manufacturer. Power higher than 4 W continuously may alter the sensor electrodes. Normal operating current was expected to be around 0.35 A_{rms}. With 2.8-3 W power supplied to the heater element, monitored by recording the voltage and current across it, the sensor was ensured to reach and maintain its required operating temperature throughout testing. It is important to note that, as received and tested, Sensor B was configured for evaluation, not installation in a gas appliance during full scale production. Thus, the power would most likely be obtained directly from the appliance, not a separate power supply.

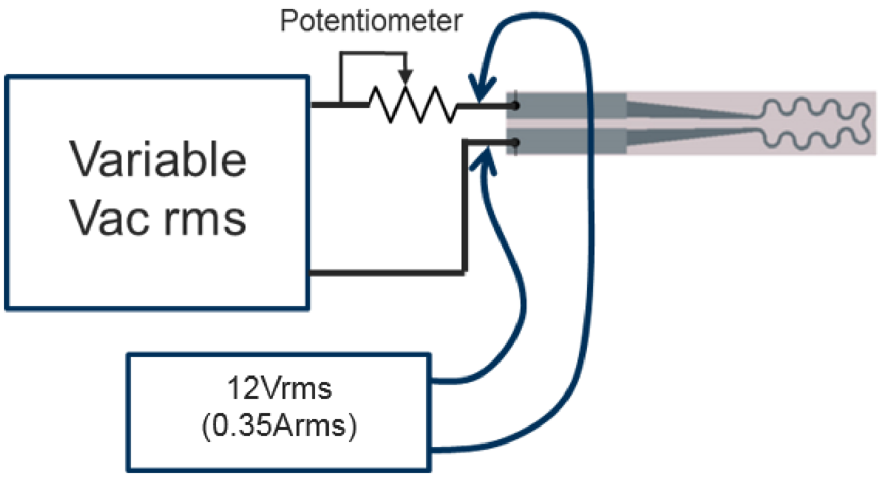


Figure 16: Sensor B for Heating Element

For TC testing, a programmable power supply was used to vary voltage to achieve an upper and lower temperature extreme through the heater element for each cycle.

The two sense lines (U_{sen1} and U_{sen2}, Figure 17) were monitored during aging and during the gas sensitivity testing (at test intervals equivalent to about 1 year).

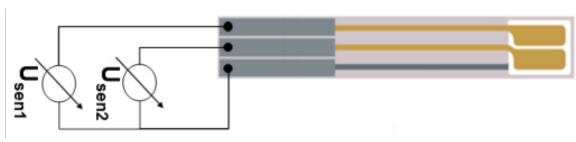


Figure 17: Sensor B Electrodes and Signal Outputs

2.10 Gas Sensitivity Performance

To assess the performance of the sensors when exposed to temperature cycling and THB stresses, the sensors were monitored and recorded for functional degradation through periodic sensitivity testing to known gas concentrations. A total of 5 certified gas concentrations were utilized, each progressively more concentrated in CO, H_2, and CO_2 than the first (Table 13). These concentrations capture the capability of the sensors tested. Ansys-DfR Solutions performed these gas checks at time intervals that equate to about 1-2 years in the field.

Table 13: Gas Sensitivity Concentrations in Test

Tank	CO (ppm)	H2 (ppm)	CO2 (%)	O2 (%Mol/Mol)	N2
1	350	175	8% (80,000 ppm)	3%	Bal
2	400	200	9% (90,000 ppm)	3%	Bal
3	700	350	10% (100,000 ppm)	3%	Bal
4	1000	500	11% (110,000 ppm)	3%	Bal
5	1500	750	12% (120,000 ppm)	3%	Bal

2.10.1 Sensor A Sensitivity Performance

Sensor A samples were tested in the flow-through mode at room temperature conditions (after minimum 24 hours for unit to self-calibrate at room temperature). Sensor signal output is 0-4 V depending upon the gas concentration. Sensor output temperature dependence is 0.4% FS per °C from calibration temperature, and pressure dependence is 0.135% of reading per mmHg. Sensor specifications for evaluation are indicated in Table 14 below.

Table 14: Sensor A Performance Specifications

Parameter	Specification
Accuracy	±5% reading (from 3-20% concentration)
Stability over life of sensor (rated at 10 yrs)	<5% FS or <10% reading, per year

2.10.2 Sensor B Sensitivity Performance

Sensor B samples are tested with only the sensor tips exposed to the gas environment. There are no specifications for accuracy, but the manufacturer indicated it is essentially a binary sensor. If bad combustion occurs in the furnace in which it is installed, the sensor will output above 100 mV signal. If there is more than 25% variation after aging, it is a sign that something could have degraded. A characteristic sensor response curve from the manufacture's published literature is shown in Figure 18 below.

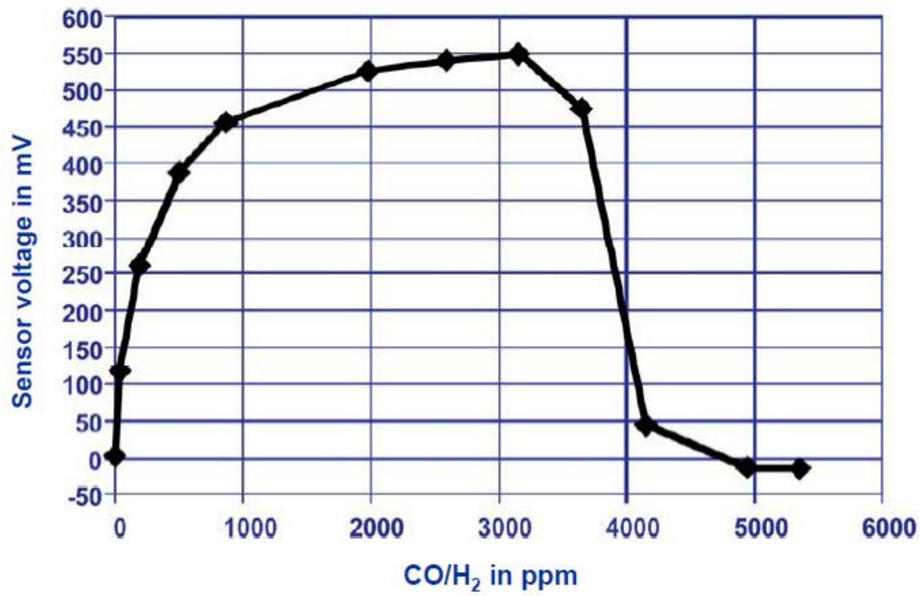


Figure 18: Sensor B Characteristic Sensor Output

2.11 Failure Criteria

Input voltage and current were continuously monitored and recorded of each sensor during exposure testing and gas sensitivity testing to provide evidence of any degradation in performance. Sensor signal output voltage was also continuously monitored and recorded to observe for any unexpected changes or anomalies during exposure testing, and for repeatability and stability during periodic gas sensitivity checks relative to the initial baseline results. Changes in voltage provide evidence as to whether the sensors operated according to manufacturer's specifications or degraded to a point where they could no longer be effective in sensing gas concentrations.

Failures are characterized among two criteria:

1. Soft Failures: Sensor signal output voltage does not meet the accuracy or stability specifications outlined in Section 2.10. However, an output signal is present, detecting some level of its intended target gas range.
2. Hard Failures: Sensor signal output voltage severely degraded or absent, unable to detect some level of its intended target gas range.

If a sensor was a hard failure, it was generally kept in test to see if it recovers in subsequent gas sensitivity checks. If it does not, it is removed from test. A failure analysis was planned on up to 2 failed samples from each sensor type from each test.

3 Test Setup and Procedure

The test setup and procedure followed for temperature cycling and THB testing, as well as the periodic gas sensitivity checks, were unique to each of the two sensors. The sensor's geometry, the allowable test temperature ranges determined for each, and the equipment used to achieve the prescribed test conditions all influenced how the sensors were tested.

3.1 Thermal Cycling Setup

Sensor A units were placed completely inside the chamber. They were designed to accommodate this placement and the materials could withstand the test temperatures. Sensor B units were installed in a panel, with the sensor tips on one side isolated from the back-half of the sensor. This setup replicates the sensor environment in the field, where part of the sensor is inside the high stress environment and part is outside (e.g., sensor mounted through the wall of the primary heat exchanger and electronic controls mounted outside of the furnace).

3.1.1 Sensor A TC Setup

Sensor A units were placed in a small Sun Systems thermal chamber (EC10, 0.7 cu-ft) for exposure testing. The 8 sensors were connected in series in two groups of 4 via high-temperature silicone tubing (3/32" ID (same as stock) and 1/16" wall) connected to the inlet and outlet ports of each sensor (Figure 19). This allowed gas sensitivity checks to be performed in-situ in the flow-through mode, while limiting the number of sensors checked in series simultaneously. Gas flow through the sensor starts to be affected if a much larger number of daisy-chained samples are used.

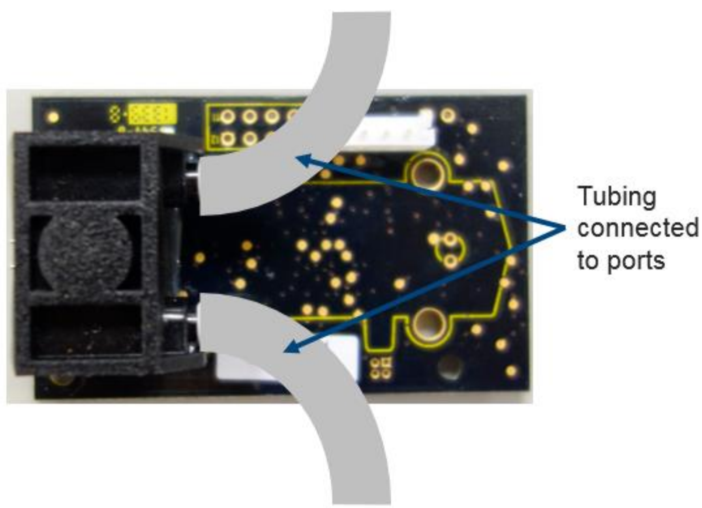


Figure 19: Tubing Connections for Flow-Through Mode

Samples were suspended from a rack within the chamber using cable ties, keeping adequate space in between for proper air circulation and temperature distribution within the chamber (Figure 20). The chamber was started in the hot cycle and set to achieve the temperature conditions in Section2.7.1 based on the thermal profile of the chamber and confirmed in the first cycles (Figure 21).

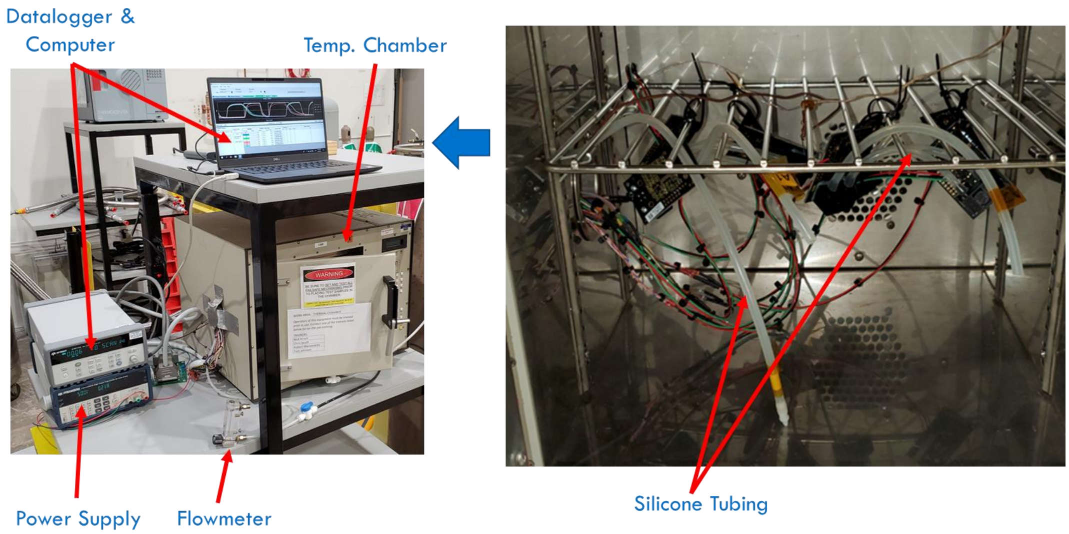


Figure 20: Sensor A TC Setup

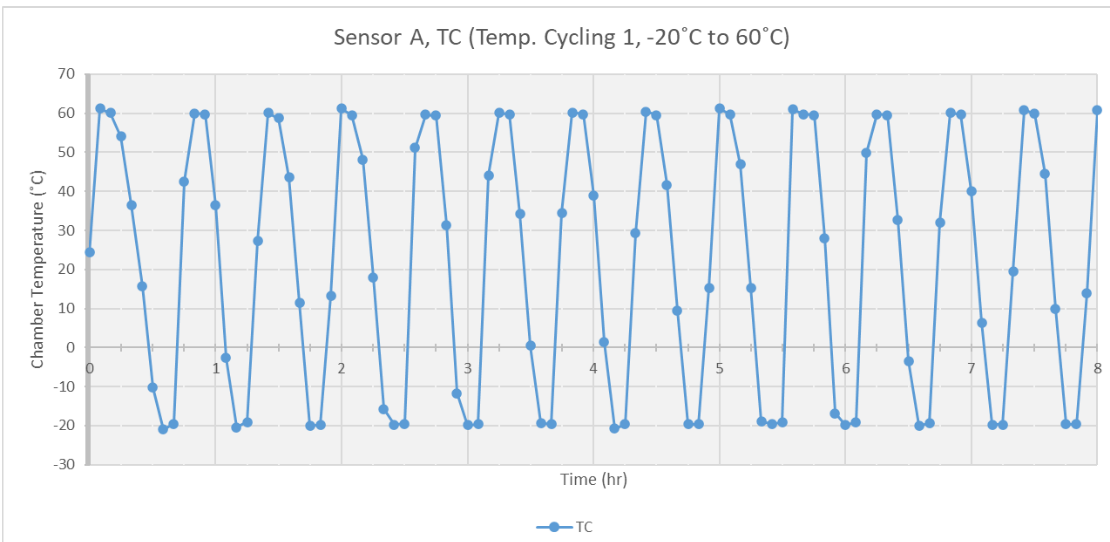


Figure 21: Sensor A TC Chamber Thermal Profile

The samples were continuously powered per the requirements in Section 2.9.1 and continuously monitored for input power (voltage and current) and signal output voltage via the datalogger and computer. A separate break-out board with 0.5 ohm sense resistors was used for these measurements, allowing determination of the input current by measuring the voltage drop across the sense resistor (Figure 22). The schematic for this setup is shown in APPENDIX A: Sensor A TC and THB schematic.

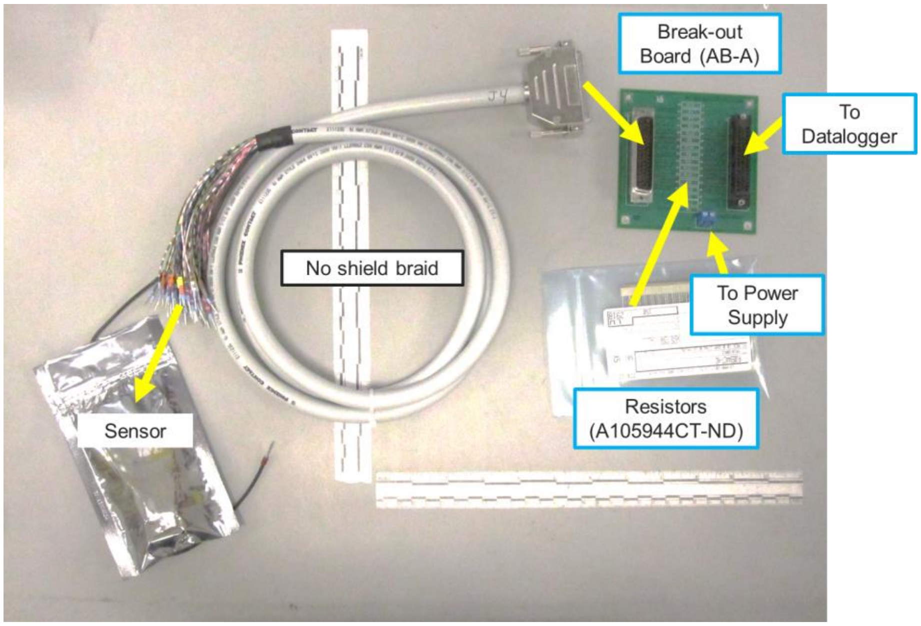


Figure 22: Sensor A TC Break-out Board for Data Monitoring

3.1.2 Sensor B TC Setup

Because Sensor B units were power cycled to achieve a test temperature change of 210˚C at the heating element with each cycle, the voltage required to achieve this needed to be determined prior to testing. Six (6) test samples were subjected to 4 temperatures and allowed to come to thermal equilibrium with the air temperature within a thermal chamber. At each of the 4 temperatures (-10˚C, 10˚C, 30˚C, and 60˚C), resistance of the heater element was measured through leads to each sample. The resistance of the leads was sufficiently low (about 0.28 Ohm two-wire resistance) compared to the nominal resistance of the heater (about 10.5 Ohm two-wire resistance), using a Keysight 6.5 Digit DMM for measurement.

A resistance method calculation was used to determine the expected resistance given a change in temperature. The relationship between resistance and temperature is quite linear, and an alpha parameter, α, can be determined from the following equation:

$$\alpha = \frac{\left(\frac{R_{DUT}}{R_{ref}} - 1\right)}{T - T_{ref}} \tag{1}$$

where T = Temperature of DUT (˚C)
T_{ref} = Alternate temperature of DUT at which resistance is known (˚C)
R_{DUT} = Resistance of DUT (Ohm) at temperature, T
R_{ref} = Resistance of DUT (Ohm) at temperature, T_{ref}

Using an average calculated α=0.003324, resistances at much higher temperatures can be extrapolated (Figure 23).

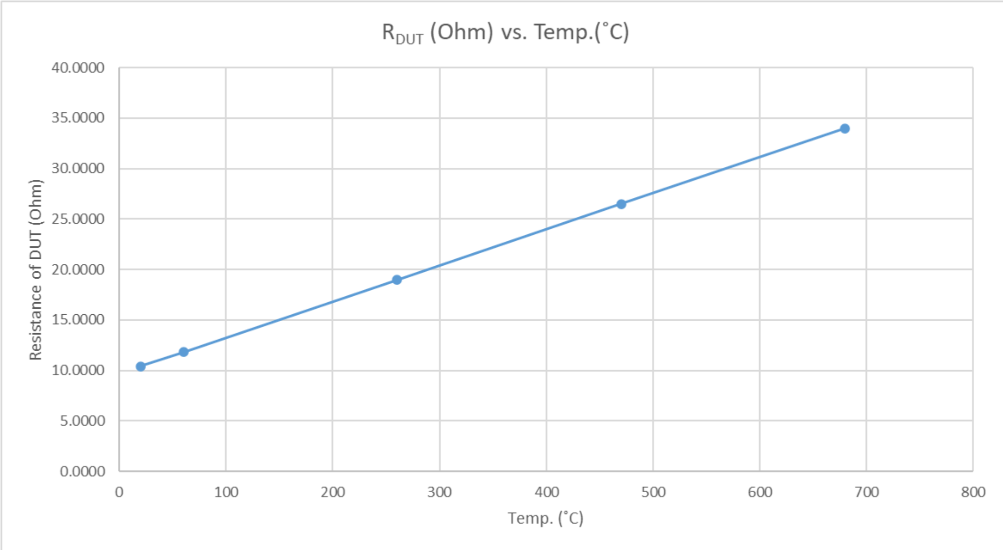


Figure 23: Resistance Method Calculation for Heater Element

Re-arranging equation (1), R_{DUT} can be calculated over an operating temperature range from 345˚C to 555˚C, giving a desired 210˚C temperature delta. The determined resistance delta over this range is shown in Table 15 below.

Table 15: Calculated Resistance Delta

Calc. Temp. for 210˚C Delta (C)	Calc. R_{DUT} (Ohm)	Delta (Ohm)
345	22.0223	7.51
555	29.5318	

Sensor B units were placed into a custom panel on a lab benchtop exposed to ambient room temperature conditions (Figure 24).

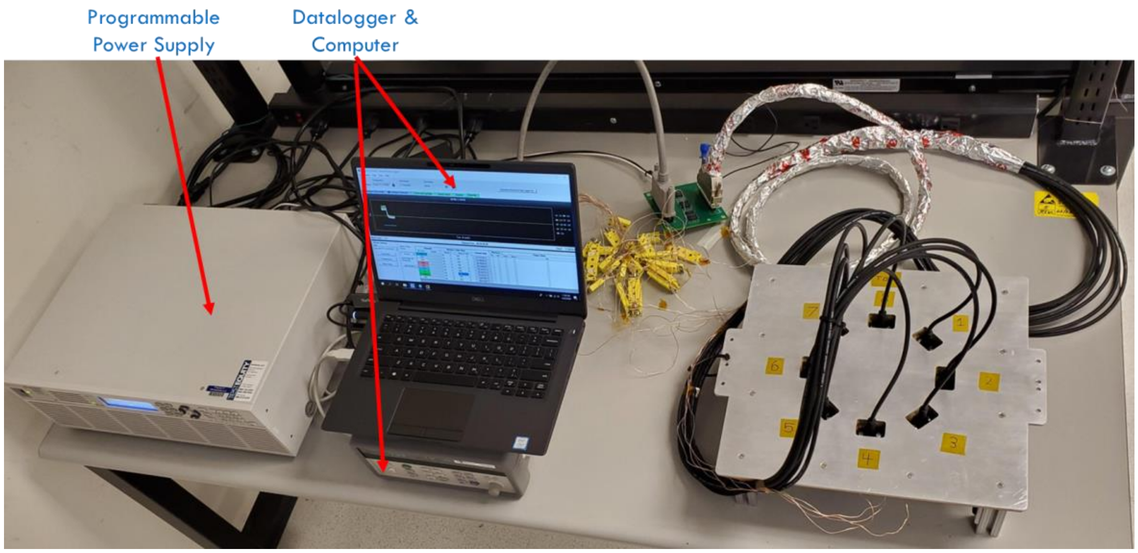


Figure 24: Sensor B TC Setup

The samples were continuously powered per the requirements in Section 2.9.2 and continuously monitored for input power (voltage and current) and signal output voltage (U_{sen1} and U_{sen2}) via the datalogger and computer. A separate break-out board with 5 Ohm sense resistors was used for these measurements, allowing determination of the input current by measuring the voltage drop across the known resistance (Figure 25). The power consumed by the heater element and its resistance could then be calculated from the current and voltage measured across it (Power = Current x V_{heater}, and Resistance = V_{heater} / Current). Aluminum foil tape was additionally wrapped around the cable from the breakout board up to where each sensor cable wire separates out to the individual sensor (to further mitigate any potential interference on the low voltage signal output). The wiring diagram for this setup is shown in APPENDIX B: Sensor B TC and THB schematic.

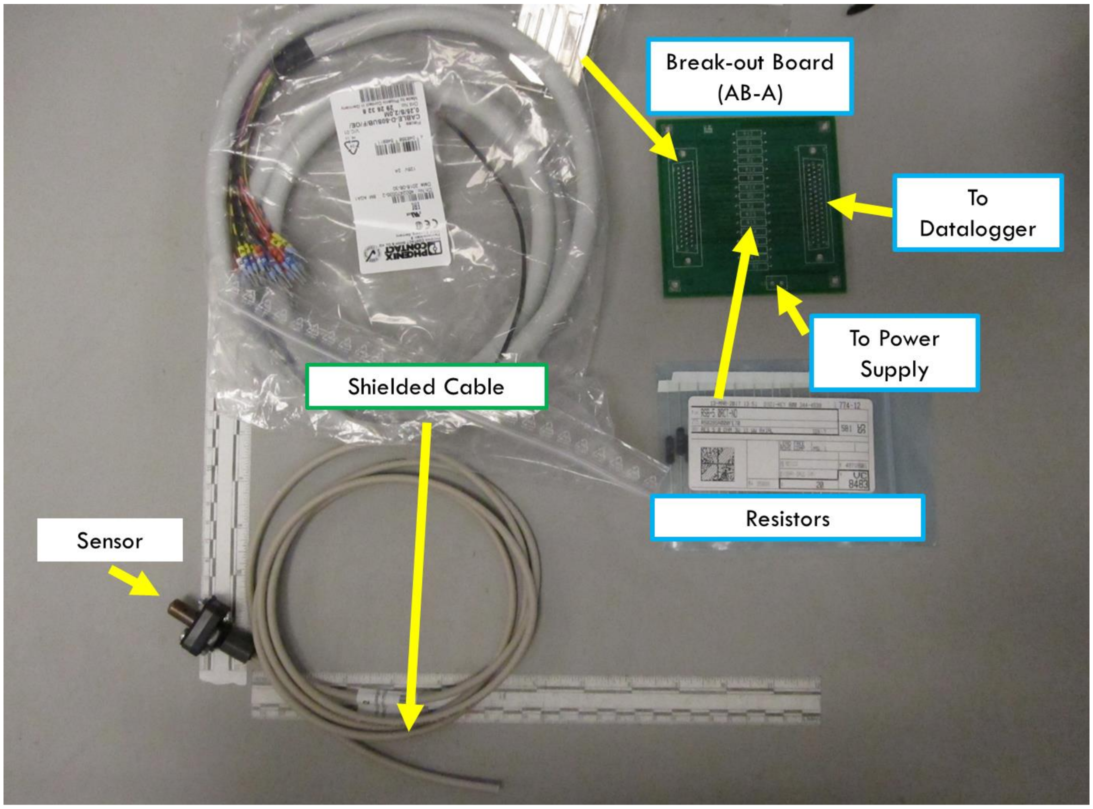


Figure 25: Sensor B TC Break-out Board for Monitoring

Prior to test, samples were subjected to a limited number of varying voltages to achieve the desired calculated resistances across the heater element. A programmable power supply was set to cycle between 8V and 13V, resulting in an average measured resistance of 22.08 Ohm and 29.57 Ohm, respectively (Figure 26), based on the voltage and current measured across it. This varying voltage produced a resistance change of 7.50 Ohm, achieving the 210˚C desired temperature change for each cycle.

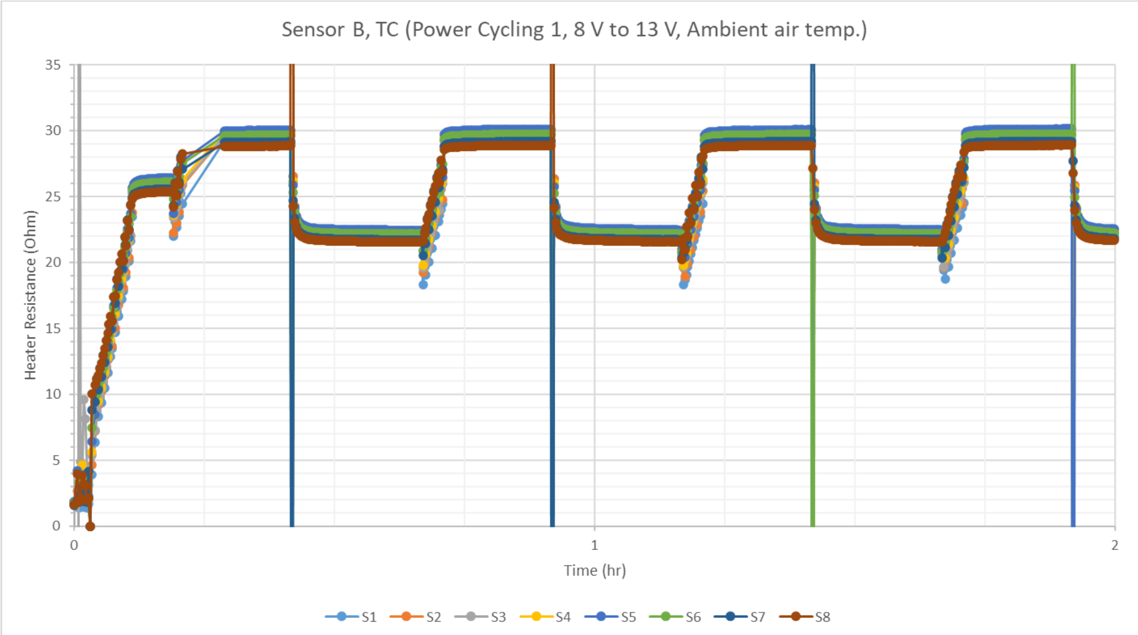


Figure 26: Measured Resistance with 8V to 13V Power Cycling

3.2 THB Setup

Similar to temperature cycling testing, the Sensor A units were placed completely inside the environmental chamber. The front half of the Sensor B units were tested completely inside the autoclave, modified with a clamp connector on the back half that was able to withstand the temperature and humidity conditions in test. The remaining back half of the sensor was tested as a complete unit inside a traditional temperature humidity chamber.

3.2.1 Sensor A THB Setup

Sensor A units were placed in an ESPEC thermal humidity chamber (EPX-2H) for exposure testing. This chamber has the ability to achieve 98% RH up to 85C. As in TC, the 48 sensors were connected in series in 12 groups of 4 via high-temperature silicone tubing (3/32” ID (same as stock) with 1/16” wall) connected to the inlet and outlet ports of each sensor.

Samples were suspended from a rack within the chamber using cable ties, keeping adequate space in between for proper air circulation and temperature/humidity distribution within the chamber (Figure 27). To prevent condensation from forming on the sensors, the chamber was programmed to ramp up temperature first to allow sensors to come to equilibrium with chamber air temperature (ramp up in about 1 hour and dwell for 1 hour), and then ramp up the humidity to the prescribed conditions in Section 2.8.2 (ramp up in 1 hour). Similarly, the humidity was ramped down prior to lowering temperature when returning back to room temperature conditions for periodic gas sensitivity checks made in-situ.

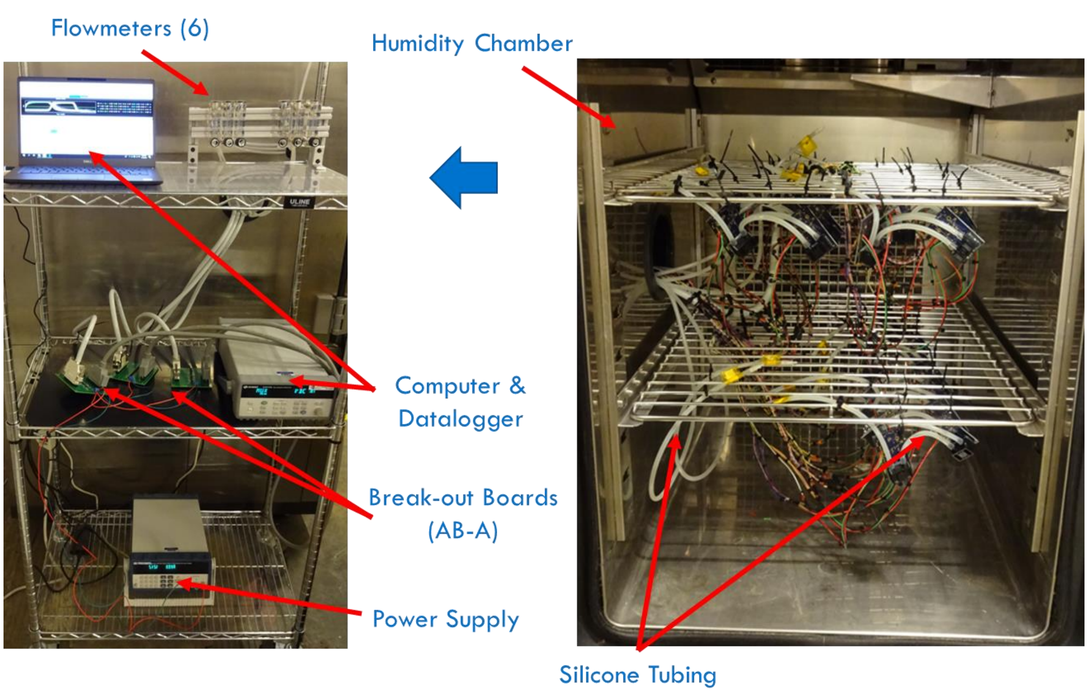


Figure 27: Sensor A THB Setup

The samples were continuously powered per the requirements in Section 2.9.1 and continuously monitored for input power (voltage and current) and signal output voltage via the datalogger and computer. Separate break-out boards with 0.5 ohm sense resistors were used for these measurements, allowing determination of the input current by measuring the voltage drop across the known resistance. The wiring diagram for this setup is shown in APPENDIX A: Sensor A TC and THB schematic.

3.2.2 Sensor B THB Setup – Front Half of Sensor

Ten (10) qty. Sensor B units were placed in an ESPEC HAST System chamber (EHS-221M) for exposure testing (Figure 28). This chamber has the ability to achieve 75% to 100% RH relative humidity at temperatures of 105.0°C to 142.9°C (in unsaturated control mode).

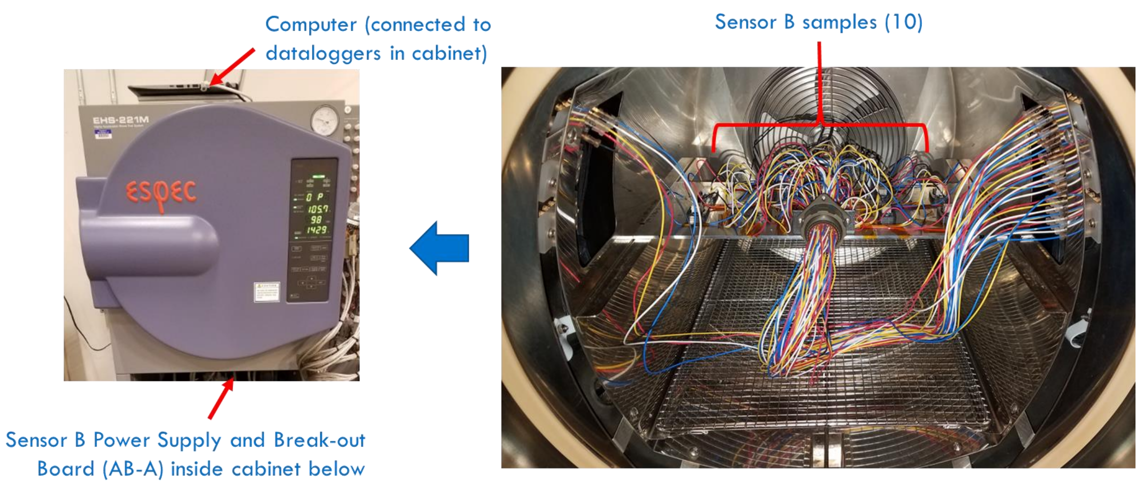


Figure 28: Sensor B THB Setup – Front Half of Sensor

The autoclave was operated in the unsaturated control mode. It was set to the maximum temperature of 133.6°C to achieve the 98% RH condition prescribed in Section 2.8.3. It automatically ramped up temperature, pressure, and humidity to control to the setpoints and prevent condensing conditions. Drip loops were established within the chamber from the signal terminals inside to mitigate any condensation on sensors.

A custom mounting plate, made of aluminum sheet metal, served to fixture the 10 qty. Sensor B units and provide strain relief on the wires coming off the clamp adapter (Figure 29). The samples were positioned vertically to minimize any chance of moisture condensing on the surrounding fixture and collecting inside the sensing element.

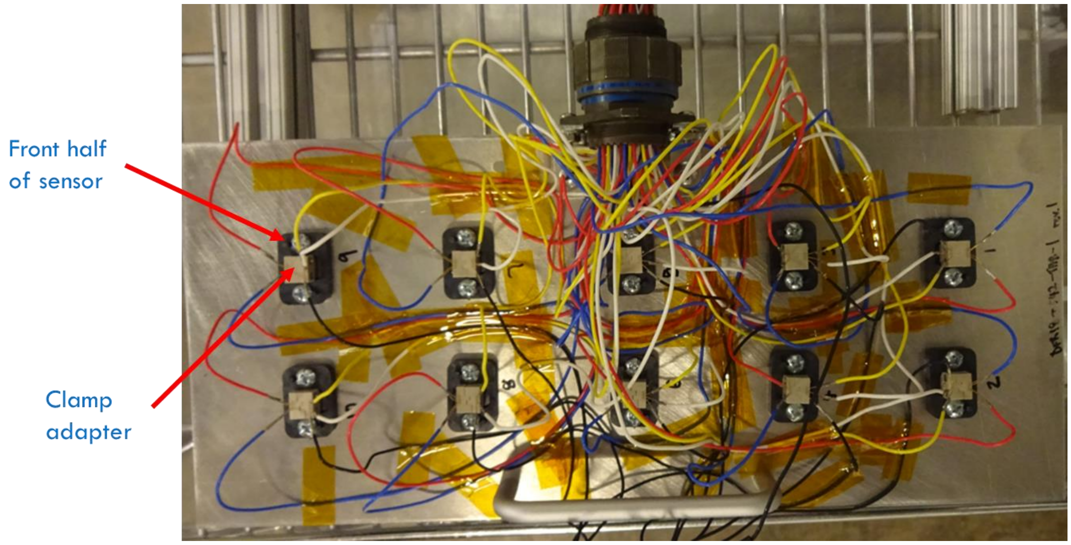


Figure 29: Sensor B THB Mounting Plate – Front Half of Sensor

An aerospace MIL-DTL-38999 Series III TV connector containing 41 contacts was used to connect the power and signal output leads from each sensor to the internal autoclave signal terminals (Figure 30). The connector was designed for surviving the harsh temperature and humidity environment:

- Temperature rated -65°C to 175°C
- 50 micro-inch gold plated crimp-style pins
- Sealed connector meets MIL-DTL-38999 Series III requirements for electrolytic erosion resistance
- Cadmium plated aluminum housings
- 500-hr salt spray rated

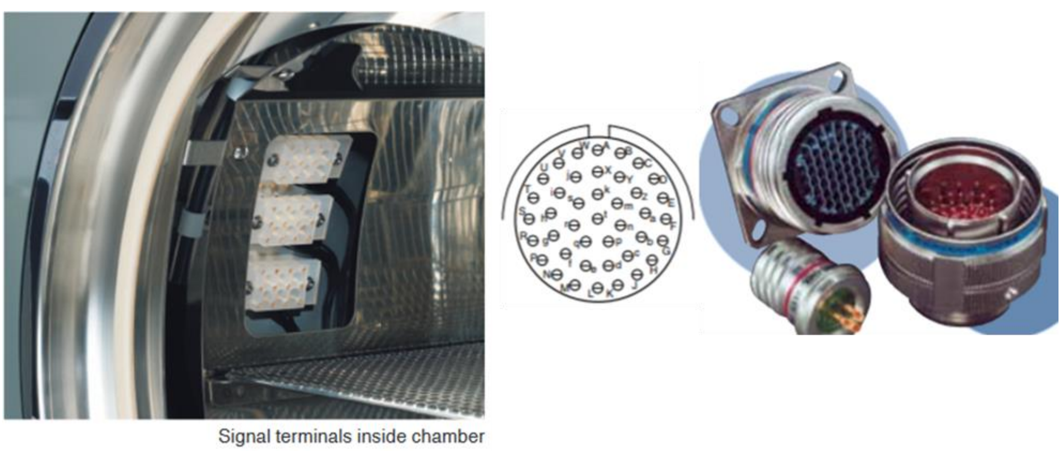


Figure 30: Aerospace MIL-DTL-38999 Series III TV Connector

The wire coming off the connector was made with PTFE insulation to also withstand the extreme conditions within the autoclave. Both the aerospace connector and PTFE wire helped prevent any interconnect issues or false failures from the sensors to the internal chamber terminals.

The samples were continuously powered per the requirements in Section 2.9.2 and continuously monitored for input power (voltage and current) and signal output voltage (U_{sen1} and U_{sen2}) via the datalogger and computer. A separate break-out board with 5 ohm sense resistors was used for these measurements, allowing determination of the input current by measuring the voltage drop across the known resistance. The power consumed by the heater element and its resistance could then be calculated from the current and voltage measured across it (Power = Current x V_{heater}, and Resistance = V_{heater} / Current). The wiring diagram for this setup is shown in APPENDIX B: Sensor B TC and THB schematic.

3.2.3 Sensor B THB Setup – Back Half of Sensor

Eight (8) qty. Sensor B units were placed in an ESPEC thermal humidity chamber (EPL-3H) for exposure testing (Figure 31). This chamber has the ability to achieve 98% RH up to 85C.

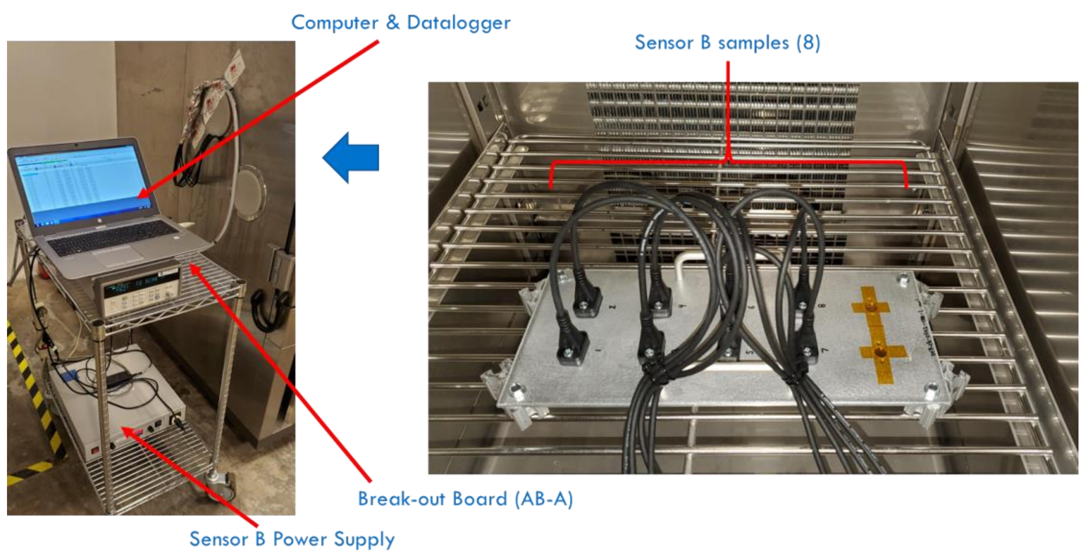


Figure 31: Sensor B THB Setup – Back Half of Sensor

A custom mounting plate, made of aluminum sheet metal, served to fixture the 8 qty. Sensor B units and provide strain relief on the cables. The samples were positioned vertically to minimize any chance of moisture condensing on the surrounding fixture and collecting inside the sensing element.

The samples were continuously powered per the requirements in Section 2.9.2 and continuously monitored for input power (voltage and current) and signal output voltage (U_{sen1} and U_{sen2}) via the datalogger and computer. A separate break-out board with 5 ohm sense resistors was used for these measurements, allowing determination of the input current by measuring the voltage drop across the known resistance. The power consumed by the heater element and its resistance could then be calculated from the current and voltage measured across it (Power = Current x V_{heater}, and Resistance = V_{heater} / Current). The wiring diagram for this setup is shown in APPENDIX B: Sensor B TC and THB schematic.

3.3 Gas Sensitivity Testing Setup

3.3.1 Sensor A TC and THB Gas Sensitivity Setup

For both TC and THB testing, the environmental chambers were brought to room temperature conditions prior to gas sensitivity testing. Once at room temperature conditions, the sensors were retained there for a minimum of 25 hours before gas sensitivity measurements were made in-situ with tubing through the access port of the environmental chamber. This allowed for self-calibration to surrounding room temperature conditions under which the devices were tested.

The sensors' warm-up time to be operational was within 2 minutes, but since they were continuously powered as they acclimated to room temperature conditions and later tested, no additional warm-up time was needed. After an initial 5 minutes exposure to air, the sensors were exposed to gas flow at each concentration for 10 minutes (reasonably minimal time for stabilized measurements) with a 0.2 LPM flowrate. A nitrogen purge of 0.2 LPM for 5 minutes was used in between each gas concentration exposure to purge out residual gas in the silicone tubes from the previous tank (going from Tank 2 (T2) to Tank 3 (T3) on a group of 4 daisy-chained sensors, for instance).

Figure 32 shows a summary of the general test sequence. The inlet gas from a single flowmeter was connected to a first set of 4 daisy-chained sensors, and then was manually switched over (within the chamber) to the inlet of the second set of 4 daisy-chained sensors. This was an efficient method to test all 8 sensors in TC testing (using one flowmeter) or all 48 sensors in THB testing (using 6 flowmeters) for each of the 5 test gas concentrations.

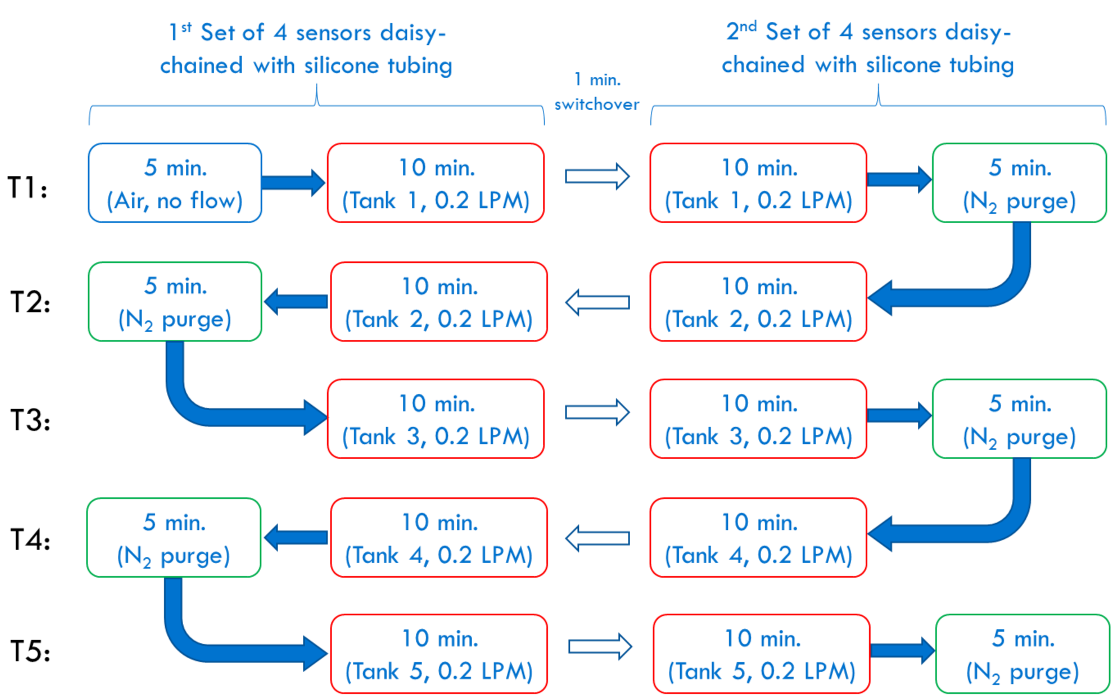


Figure 32: Sensor A Gas Sensitivity Test Sequence

For THB testing, the supply lines from the flowmeters to the sensors were purged after exposure to temperature/humidity with nitrogen. This was done to remove condensed water inside the lines prior to gas-sensitivity testing.

3.3.2 Sensor B TC Gas Sensitivity Setup

Eight (8) qty. Senor B units remained attached to the custom panel when transferred to the gas sensitivity vessel for gas sensitivity testing (Figure 33). The vessel was an approximately 0.15 cu-ft volume plastic container with a smooth flat top to seal against the inside of the custom door, encompassing the 8 sensors. This was not an air-tight seal, as the incoming gas needed to displace the existing air in the vessel. The panel was positioned with sensor no. 8 closest to the inlet.

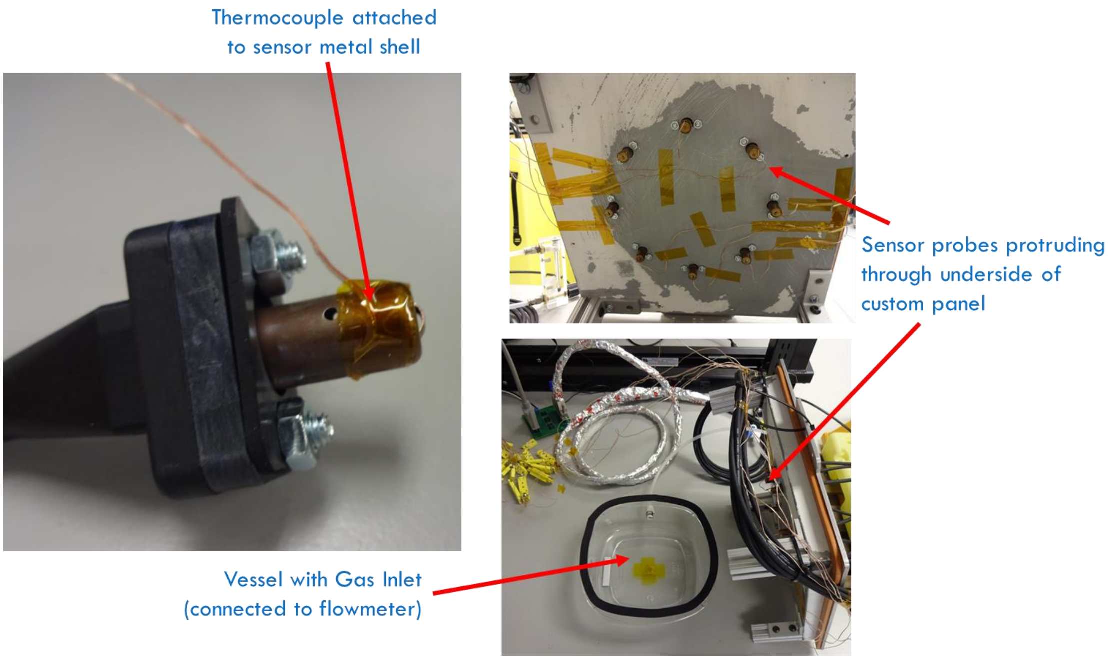


Figure 33: Sensor B TC Gas Sensitivity Setup

Figure 34 shows a summary of the test sequence. The test gas was applied for 25 minutes, allowing for stabilized signal output from the sensors within a reasonable time period. For purging the vessel in between switching to a different tank concentration, the custom panel was lifted off of the vessel and set aside for 5 minutes to let the gas dissipate from the container and sensors.

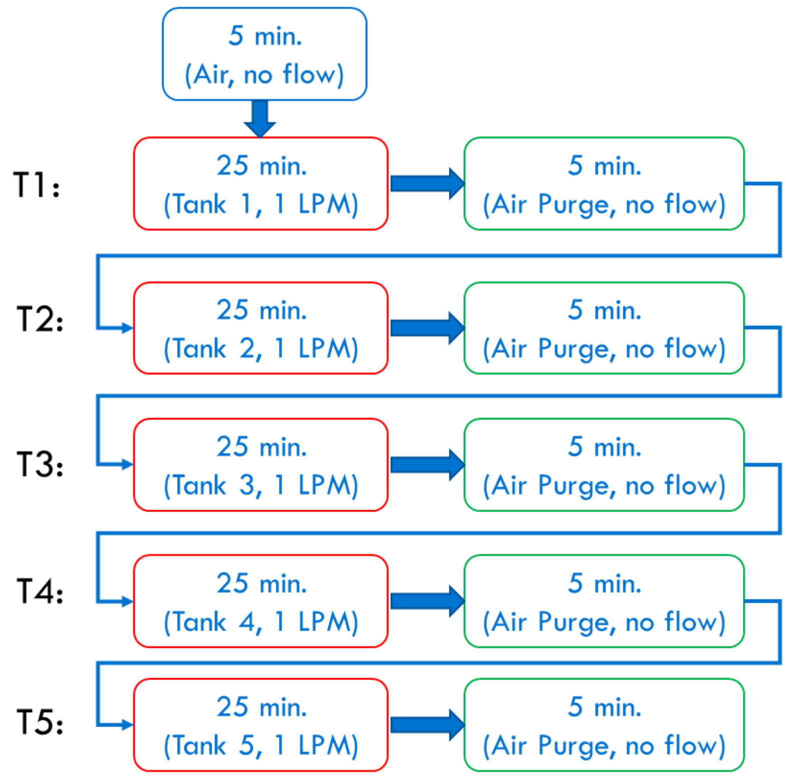


Figure 34: Sensor B TC and THB Gas Sensitivity Test Sequence

3.3.3 Sensor B THB Gas Sensitivity

For the front half sensor gas sensitivity testing, power was turned off to remove the sensors from the autoclave. Power was turned back on slowly to bring the heater element to 2.8-3 W. These sensors were operational within 60 seconds, but could need 2-3 more minutes for most stable results per the manufacturer. The sensors on the custom plate were placed atop a gas sensitivity vessel and exposed to gas concentrations after the proper heater element power was achieved (Figure 35). A closed-cell EPDM ultra-soft adhesive-backed strip was aligned along the top perimeter of the box to help affect a seal. Samples 1 and 2 were closest to the inlet.

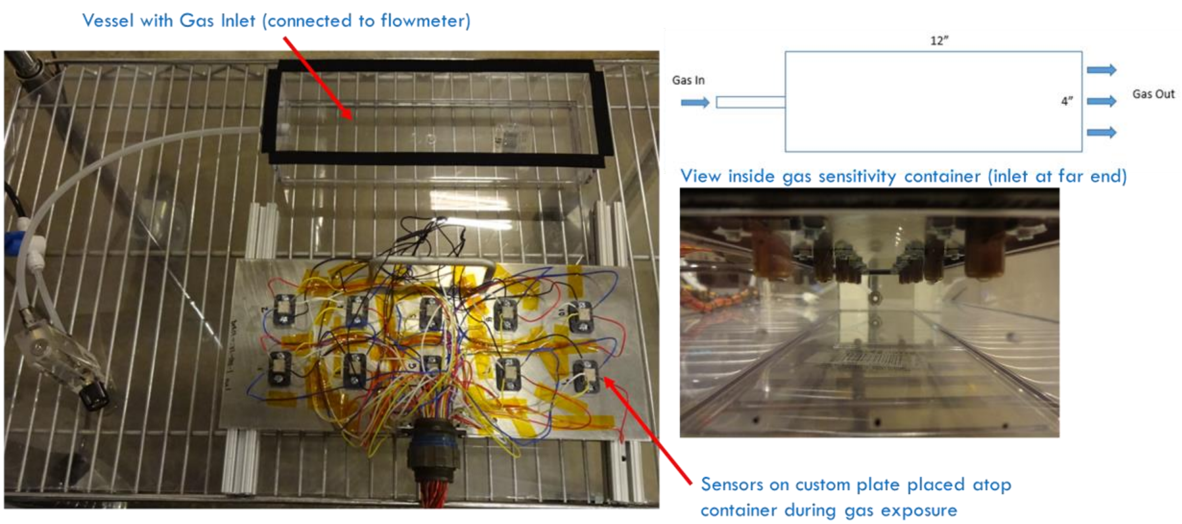


Figure 35: Sensor B THB Gas Sensitivity Setup – Front Half

For the back half sensor gas sensitivity testing, the samples remained powered as they were placed on the gas sensitivity container (Figure 36). Samples 7 and 8 were the closest to the inlet.

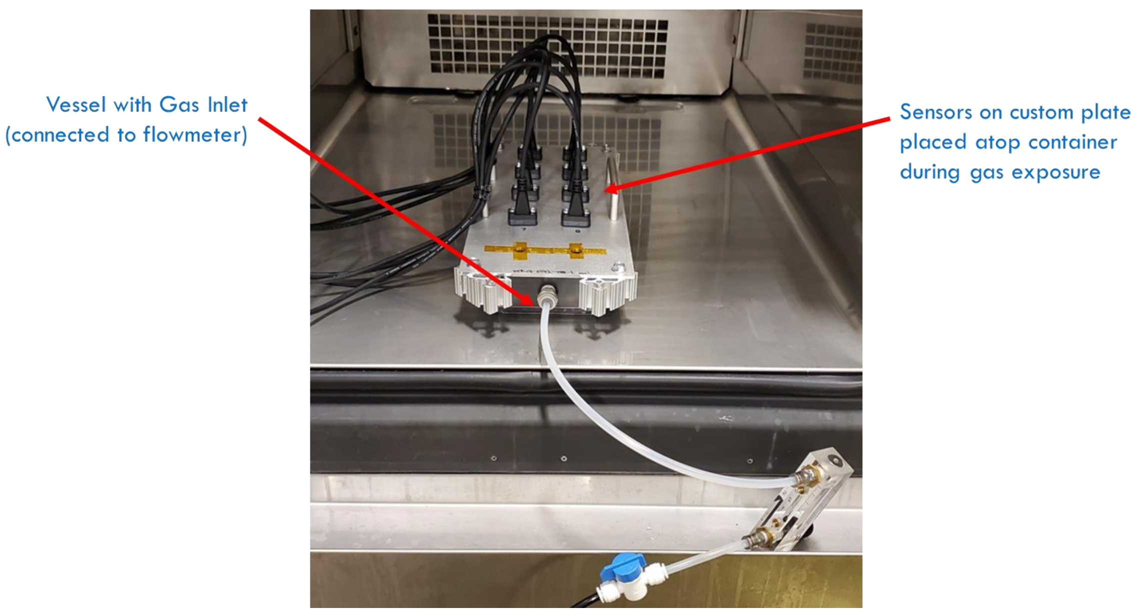


Figure 36: Sensor B THB Gas Sensitivity Setup - Back Half

The same general test sequence used for TC gas sensitivity testing was used for THB gas sensitivity testing also (reference Figure 34).

3.4 Data Monitoring

An Agilent 34970A data acquisition systems with the 34908A 40-channel multiplexer cards was used to monitor power input to the sensors and signal output while in the chambers (Figure

37). These data acquisition systems can monitor up to 120 single ended channels with reading rates of up to 600 readings per second on a single channel, and scan rates of 250 channels per second. Data was transferred to a host PC through a GPIB (IEEE-488) interface.

Figure 37: Agilent 40 Channel Data Acquisition/Switch System for Monitoring Sensors

3.5 Equipment List

The equipment list for the temperature cycling and THB testing is found in APPENDIX C: Major Equipment List. This list includes the environmental chambers, power supplies, and data loggers. In addition, custom-designed break-out boards are indicated in APPENDIX A: Sensor A TC and THB schematic and APPENDIX B: Sensor B TC and THB schematic.

4 Test Results

Test results are presented for each sensor type with respect to the two accelerated life tests performed: temperature cycling and temperature humidity bias.

4.1 Sensor A

4.1.1 TC Results

A baseline gas sensitivity check (GS0) was performed with each of the five tanks (gas concentrations listed in Table 13). Proportional response to gas exposure and return to zero signal output afterwards was observed across all 8 samples (Figure 38).

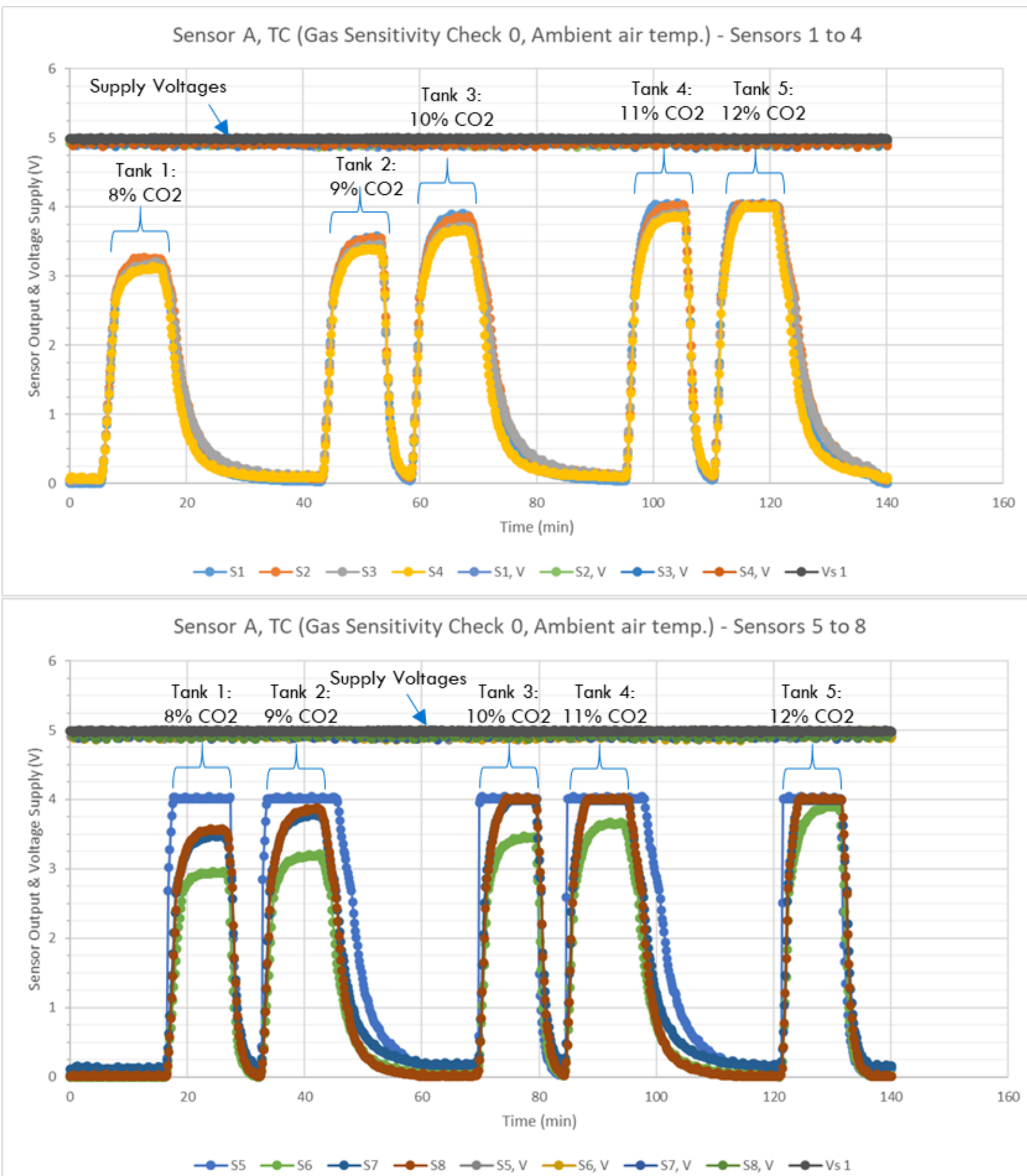


Figure 38: Sensor A TC, Baseline Gas Sensitivity Check (GS0)

Baseline electrical current measurement results are shown in APPENDIX D: Baseline Electrical Measurements. Sensor current remained within expected range throughout testing, indicating no short circuiting within the sensor.

Temperature cycling exposure between gas sensitivity checks was indicated by "cycling", followed by the sequential exposure number. Fluctuation in signal output voltage was evident during exposure to temperature cycling. The self-calibration performed every 24 hours was affected by these temperature swings. Figure 39 shows a typical sensor response throughout exposure cycles, with sensor signal output returning to baseline zero within 25 hours of being brought down to room temperature.

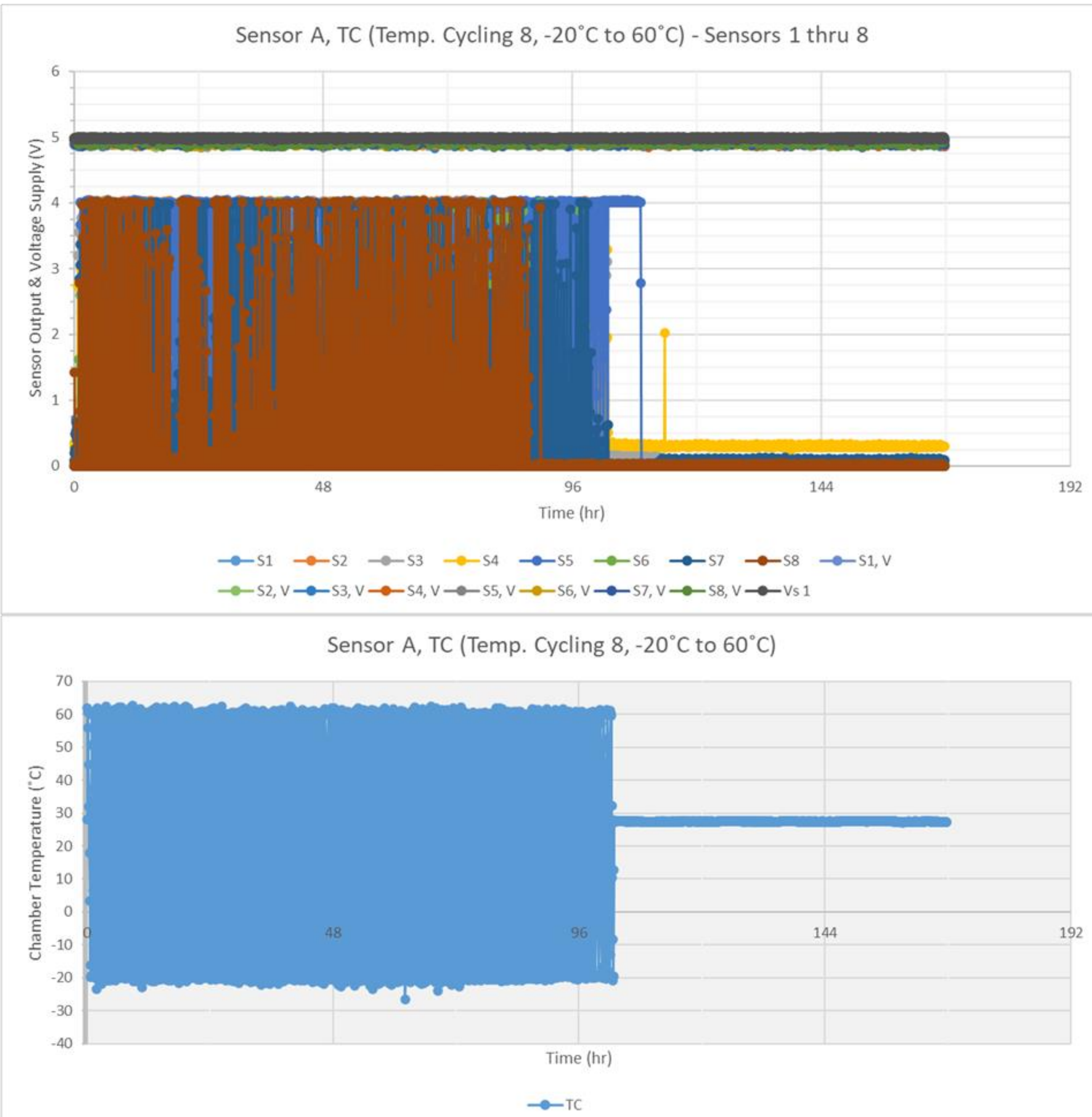


Figure 39: Sensor A TC, Sensor Output and Chamber Temperature during Cycling

During gas sensitivity check 9 (GS9), between Tank 3 and Tank 4 gas concentrations (when no gas was supplied), sample S1 momentarily went to 2V signal output and S4 momentarily went to 4V and then 2V (Figure 40) before returning to zero. Both sensors performed as expected afterwards and to the end of testing. This was observed during temperature cycling exposure, and may be related to the automated self-calibrations performed within every 24 hrs.

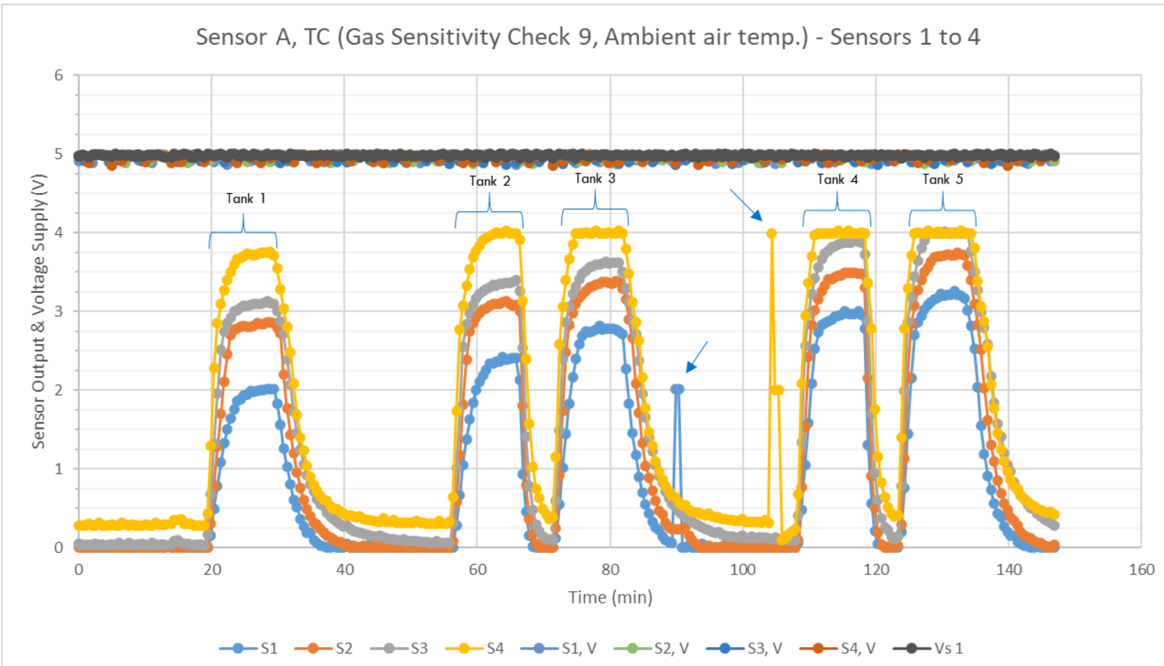


Figure 40: Sensor A TC, Momentary 2V and 4V Output

The last gas sensitivity check (GS12) showed each sample sensing each gas concentration as expected (Figure 41). Sample S4 had some offset from zero (about 0.25 V) when no gas concentration was applied. All 8 samples survived through 2292 thermal cycles without any hard failures.

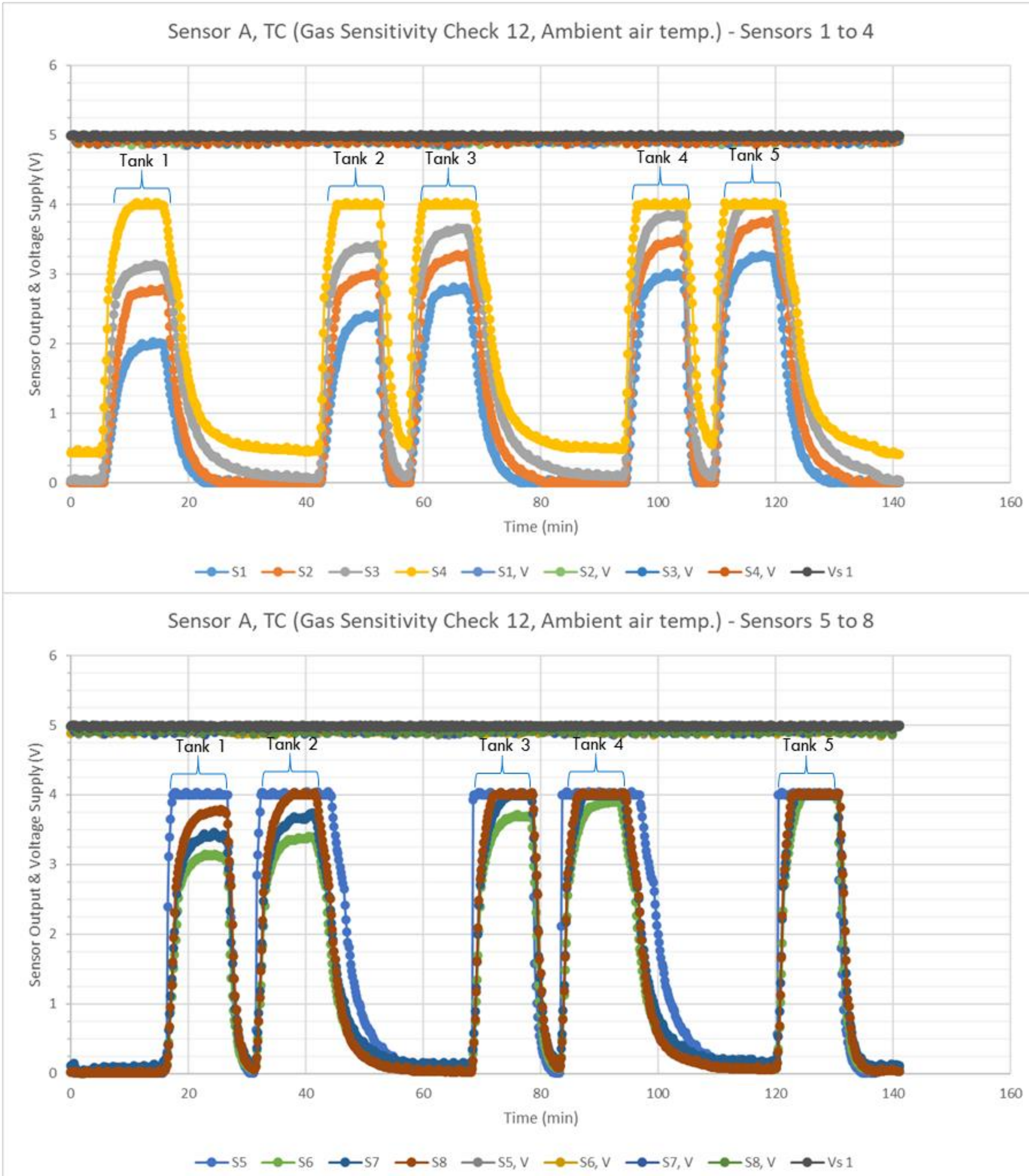


Figure 41: Sensor A TC, Final Gas Sensitivity Check (GS12)

Performance results for accuracy and stability were also evaluated against the specification (reference Table 14) by averaging the first 8 minutes of response to each gas exposure for each sample. This takes into account response time, as the averaging begins with start of exposure to each gas concentration. The signal output response from baseline and the last gas sensitivity check, and percent change, is shown in APPENDIX E: Signal Output Response Change.

All samples exceeded the accuracy specification across multiple gas concentrations, even when accounting for additional tolerance due to an assumed ±5˚C temperature variation and +/- 1 inHg (25.4 mmHg) pressure variation from baseline. The stability specification was also exceeded by many samples. With an allowable increase in stability of 10% per year in the field, only sample S4 exceeded the stability specification after gas sensitivity check 2 (GS2), where it exhibited about a 0.25 V offset from zero.

4.1.2 THB Results

During adjustment of the power supply prior to testing, samples S1 thru S3 and S5 thru S16 had up to 9.3 V inadvertently applied for less than 20 seconds. The power supply was changed to a BK Precision unit that was more easily adjusted. After the samples were powered up and initial pre-testing was performed with gas sensitivity concentrations from Tanks 1 and 2 (gas concentrations listed in Table 13), no issues were noted on these samples relative to the other 33 samples also tested. Afterwards, a baseline gas sensitivity check (GS0) was performed with each of the five tanks. Steady response to gas exposure and return to zero signal output afterwards was observed across all 48 samples (Figure 42, Figure 43, and Figure 44).

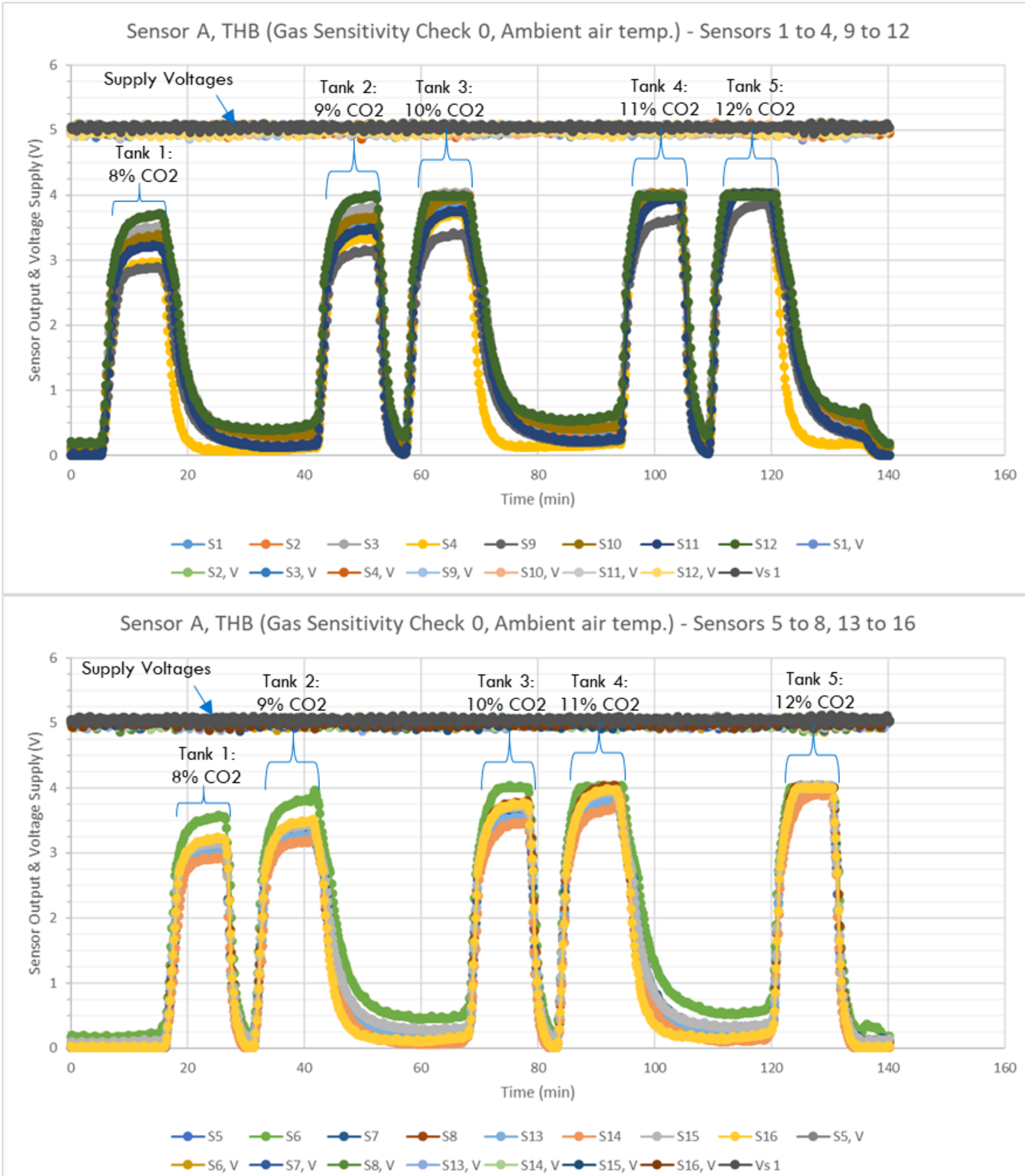


Figure 42: Sensor A THB, Samples 1 thru 16, Baseline Gas Sensitivity Check (GS0)

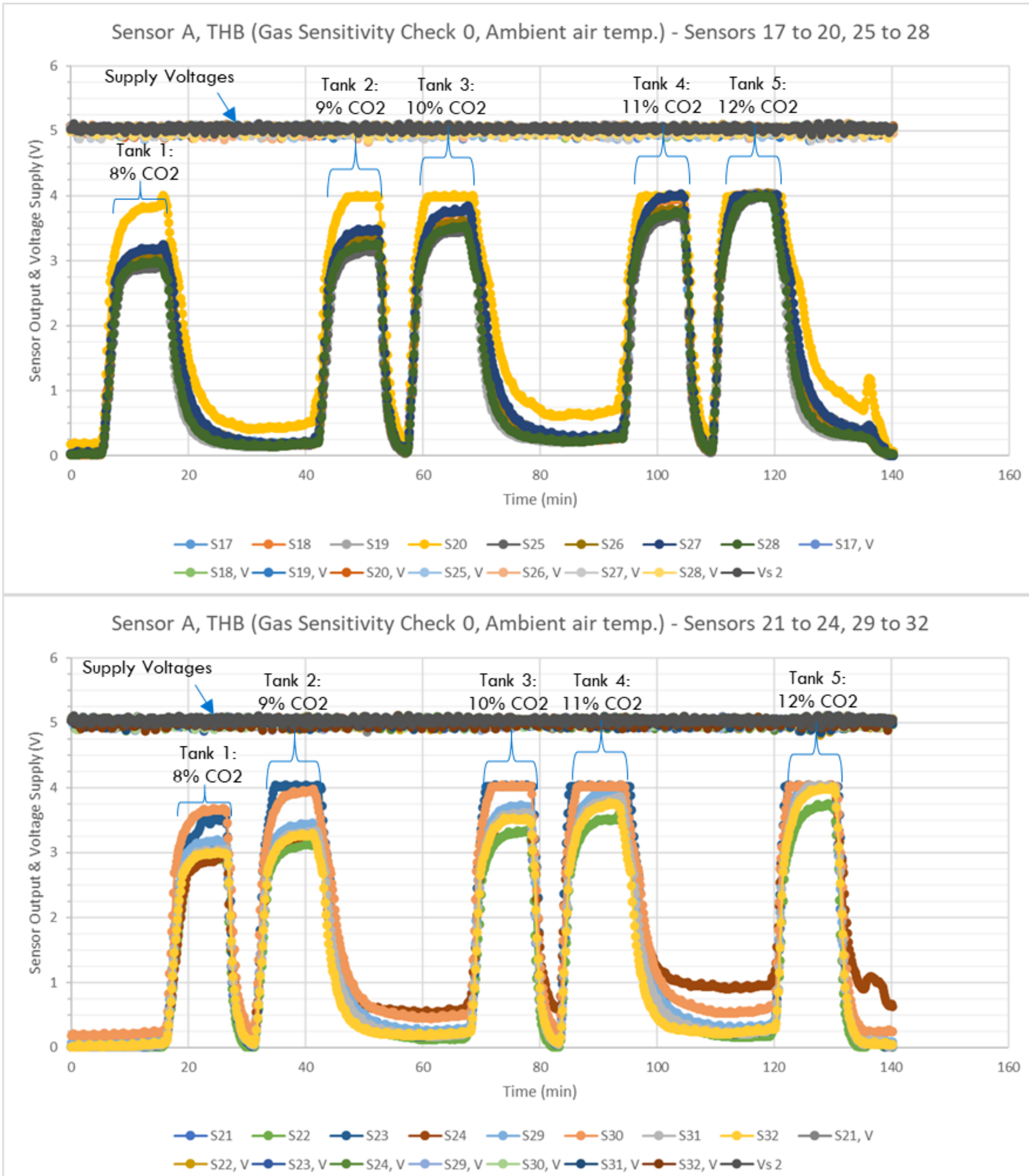


Figure 43: Sensor A THB, Samples 17 thru 32, Baseline Gas Sensitivity Check (GS0)

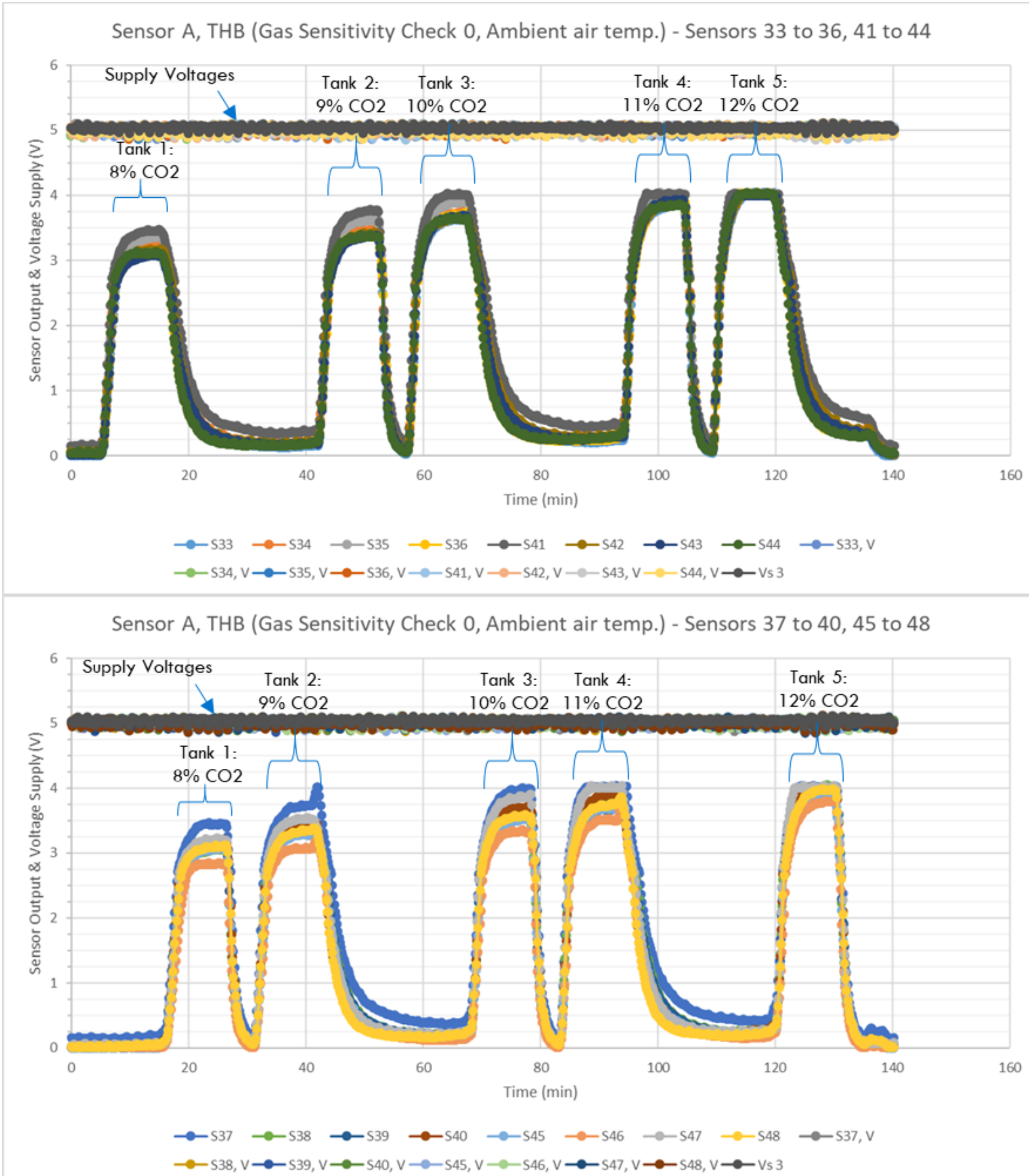


Figure 44: Sensor A THB, Samples 33 thru 48, Baseline Gas Sensitivity Check (GS0)

Baseline electrical current measurement results are shown in APPENDIX D: Baseline Electrical Measurements. Sensor current remained within expected range throughout testing, indicating no short circuiting within the sensor.

Temperature-humidity bias exposure between gas sensitivity checks was indicated by “heat/humidity (HH)”, followed by the sequential exposure number. During the first temperature/humidity exposure of 840 hours, break-out board #2 used with samples 17 thru 32 had corroded outside the chamber. Water had condensed in the line at the chamber port hole and overcame the drip loop, leaking out from the connector onto the break-out board.

This occurred around 58 hours of exposure and continued to 133 hours exposure before power was removed and testing stopped. Voltage supplied to samples affected was within specification, except for samples 25, 26, 28 and 32, whose voltages dropped below the 5 V +/- 5% power supply required due to shorting on board. The break-out board was replaced and samples powered to complete the remaining exposure time. No issues were noted on these samples relative to the other samples in test.

All samples showed expected results in the subsequent temperature/humidity exposure of 840 hours, except for some offset in signal output noted on sample S42, and some fluctuation in signal output noted on sample S44 (Figure 45). Sample S44 had previously shown some fluctuation up to 4V signal output in the first 840 hour exposure period. All samples returned to zero within 25 hours of being brought down to room temperature. Subsequent gas sensitivity checks were similar to baseline results.

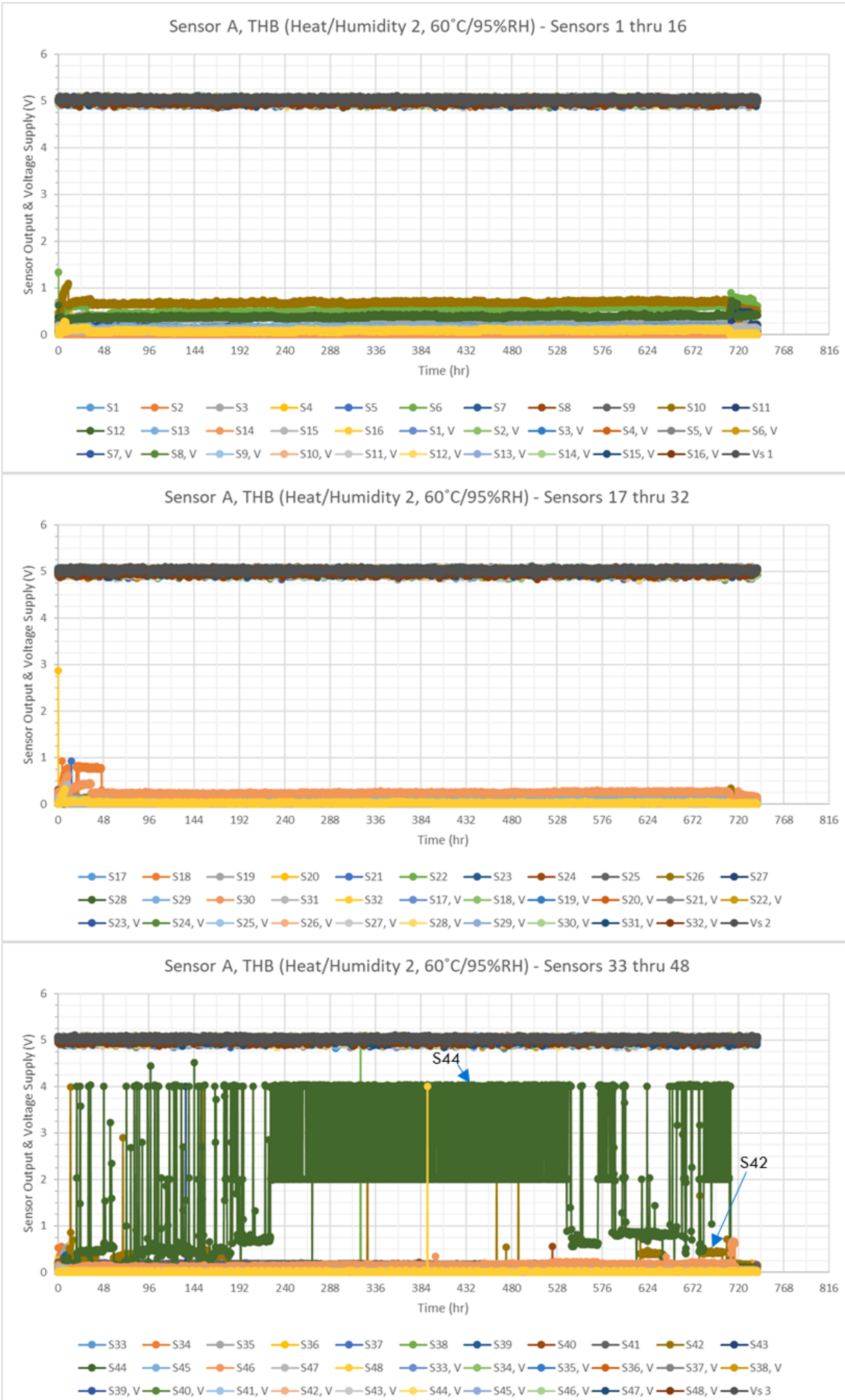


Figure 45: Sensor A THB, Sensor Output during THB Exposure (Heat/Humidity 2)

After 2520 hrs accumulated under temperature/humidity and bias, HH4 exposure started. Early during this exposure, a heater coil and fuse blew in the chamber. After replacement, the chamber had gone from 20C to -20C over 1 hour (without humidity) before being turned off. Samples were checked and there was no indication of condensation. The chamber was re-started after the coil wiring was corrected for the remaining 806.5 hrs at 60C/95%RH.

During gas sensitivity check 6 (GS6), after 5018 hrs exposure to temperature/humidity and bias, sample S2 exhibited fluctuating signal output between 2-4 V (Figure 46). As early as 3482 hrs of exposure to temperature/humidity and bias (during HH5), this sample had begun to fluctuate between 2-4 V, but responded to each gas concentration during the subsequent gas sensitivity check (GS5). Because of this, testing continued until this sensor was removed after GS6 as a hard failure.

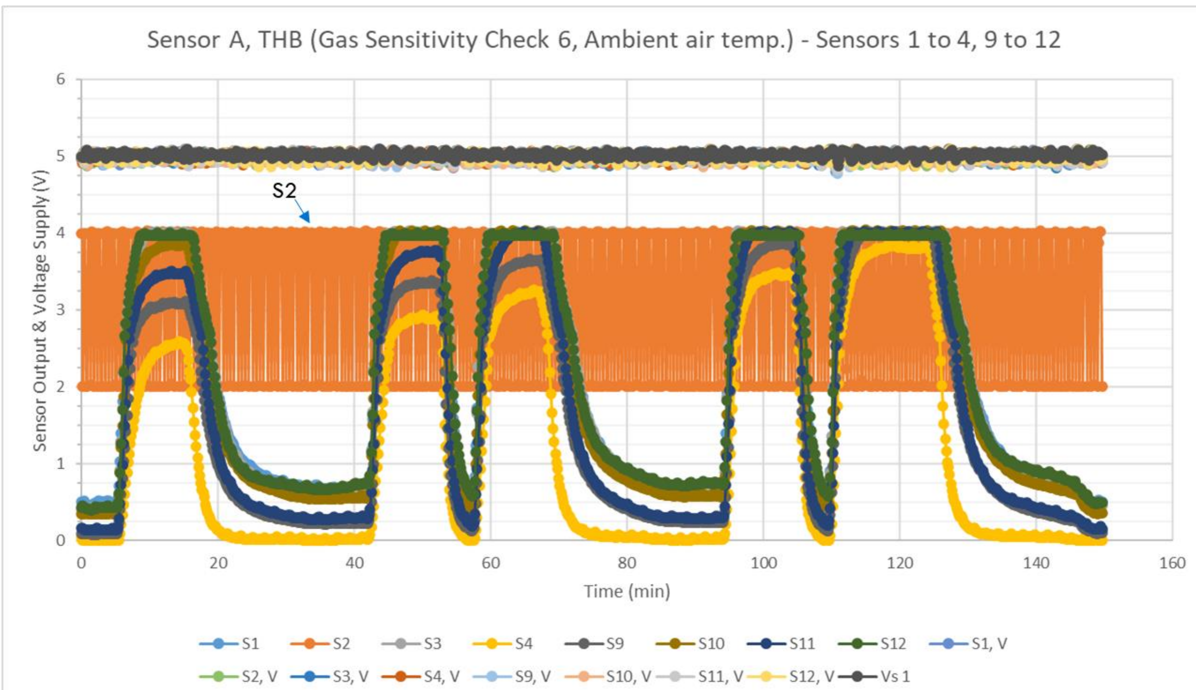


Figure 46: Sensor A THB, S2 Hard Failure

Also during GS6, sample S44 exhibited fluctuation momentarily between 2-4 V when exposed to only air between Tank 1 and Tank 2 gas concentrations (gas concentrations listed in Table 13). As early as 1062 hrs of exposure to temperature/humidity and bias (during HH2), this sample had begun to fluctuate between 2-4 V, but responded to each gas concentration during all subsequent gas sensitivity checks to the end of testing. Despite continued functional response, this was considered a hard failure due to the false positive response during GS6.

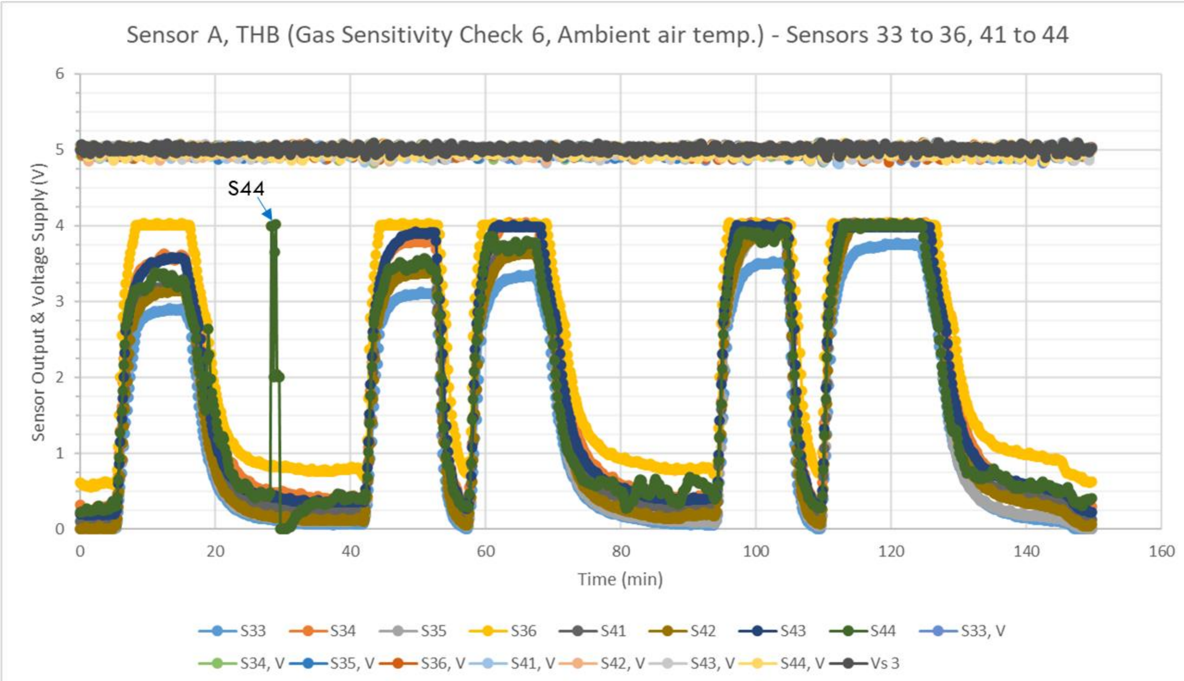


Figure 47: Sensor A THB, S44 Hard Failure (False Positive)

During GS7, after 5880 hrs exposure to temperature/humidity and bias, sample S4 exhibited fluctuating signal output between 1.4-2.8 V (Figure 48). As early as 5003 hrs of exposure to temperature/humidity and bias (during HH6), this sample peaked at 2 V and then 4 V shortly after, but responded to each gas concentration during the subsequent gas sensitivity check (GS6). Because of this, testing continued. It was considered a hard failure during GS7.

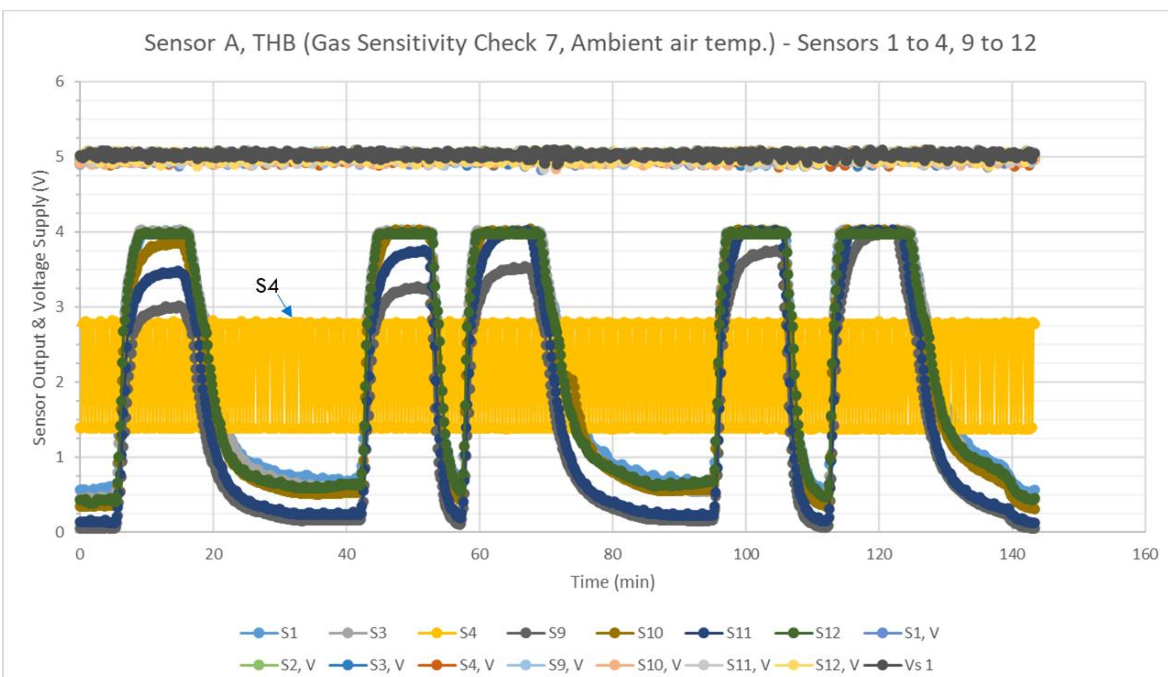


Figure 48: Sensor A THB, S4 Hard Failure

Also during GS7, sample S5 exhibited no response to target gas concentrations and instead had a 0.5 V steady signal output (Figure 49). As early as 5411 hrs of exposure to temperature/humidity and bias (during HH7), this sample exhibited intermittent fluctuation going up to 2.7 V before later settling around 0.5 V at room temperature conditions. It was considered a hard failure with no output response during GS7.

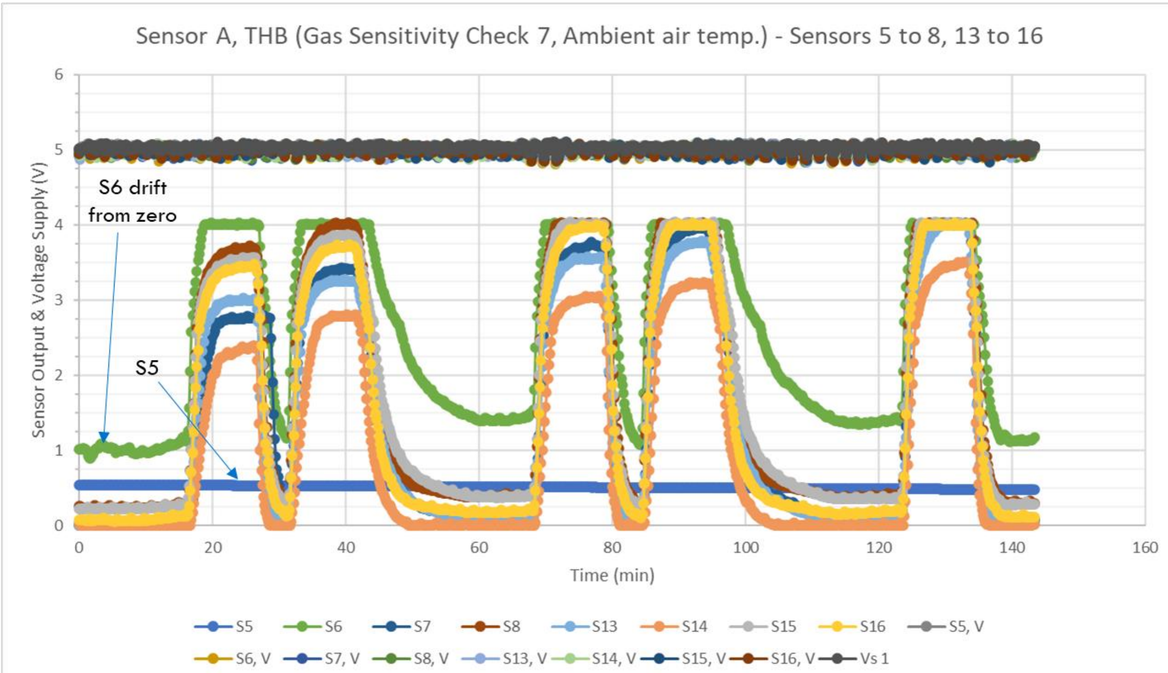


Figure 49: Sensor A THB, S5 Hard Failure

Also during GS7, sample S23 exhibited no response to target gas concentrations and instead had a 0.8 V steady signal output (Figure 50). As early as 5709 hrs of exposure to temperature/humidity and bias (during HH7), this sample exhibited intermittent fluctuation going to 3.6 V and above before decreasing to 0.8 V at room temperature conditions. It was considered a hard failure with no output response during GS7.

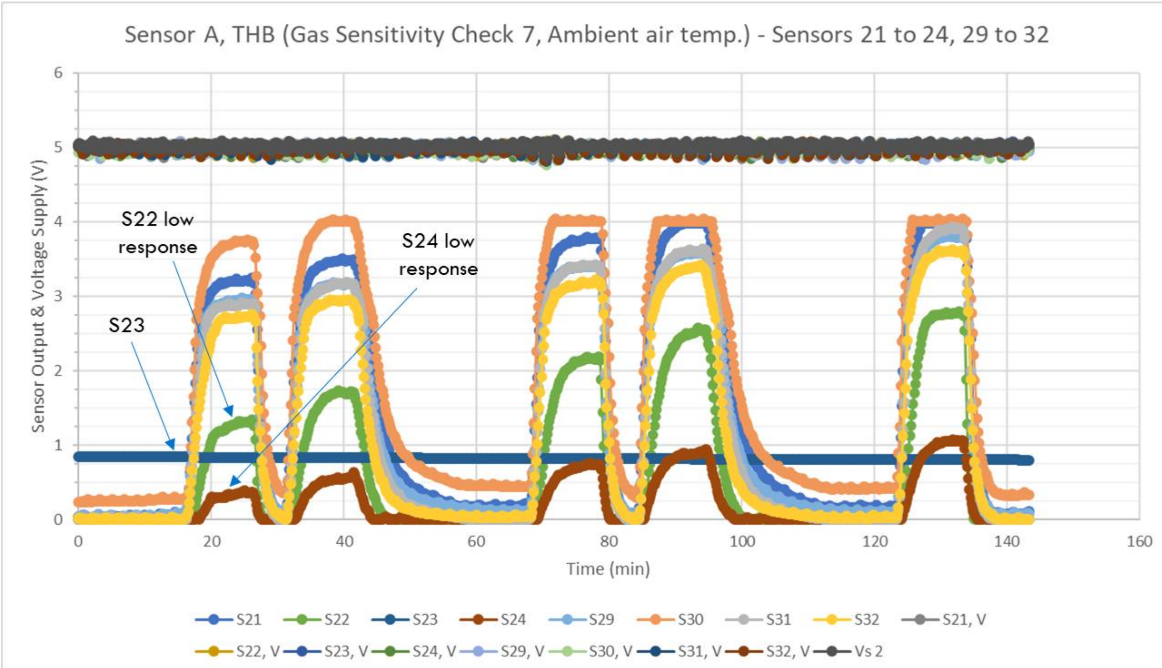


Figure 50: Sensor A THB, S23 Hard Failure

Also during GS7, sample S33 exhibited no response to target gas concentrations and instead had a 0.25 V noisy signal output (Figure 51). It was considered a hard failure with no output response during GS7.

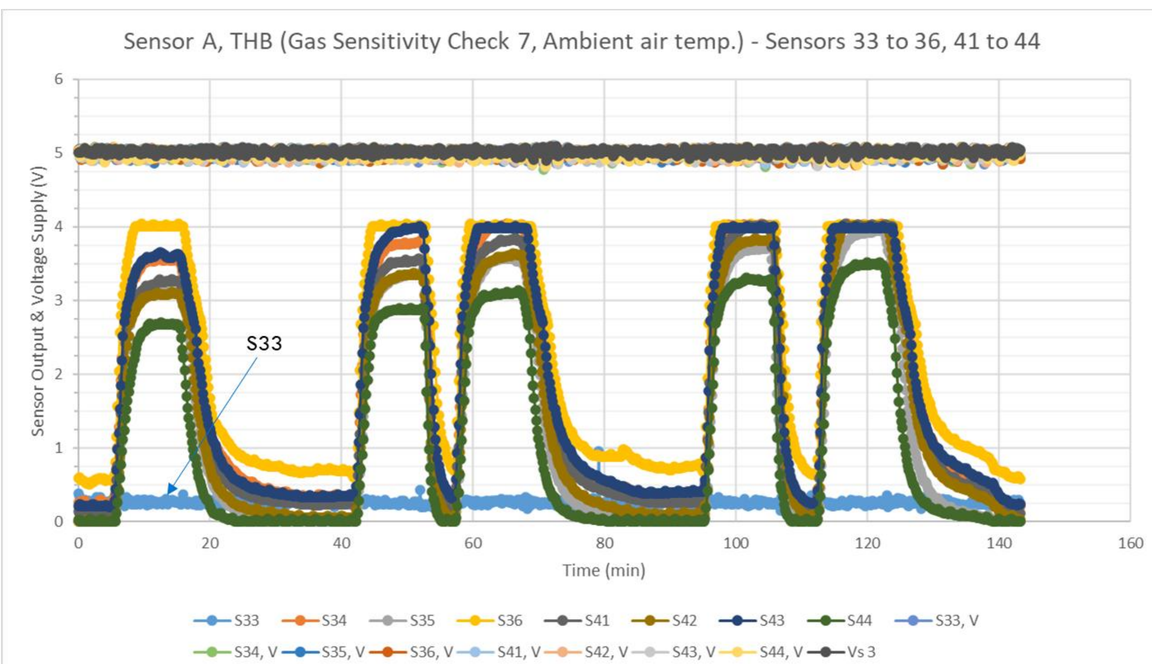


Figure 51: Sensor A THB, S33 Hard Failure

During GS8, after 6720 hrs exposure to temperature/humidity and bias, sample S17 exhibited no response to target gas concentrations. Sample S19 exhibited a drifting output (2+ V) without any real response to target gas concentrations (Figure 52). Both were hard failures during GS8.

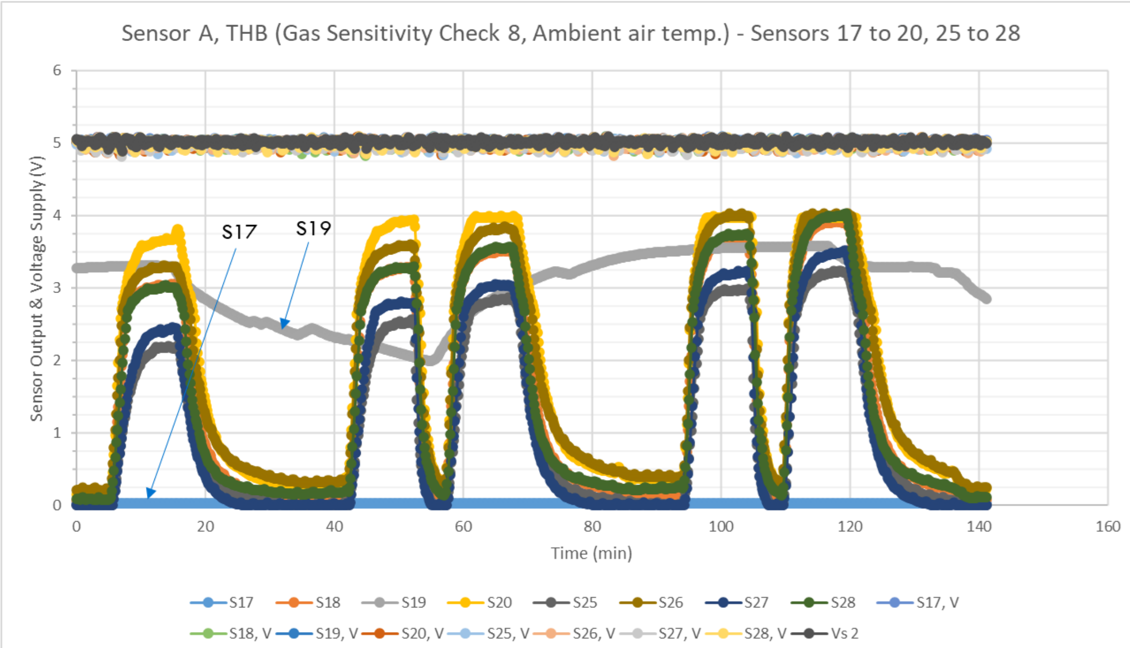


Figure 52: Sensor A THB, S17 & S19 Hard Failures

Also during GS8, sample S45 exhibited no response to target gas concentrations and instead had a steady output of 4 V (Figure 53). This was a hard failure during GS8.

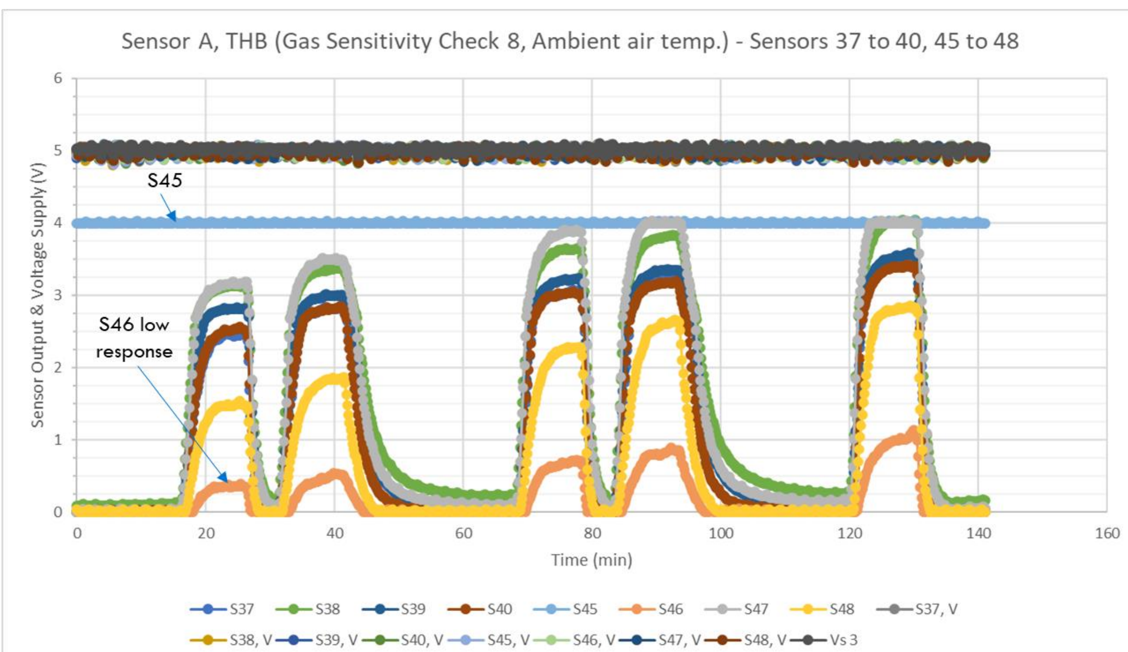


Figure 53: Sensor A THB, S45 Hard Failure

Samples were exposed to an additional 360 hrs of temperature/humidity and bias (HH9) to get to a total of 7080 accumulated hours. Samples had been at room temperature conditions for about 14.5 days and unpowered for about 10 days. Power had gone out for about 15 hrs during this period. There was no sign of condensation on boards and testing was re-started.

During GS9, after 7080 hrs exposure to temperature/humidity and bias, additional samples failed with no response to target gas concentrations: samples S9, S16, S22, S32, and S48. Sample S12 was offset from zero by greater than 1 V, but did respond to each target gas concentration (similar to sample S6) and therefore not a hard failure.

A summary of the hard failures is shown in Table 16 below.

Table 16: Sensor A THB, Hard Failure Summary

GS Check	Accumulated Temperature/humidity and Bias (hrs)	Hard Failure	Failure Mode
6	5018	S2	Fluctuated 2-4 V output
6	5018	S44	Fluctuated 2-4 V output momentarily
7	5880	S4	Fluctuated 1.4-2.8 V output
7	5880	S5	No response (0.5 V steady output)
7	5880	S23	No response (0.8 V steady output)
7	5880	S33	No response (0.25 V noisy output)
8	6720	S17	No response (no output)
8	6720	S19	No response (drifting 2+ V output)
8	6720	S45	No response (4 V steady output)
9	7080	S9	No response (no output)
9	7080	S16	No response (2.1 V steady output)
9	7080	S22	No response (2.2 V steady output)
9	7080	S32	Fluctuated 1.3-2 V output
9	7080	S48	No response (2.1 V steady output)

Performance results for accuracy and stability were also evaluated against the specification (reference Table 14) by averaging the first 8 minutes of response to each gas exposure for each sample. This takes into account response time, as the averaging begins with the start of exposure to each gas concentration. The signal output response from baseline and the last gas sensitivity check, and percent change, is shown in APPENDIX E: Signal Output Response Change.

Many samples exceeded the accuracy specification across multiple gas concentrations early in testing, even when accounting for additional tolerance due to an assumed ±5˚C temperature variation and +/- 1 inHg (25.4 mmHg) pressure variation from baseline. By end of testing, most samples had exceeded the accuracy specification. The stability specification was also exceeded by many samples. With an allowable increase in stability of 10% per year in the field, the following samples exceeded the stability spec. in air (no gas concentration applied): S1, S3-S6, S8-S12, S15-S16, S22-S23, S26, S32, S34, S36, S38, S43-S44, S46, and S48.

Several samples exhibited fluctuation in signal output response during temperature/humidity exposures, but performed ok during gas sensitivity checks by responding to the target gas concentrations. Some samples, like S22 and S24 (Figure 50) and S46 (Figure 53), exhibited lowered signal output, but still responded to the target gas concentrations. These were not considered hard failures.

4.2 Sensor B

4.2.1 TC Results

A baseline gas sensitivity check (GS0) was performed with each of the five tanks (gas concentrations listed in Table 13). Steady response to gas exposure and return to zero signal output afterwards was observed across all 8 samples (Figure 54).

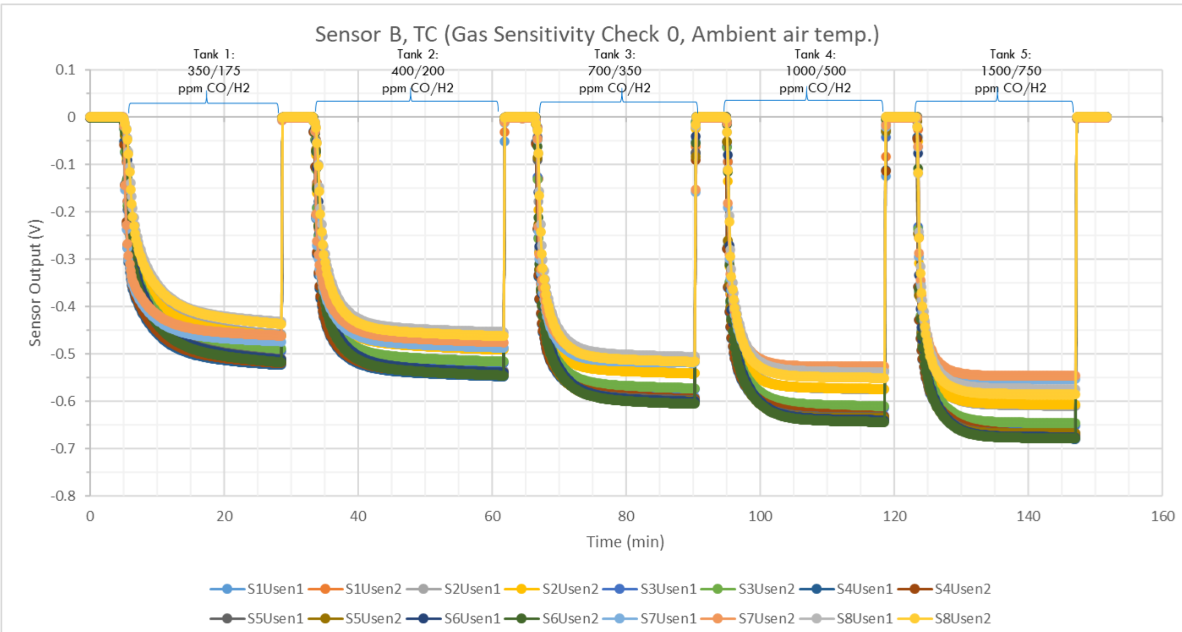


Figure 54: Sensor B TC, Baseline Check (GS0) Signal Output

The programmable power supply provided an AC voltage of about 10.45 V to the break-out board (resulting in about 8.7-8.8 V to each sample's heater element) during gas sensitivity checks. Heater power was maintained between 2.9-3 W (within the approximate 2.8 to 3 W desired range), with a heater current of 0.33-0.34 A and an average heater resistance of 26-27 Ohm. APPENDIX D: Baseline Electrical Measurements shows the baseline power, current, resistance, and thermocouple measurements of the sensors (where T_a is the ambient air temperature).

Temperature cycling exposure was conducted via power cycling between gas sensitivity checks. Each temperature cycle exposure was indicated by the term "power cycling", followed by the sequential exposure number. Initial signal output response over the first 672 cycles, along with heater power, current, resistance, and thermocouple measurements (as voltage is varied between 8-13 V), are shown in APPENDIX D: Baseline Electrical Measurements. Program controlling power supply had stopped in low voltage (8 V) at about 320 hr mark before manually being resumed.

During power cycling 2 (PC2), after about 905 total cycles, the heater for sample S6 stopped working. Heater power and operating temperature were lost (Figure 55). This was considered a hard failure. Before this, during gas sensitivity check 1 (GS1), sample S6-Usen2 channel was not responding to target gas concentrations, and sample S6-Usen1 had an initial delay of up to a few minutes with tanks T2 thru T5.

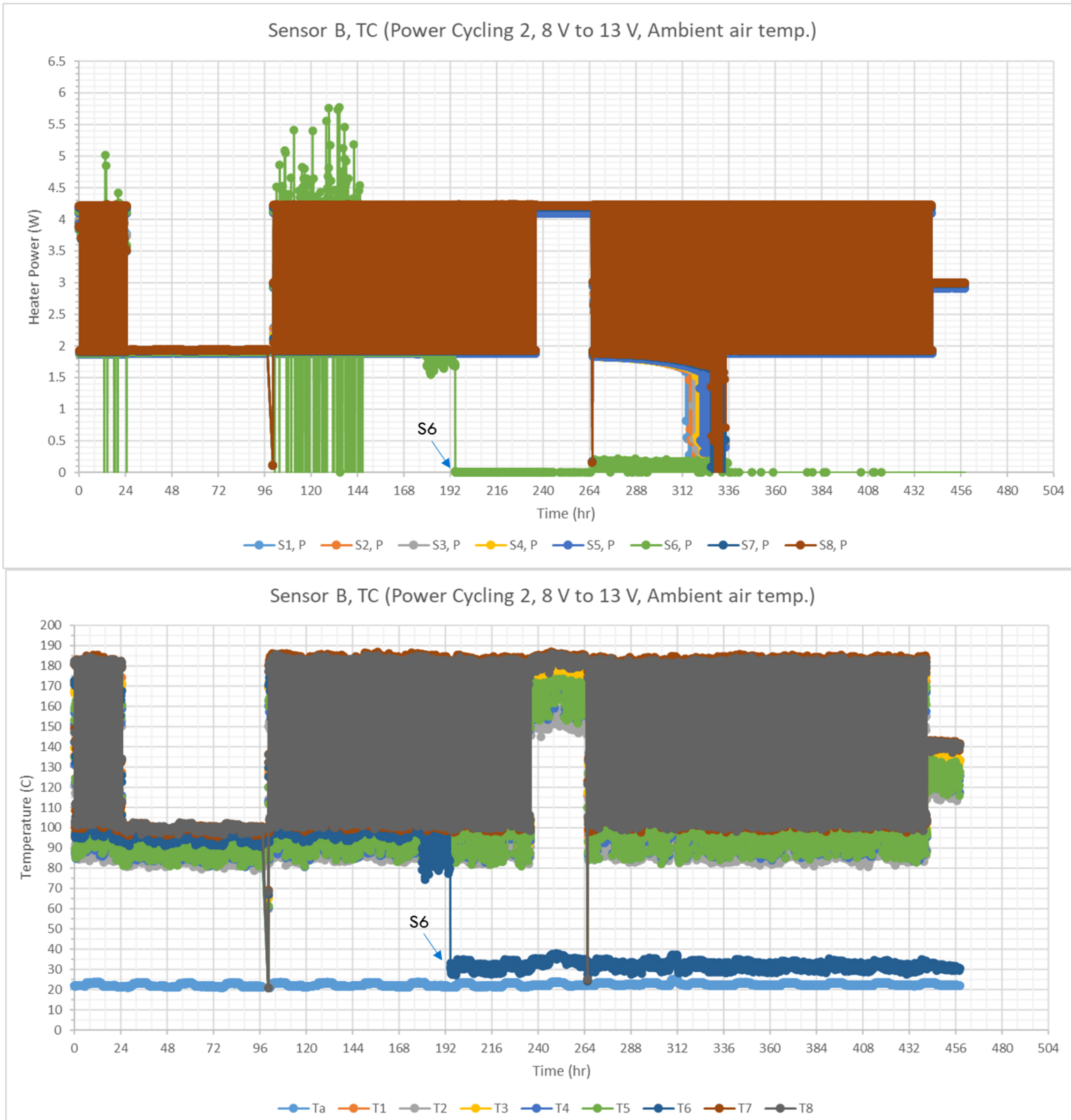


Figure 55: Sensor B TC, S6 Hard Failure (No Heater Power)

In the subsequent gas sensitivity check (GS2), sample S6-Usen1 and -Usen2 channels exhibited no response to target gas concentrations (Figure 56). There was no heater power present. Sample S6 was removed from test.

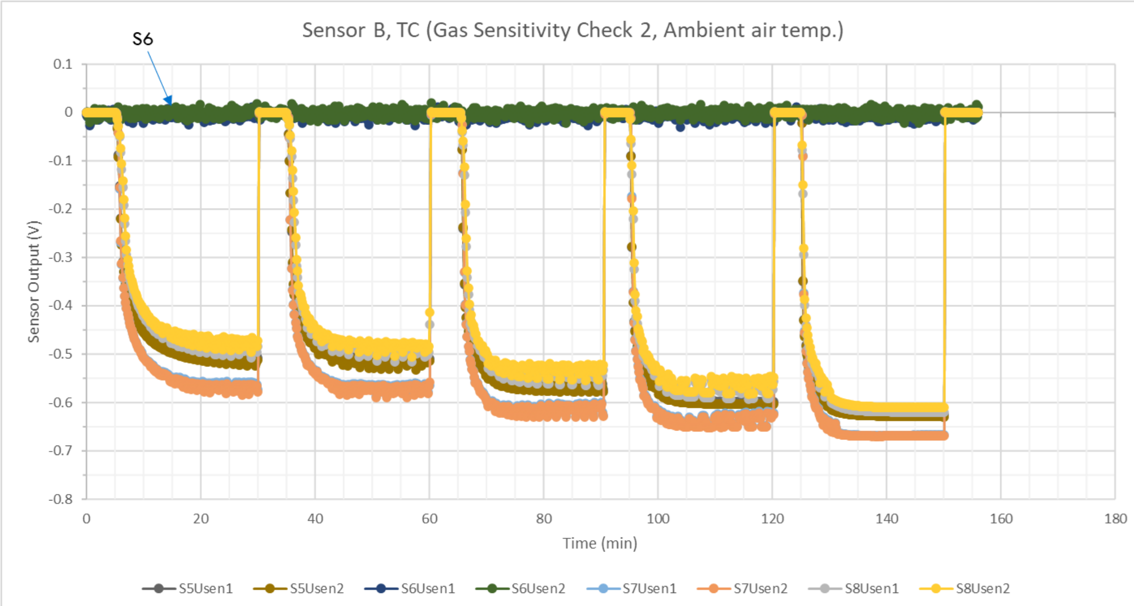


Figure 56: Sensor B TC, S6 Hard Failure (No Response)

During PC2 and PC4, the power supply had stopped a few times. In one case, the samples were exposed to the high voltage setting of 13 V for about 63 hrs. This occurred due to a program error running the power supply. While this just exceeded 4 W for an extended period of time, power consumption remained below the 6W recommended maximum. In all cases, power was manually resumed, following the same slow ramp-up in voltage to minimize in-rush current at startup.

During power cycling 7 (PC7), after about 4215 total cycles, the heater for sample S1 stopped working. Heater power and operating temperature were lost (Figure 57). This was considered a hard failure.

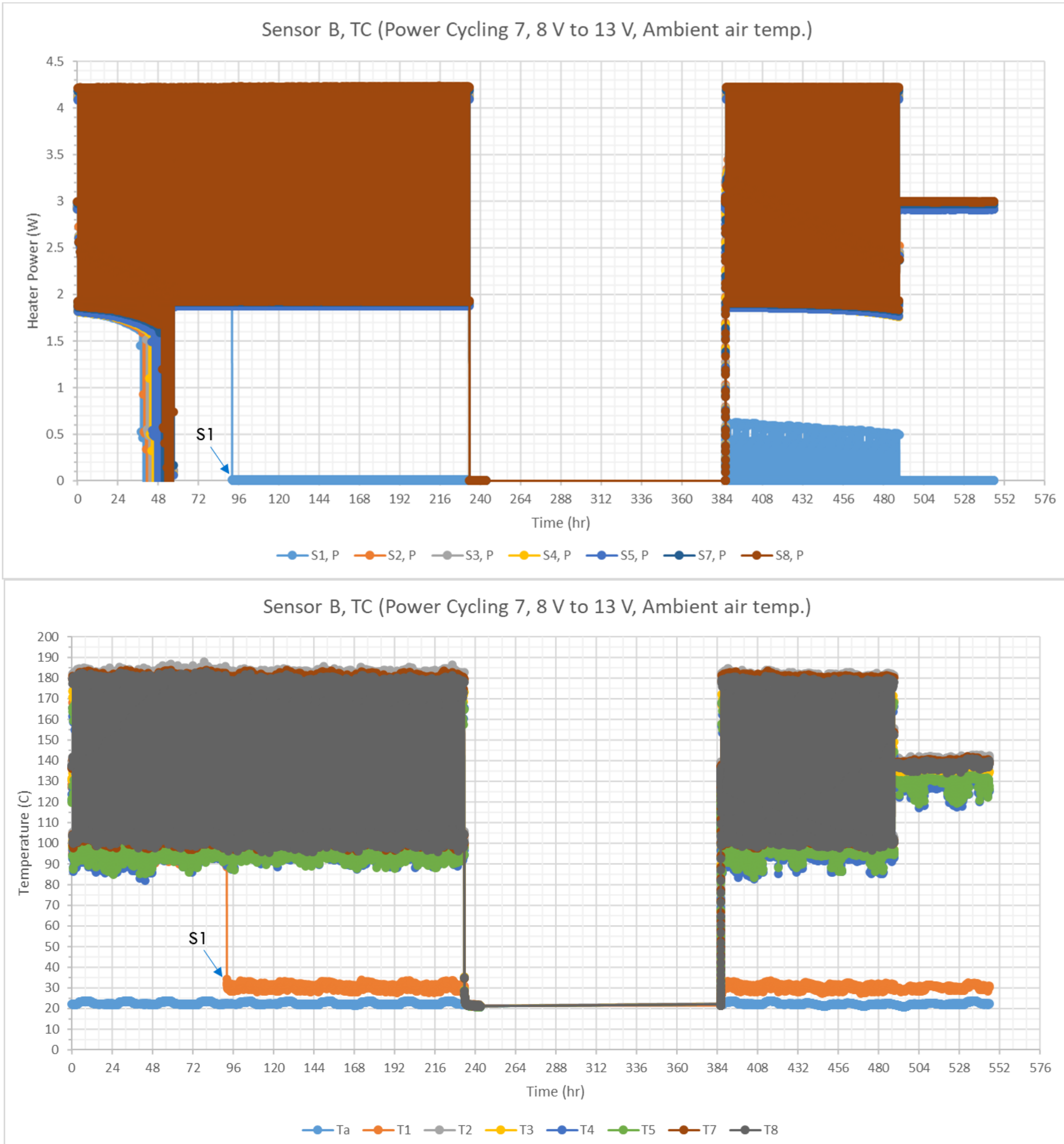


Figure 57: Sensor B TC, S1 Hard Failure (No Heater Power)

In the subsequent gas sensitivity check (GS7), sample S1-Usen1 and -Usen2 channels exhibited no response to target gas concentrations (Figure 58). There was no heater power present. Sample S1 was removed from test.

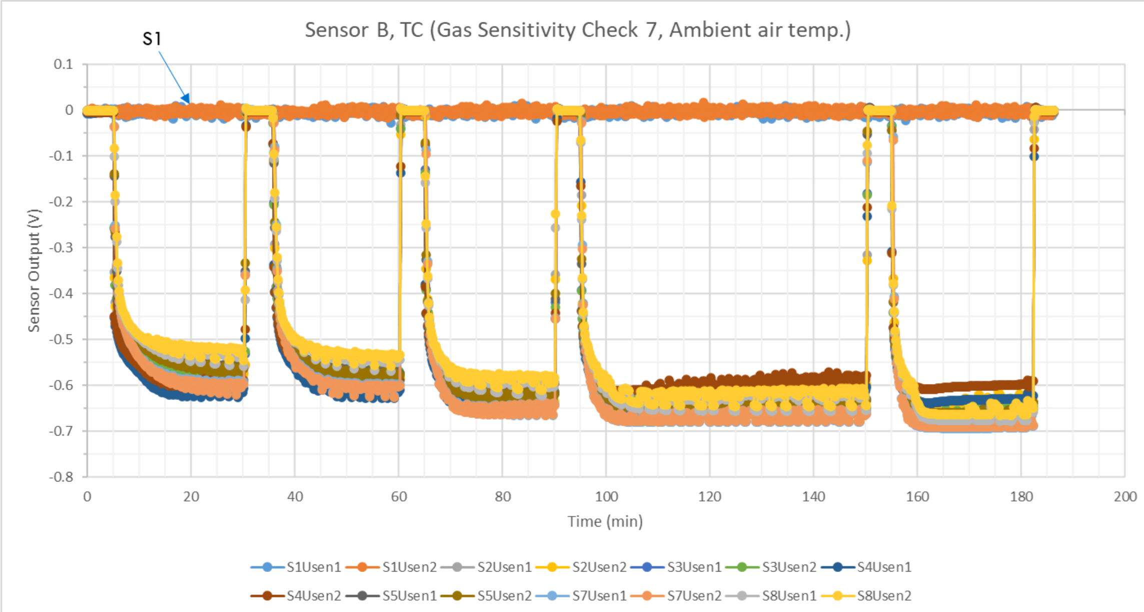


Figure 58: Sensor B TC, S1 Hard Failure (No Response)

The last gas sensitivity check (GS18) showed each of the remaining 6 samples sensing each gas concentration as expected (Figure 59). The 6 samples completed testing of 12,113 cycles, meeting the 11,998 cycles required with 2 hard failures in test.

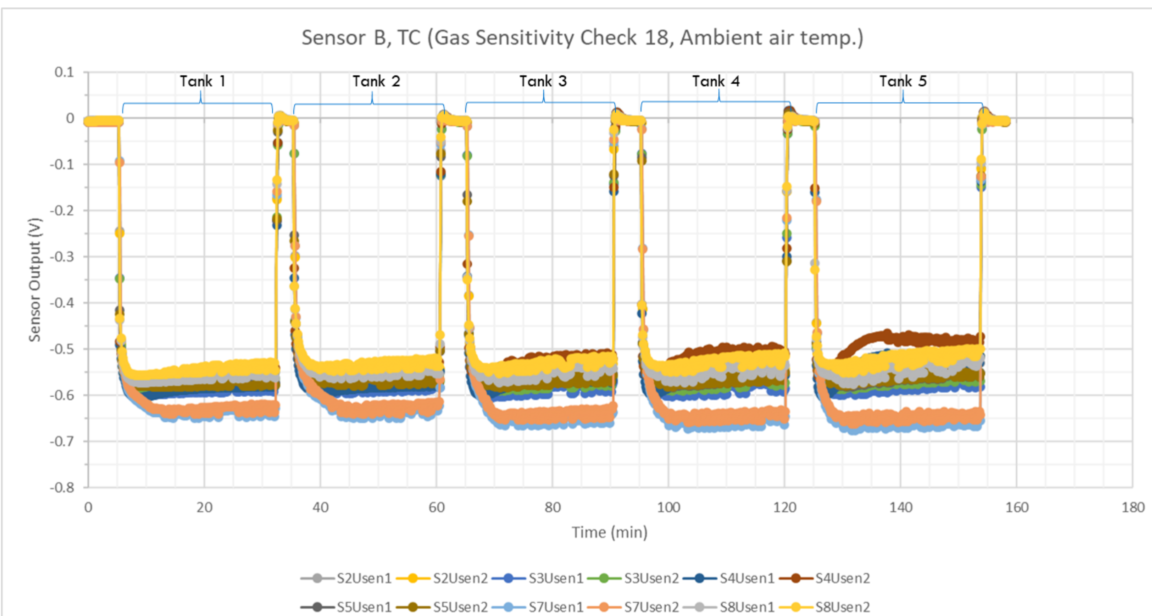


Figure 59: Sensor B TC, Final Gas Sensitivity Check (GS18)

A summary of the 2 qty. hard failures is shown in Table 17 below.

Table 17: Sensor B TC, Hard Failure Summary

GS or Power Cycling Period	Accumulated Cycles	Hard Failure	Failure Mode
PC2	905	S6	Heater power lost.
PC7	4215	S1	Heater power lost.

4.2.2 THB Results – Front Half of Sensor

A baseline gas sensitivity check (GS0) was performed with each of the five tanks (gas concentrations listed in Table 13). Steady response to gas exposure and return to zero signal output afterwards was observed across all 10 samples (Figure 60).

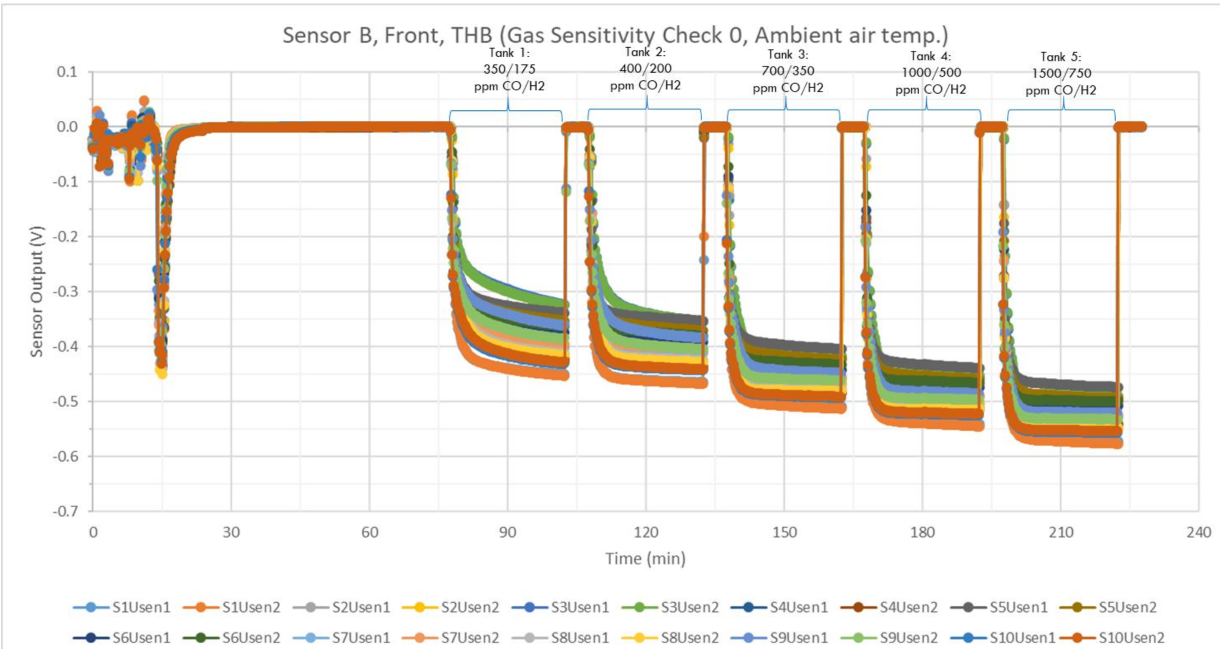


Figure 60: Sensor B THB - Front Half, Baseline Check (GS0) Signal Output

The power supply provided an AC voltage of about 10.2-10.3 V to the break-out boards (resulting in about 8.4-8.7 V to each sample's heater element) during gas sensitivity checks and temperature/humidity exposure. Heater power was maintained between 2.8-3 W (within the approximate desired range), with a heater current of 0.32-0.35 A and an average heater resistance of 25-26 Ohm. APPENDIX D: Baseline Electrical Measurements shows the baseline power, current, and resistance measurements of the samples.

Temperature-humidity bias exposure between gas sensitivity checks was indicated by "heat/humidity", followed by the sequential exposure number. Initial signal output response over the first 840 hrs, along with heater power, current, and resistance, are shown in APPENDIX D: Baseline Electrical Measurements.

During gas sensitivity check 2 (GS3), after 2520 hrs exposure to temperature/humidity and bias, sample S7-Usen1 channel and S9-Usen1 channel exhibited limited response across all 5 target gas concentrations (Figure 61). The other -Usen2 channels for each performed fine, and therefore this was only considered a soft failure for both samples.

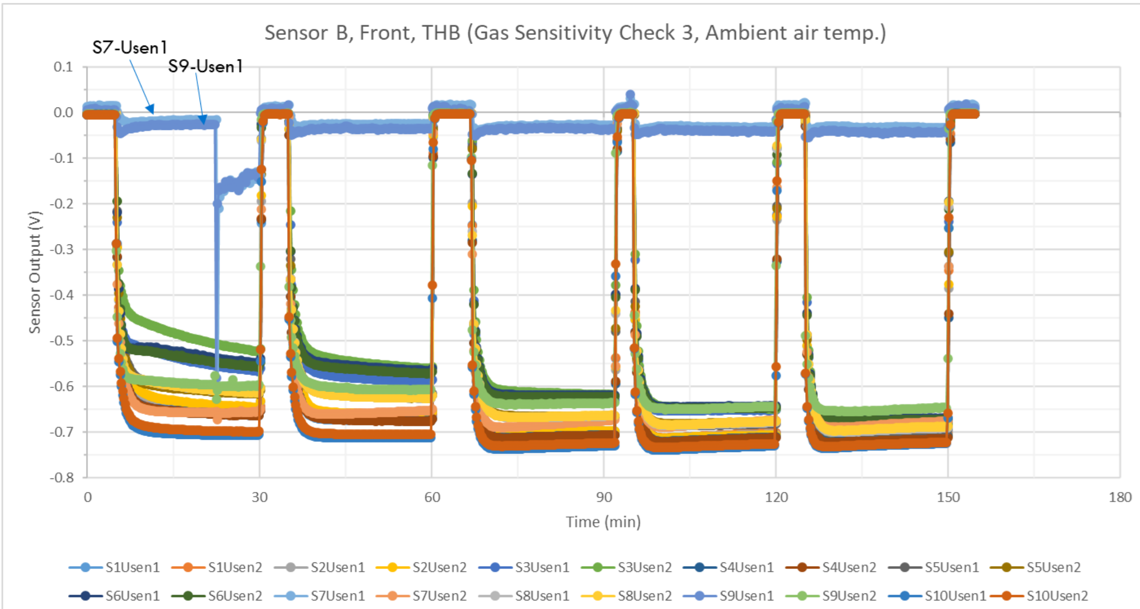


Figure 61: Sensor B THB - Front Half, S7 and S9 Soft Failures

In the subsequent gas sensitivity check (GS4), both channels for each of samples S7 and S9 performed as expected, responding as expected to each target gas concentration. Sample S2-Usen2 had a partial response around 0.25-0.3 V when exposed to Tank 1 gas concentration, but performed as expected for the remaining Tank 2 thru Tank 5.

During GS5, after 4200 hrs exposure to temperature/humidity and bias, sample S7-Usen1 channel exhibited limited response across Tank 4 and Tank 5 target gas concentrations (Figure 62). Samples S5 and S10 also began to show some degradation in signal output at the highest target gas concentration, but still remained above 100 mV (absolute value) signal output.

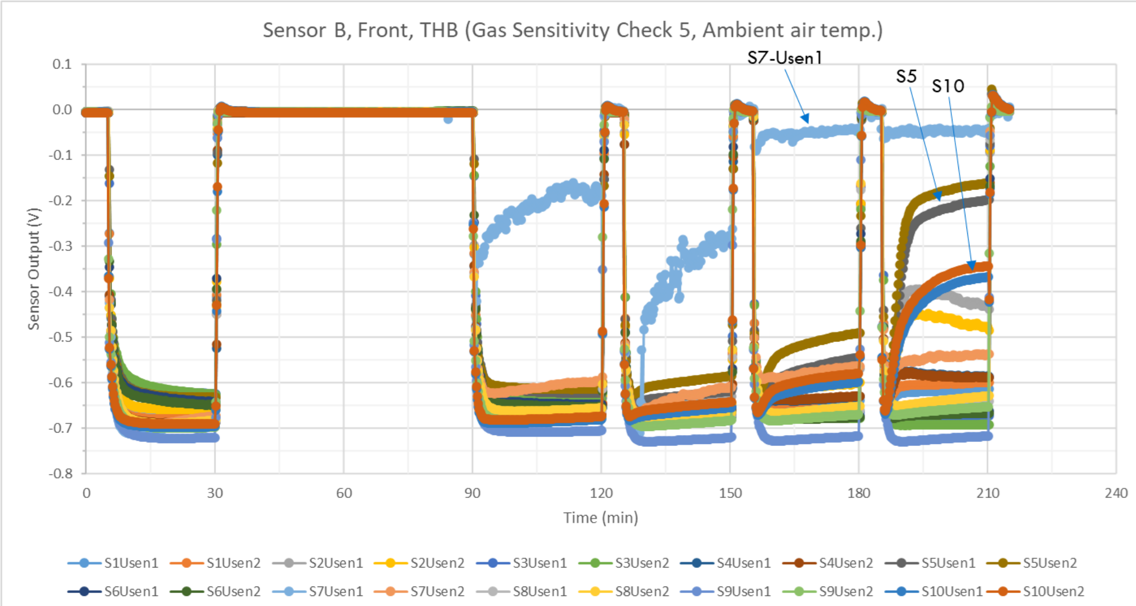


Figure 62: Sensor B THB - Front Half, S7 Soft Failure, S5 & S10 Degraded Output

During GS6, after 5040 hrs exposure to temperature/humidity and bias, sample S5 exhibited significantly degraded output (<100 mV absolute value) with Tank 4 and Tank 5 target gas concentrations (Figure 63). This occurred within minutes of responding with peak signal outputs of about 600 mV absolute value to each of those two target gas concentrations.

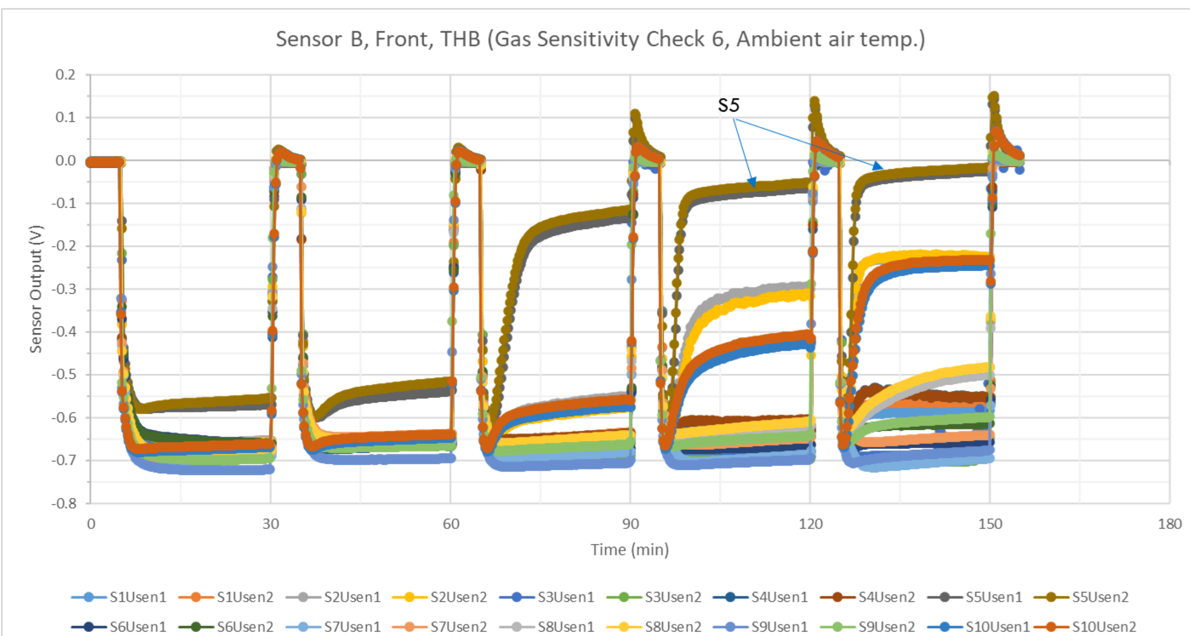


Figure 63: Sensor B THB - Front Half, S5 Significantly Degraded Output

During GS9, after 7560 hrs exposure to temperature/humidity and bias, sample S2 exhibited significantly degraded output (<100 mV absolute value) with Tank 4 and Tank 5 target gas concentrations (Figure 64). Behavior was similar to sample S5, which now had significantly degraded response beginning with Tank 1. Additional samples also show some degraded signal output at higher target gas concentrations.

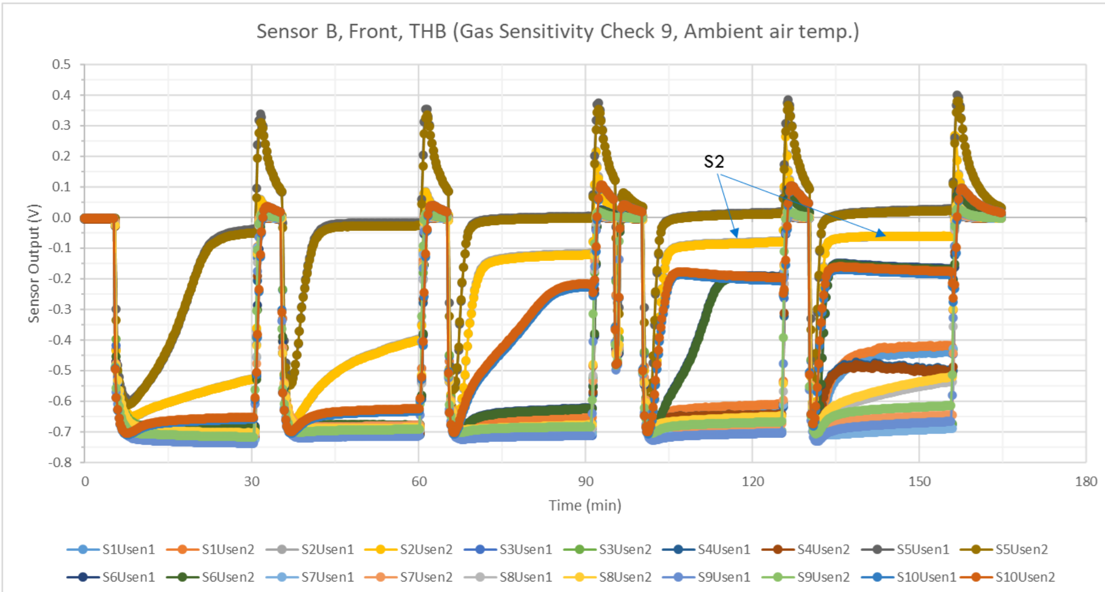


Figure 64: Sensor B THB - Front Half, S2 Significantly Degraded Output

During the subsequent and last temperature/humidity and bias exposure for 840 hrs, the HAST autoclave chamber breaker tripped several times due to a failing heater coil within the chamber. In one case, the chamber had shut down and cooled long enough to create a negative pressure (vacuum) before being re-started. The top surface of the aluminum bracket appeared to have gotten wet near sample S10, but likely dried with bias remaining applied to the samples, keeping them at operating temperature and therefore above temperatures required for condensation to occur. There were no signs of water damage. A total of about 65 hours of temperature/humidity and bias had been achieved during this exposure period.

Due to supply chain issues during the COVID-19 pandemic, the test had to be put on hold for 6 months before new heater parts were obtained and installed to correct the issue. Samples were kept at room temperature conditions during this time. A repeat gas sensitivity check (GS9.1) was performed afterwards (Figure 65). This confirmed function of all samples before the last temperature/humidity and bias exposure began. Results were similar to the original GS9.

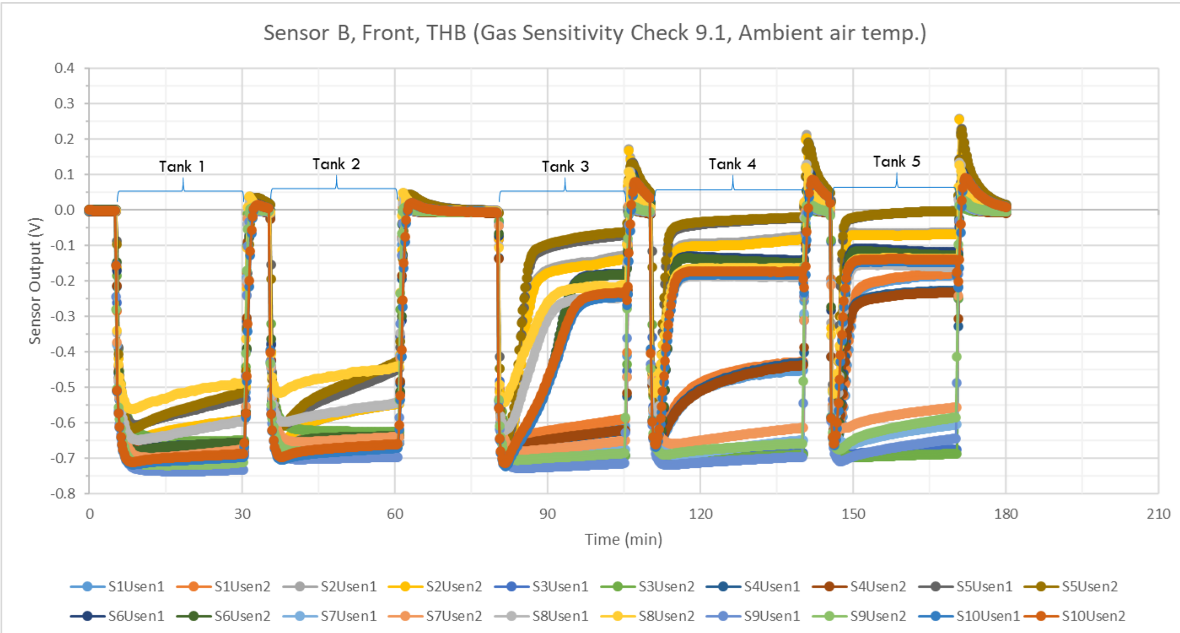


Figure 65: Sensor B THB - Front Half, Retest (GS9.1)

During GS10, after 8465 hrs exposure to temperature/humidity and bias, samples S2 and S5 continued to exhibit significantly degraded output (<100 mV absolute value) across 4 and all 5 target gas concentrations, respectively (Figure 66). In addition, samples S1 and S6 exhibited significantly degraded output (<100 mV absolute value) with Tank 5 target gas concentration. Sample S7-Usen1 channel only responded to the initial Tank 1 gas concentration. Sample S9-Usen1 channel had minimal response that was also noisy to the initial Tank 1 gas concentration, but recovered with the retest of Tank 1 afterwards.

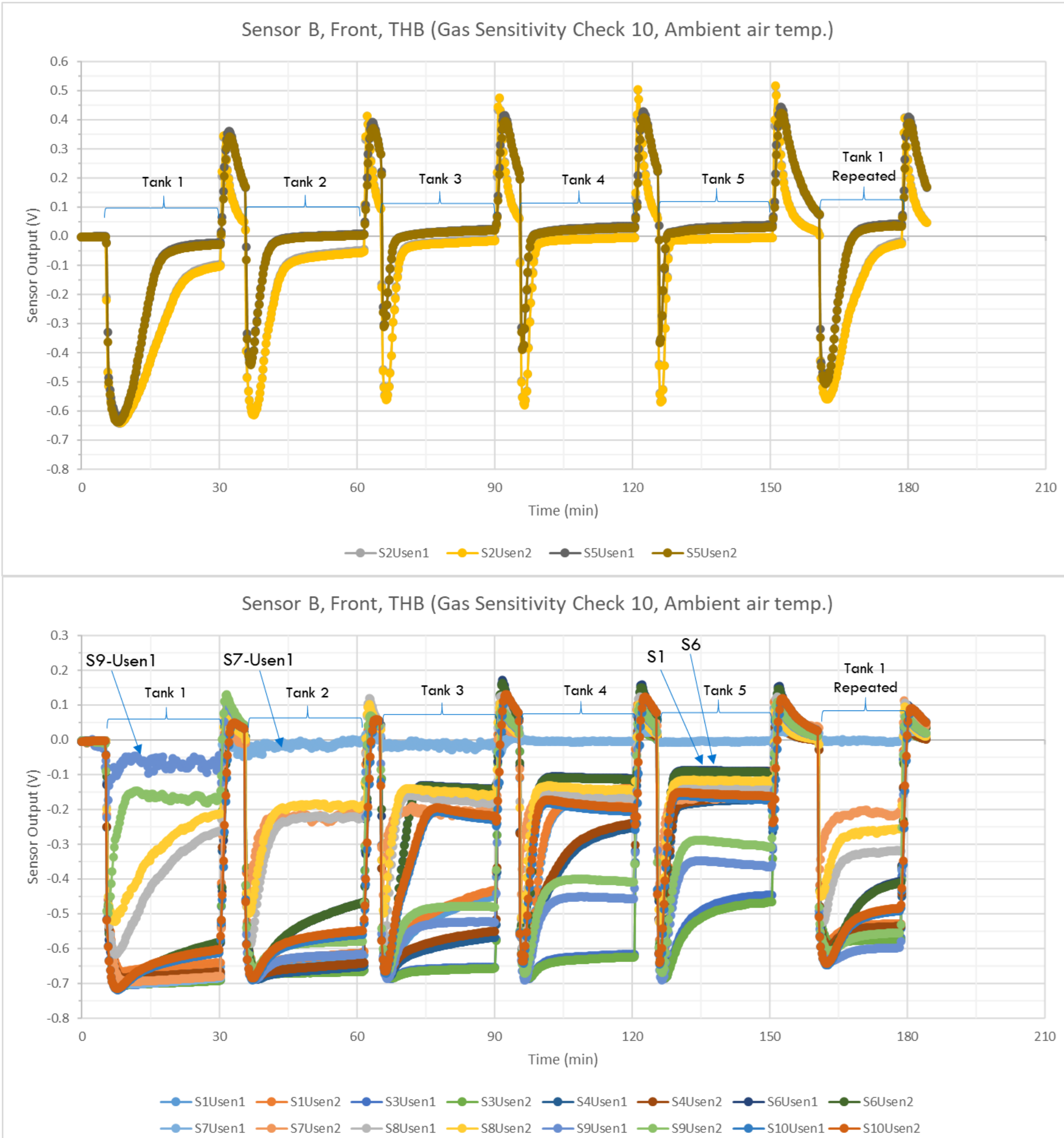


Figure 66: Sensor B THB - Front Half, Final Gas Sensitivity Check (GS10)

All 10 samples completed testing of 8465 hrs of temperature/humidity and bias, meeting the 8335 hrs required with zero hard failures in test.

A summary of the 4 qty. soft failures observed on both channels of each sample is shown in Table 18 below.

Table 18: Sensor B THB - Front Half, Soft Failure Summary

GS Check	Accumulated Temperature/humidity and Bias (hrs)	Soft Failure	Failure Mode
6	5040	S5	Significantly degraded response (<100 mV) after initial peak to about 600 mV (absolute value)
9	7560	S2	Significantly degraded response (<100 mV) after initial peak to about 600 mV (absolute value)
10	8465	S1	Significantly degraded response (<100 mV) after initial peak to about 650 mV (absolute value)
10	8465	S6	Significantly degraded response (<100 mV) after initial peak to about 650 mV (absolute value)

4.2.3 THB Results – Back Half of Sensor

A baseline gas sensitivity check (GS0) was performed with each of the five tanks (gas concentrations listed in Table 13). Steady response to gas exposure and return to zero signal output afterwards was observed across all 8 samples (Figure 67).

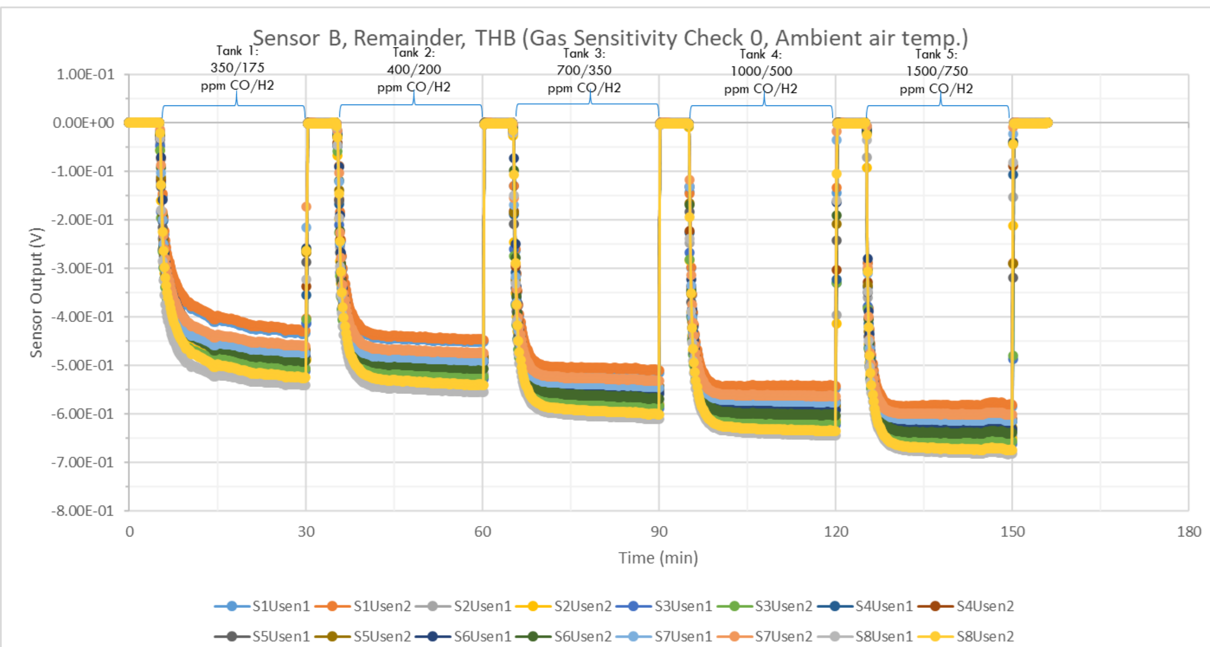


Figure 67: Sensor B THB - Back Half, Baseline Check (GS0) Signal Output

The power supply provided an AC voltage of about 10.3-10.4 V to the break-out board (resulting in about 8.5-8.7 V to each sample's heater element) during gas sensitivity checks and temperature/humidity exposure. Heater power was maintained between 2.8-3 W (within the approximate desired range), with a heater current of 0.33-0.35 A and an average heater resistance of 25-26 Ohm. APPENDIX D: Baseline Electrical Measurements shows the baseline power, current, and resistance measurements of the samples.

Temperature-humidity bias exposure between gas sensitivity checks was indicated by “heat/humidity”, followed by the sequential exposure number. Initial signal output response over the first 840 hrs, along with heater power, current, and resistance, are shown in APPENDIX D: Baseline Electrical Measurements.

All 8 samples completed testing of 4110 hrs of temperature/humidity and bias without any failures. Samples were tested beyond the 2534 hrs required with zero hard failures in test. The last gas sensitivity check (GS5) shows results similar to baseline, with some initial increase in sensor output at lower target gas concentrations (Figure 68).

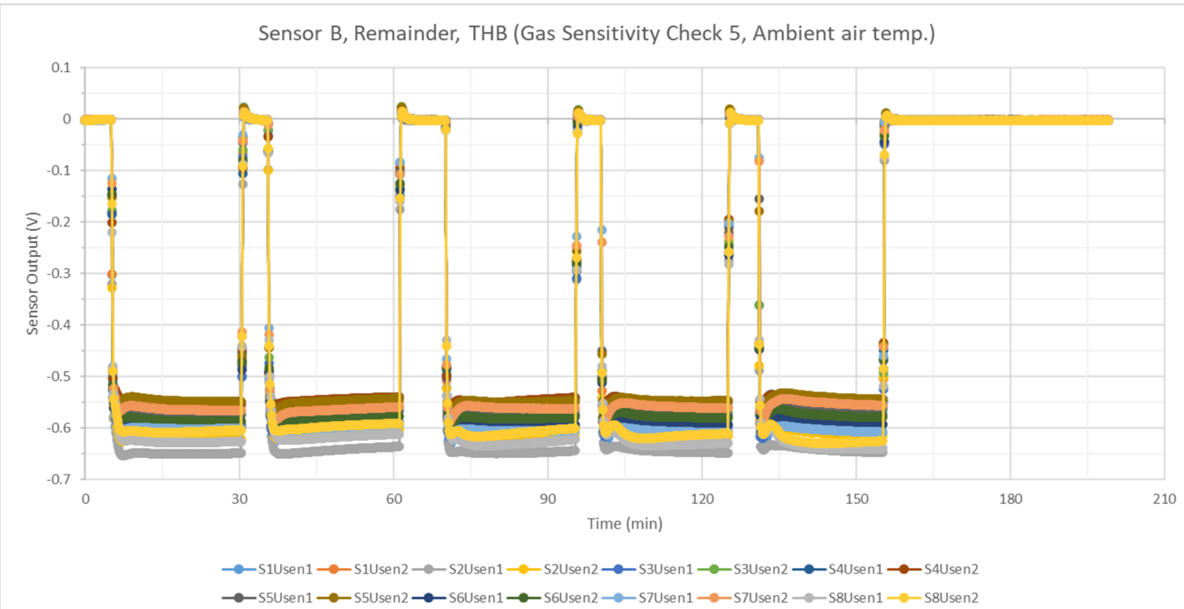


Figure 68: Sensor B THB - Back Half, Final Gas Sensitivity Check (GS5)

5 Failure Analysis

5.1 Sensor A, THB Failure Analysis

Sensor A is a proprietary design. To get a more detailed analysis on the 6 qty. hard failure modes observed in THB testing (fluctuated output, no output, and constant output), the samples listed in Table 19 below were sent to the manufacturer for evaluation. A seventh sample was sent for analysis of the offset drift soft failure mode.

Table 19: Sensor A THB, Samples for Failure Analysis

Sample	Failure	Failure Mode
S2	Hard	Fluctuated 2-4 V output
S4	Hard	Fluctuated 1.4-2.8 V output
S9	Hard	No response (no output)
S5	Hard	No response (0.5 V steady output)
S16	Hard	No response (2.1 V steady output)
S23	Hard	No response (0.8 V steady output)
S12	Soft	Offset drift from zero by > 1 V

At the time of this report, the samples were undergoing analysis by the manufacturer.

5.2 Sensor B, TC Failure Analysis

Sample S1 experienced a loss of power from the heater coil on the ceramic substrate. The back half of the sensor was removed from the front half, and the gold contact pads were measured with a digital multimeter (DMM) as open circuit.

The heater coil was examined and found to have an anomaly in the metal trace (Figure 69). After the coating over the trace on either side of the anomaly was removed, electrical characterization directly across this site confirmed the open failure. This was likely a defect in the manufacturing process that created a weak point in the heater coil trace. This weak point subsequently opened after 4215 thermal cycles, likely due to the thermo-mechanical fatigue stress imparted.

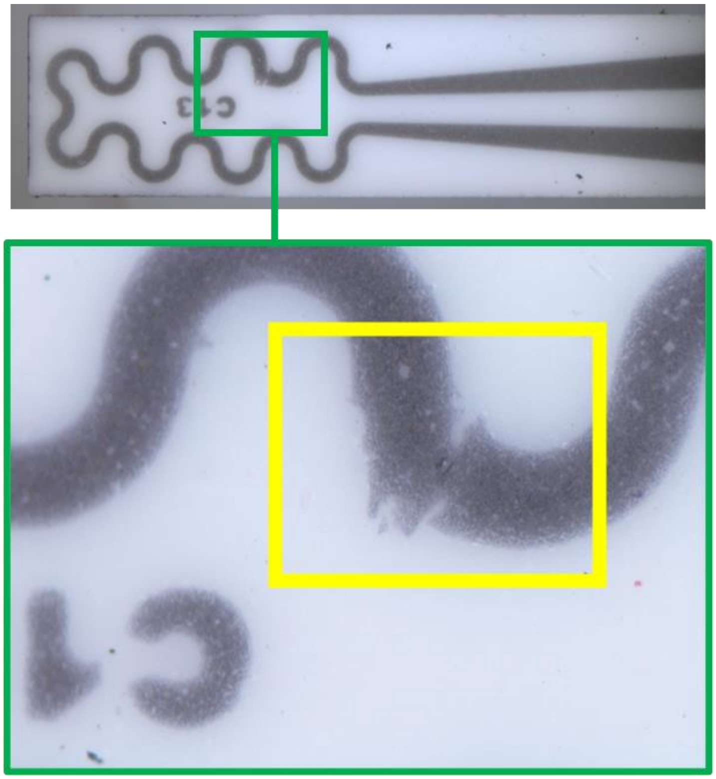


Figure 69: Sensor B TC, Sample S1 Heater Coil Defect

Sample S6 also experienced a loss of power from the heater coil on the ceramic substrate. The female Dsub50 connector at the break-out board from the samples was removed. With pins attached to the removed connector, a DMM measured open circuit on the sample S6 heater coil. After cutting the unit at the cable on the back half of the sensor, a DMM connected to the heater coil wires measured 25.8 Ohm. The back half of the sensor was removed from the front half, and the gold contact pads were measured with a DMM as expected: 9.5 Ohm at room temperature.

Spacing between the contacts on the back half of the sensor appeared to have similar gaps as a known untested sample (Figure 70).

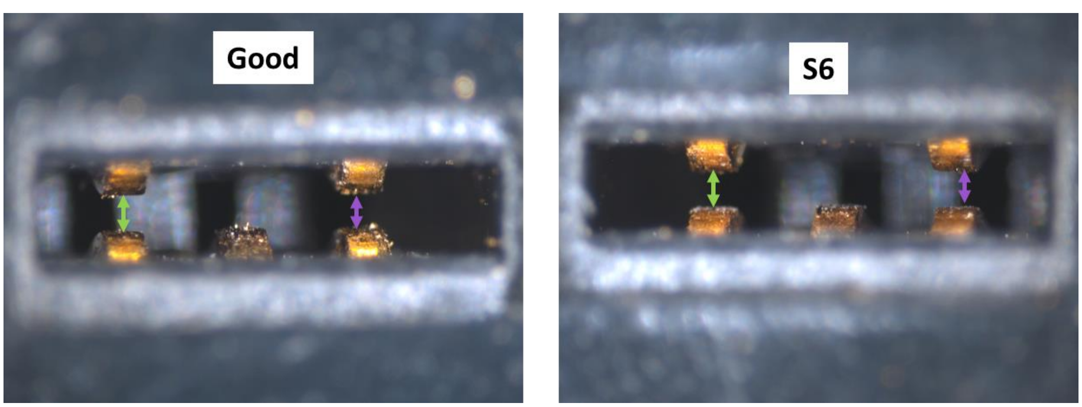


Figure 70: Sensor B TC, Sample S6 Contacts

The heater coil was also evaluated, and an anomaly was found on the trace (Figure 71). Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS) analysis, penetrating just beyond the glass coating surface, revealed a piece of Magnesium material (not seen elsewhere). It is not known if this anomaly had any effect on the failure mode observed.

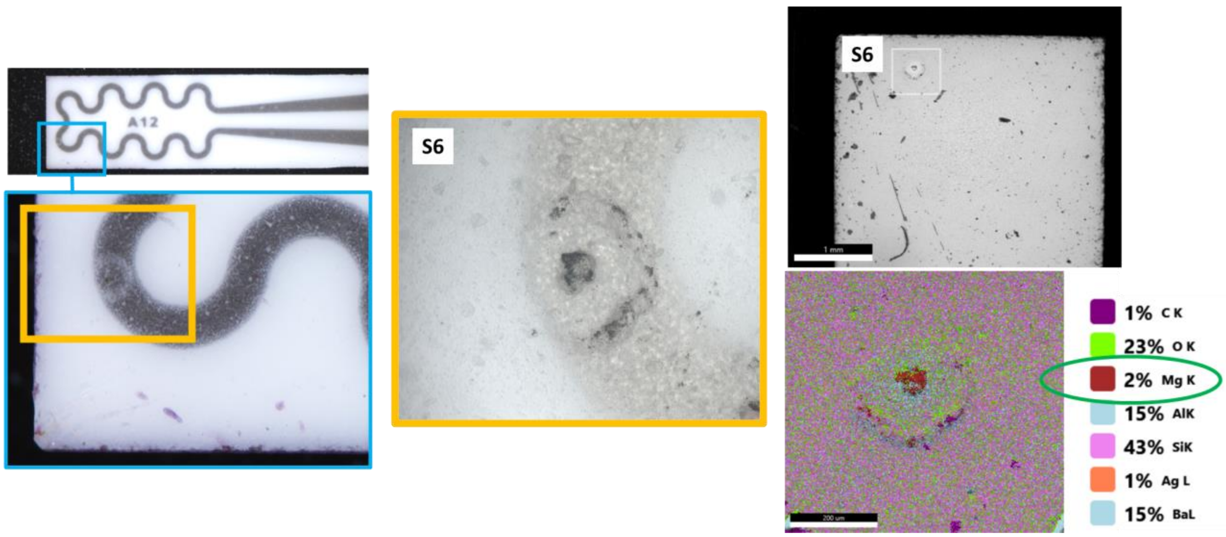


Figure 71: Sensor B TC, Sample S6 Heater Trace

It appears there was a connection issue somewhere between the break-out board and the heater coil on the ceramic substrate. However, failure analysis results are inconclusive as to the specific failure site or mechanism.

5.3 Sensor B, THB Front Half Failure Analysis

Sample S5 was the first sample to have significantly degraded signal output. In the analysis this was compared to sample S3, which had the least amount of degraded signal output (and only at the highest gas concentration). The electrodes on sample S5 had a brown tint to them and did not exhibit the white coating observed on sample S3 (Figure 72). The heater side for each did not exhibit a color difference.

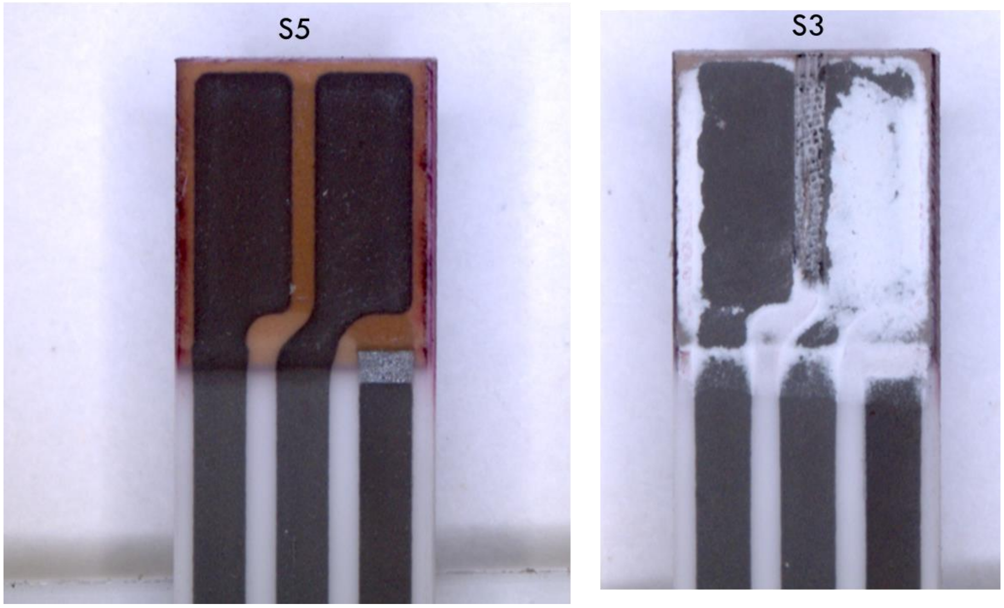
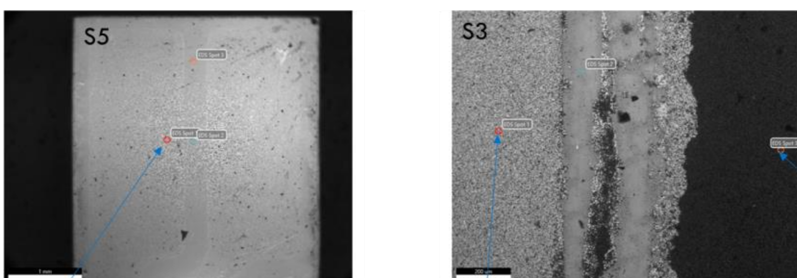


Figure 72: Sensor B THB Front Half, S5 Electrode Discoloration

SEM/EDS analysis was performed on the electrode surface. On a similar spot between sample S5 and sample S3, the elemental weight percentages are shown in Figure 73 below. Sample S5 had less platinum (Pt) than sample S3. It also did not have aluminum, which appears to be an aluminum oxide (white in color) found on sample S3.



S5 – Spot 1:

Element	Weight %
O K	17.5
Si K	5.8
Cu K	3.5
Ir M	8.0
Pt M	39.7
Au M	25.5

S3 – Spot 1:

Element	Weight %
O K	21.2
Al K	0.6
Si K	3.4
Ir M	6.5
Pt M	68.4

S3 – Spot 3:

Element	Weight %
O K	52.5
Al K	25.9
Si K	6.5
Br L	11.2
Zr L	3.9

Figure 73: Sensor B THB Front Half, SEM/EDS

The degradation in signal output correlates with increased gas concentrations and has been observed in previous THB testing with these types of sensors. Differences in the electrode elemental makeup could be a failure mechanism since it can cause a difference in the catalyst reaction with combustion gases, and therefore affect how the signal output is created. This failure mode was discussed with the manufacturer during previous testing, but unfortunately the specific failure mechanism for this phenomenon has not been confirmed.

6 Discussion

6.1 Sensor A

Sensor A samples underwent both thermal cycling and temperature/humidity with bias testing to accelerate life testing and demonstrate 10- to 20-year equivalent field life expectancy.

All 8 samples undergoing thermal cycling survived through 2292 thermal cycles without any hard failures. A 20-year equivalent field life expectancy is demonstrated per the test plan parameters (reference Table 4).

Accuracy and stability performance in both TC and THB testing exceeded the manufacturer’s published specification limits. However, the average is time-based and takes into account the response time of the sensor. Details on settling time, including expected variation on rise time, are not defined by the manufacturer. A consistent approach was used in test to serve as a comparison on overall signal output response over time. These deviations are only considered soft failures. Functionality with response to target gas concentrations was maintained.

In THB testing for 10-year equivalent life expectancy, the demonstration test requirement of up to 7957 hrs with 2 hard failures was not met. The test was run to a total of 7080 hrs exposure under temperature/humidity and bias. A total of 14 samples out of 48 sample in test were hard failures at that point, and the test was stopped early.

Table 20 summarizes the failures and suspensions in test. The “state” refers to whether the unit failed (in this case, whether the unit was a hard failure) or was suspended (did not meet the failure criteria and therefore survived). The time at which the unit was observed as failed is recorded as the “state end time”. The unit could have failed a gas sensitivity check somewhere in between the previous gas sensitivity check (inspection point) and the state end time, and so the last inspection point in cycles is recorded. This is known as interval data, since the exact point in time of failure is not known (but it is known to have occurred somewhere within the interval).

Table 20: Sensor A THB, Hard Failures and Suspensions (48 total samples)

Number of Units in State	Last Inspected (hrs)	State (Failed (F) or Suspended (S))	State End Time (hrs)
2	4200	F	5018
4	5018	F	5880
3	5880	F	6720
5	6720	F	7080
34	7080	S	7080

Analysis on the failures was performed using ReliaSoft Weibull++. The life data was evaluated using the following analysis settings:

- Analysis Method: Maximum Likelihood Estimation (MLE). This is good when heavy censoring is present (in this case, a relatively large number of suspensions). Unbiasing of parameters is utilized (uses a correction factor for the biased estimate of the Weibull beta parameter due to MLE sampling error for both censored and non-censored data).
- Rank Method: Median Ranks (MED)
- Confidence Bounds Method: Fisher Matrix

Figure 74 shows the plot of Unreliability (F(t)) in percent versus time (t) in hrs. Unreliability is equal to 1 – R(t), where R(t) is Reliability. For instance, 15% unreliability is equivalent to 85% reliability. The expected time in test for 85% reliability is the corresponding time where the probability line intersects with the 15% unreliability line. This value is determined to be 6184 hours in test. To determine the equivalent field life in hours, this value must be multiplied by the equivalent acceleration factor.

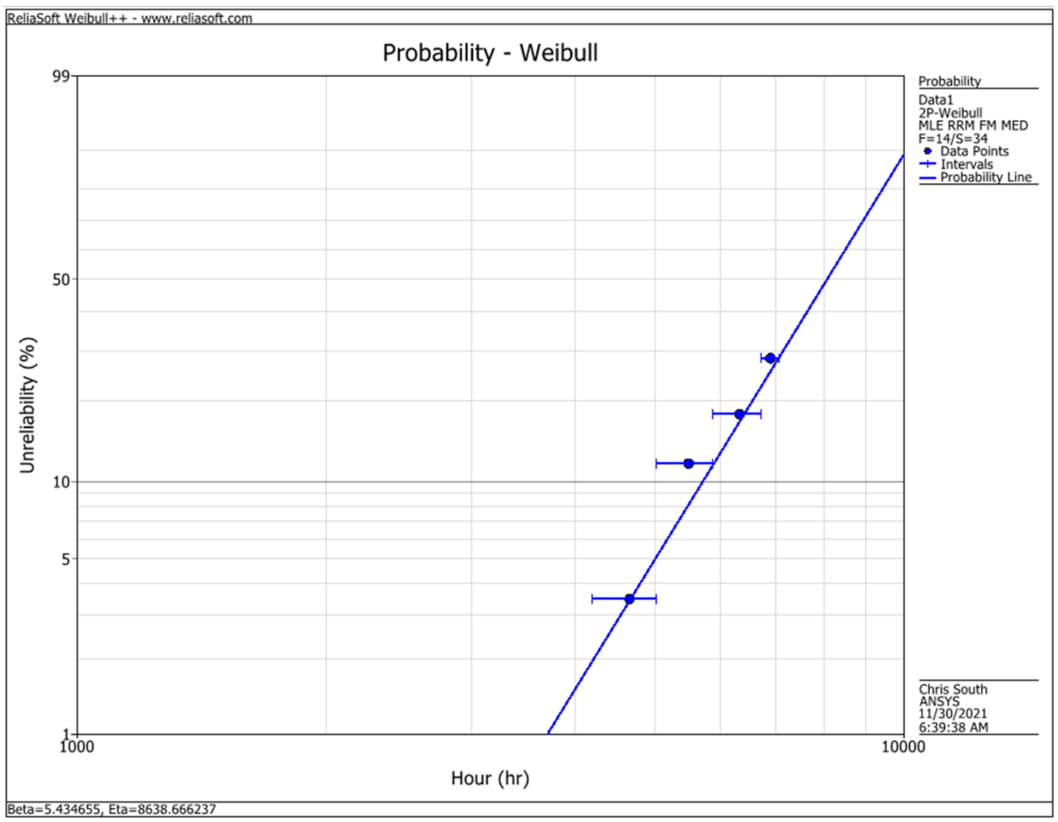


Figure 74: Sensor A THB, Weibull Probability Plot

The equivalent acceleration factor is equal to just the acceleration factor if the field stress and test stress are held constant. In this case, the field stress is comprised of both OFF-cycle and ON-cycle conditions. The test stress (consisting of exposure to 60°C and 95% RH) is held constant. The equivalent stress therefore needs to be calculated from the following equations [21]:

[21] Reliability Hot Wire, 144, Feb. 2013. https://www.weibull.com/hotwire/issue144/hottopics144.htm

$$AF_e = \frac{T_{field}}{T_t} \qquad (2)$$

where AF_e = Acceleration factor, equivalent
T_{field} = Time in field
T_t = Time in test, which can be made up of T_{t1}, T_{t2}, $T_{t3,}$ etc. for each set of test stress conditions

$$T_t = \frac{T_{field}}{AF_e} = \sum_i \left(\frac{P_i T_{field}}{AF_i}\right) = T_{field} \sum_i \left(\frac{P_i}{AF_i}\right)$$

$$T_{field} = \frac{T_t}{\sum_i \left(\frac{P_i}{AF_i}\right)} = \frac{T_{t1}}{\sum_i \left(\frac{P_i}{AF_i}\right)} + \frac{T_{t2}}{\sum_i \left(\frac{P_i}{AF_i}\right)} + \frac{T_{t2}}{\sum_i \left(\frac{P_i}{AF_i}\right)} + \ldots \qquad (3)$$

where P_i = Probability of time in field under the i^{th} field conditions
AF_i = Acceleration factor under the i^{th} field conditions

Table 21 shows the values used in the above equations and the calculated equivalent acceleration factor. Values for P_i are based on the assumed 10 min ON and 10 min OFF cycles of the furnace in the field.

Table 21: Sensor A THB, Calculated Equivalent AF

	i^{th} Field Conditions	
Values	**OFF-cycle**	**ON-cycle**
Inputs:		
P_i	0.5	0.5
AF_i for T_{t1}	10.69	2.70
T_{t1}	7080 hrs	
Results:		
T_{field}	30,523 hrs	
AF_e	4.31	

The equivalent field life at 85% reliability is then the reliability in test (from the Weibull++ analysis) multiplied by the equivalent acceleration factor (AF_e). This is converted to years in the field based on the heating season of 4160 hours per year.

$$Equivalent\ Field\ Life = \frac{(6184\ hrs)(4.31)}{4160\ hrs/yr} = \frac{26{,}653\ hrs}{4160\ hrs/yr} = 6.4\ yrs$$

The two-sided confidence level of 80% can be applied to determine the upper and lower bounds of the equivalent field life. Weibull++ is used to determine the times in test that encompass 80% of units expected to survive with 85% reliability (Figure 75). The equivalent acceleration factor and heating season hours are then used to calculate the upper (90%) and lower (10%) bounds of equivalent field life.

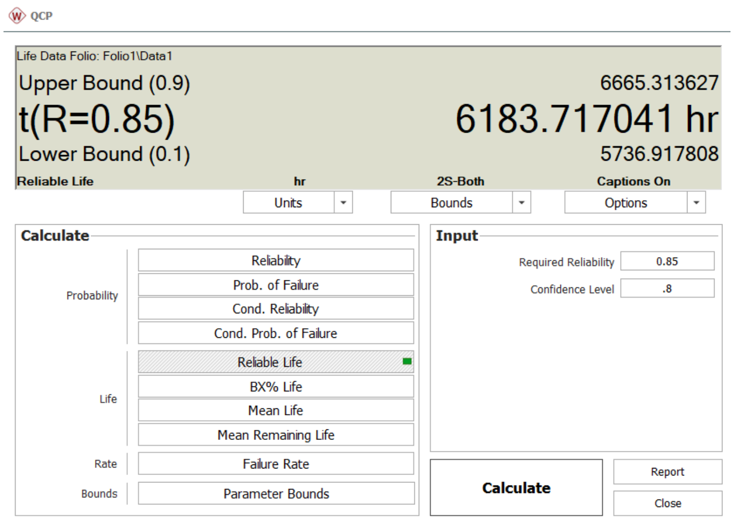


Figure 75: Sensor A THB, Confidence Level Results

Table 22 summarizes the expected field life results for THB-induced failure mechanisms.

Table 22: Sensor A THB, Expected Field Reliability Summary

		Expected Field Life Equivalent
Reliability of 85%		6.4 years
w/ Confidence Level of 80%	Upper Bound (90%)	6.9 years
	Lower Bound (10%)	5.9 years

Sensor A is expected to have a lower life prediction under THB-induced failure mechanisms compared to thermo-mechanical failure mechanisms. The predominant failure mechanism is likely humidity-based given the relatively benign temperatures experienced in the vent pipe application compared to humidity levels expected to have been encountered in the vent pipe. Based on this, the conservative approach was to take the 6.4-year expected field life from THB testing as the overall life prediction. The 85% reliability result of 6.4 years falls short of the 10-year goal by 3.6 years.

6.2 Sensor B

Sensor B samples underwent both thermal cycling and temperature/humidity with bias testing to accelerate life testing and demonstrate 10- to 15-year equivalent field life expectancy.

Six (6) of eight (8) samples undergoing thermal cycling survived through 12,113 thermal cycles (via power cycling) without hard failures. A 15-year equivalent field life expectancy is demonstrated per the test plan parameters (reference Table 5) given 2 hard failures.

All 10 samples undergoing THB testing on the front half of the sensor survived through 8465 hrs exposure under temperature/humidity and bias without hard failures. There were 4 samples that exhibited soft failure, in which signal output degraded significantly (<100 mV) with one or more of the target gas concentrations. However, these four samples still responded to all target gas concentrations, even if for only a few minutes or less. A 10-year equivalent field life expectancy is demonstrated per the test plan parameters (reference Table 11). The peak response before attenuating to a lower output would have to be resolved if a time-weighted average algorithm were to be used reliably and not indicate a false negative.

All 8 samples undergoing THB testing on the back half of the sensor survived through 4110 hrs of temperature/humidity and bias without any failures. Samples were tested beyond the 2534 hrs required with zero hard failures in test, demonstrating beyond a 10-year equivalent field life expectancy per the test plan parameters (reference Table 12).

Sensor B was limited to a 10-year equivalent field life demonstration for THB-induced failure mechanisms due to the test time and sample size constraints in test. This was less than the 15-year equivalent field life demonstrated for thermo-mechanical-induced failure mechanisms. The predominant failure mechanism appears to be from thermal cycling given the application and failures observed in test. However, without additional testing under THB, the conservative approach was to take the 10-year expected field life as a minimum overall life prediction for the given reliability metrics.

APPENDIX A: Sensor A TC and THB schematic

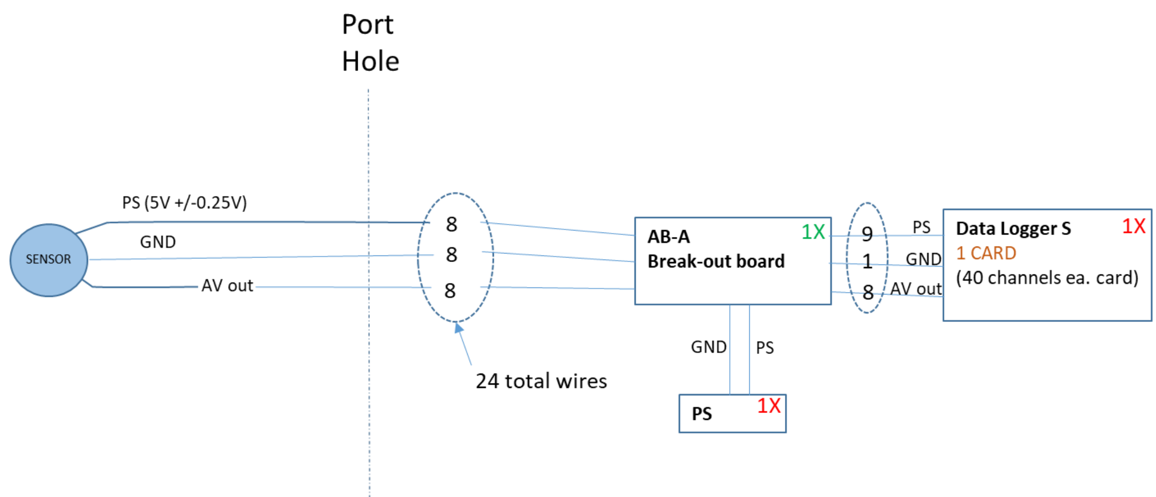


Figure 76: Sensor A TC Schematic

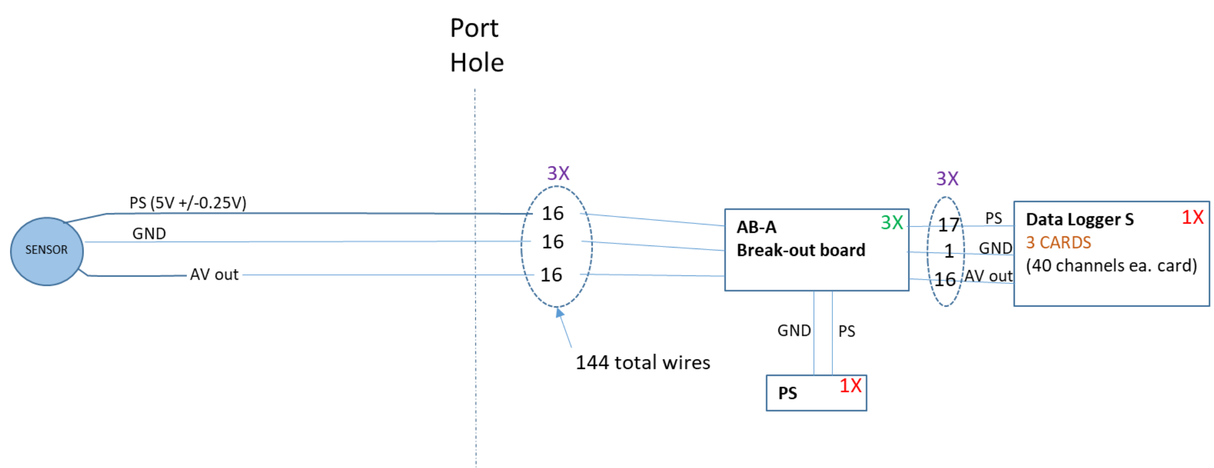


Figure 77: Sensor A THB Schematic

APPENDIX B: Sensor B TC and THB schematic

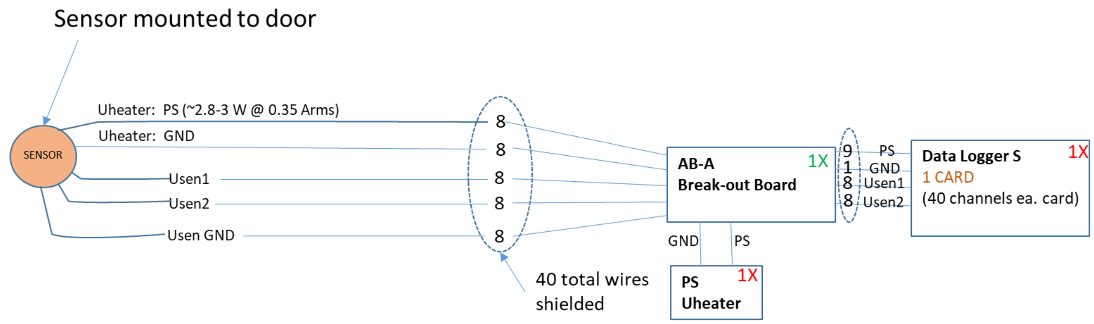


Figure 78: Sensor B TC Schematic

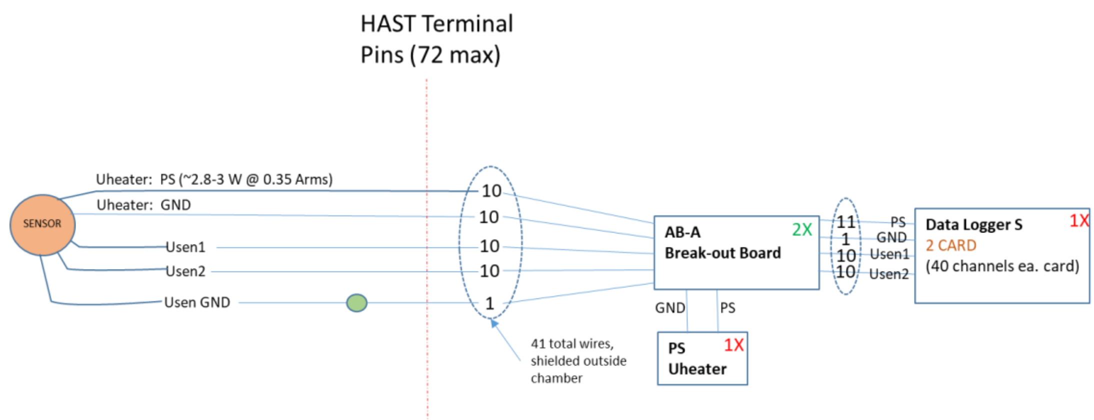


Figure 79: Sensor B THB Front Half Schematic

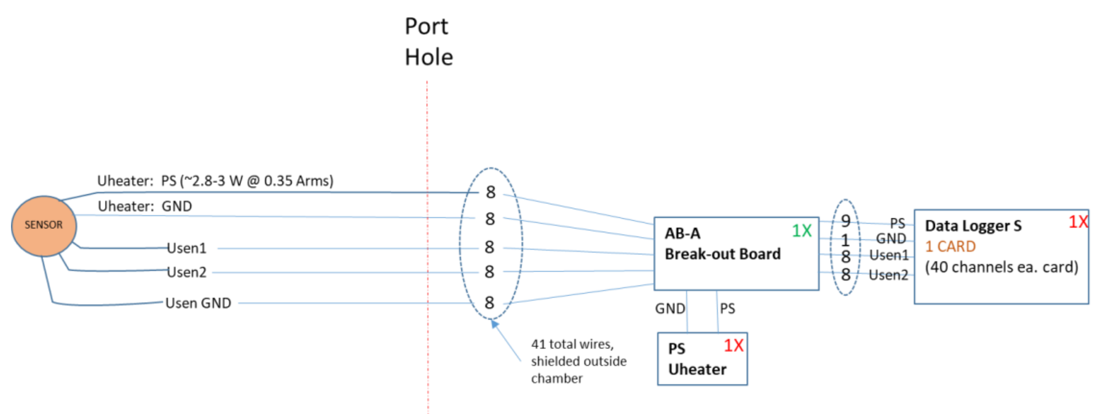


Figure 80: Sensor B THB Remainder Schematic

APPENDIX C: Major Equipment List

Equipment Description	Asset Number	Calibration Date	Calibration Due
Keysight 34970A Datalogger	1515	1/21/2020	1/31/2022
BK Precision 1788, 0-32V/0-6A	1564	n/a	n/a
Sun Chamber EC10	1368	n/a	n/a
HP 34970A Datalogger	1561	3/5/2019	3/31/2021
BK Precision 1788, 0-32V/0-6A	1564	n/a	n/a
ESPEC EPX-2H, Humidity Chamber	1488	1/25/2019	1/25/2021
HP 34970A Datalogger	1474	3/5/2019	3/31/2021
Keysight AC6802A, AC Power Supply	1699	n/a	n/a
Digital Multimeter (DMM)	1510	3/5/2019	3/31/2021
HP 34970A Datalogger	1299	11/7/2019	11/30/2021
Behlman Oscillator ACM Series, AC Power Supply	1570	n/a	n/a
ESPEC EHS-221M, HAST System	1560	2/21/2019	2/21/2021
HP 34970A Datalogger	1175	1/21/2020	1/31/2022
Behlman Power Passport, AC Power Supply	1361	n/a	n/a
ESPEC EPL-3H, Humidity Chamber	1507	3/25/2019	3/25/2021
Keysight 34465A 6.5 Digit DMM	1567	3/5/2019	3/31/2021

APPENDIX D: Baseline Electrical Measurements

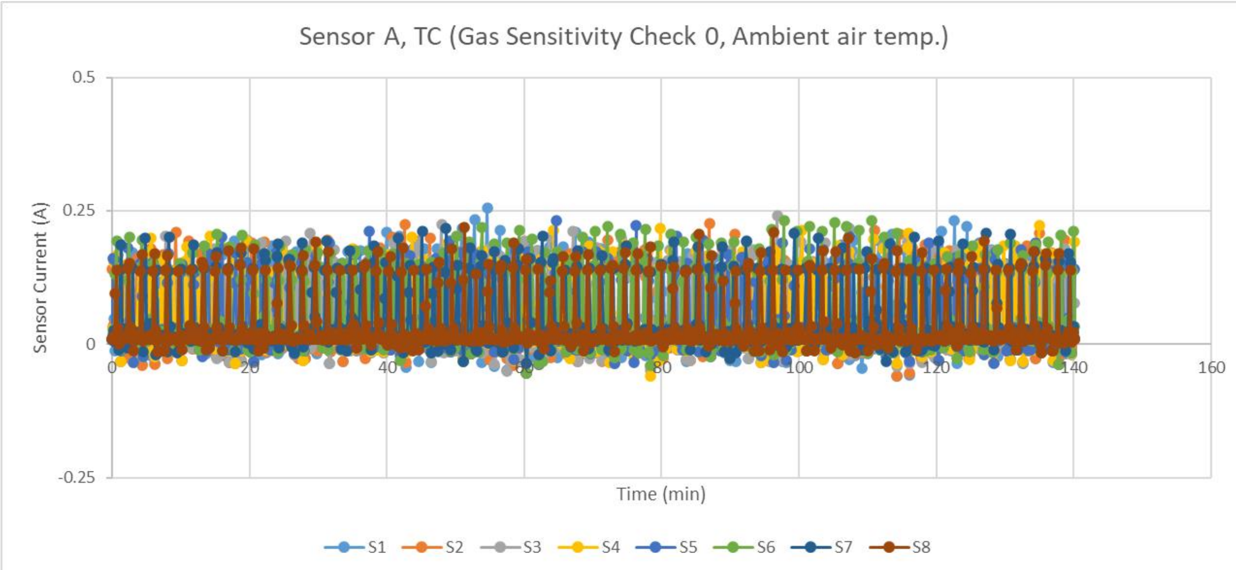


Figure 81: Sensor A TC, Baseline Check (GS0) of Current

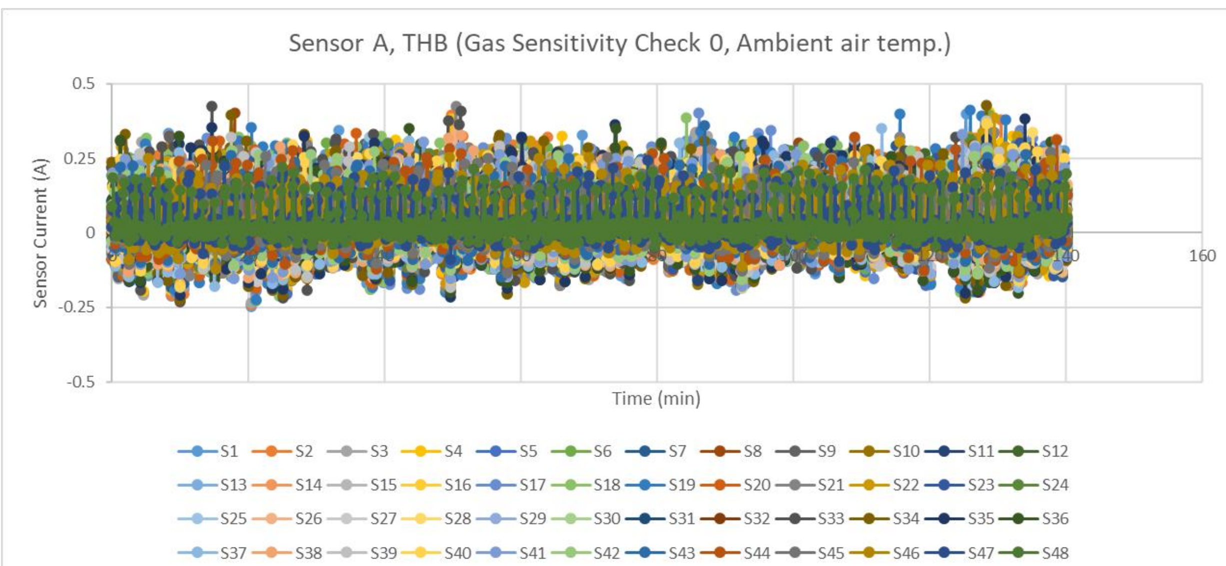


Figure 82: Sensor A THB, Baseline Check (GS0) of Current

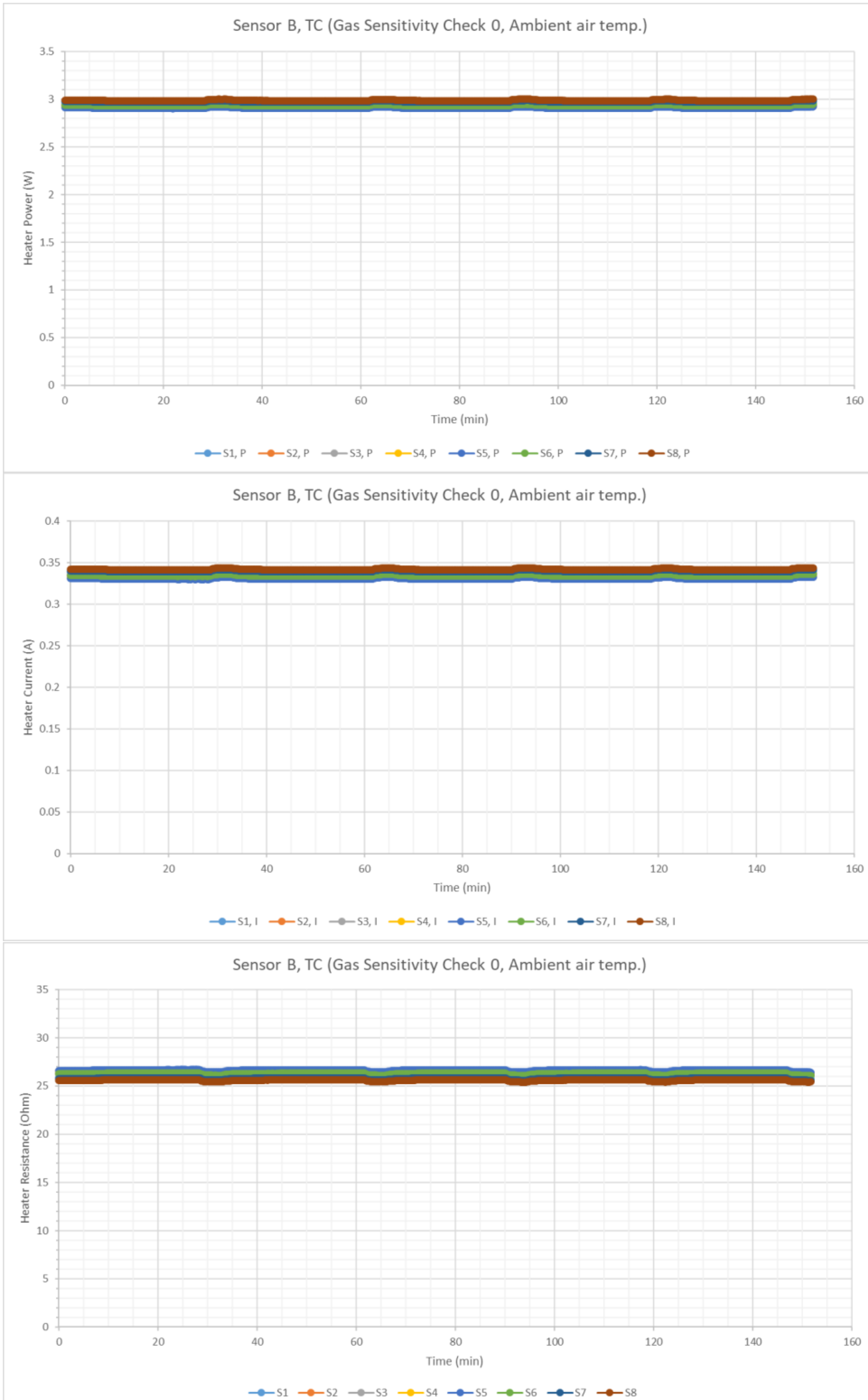


Figure 83: Sensor B TC, Baseline (GS0) Power/Current/Resistance across Heater

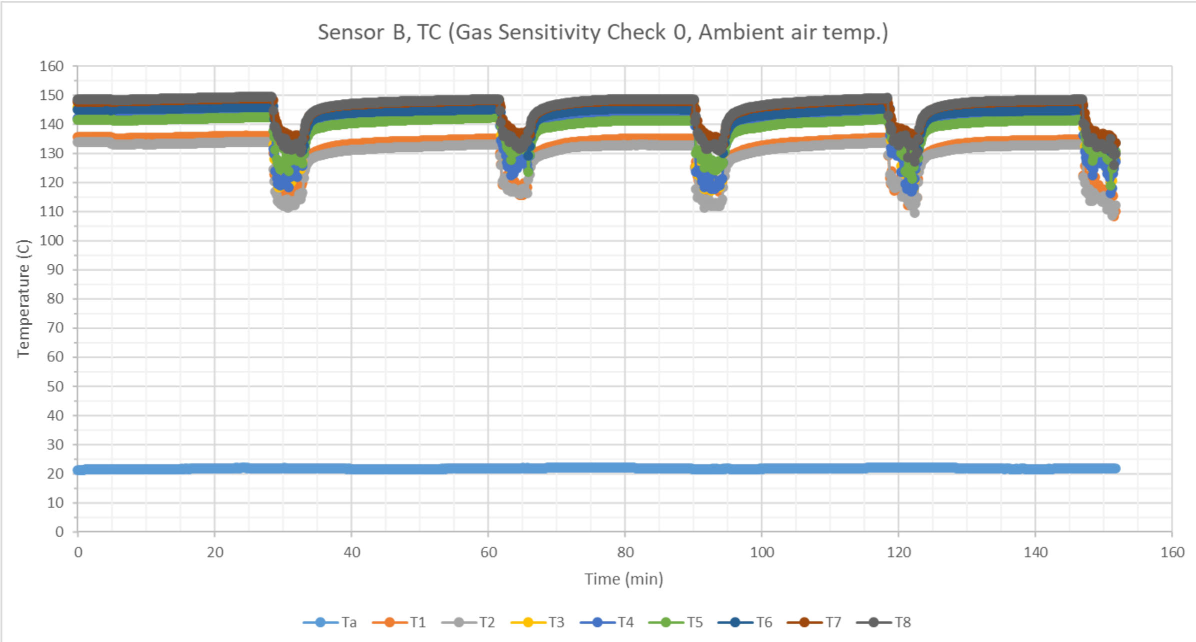


Figure 84: Sensor B TC, Baseline (GS0) Thermocouple Measurements

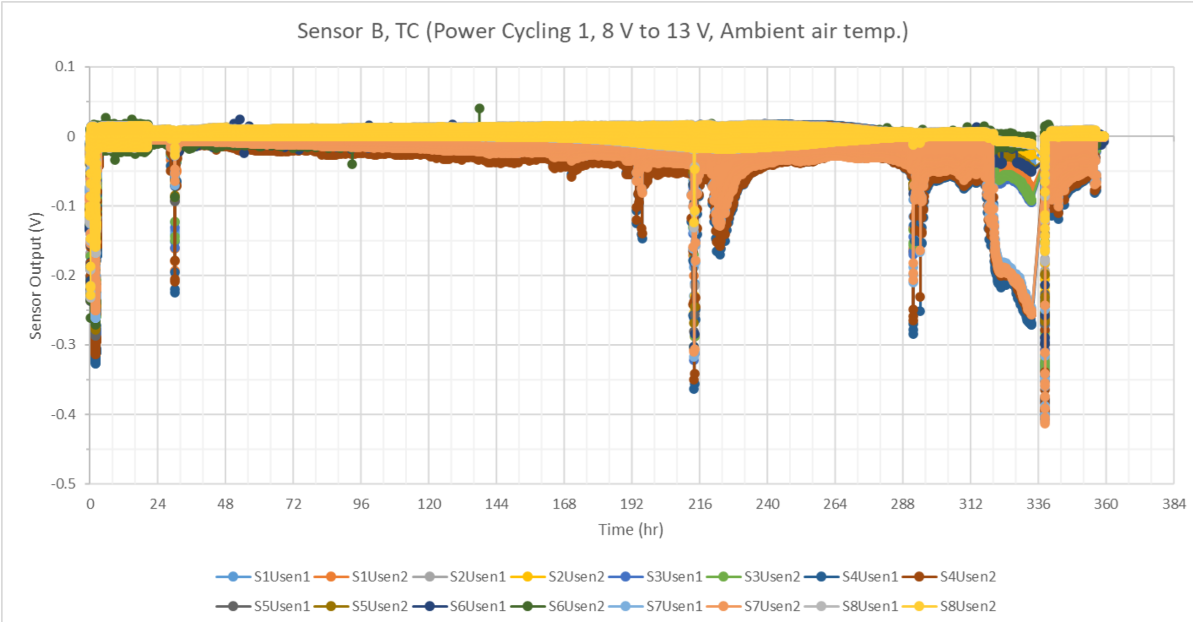


Figure 85: Sensor B TC, Baseline Signal Output during Initial Power Cycling (PC1)

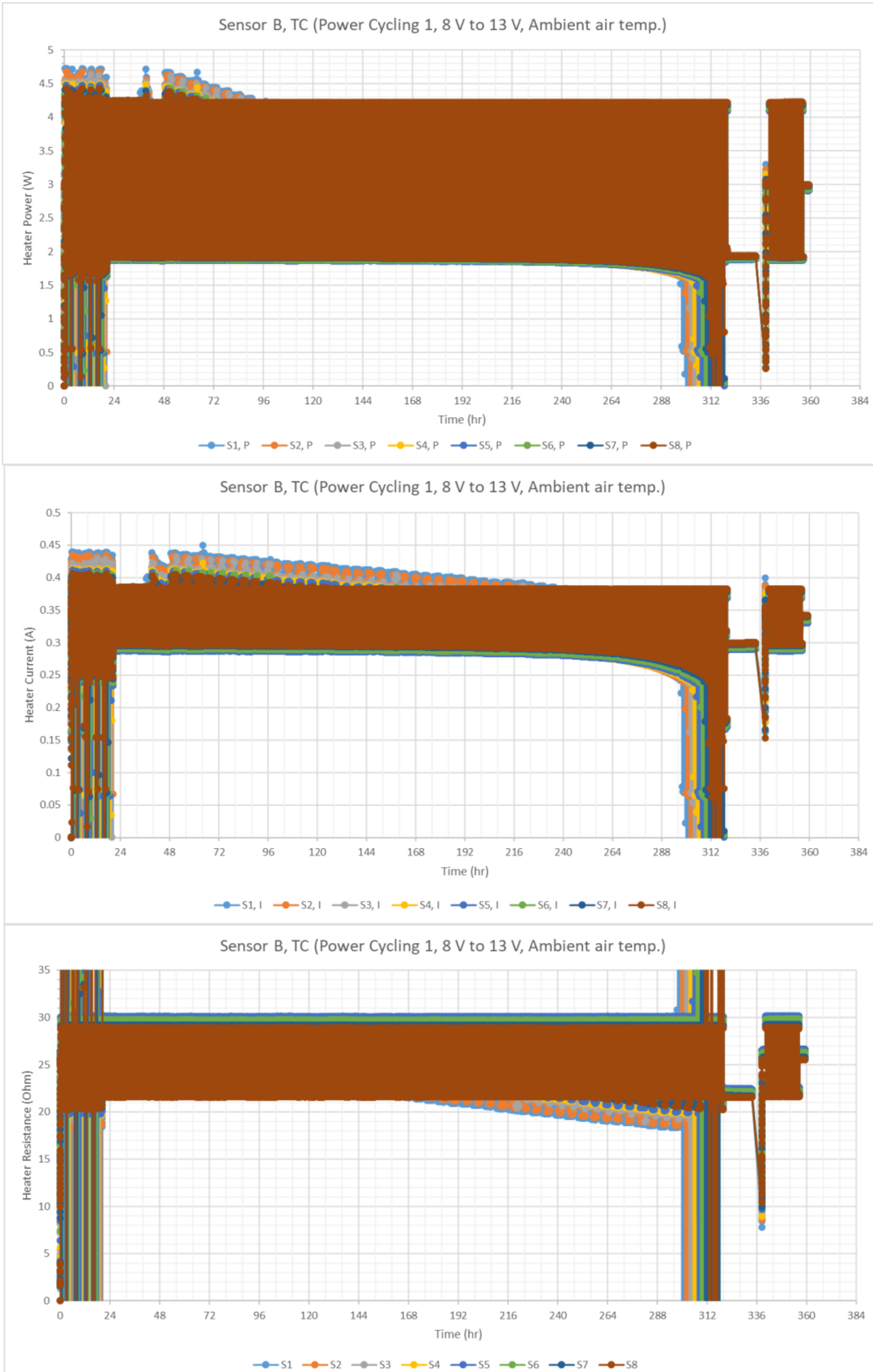


Figure 86: Sensor B TC, Baseline Power/Current/Resistance across Heater during Initial Power Cycling (PC1)

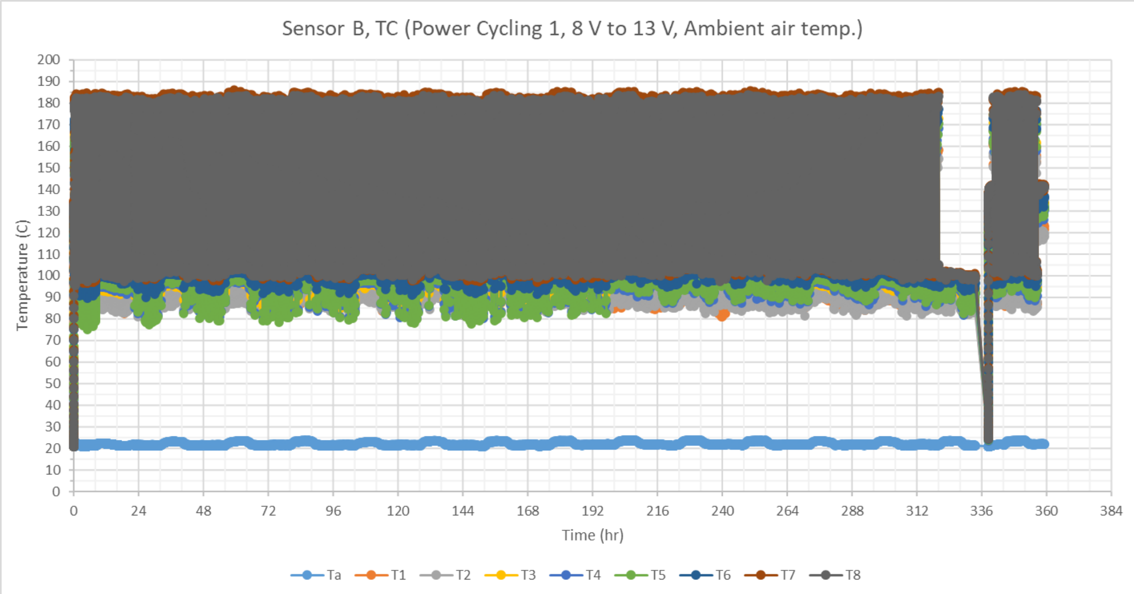


Figure 87: Sensor B TC, Baseline Thermocouple Measurements during Initial Power Cycling (PC1)

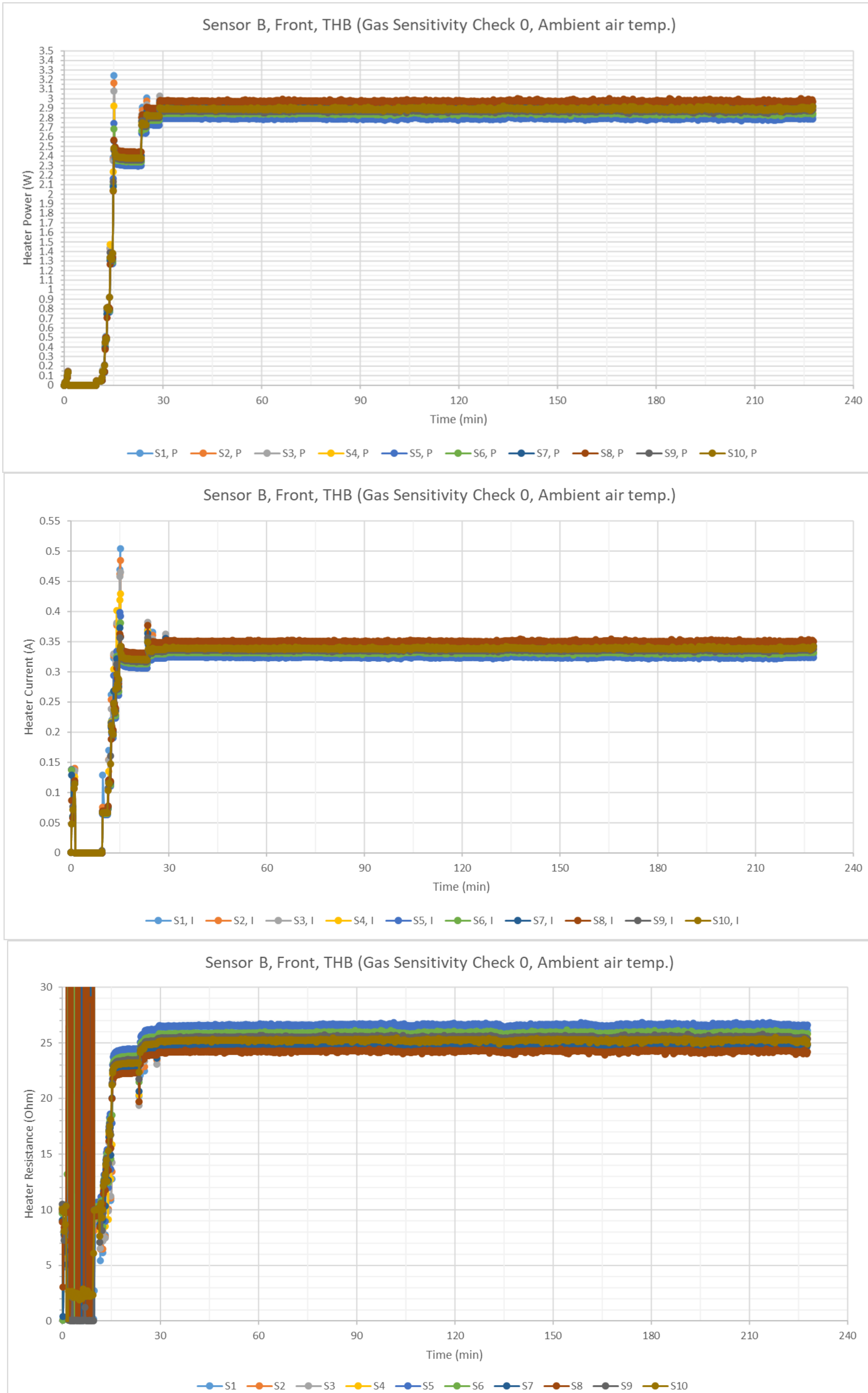


Figure 88: Sensor B THB – Front Half, Baseline (GS0) Power/Current/Resistance across Heater

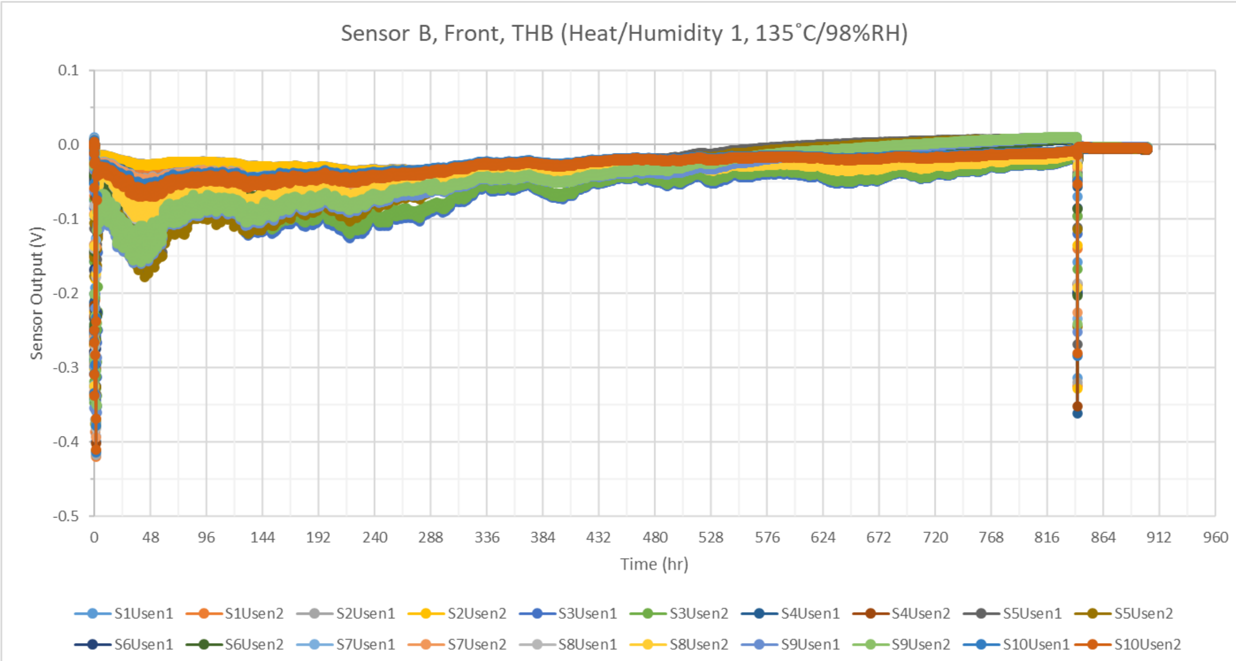


Figure 89: Sensor B THB – Front Half, Baseline Signal Output during Initial Heat/Humidity (HH1)

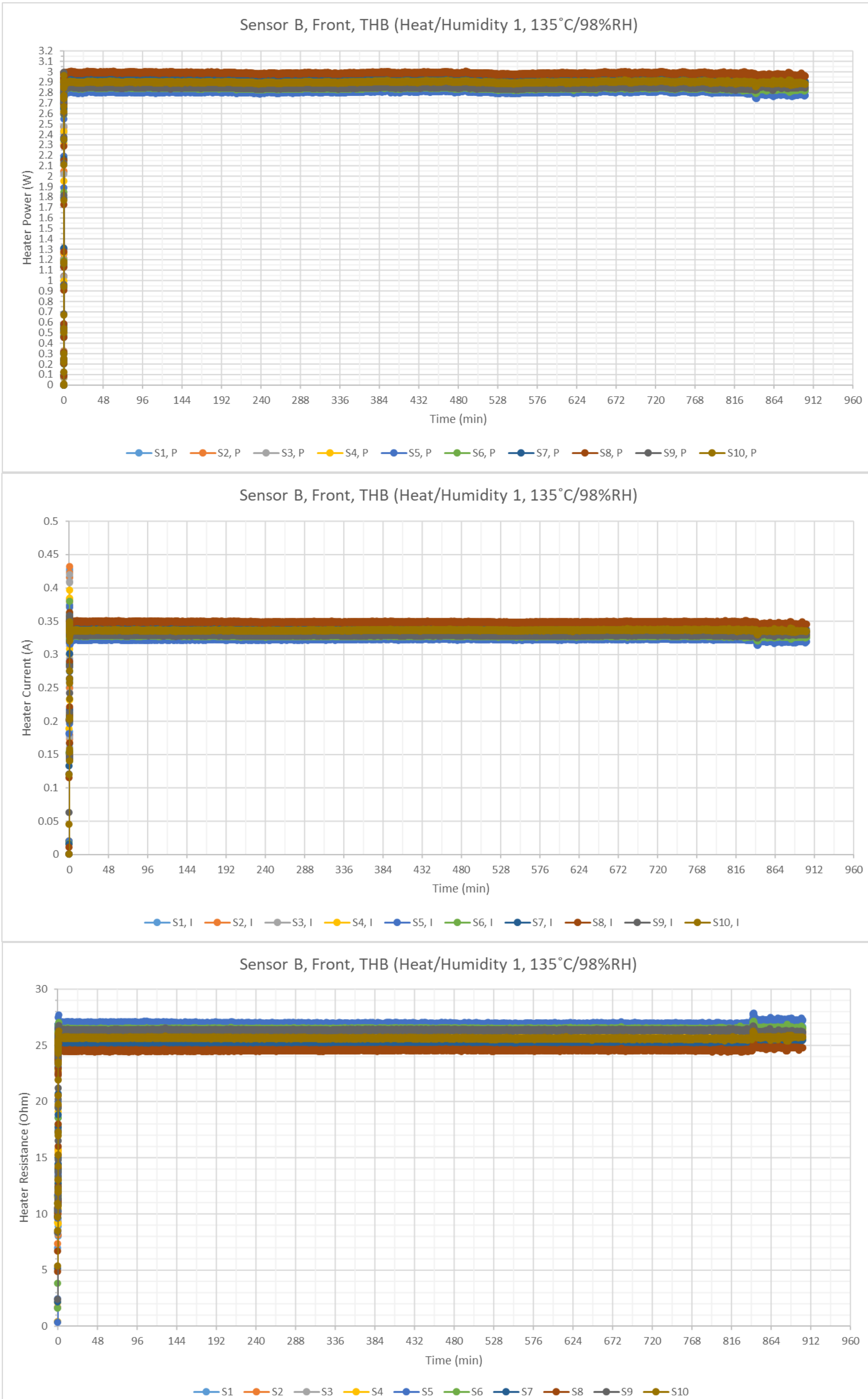


Figure 90: Sensor B THB – Front Half, Baseline Power/Current/Resistance across Heater during Initial Heat/Humidity (HH1)

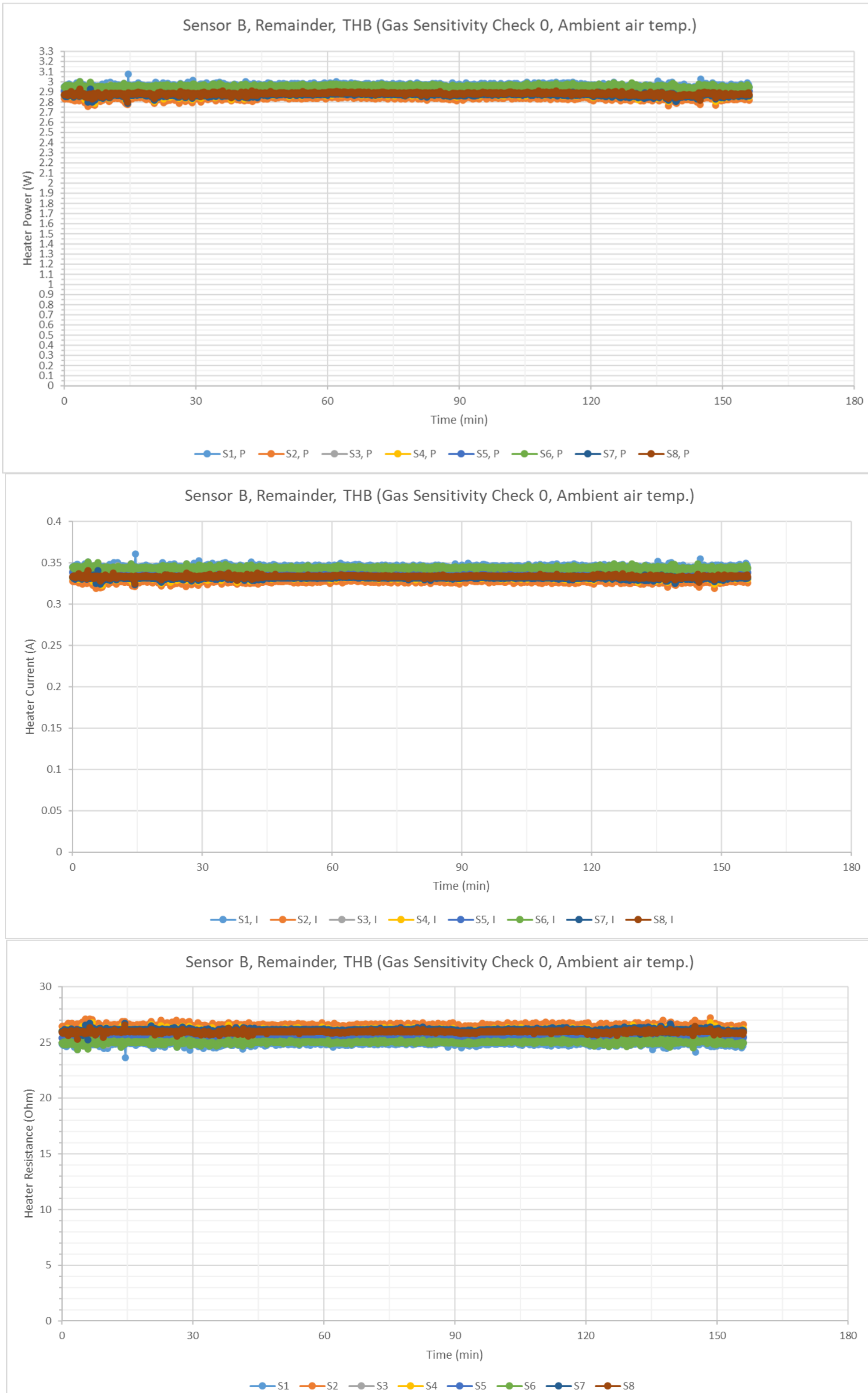


Figure 91: Sensor B THB – Back Half, Baseline (GS0) Power/Current/Resistance across Heater

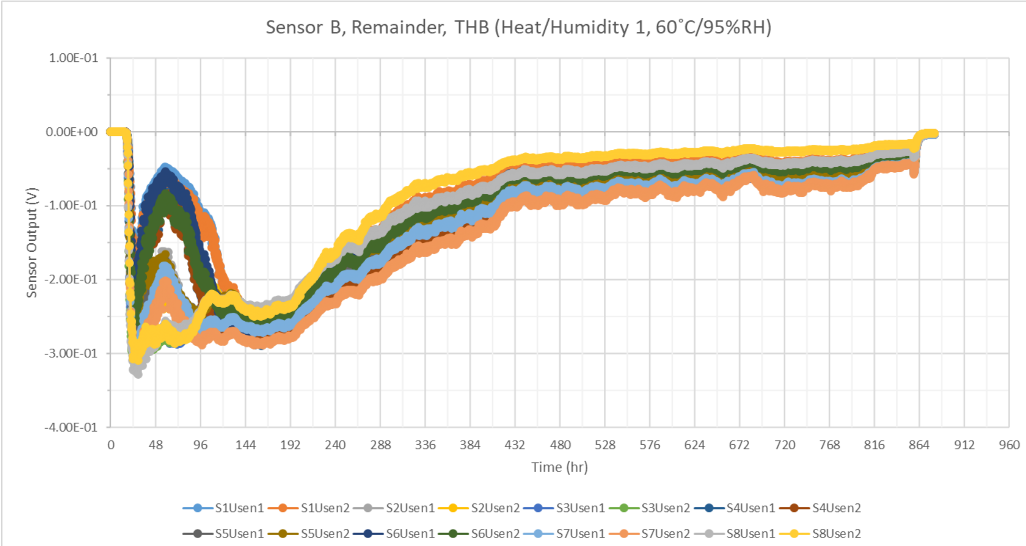


Figure 92: Sensor B THB – Back Half, Baseline Signal Output during Initial Heat/Humidity (HH1)

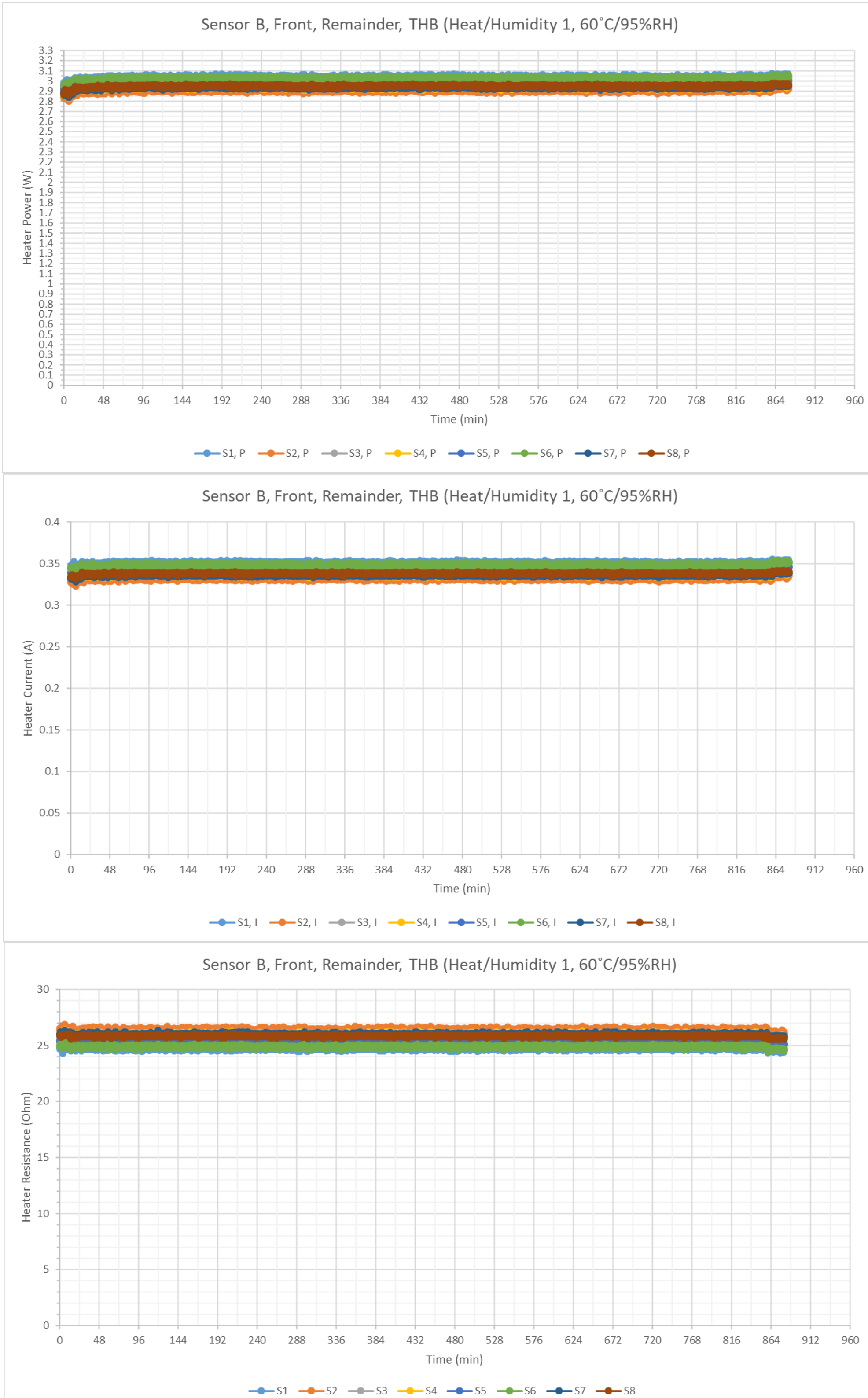


Figure 93: Sensor B THB – Back Half, Baseline Power/Current/Resistance across Heater during Initial Heat/Humidity (HH1)

APPENDIX E: Signal Output Response Change

Table 23: Sensor A TC, Signal Output Response and Delta

GS0 (Baseline)

Sample	Air	T1	T2	T3	T4	T5
S1	0.011	2.340	2.728	2.895	3.166	3.207
S2	0.057	2.415	2.725	2.865	3.092	3.166
S3	0.057	2.345	2.669	2.793	3.026	3.125
S4	0.067	2.295	2.606	2.748	2.967	3.091
S5	0.022	3.690	3.629	3.629	3.663	3.746
S6	0.008	2.246	2.382	2.581	2.767	3.017
S7	0.130	2.752	2.895	3.088	3.199	3.310
S8	0.008	2.734	2.859	3.017	3.134	3.272

GS12 (Final)

Sample	Air	T1	T2	T3	T4	T5
S1	0.009	1.353	1.600	1.912	2.202	2.395
S2	0.010	1.910	2.127	2.379	2.682	2.814
S3	0.037	2.438	2.652	2.819	3.080	3.190
S4	0.436	3.354	3.416	3.457	3.558	3.547
S5	0.013	3.778	3.714	3.850	3.806	3.858
S6	0.019	2.490	2.648	2.938	3.093	3.298
S7	0.072	2.746	2.883	3.194	3.287	3.413
S8	0.013	2.966	3.093	3.289	3.338	3.440

Delta (%)

Sample	Air	T1	T2	T3	T4	T5
S1	20%	73%	71%	51%	44%	34%
S2	478%	26%	28%	20%	15%	13%
S3	54%	-4%	1%	-1%	-2%	-2%
S4	-85%	-32%	-24%	-21%	-17%	-13%
S5	68%	-2%	-2%	-6%	-4%	-3%
S6	-58%	-10%	-10%	-12%	-11%	-9%
S7	82%	0%	0%	-3%	-3%	-3%
S8	-38%	-8%	-8%	-8%	-6%	-5%

Table 24: Sensor A THB, Signal Output Response and Delta

GS0 (Baseline)

Sample	Air	T1	T2	T3	T4	T5
S1	0.068	2.567	2.799	3.011	3.229	3.303
S2	0.035	2.660	2.911	3.095	3.293	3.336
S3	0.140	2.797	3.080	3.246	3.418	3.421
S4	0.006	2.241	2.598	2.840	3.139	3.248
S5	0.019	2.444	2.628	2.923	3.028	3.314
S6	0.172	2.888	3.038	3.328	3.341	3.482
S7	0.009	2.358	2.581	2.902	3.024	3.304
S8	0.039	2.477	2.677	3.011	3.139	3.334
S9	0.005	2.186	2.485	2.647	2.901	3.022
S10	0.130	2.674	2.989	3.161	3.358	3.383
S11	0.009	2.472	2.756	2.923	3.165	3.240
S12	0.187	2.929	3.247	3.312	3.467	3.441
S13	0.008	2.366	2.539	2.840	2.983	3.267
S14	0.009	2.198	2.405	2.692	2.816	3.103
S15	0.079	2.530	2.716	3.014	3.115	3.347
S16	0.010	2.506	2.674	2.979	3.070	3.298
S17	0.042	2.373	2.637	2.828	3.059	3.214
S18	0.014	2.476	2.767	2.961	3.200	3.298
S19	0.040	2.260	2.506	2.745	2.953	3.189
S20	0.174	3.077	3.358	3.353	3.541	3.453
S21	0.010	2.377	2.594	2.856	2.980	3.257
S22	0.007	2.166	2.386	2.602	2.720	2.957
S23	0.008	2.579	3.251	3.372	3.485	3.530
S24	0.010	2.150	2.580	2.924	3.229	3.451
S25	0.032	2.191	2.443	2.670	2.881	3.097
S26	0.033	2.378	2.679	2.805	3.078	3.196
S27	0.036	2.472	2.776	2.950	3.213	3.280
S28	0.023	2.263	2.561	2.720	2.985	3.138
S29	0.052	2.555	2.720	3.023	3.103	3.357
S30	0.186	3.004	3.181	3.430	3.423	3.559
S31	0.008	2.367	2.549	2.878	2.951	3.257
S32	0.017	2.318	2.515	2.814	2.898	3.188
S33	0.008	2.429	2.718	2.843	3.098	3.226
S34	0.061	2.539	2.794	2.953	3.198	3.286
S35	0.032	2.609	2.912	3.052	3.309	3.323
S36	0.055	2.406	2.701	2.870	3.119	3.250
S37	0.149	2.780	2.980	3.217	3.301	3.416
S38	0.012	2.420	2.597	2.878	2.989	3.266
S39	0.009	2.456	2.580	2.846	2.905	3.172
S40	0.024	2.510	2.686	2.962	3.053	3.318
S41	0.150	2.799	3.091	3.257	3.437	3.428
S42	0.045	2.477	2.749	2.900	3.168	3.260
S43	0.020	2.378	2.689	2.884	3.174	3.264
S44	0.039	2.526	2.771	2.945	3.213	3.320
S45	0.007	2.374	2.545	2.785	2.904	3.135
S46	0.005	2.155	2.352	2.616	2.727	2.973
S47	0.036	2.547	2.778	3.097	3.234	3.407
S48	0.011	2.426	2.590	2.861	2.932	3.189

GS9 (Final)

Sample	Air	T1	T2	T3	T4	T5
S1	0.581	3.419	3.514	3.454	3.684	3.374
S2	0.039	0.293	0.294	0.297	0.315	0.297
S3	0.551	3.454	3.566	3.480	3.703	3.396
S4	2.329	2.370	2.408	2.325	2.386	2.325
S5	0.252	0.256	0.254	0.285	0.282	0.275
S6	1.103	3.668	3.426	3.839	3.546	3.713
S7	0.009	2.123	2.042	2.759	2.608	2.963
S8	0.236	2.910	2.751	3.430	3.145	3.363
S9	0.235	0.239	0.262	0.260	0.254	0.255
S10	0.360	3.091	3.240	3.241	3.486	3.172
S11	0.225	2.888	3.109	3.166	3.428	3.115
S12	0.871	3.444	3.554	3.492	3.663	3.420
S13	0.010	2.352	2.206	2.983	2.775	3.132
S14	0.007	0.982	1.073	1.786	1.786	2.122
S15	0.261	2.953	2.793	3.484	3.174	3.394
S16	2.146	2.136	2.138	2.118	2.122	2.130
S17	0.020	0.024	0.028	0.026	0.022	0.023
S18	0.107	2.444	2.716	2.806	3.159	2.954
S19	0.007	1.007	1.290	1.407	1.672	1.715
S20	0.209	3.021	3.248	3.246	3.504	3.162
S21	0.018	2.458	2.353	3.046	2.893	3.205
S22	2.179	2.178	2.174	2.162	2.167	2.166
S23	1.227	1.229	1.227	1.234	1.232	1.230
S24	0.006	0.236	0.324	0.501	0.614	0.736
S25	0.030	1.856	2.195	2.378	2.630	2.551
S26	0.240	2.685	3.006	3.120	3.400	3.099
S27	0.010	1.691	2.080	2.288	2.559	2.440
S28	0.103	2.335	2.617	2.719	3.055	2.882
S29	0.011	1.967	1.900	2.531	2.351	2.697
S30	0.280	3.063	2.887	3.536	3.226	3.456
S31	0.008	2.276	2.161	2.904	2.720	3.048
S32	0.462	1.923	1.888	1.837	1.807	1.801
S33	0.025	2.320	2.617	2.692	3.015	2.823
S34	0.251	2.877	3.265	3.277	3.506	3.200
S35	0.007	2.311	2.552	2.653	3.013	2.813
S36	0.574	3.428	3.549	3.496	3.680	3.382
S37	0.008	2.054	1.952	2.668	2.558	2.820
S38	0.118	2.563	2.424	3.137	2.938	3.260
S39	0.007	2.100	1.955	2.590	2.393	2.688
S40	0.007	1.862	1.785	2.497	2.347	2.634
S41	0.169	2.650	2.888	2.981	3.326	3.054
S42	0.048	2.536	2.791	2.898	3.265	2.994
S43	0.276	2.926	3.163	3.234	3.472	3.162
S44	0.250	3.000	3.309	3.311	3.545	3.216
S45	0.007	2.249	2.072	2.754	2.562	2.855
S46	0.225	2.848	2.697	3.320	3.132	3.356
S47	0.008	2.402	2.316	3.130	2.949	3.237
S48	2.190	2.192	2.195	2.175	2.175	2.180

Delta (%)

Sample	Air	T1	T2	T3	T4	T5
S1	-88%	-25%	-20%	-13%	-12%	-2%
S2	-9%	808%	889%	940%	944%	1024%
S3	-75%	-19%	-14%	-7%	-8%	1%
S4	-100%	-5%	8%	22%	32%	40%
S5	-92%	855%	933%	926%	973%	1104%
S6	-84%	-21%	-11%	-13%	-6%	-6%
S7	2%	11%	26%	5%	16%	11%
S8	-83%	-15%	-3%	-12%	0%	-1%
S9	-98%	814%	850%	917%	1041%	1087%
S10	-64%	-13%	-8%	-2%	-4%	7%
S11	-96%	-14%	-11%	-8%	-8%	4%
S12	-78%	-15%	-9%	-5%	-5%	1%
S13	-19%	1%	15%	-5%	8%	4%
S14	26%	124%	124%	51%	58%	46%
S15	-70%	-14%	-3%	-13%	-2%	-1%
S16	-100%	17%	25%	41%	45%	55%
S17	112%	9640%	9262%	10721%	14025%	13936%
S18	-87%	1%	2%	6%	1%	12%
S19	443%	125%	94%	95%	77%	86%
S20	-17%	2%	3%	3%	1%	9%
S21	-47%	-3%	10%	-6%	3%	2%
S22	-100%	-1%	10%	20%	26%	36%
S23	-99%	110%	165%	173%	183%	187%
S24	65%	811%	696%	484%	426%	369%
S25	8%	18%	11%	12%	10%	21%
S26	-86%	-11%	-11%	-10%	-9%	3%
S27	280%	46%	33%	29%	26%	34%
S28	-78%	-3%	-2%	0%	-2%	9%
S29	362%	30%	43%	19%	32%	24%
S30	-34%	-2%	10%	-3%	6%	3%
S31	-4%	4%	18%	-1%	9%	7%
S32	-96%	21%	33%	53%	60%	77%
S33	-69%	5%	4%	6%	3%	14%
S34	-76%	-12%	-14%	-10%	-9%	3%
S35	382%	13%	14%	15%	10%	18%
S36	-90%	-30%	-24%	-18%	-15%	-4%
S37	1672%	35%	53%	21%	29%	21%
S38	-89%	-6%	7%	-8%	2%	0%
S39	19%	17%	32%	10%	21%	18%
S40	226%	35%	50%	19%	30%	26%
S41	-11%	6%	7%	9%	3%	12%
S42	-6%	-2%	-2%	0%	-3%	9%
S43	-93%	-19%	-15%	-11%	-9%	3%
S44	-84%	-16%	-16%	-11%	-9%	3%
S45	-5%	6%	23%	1%	13%	10%
S46	-98%	-24%	-13%	-21%	-13%	-11%
S47	355%	6%	20%	-1%	10%	5%
S48	-99%	11%	18%	32%	35%	46%

Note: Sample S2 had already been removed from test when GS9 measurements were conducted.

Revision History

Version	Description of Change	Date	Author
1	Initial release.	11/30/2021	CS
2	Editorial updates and comments made, footnote references added (Section 1.1).	2/25/2022	CS
3	Removal of Figure 86-93 from sections 4.1.1 and 4.1.2, but maintained in Appendix. Editorial update for potential failure mechanism in section 5.3 and for potential gas sensitivity check failure in section 6.1.	3/18/2022	CS
4	Updated Executive Summary with added headers, discussion on expected overall life prediction for each sensor, note for Sensor C from previous testing, and editorial updates. Added discussion on expected overall life prediction for each sensor in Section 6.	9/1/2022	CS
5	Updated Executive Summary, page 9, first paragraph, with editorial clarification on likely predominant failure mechanism.	9/16/2022	CS

Sample Disposition

If you would like your samples returned, please provide:

- Shipping account number
- Shipment type (FedEx 2-day or overnight, UPS, DHL, etc.)
- Complete shipping address
- Recipient's name, phone number, and email address
- Insured value (if any)
- Customer information (when returning to overseas location)

If no disposition instructions are received, samples will be retained for 6 months before being recycled and destroyed.

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TAB D: Memorandum from the Directorate for Economic Analysis – Preliminary Regulatory Analysis

United States
Consumer Product Safety Commission

Memorandum

TO: Ronald Jordan, Project Manager
Division of Mechanical and Combustion Engineering,
Directorate for Engineering Sciences

DATE: September 20, 2023

THROUGH: Alexander Moscoso, Associate Executive Director
Directorate for Economic Analysis

FROM: Bretford Griffin, Economist,
Directorate for Economic Analysis

Jeffrey Giliam, Economist
Directorate for Economic Analysis

SUBJECT: Residential Gas Furnaces and Boilers Preliminary Regulatory Analysis

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Executive Summary

The U.S. Consumer Product Safety Commission (CPSC) is considering a draft proposed rule recommended by staff for residential gas furnaces and boilers to address the risk of carbon monoxide (CO) poisoning from CO leakage associated with these products. The proposed standard addresses CO exposure risks that are not currently covered by the existing voluntary performance and safety standards for these products (American National Standards Institute (ANSI) Z21.47, Standard for Gas-fired Central Furnaces: ANSI Z21.13, Standard for Gas-Fired Low Pressure Steam and Hot Water Boilers and ANSI Z21.86, Standard for Vented Gas-Fired Space Heating Appliances). The proposed standard would establish a mandatory performance requirement to reduce the risk of serious injury or death caused by CO poisoning from CO leakage from gas furnaces and boilers. The performance requirements would require gas furnaces and boilers to modulate or shut off when CO levels reach certain amounts for a certain duration (TAB B). CPSC staff assesses that the draft proposed rule would be highly effective, 90 to 100 percent, in mitigating deaths and injuries from CO leakages from gas furnaces and boilers. This is because the recommended mitigation requirements – installing a sensor and shut off device as a fail-safe system – would prevent CO levels from increasing to the point of causing deaths and injuries.[41] Additionally, the technology in the CO sensor would, upon failure of the CO sensor, cause the gas furnace to shutdown and restart after 15 minutes and repeat this cycle until the failed component is replaced. This additional layer of safety prevents gas furnaces running normally with a failed CO sensor but allows for some operation so no consumer is without any heat in cases of emergency.

[41] Subject matter experts from CPSC's Directorate of Engineering estimate an effective rate between 90 and 100 percent for mitigating the risk of death and injury. This analysis uses the midpoint of the range of 95 percent to estimate the benefits of the draft proposed rule.

Staff identified 108 deaths from CO poisoning from gas furnace and boilers that occurred from 2014 through 2018. Staff estimates that there were 30,587 nonfatal injuries in the same period.[42] The injuries are comprised of 7,358 injuries that resulted in an emergency department (ED) visit, 79 injuries resulted in hospital admissions, 333 injuries resulted in hospital admissions via the ED, and 22,817 injuries resulted in a doctor's or clinic' visit.

The proposed standard would impose the following costs: increased variable costs of producing furnaces and boilers with CO sensors and shutoff capabilities; one-time conversion costs of redesigning and modifying factory operations for installing CO sensors; increased maintenance costs of gas furnaces and boilers to consumers, and deadweight loss[43] in the market caused by the increasing price due to regulation and the subsequent decline in demand. Staff performed a 30-year prospective cost assessment (2025-2054) on all four cost categories and estimated the total annualized cost from the draft proposed rule to be $602.27 million, discounted at 3 percent.[44] Staff estimated the per-unit (of a gas furnace or boiler) costs from the draft proposed rule to be $158.11, discounted at 3 percent.

Staff also conducted a benefits assessment of the draft proposed rule. The benefits assessment accounted for the prevention of deaths and injuries from compliant gas furnaces and boilers, which staff monetized using the value of statistical life (VSL) for deaths, and the Injury Cost Model (ICM) for injuries. Over the 30-year study period, staff estimated the draft proposed rule would prevent 576 deaths (19.20 deaths per year) and 160,699 injuries (5,357 per year). The total annualized benefits from the draft proposed are $356.52 million, discounted at 3 percent. Staff estimated the per-unit benefits from the draft proposed rule to be $93.60, discounted at 3 percent.

When costs are compared to benefits, the estimated costs of the rule are greater than the estimated benefits. Staff calculates net benefits (benefits less costs) to be -$245.74 million on annualized basis, discounted at 3 percent. The net benefits on per-unit basis are -$64.51, discounted at 3 percent. Alternatively, this can be described as the draft proposed rule being a net cost of $64.51 per gas furnace or boiler, which represents approximately 3 percent of the average price of a gas furnace or boiler. Overall, the draft proposed rule has a benefit-cost ratio of 0.59; in other words, for every $1 in cost of the draft proposed rule, there is a return of $0.59 in benefits from mitigated deaths and injuries.

Finally, staff conducted a sensitivity analysis that showed if, by 2035, manufacturers were able to develop compliant gas furnaces and boilers with CO sensors that did not need replacement, and if the analysis took into account that a child's death is considered twice as costly as an adult death, the benefit-cost ratio would increase to 0.78.

Introduction

[42] Staff estimated nonfatal injuries using its Injury Cost Model. The Injury Cost model generates national estimates from the observed 236 nonfatal injuries from CO leakage in gas furnaces and boilers through CPSC's National Electronic Information System. Eighteen injuries resulted in hospital admissions via the emergency department and 218 were treated in the emergency department and released. The Injury Cost Model uses the observed incidents in conjunction with information it has about the injury and other factors to extrapolate it into a national estimate.

[43] Deadweight loss is the value of lost transactions that may occur after major market events such as a new regulation.

[44] Staff uses a discount rate to incorporate the time value of money during the 30-year study period. In the analysis, staff presents both costs and benefits in undiscounted dollars, discounted at 3 percent, and discounted at 7 percent.

The CPSC is considering a draft proposed rule to establish a mandatory performance requirement and test procedure to reduce the risk of CO poisoning from gas-fired ("gas") central furnaces, boilers, wall furnaces, and floor furnaces. Gas central furnaces and boilers have historically been among the leading consumer products that cause non-fire CO poisoning deaths (Topping 2022). In the late 1980s, ANSI revised its voluntary standards for a variety of gas appliances, including gas furnaces and boilers, to address some of the operation, installation, or usage conditions of the products that could result in hazards, such as fire, explosion, and leakage of CO into the living space. Despite these revisions, gas furnaces and boilers continue to be the second leading cause of CO deaths and the leading cause of deaths among heating systems. Staff assesses that these incidents continue to occur because the voluntary standards are not stringent enough to eliminate this hazard.

The Commission published an Advance Notice of Proposed Rulemaking (ANPR) on August 19, 2019 (84 FR 42847) that requested comments on the potential establishment of performance requirements and/or warning and instructions for residential gas furnaces and boilers. This document is a preliminary regulatory analysis of the proposed standard in the draft proposed rule.

1.1. Draft Proposed Rule

The draft proposed rule would establish performance requirements to reduce the risk of serious injury or death caused by CO poisoning that can occur due to leakage from furnaces and boilers. The performance requirement would require gas furnaces and boilers to modulate or shut off when CO levels reach specified amounts for a certain duration (TAB B). To comply with the proposed standard, these appliances need to monitor post-combustion CO production. This can be achieved by installing sensors in the appliances that monitor flue gases and then can shut off or modulate combustion in the device. There is also a performance requirement that upon failure of the CO sensor, manufacturers should include technology that causes the gas furnace to shutdown and restart after 15 minutes and repeat this cycle until the failed CO sensor is replaced.

1. Effective Date

Our assessment is guided by section 9 of the CPSA. Section 9(f)(3) provides "that the rule (including its effective date)" must be "reasonably necessary to eliminate or reduce an unreasonable risk injury associated with such product." Consistent with the judicial review provision of CPSA section 11(c), the determination of reasonable necessity should be supported by substantial evidence. Section 9(g)(1) addresses effective dates in greater detail and requires that the effective date shall not exceed 180 days from the date the rule is promulgated, "unless the Commission finds, for good cause shown, that a later effective date is in the public interest and publishes its reasons for such finding." Similarly, the effective date must not be less than 30 days after promulgation "unless the Commission for good cause shown determines that an earlier effective date is in the public interest."

The CPSC Commissioners determine what effective date is in the public interest, utilizing information and recommendations provided by staff along with other record evidence and policy considerations. These factors will be documented in the Commission's final decision. Given the explicit statutory preference for an effective date in the 30-day to 180-day range, the Economics Staff has examined whether there is specific, detailed, and credible evidence that the public interest supports setting an earlier or later effective date. This economic analysis uses the best available evidence (including data collected by CPSC, inputs from received from the public during the notice and comment process, and the professional judgment of CPSC's technical staff) to characterize the impacts to the American economy, including the statutorily required analysis of impacts to small entities. The analysis includes review of various effective date options. Given the statutory direction in the CPSA, staff's economic analysis will recommend an effective date within the 30-day to 180-day range unless (i) there is clear evidence that a shorter or longer period is required to prevent unreasonable burdens, or (ii) a shorter or longer period would ensure a reasonable relationship between expected benefits and costs. This information is intended to assist the Commission's ultimate determination of the appropriate effective date. See, e.g., CPSA § 9(f)(3)(E), (F).

Staff initially considered an effective date of 180 days or less as required in the Consumer Product Safety Act; however, staff assesses that it would be unfeasible for manufacturers to comply with the draft proposed rules in 180 days. The number of actions needed to implement the draft proposed rule, along with their complexity, cannot be reasonably planned, implemented, and tested before 180 days. A full description of these actions, along with further rationale for good cause to have an effective date longer than 180 days, can be found in the Effective Date section of the briefing memorandum for this briefing package. Given this, staff recommends an effective date of 18 months from the date of publication of the final rule in the Federal Register which would allow gas appliance manufacturers adequate time to do the necessary actions in preparation for compliance with the new rule. An 18-month effective date would follow the industry standard of time to adopt and implement new requirements.

This regulatory analysis for the draft proposed rule assumes that CPSC promulgates an 18-month effective date and that all manufacturers can comply with the rule in that time frame. Staff assessed that an effective date less than an 18-month effective would introduce the risk of a significant number of manufacturers being unable to comply with the rule, with the risk of noncompliance increasing the earlier the effective date is from 18 months.

Potential costs from significant supply chain disruptions or shortages include:

Shortage Cost to the Supply Chain.

Manufacturers that are unable to produce a compliant product or are not yet able to produce enough compliant products to meet their typical demand would likely cause a shortage of product. The inability to produce enough compliant gas furnaces and boilers would generate revenue loss to all levels of the supply chain – suppliers, producers, intermediaries, transporters, wholesalers, and retailers. There could also be additional cost such as penalties from broken or unfulfilled contracts due to the shortage. These costs could be significant. Some or most of this revenue may be an economic transfer because some consumers would purchase substitute products, but not all would, and that fraction could still be a significant cost. Additionally, the individual firms and brands would still feel the full impact of the revenue loss which could trigger costly business decisions by management (e.g., layoffs).

Shortage Cost to the Consumers.

A shortage of product would deny consumers availability of their preferred product. The cost to consumers is a loss of utility and potentially a financial loss from buying a more expensive substitute or potentially a more dangerous substitute. Consumers who prefer gas furnaces or boilers but cannot buy them in the short-term due to a shortage would either purchase a substitute product, wait until their preferred gas furnaces and boilers became available again, or forego the purchase altogether. Staff assesses that more consumers would likely purchase a substitute product because of the perceived necessity of the product. Consumers could purchase an electric furnace which would also provide safety benefits of having no risk of a CO leak but would be more expensive than a gas furnace or boiler.[45] Consumers could also purchase an oil furnace which also produces CO. There would be a loss of utility as these consumers prefer gas furnaces and boilers over electric or oil furnaces, and the intrinsic value they place on gas furnaces or boilers is lost. Those consumers who wait until a gas furnace or boiler becomes available again would have their utility for the product reduced because of the delay. Consumers who drop out of the market have an incremental loss of utility because they would use the money which would have purchased the gas furnace or boiler for another product or activity that is their second choice.

Loss of benefits.

While not a cost compared to the status quo, a shortage would reduce the expected benefits from the draft proposed rule. Each gas furnace or boiler not available because manufacturers were unable to be produce compliant products by the effective date means there are fewer potential benefits from the draft proposed rule. Especially if consumers choose to drop out of the market and continue to operate noncompliant products that have a risk of CO leaks.

Unforeseen quality control issues.

Some manufacturers may be able to produce compliant gas furnaces and boilers at an earlier effective date than 18 months. However, an expedited process may lead to unforeseen mechanical or operational issues. Staff does not assume manufacturers would knowingly deliver faulty products, but a condensed production and testing timeline could increase the risk of latent operational issues with the compliant gas furnaces and boilers such as nuisance shut-downs. These issues would potentially cost consumers by inconveniencing them with operational issues, and potentially costing manufacturers if a recall is needed, including any harm in brand reputation.

Displaced companies and their employees. A potentially costly effect to producers from shortages is sustained or permanent harm to business operations. This could include a company reacting to a loss of revenue from shortages by laying off employees or, for some small businesses, structured bankruptcy or liquidation. In either scenario, the laid off employees and their families incur the cost of unemployment which includes loss of income and the intangible costs of anxiety due to financial insecurity. The Bureau of Labor Statistics reports the average wage of a worker in production operations in household appliance manufacturing to be $40,770 per worker per year.[46] Prolonged unemployment from many laid off workers could cost millions of dollars. Finally, the loss of income from

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[45] As of this document, electric heating was more expensive than natural gas and heating oil, but less expensive than propane, according to EIA's Winter Fuels Outlook, October 2022. https://www.eia.gov/outlooks/steo/report/winterfuels.php

[46] Bureau of Labor Statistics, "May 2021 National Industry-Specific Occupational Employment and Wage Estimates, NAICS 335200 - Household Appliance Manufacturing", 51-0000 Production Operations, Annual Mean Wage, https://www.bls.gov/oes/current/naics4_335200.htm#51-0000

these households can have a ripple effect to the local economy depending on the number of unemployed and their geographical concentration.

The proposed effective date would help ensure that manufacturers have adequate time to properly transition to the new rule and design and test new products before they are placed into commerce. Staff seeks comments on the effective date, with specific information to explain any need for a longer effective date.

2. Stockpiling

The proposed rule includes an anti-stockpiling provision[47] that would prohibit firms from manufacturing or importing gas furnaces or boilers that are noncompliant with the draft proposed rule between the promulgation of the final rule and the effective date, at a rate greater than 106 percent of the base period in the first 12 months after promulgation, and 112.50 percent of the base period for the duration of 12 months after promulgation until the effective date. The base period is defined in the draft proposed rule as the calendar month with the median manufacturing volume, among months with manufacturing volume, during the last 13 months prior to rule publication. For example, if CPSC promulgates the rule in July 2024, then base period would be the median monthly production from June 2023 and June 2024, for the months that manufacturer had production. If the median monthly production was 1,000 units, then the manufacturer would be able to manufacture 1,060 units a month from July 2024 until June 2025, and 1,125 units from July 2025 until December 2025 (18 months after promulgation).

Staff recommends a rate of 106 percent for the first 12 months and a rate 112.50 percent in the final 6 months between promulgation and effective date based on historical growth of the industry. Historical data on shipments going back to 2013 show year-over-year growth between 4.5 percent and 7.1 percent.[48] The midpoint of this range is 5.8 percent, which staff rounds up to 6 percent growth and applies it to the anti-stockpiling provision. Staff recommends a higher rate of 112.50 percent for the second year to account for the secular growth of the industry in the second year. Without higher rate in the second year, the stockpiling amendment would constrain manufacturers to zero percent growth in the second year.

The historical shipment data is of the entire industry. Individual manufacturers may experience growth rates outside the historical range. Shipment data for gas furnaces and boilers show a steady, yet seasonal, market. Shipments of gas furnaces and boilers begin to rise in March and continuously increase until December, after which they fall off sharply. Staff recommends that the Commission seek public comment on manufacturing, the seasonality of sales, and supply chain of gas furnaces and boilers to further understand these topics.

1.2. Preliminary Regulatory Analysis

[47] According to Section 9 paragraph (g)(2) of the CPSA, CPSC is required to consider whether to prohibit stockpiling from the date of promulgation of the rule to the effective date of the rule. Stockpiling is defined as manufacturing or importing a non-complying product which is significantly greater than the rate at which such products were produced or imported during a base period. The base period is defined as the 13 months preceding promulgation of the rule.

[48] Monthly gas furnace shipments data come from American Heating/Cooling Research Institute) (AHRI). Note that these data include both residential and commercial gas furnaces but does not include gas boilers. Staff assumes that any annual and seasonal variation in demand for residential and commercial furnaces are similar and that these annual and seasonal patterns can also be applied to gas boilers.

Pursuant to section 9(c) of the Consumer Product Safety Act, publication of a proposed rule must include a preliminary regulatory analysis containing the following:

1. a preliminary description of the potential benefits and costs of the proposed rule, including any benefits or costs that cannot be quantified in monetary terms, and an identification of those likely to receive the benefits and bear the costs;
2. a discussion of the reasons any standard or portion of a standard submitted to the Commission under subsection (a)(5) was not published by the Commission as the proposed rule or part of the proposed rule;
3. a discussion of the reasons for the Commission's preliminary determination that efforts proposed under subsection (a)(6) and assisted by the Commission as required by section 5 (a)(3) [of the CPSA] would not, within a reasonable period of time, be likely to result in the development of a voluntary consumer product safety standard that would eliminate or adequately reduce the risk of injury addressed by the proposed rule; and
4. a description of any reasonable alternatives to the proposed rule, together with a summary description of their potential costs and benefits, and a brief explanation why such alternatives should not be published as a proposed rule.[49]

An overview of the gas furnace and boiler market can be found in section 2 of this memorandum. A preliminary description of the potential costs and benefits of the draft proposed rule can be found in sections 3 and 4 of this memorandum, respectively. No voluntary standard or portion of a voluntary standard was submitted to the Commission during the ANPR comment period, and therefore such a voluntary standard is not discussed in this memorandum. However, some commenters stated that CPSC should rely on existing voluntary standards. A discussion of this relevant voluntary safety standard can be found in section 6 of this TAB. An analysis of benefits relative to costs can be found in section 5 in this memorandum. Finally, a discussion of the reasonable alternatives to the draft proposed rule can be found in section 7 in this memorandum.

2. Market Information

2.1. The Product

The draft proposed rule provides requirements for residential, gas-fired central furnaces, boilers, wall furnaces, and floor furnaces (referred to as "gas furnaces and boilers" for the remainder of this Tab). Gas furnaces and boilers are vented gas heating appliances that heat residential dwellings. The average product life of gas furnaces and boilers ranges from 20 to 26 years.[50]

There are two categories of gas furnaces and boilers: (1) central warm-air furnaces and boilers and (2) floor, wall, or pipeless furnaces.

1. <u>Central warm-air furnaces and boilers</u> use a central combustor, or boiler, to heat air using natural gas, liquid propane, or fuel oil. Some of these furnaces move the heated air using a blower or fan through ducts while others rely on the natural flow of warm air going up and cold air down to circulate air. Most boilers supply steam or hot water through conventional radiators or baseboard radiators.

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[49] 15 U.S.C. § 2058(c).

[50] Lutz, J., Hopkins, A., Letschert, V., Franco, V., and Sturges, A., "Using National Survey Data to Estimate Lifetimes of Residential Appliances", *Ernest Orlando Lawrence Berkley National Laboratory*, October 2011, Tables 4 and 5.

2. Floor, wall, or pipeless furnaces are less common than central furnaces and boilers and consist of ductless combustors to heat air. A floor furnace and wall furnace heat the physical parts of the house (i.e., floor or wall) to heat the dwelling. A pipeless furnace is typically located in a basement and delivers heated air through a large register in the floor above it.

Consumers purchase gas furnaces and boilers primarily through contracted installers but may also purchase units at retail stores and online retailers. Staff used information from the U.S. Department of Energy's Government Regulatory Impact Model (GRIM) and a Guidehouse Inc. report (Guidehouse 2021) to estimate the average retail price of gas furnaces to be $1,660 and $3,719 for gas boilers.[51]

2.2. Current Market Trends for Gas Furnaces and Boilers

Staff identified as many as 70 firms that supply residential gas furnaces and boilers (Freedonia 2017). When accounting for subsidiaries and multiple brands provided by the same company, staff identified 20 parent firms.[52] In 2016, the largest 10 firms by revenue accounted for 83.3 percent of heating equipment sales. Seven of these firms are based in the U.S.[53]

DOE's Energy Information Administration (EIA) conducts the Residential Energy Consumption Survey (RECS) at irregular intervals. EIA published the most recent RECS in 2021, which reports the total number of gas furnaces, gas boilers, and wall furnaces in-use to be 60.94 million[54] in 2020. This is an increase from 57.90 million in 2015 – the most recent EIA survey before 2020. Between 2015 and 2020, the number of in-scope gas furnaces and boilers grew at an average annual rate of 1.03 percent.

Staff used the DOE's GRIM to estimate sales for gas furnaces and boilers. GRIM projected gas furnace sales in 2021 to be 3.58 million units[55] and gas boilers to be 0.30 million units. Staff estimates that residential gas furnaces and boilers sales in 2021 are $5.94 billion and $1.12 billion, respectively.[56]

The CPSC Office of Import Surveillance reports that firms imported approximately $287 million worth of gas boilers annually from 2019-2021.[57] CPSC staff estimated that residential gas boiler imports average $117.67 million annually.[58] CPSC staff are unable to determine the number of imports for gas furnaces. Staff recommends requesting comment on the value and quantity of gas furnaces and boilers imports that would be subject to a proposed rule.

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[51] Staff calculated a weighted average manufacturing selling price for furnaces (for nonweatherized furnaces; PC1 and PC3) and boilers (hot water and steam boilers, PC1 and PC2) based on estimated 2021 sales. Staff then applied the markup multipliers from the Guidehouse report for gas furnaces and boilers, 3.19 and 3.3, respectively, to calculate average retail prices. Staff then inflated prices to 2022 dollars using the Consumer Product Index from the Bureau of Labor Statistics.
[52] Freedonia 2017 Report.
[53] Based on an internet search of their corporate address.
[54] Staff used the microdata provided by RECS for its 2020 survey to aggregate units for gas appliances of equipment that are either "central furnace" or "Steam or hot water system with radiators or pipes".
[55] GRIM's shipment estimate for 2021 was 3.41 million, which did not include wall or floor furnaces. Staff imputed wall and floor furnaces using the 4.68% estimate of built-ins of total furnace population by DOE's 2020 RECS microdata. This likely overestimates the in-scope population for this rule as built-ins include more types of furnaces than wall or floor furnaces.
[56] 3.58 million furnace units × $1,660 = $5.94 billion in estimated furnace revenue in 2022. 0.30 million boiler units × $3,719 = $1.12 billion in estimated boiler revenue in 2022.
[57] CPSC Executive Office of Import Surveillance tabulation of import data from Customs and Border Protection (DHS)
[58] Staff applied the 41 percent market share estimate of residential heating equipment to total imports from Freedonia Group (2021) to estimate share of imported residential boilers. $117.67 million = $287 million × 41 percent.

2.3. Future Market Size for Gas Furnaces and Boilers

GRIM projects sales for gas furnaces up to the year 2051, and boilers up to the year 2050. Projected gas furnace sales are 3.65 million in 2025 and grow to 4.28 million in 2051; gas boiler sales are 0.31 million in 2025 and grow to 0.34 million in 2050. Staff imputed sales for 2051 (for boilers only), 2052, 2053, and 2054 using a moving 10-year average compounding growth rate.[59] With these imputations, staff estimates that gas furnace sales will be 4.38 million in 2054 and gas boilers sales will be 0.34 million. Summed together, the projected sales of all in-scope products of the rule are estimated to be 3.96 million 2025 and will grow to 4.72 million in 2054.

Staff used the 1.03 percent annual growth rate between the most recent in-use estimates from RECS for in-scope products – 2020 and 2015 – to project out into the future. Using this approach, staff estimates the number of in-use, in-scope gas furnaces and boilers will grow from 64.13 million in 2025 to 90.49 million in 2054.

Figure 1 below displays both the projected number of sales and in-use units of gas furnaces and boilers from 2025 through 2054. The right axis corresponds to the number of sales units in each year which is represented by the orange line. The left axis corresponds to the number of units in-use in each year which is represented by the blue bars.

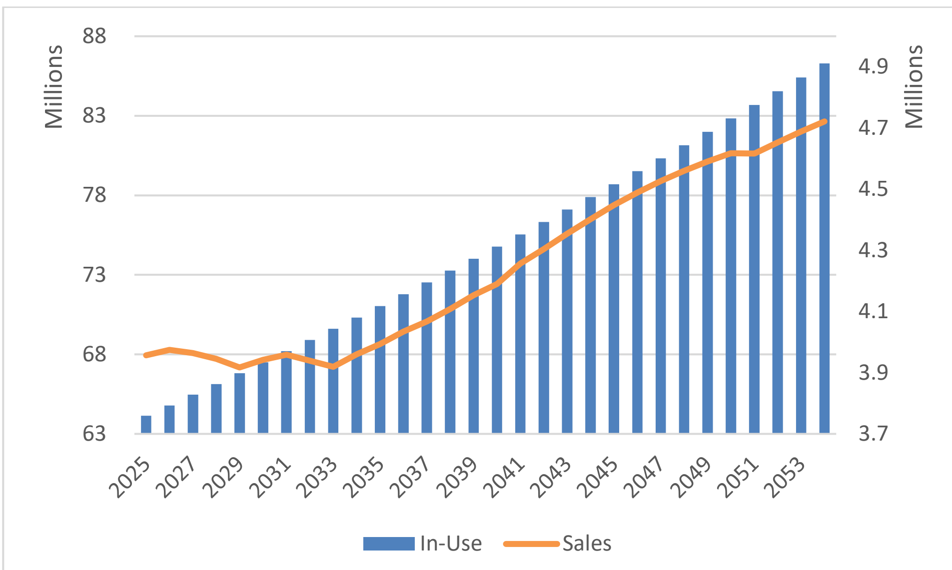

Figure 1: Gas Furnace and Boilers Forecast of Sales and In-Use Units, 2025 - 2054

3. Preliminary Regulatory Analysis: Cost Analysis

This section discusses the costs the draft proposed rule would impose on industry and consumers. For this regulatory analysis, staff considers one solution to address CO leakage in gas furnaces and boilers: manufacturers redesign their gas furnaces and boilers to accommodate

[59] For 2052, staff calculated the compounded annual growth rate from the previous ten years timeframe, 2042 through 2051, and applies this rate to 2051 sales. This projects 2052 sales with the assumption that it will grow at the same rate as the previous 10 years. This approach is applied to project 2053 sales; however, the window of trend is now 2043 through 2052. The same method is applied for 2054.

installation of CO sensors and shutoff capabilities.[60] Staff estimated the full cost of the draft proposed rule based on the assumption that 100 percent of manufacturers adopt this solution.

There are four cost components discussed under this cost section: (1) the increased variable costs of producing furnaces and boilers with CO sensors and shutoff capabilities; (2) the one-time conversion costs of redesigning and modifying factory operations for installing CO sensors; (3) the increased maintenance cost to consumers which includes the cost of replacing CO sensors throughout the appliance's product life; and (4) the deadweight loss or market impact caused by the increasing price due to regulation and the subsequent decline in demand.

The time span of the cost analysis covers a 30-year period that starts in 2025, which is the expected year of implementation of the rule. This cost analysis presents all cost estimates in 2022 dollars. This cost analysis also discounts costs in the future and uses 3 and 7 percent discount rates to estimate their present value.[61]

This section first covers the unit cost or a general description of the costs, then it calculates costs for each category over the 30-year study period, and finally it presents total cost from the draft proposed rule in both annualized and per-unit terms. An annualized output converts the aggregate costs over 30 years into a consistent annual amount while considering the time value of money. This metric is helpful when comparing the costs among different rules or policy alternatives that may have different timelines; or those that have similar timelines but costs for one are front-loaded while the other's maybe back-loaded.[62] A per-product metric expresses the costs from the rule in one unit of product. This metric is helpful when assessing the impact in marginal terms; for example, comparing costs to an increase in retail price. Staff presents both these metrics to provide a holistic perspective of the impact from this draft proposed rule.

3.1. Unit Cost of CO Sensors with Shutoff Capabilities

Manufacturers would need to modify the design and manufacturing of gas furnaces and boilers to include sensors capable of detecting a CO leak and then shutting off the appliance. The gas furnace and boiler manufacturers would incur costs stemming from component parts, product redesign, additional labor, and additional overhead. This is a variable cost that would be applied to each unit produced.

Guidehouse Inc. conducted a report (Guidehouse 2021) for CPSC that examined regulations and standards governing CO production by gas space heating and water heating appliances in the European Union (EU) and Japan; the various technologies being used in EU and Japanese markets to meet these regulations; and the effectiveness of these regulations in reducing injuries and deaths from CO poisoning. The Guidehouse report also explored how the EU and Japanese space heating markets compare to the U.S. market.

Guidehouse estimated the retail price increase of implementing CO sensing and shutoff technologies into the U.S. market for both central furnaces and non-condensing boilers. The retail

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[60] This analysis assumes manufacturers only pursue shutoff capabilities and not modulation. Because U.S. gas furnaces and boilers are predominantly either induced draft or atmospheric venting, modulation technology is not the most adaptable technology for U.S. furnaces and boilers.

[61] Discounting future estimates to the present allows staff not only to consider the time value of money, but also the opportunity cost of the investment, that is, the value of the best alternative use of funds.

[62] The timing of costs along the period of study affects the present value of costs when considering the time value of money. Costs incurred several years into the future are discounted more heavily than costs realized in the short-term.

price increase is the appropriate value to use in this cost analysis because it not only captures the incremental production cost to manufacturers, but also the incremental downstream supply chain costs to distributors, wholesalers, and retailers. Guidehouse provided minimum and maximum values for each product.[63] Staff used the midpoint value for each in this cost analysis. Staff displays Guidehouse's retail price increase estimates, adjusted to 2022 dollars using the CPI,[64] in Table 1.

Table 1: Price Increase for CO Sensors and Shutoff Technology

	Incremental Retail Price Increase per Unit		
Product	**Min**	**Mid**	**Max**
Central Furnaces	$42.07	$70.44	$98.81
Non-Condensing Boilers	$54.42	$87.59	$120.75

3.2. Conversion Costs

The unit cost of CO sensors with shutoff technologies cited by Guidehouse does not include research and development (R&D) and production changes needed to implement this technology. In lieu of specific information on fixed and one-time costs of manufacturers converting their production of gas furnaces and boilers to include CO sensors, staff relied on a DOE technical support document[65] on conversion costs (i.e., capital expenditures) needed to meet a change in energy efficient technology as a proxy. Staff assessed that similar production changes and capital expenditures would be required to comply with the draft proposed rule. Staff seeks public comment and data or information on R&D and modifications to the production process the draft proposed rule would impose on manufacturers.

DOE divides conversion costs into two categories: Capital Conversion Costs and Production Conversion Costs. Capital Conversion Costs are the one-time conversion costs to bring their production facilities and product designs into compliance. Production Conversion Costs are the one-time investments in research, development, testing, marketing, and other costs to bring product designs into compliance.

As a conservative estimate, CPSC staff used the trial standard level 5 (TSL 5) as its proxy for fixed costs of upgrading to CO sensors and shutoff because it is the costliest option. DOE reported these costs in 2013 dollars, and staff inflated these values to 2022 dollars using the CPI.[66] Table 2 displays capital conversion costs and product conversion costs (in 2022 dollars) under TSL 5 of both gas furnaces and gas boilers for the entire industry.

[63] Table 3-4 in Guidehouse 2021 report.
[64] Bureau of Labor Statistics, "CPI for All Urban Consumers (CPI-U)", Not Seasonally Adjusted, Series Id: CUUS0000SA0
[65] DOE published technical support documents that analyzed different rule scenarios or "Trial Standard Levels" (TSL). Each TSL corresponds to producing gas furnaces and boilers with Efficiency Levels (ELs) above their baseline efficiencies. The TSL increases with stringency of the standard and thus it increases with cost. For more information in the 2015 rulemakings for residential gas furnaces (https://www.regulations.gov/document/EERE-2014-BT-STD-0031-0217) and residential gas boilers (https://www.regulations.gov/document/EERE-2012-BT-STD-0047-0036)
[66] Bureau of Labor Statistics, "CPI for All Urban Consumers (CPI-U)", Not Seasonally Adjusted, Series Id: CUUS0000SA0

Table 2: Conversion Costs for Gas Furnaces and Boilers

Product	Industry-Wide Conversion Costs for TSL 5 ($M)		
	Capital Conversion	Production Conversion	Total Conversion
Gas Furnaces	$238.61	$75.83	$314.44
Gas Boilers	$85.94	$45.97	$131.91
Total	**$324.56**	**$121.79**	**$446.35**

3.3. Unit Costs for Increased Maintenance

Consumers would incur costs from the draft proposed rule because the CO sensors installed in gas furnaces and boilers would need to be replaced at some point during the gas furnace's or boiler's product life. For some consumers whose gas furnace or boiler will experience CO leakage in the future, the compliant gas furnace or boiler will begin cycling on and off every 15 minutes and prevent serious harm (whose benefits staff accounts for in section 4), however they will incur costs to have the gas furnace or boiler repaired.

Staff studied two different sensor technologies to ascertain the expected life of CO sensors. Staff found that one technology would likely last 6 years while the other would likely last 10 years. Given the wide availability of this technology in Europe and Japan, staff assumes U.S. companies would be able to build upon existing technological development and manufacture gas furnaces and boilers with CO sensors with a product life of at least 10 years.

Assuming CO sensor have a product life of 10 years, and gas furnaces and boilers have product lives more than double that, CO sensors would need to be replaced during the lifetime of the appliance. Consumers may have a CO sensor replaced because it failed (broke) unexpectedly, i.e., an "unplanned replacement", or have it replaced during a routine inspection or an already-scheduled maintenance visit, i.e., a "planned replacement". Each type of replacement has a different cost associated with it.

In addition to the cost of replacing the CO sensors, some consumers may experience a significant inconvenience cost of having their gas furnace or boiler shut-down. Staff was unable to quantify inconvenience costs for reasons further explained in Section 5.2.2.

3.3.1. Unplanned Replacement Cost

Consumers incur an unplanned replacement cost of a CO sensor when it unexpectedly fails. The draft proposed rule requires gas furnaces and boilers to cycle on and off every 15 minutes if its CO sensor fails or turned completely off by the consumer. For the gas furnace or boiler to be fully operable again, the CO sensor would need to be replaced. Consumers could pay a heating service technician to replace it or replace it themselves. This analysis assumes that nearly all consumers would call a service technician to replace the CO sensor. The full replacement cost for a CO sensor would be the labor cost of the technician and the cost of the new CO sensor.

Guidehouse (2021) estimated the cost of a CO sensor to be $3.83, when adjusted for inflation to 2022 dollars.[67] The expected labor cost would depend on who replaced the sensor. In this analysis, staff considers three possible options:

1. Property Management Maintenance Staff – Gas furnaces and boilers in managed properties have maintenance staff on site. The cost to replace a sensor would be the direct labor cost of that maintenance staff. CPSC staff estimates it would take one hour at a labor rate of $25.25 per hour to replace the sensor, which is paid by the landlord.[68] [69]
2. Home Service Plan – Some homeowners purchase a home service plan, which is a service contract, that offsets some of the costs for typical home maintenance. Gas furnaces and boilers that require replacement in a home which has a service plan would pay a reduced service fee. Staff used prices on home service warranty plans to estimate a labor charge of $75 dollars to replace a CO sensor.[70]
3. Out-of-Pocket Service Technician - For households with neither home service plans or onsite maintenance, consumers would have to pay the market rate of a technician to replace the sensor. Staff estimates that the market rate for a technician to replace a CO sensor would be $200.[71] [72]

Next, staff needed to determine the share of households under each scenario. According to 2019 American Household Survey collected by the U.S. Census Bureau[73], 36 percent of housing units are renter-occupied while 64 percent are owner-occupied.

The 36 percent of housing units that are renter-occupied are comprised of single-family housing and multi-family housing. Staff assumes no single-family housing has onsite maintenance staff. For multi-family housing units, data from a survey on property management[74] shows that 31.2 percent of dwellings with 2 to 4 units have a property manager onsite which staff used as a proxy for maintenance staff. Staff then assumes housing with 5 or more units also have onsite maintenance staff. Given these parameters, staff calculates that 18.14 percent[75] of all housing have an onsite maintenance staff.

For the 64 percent of owner-occupied housing units, staff used estimates from the home service warranty market to estimate the number of units covered by home service plans. IBIS World

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[67] Original estimate of $3.55 in 2021 dollars. Adjusted for inflation to 2022 dollars using: Bureau of Labor Statistics, "CPI for All Urban Consumers (CPI-U)", Not Seasonally Adjusted, Series Id: CUUS0000SA0

[68] The U.S. Bureau of Labor Statistics (BLS) reports a median HVAC technician wage rate of $23.38 as of May 2021. For more information see: https://www.bls.gov/oes/current/oes499021.htm

[69] Adjusted for inflation to 2022 dollars using: Bureau of Labor Statistics, "CPI for All Urban Consumers (CPI-U)", Not Seasonally Adjusted, Series Id: CUUS0000SA0

[70] Parkman, Kathryn, "Home Service Warranty Companies and Plans, Consumer Affairs", accessed 4/14/2022, url: Best Home Warranty Companies of 2022 | https://www.consumeraffairs.com/homeowners/aaa_warranties.html

[71] Used the replacement cost for a furnace ignitor as a proxy for of the servicing cost to replace a CO sensor. Used the midpoint of the cost range of $150 to $250.

[72] Perry, Christin, and Tynan, Corrine, "How Much Does The Average Furnace Repair Cost For 2023?",accessed 4/21/2023, https://www.forbes.com/home-improvement/hvac/cost-to-repair-furnace/#:~:text=Average%20furnace%20repair%20cost%20for%20an%20electric%20furnace%20ranges%20between,for%20a%20furnace%20service%20cost

[73] To access AHS 2019 data tables more information, see https://www.census.gov/programs-surveys/ahs/data/2019/ahs-2019-summary-tables.html.

[74] See https://ipropertymanagement.com/research/property-management-industry-statistics

[75] 18.14% = 36% rental housing – 10% one-unit detached rental housing – 2% one-unit attached rental housing – 1% mobile homes – (6% two-to-four units rental housing × (1 - 31.2% two-to-four units rental housing that has a property manager)). Exact total may be off due to rounding.

(2020) reports there is a Home Service Warranty market of approximately $2.6 billion. The typical service plan costs approximately $400 per year. This implies that as many as 6.4 million homes may have a service plan.[76] However, home service warranty plans are not the only appliance maintenance plan available to homeowners. HVAC appliance installers, repairers, retailers, and even utility companies offer varying maintenance plans. Data on coverage of these plans are difficult to find. For these reasons, staff applies the same estimate of coverage for home warranty plans to alternative HVAC maintenance plans. This would equate to 12.8 million households (2 × 6.4 million = 12.8 million) in 2019. This represents 10.33 percent of the 123.91 million total households in 2019.

Staff assumes the remaining 71.53 percent of total households[77] would pay out-of-pocket to replace sensors.

Using the costs for each scenario and the share of households that fall under each of the three scenarios, staff calculates a weighted average cost of replacement which it uses in this cost analysis. Table 3 shows the costs for each scenario, the share of households in each scenario, and a weighted average cost to replace the sensors.

Table 3: Cost of Unplanned Replacement of CO Sensor

	Labor Cost	Share of Households	Weighted Labor Cost	Cost of Sensors	Total Weighted Cost
Scenario	**a**	**b**	**c = ∑(a × b)**	**d**	**e = c + d**
Property Management	$25.25	18.14%	$155.39	$3.83	$159.23
Home Service Plan	$75.00	10.33%			
Out-of-Pocket	$200.00	71.53%			

3.3.2. Planned Replacement Cost

Consumers incur a planned replacement cost when CO sensors are replaced during an annual or regularly scheduled servicing or when the CO sensor is replaced during servicing for another issue. Replacing the CO sensor during a scheduled maintenance visit is less costly than an unplanned replacement because the costs are just the incremental labor spent and the sensor replacement, avoiding fixed and other transaction costs from servicing. Staff uses an estimate from a DOE technical report[78] [79] of 0.077 incremental labor hours as a proxy for the additional time charged to replace a CO sensor on already scheduled visit. The price of parts and the incremental labor comes to $15.80.[80]

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[76] Roth Ryan, "Homecoming: Consistent improvements in the housing market are expected to boost industry demand", 2020, *IBIS World*, *Industry Report: Home Warranty Providers*.
[77] 71.53% = 100% - 18.14% housing with maintenance staff - 10.33% housing with home service plans
[78] U.S. Department of Energy, "Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Residential Furnaces", pg. 8F-2, February 10, 2015.
[79] U.S. Department of Energy, "Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Residential Boilers", pg. 8E-2, March 12, 2015.
[80] $15.80 = 0.077 hours × $155.39 per hour labor cost + $3.83 cost of sensor.

3.3.3. Repair Costs

After a gas furnace or boiler shuts down from detecting high levels of CO, the gas furnace or boiler will continue to be inoperable until someone addresses the CO leak and the CO sensor can no longer detect high levels of CO. Consumers would incur costs to repair the gas furnace or boiler. Staff found the average cost of $300 to repair a furnace.[81] [82] While repairing the furnace is a direct result from the compliant furnace's or boiler's safety mechanism, staff assesses that in the baseline scenario where there is no regulation, a gas furnace or boiler that experienced a CO leak would eventually be replaced or repaired as well (along with potentially causing injury or death). Therefore, staff assesses the incremental change in repair costs to be *de minimis*. Staff recommends the Commission seek public comment and information on the average repair costs of gas furnaces and boilers in the baseline scenario and under the draft proposed rule.

3.4. Deadweight Loss

In economics, deadweight loss refers to losses in welfare (i.e., reduction in consumer and producer surpluses[83]) from reduced demand or supply due to a major event such as a new regulation. In the analysis for this draft proposed rule, the price per unit is higher than the pre-regulation equilibrium, and the quantity demanded is less than manufacturers would be willing to supply. A marginal number of consumers would leave the gas furnace and boiler market in response to the price increases. These consumers would likely purchase a substitute such as an electric furnace.[84] Staff's deadweight loss calculation captures the welfare loss to consumers from being priced out of their preferred product.

To produce an estimate of deadweight loss, staff used the retail price increase and reduction in demand in the gas furnace and boiler market. Staff then used those estimates to calculate the deadweight loss for each year in the 30-year study period.

Table 1 showed an estimated price increase from the draft proposed rule of $70.44 per furnace and $87.59 per boiler. When compared to the average market price of $1,660 and $3,719 per furnace and boiler, respectively, it translates into a 4.24 percent price increase for furnaces and a 2.35 percent price increase for boilers. Staff expects that a price increase to consumers would lead to a decrease in demand resulting in less units sold. Staff could not find a price elasticity estimate for gas furnaces or boilers. Staff seeks public comments for any data or information on price elasticity for gas furnaces or boilers. For this analysis, staff uses the price elasticity for air conditioners[85] of -0.2292[86] as a proxy for gas furnaces and boilers. Using this elasticity, staff calculates the price increases would result in a 0.97 percent decrease in demand for gas furnaces and 0.54 percent decrease in demand for gas boilers.

[81] Perry, Christine, Pelchen, Lexie, "Learn About the Average Furnace Repair Cost for 2022", *Forbes Home*, August 22, 2022, https://www.forbes.com/home-improvement/hvac/cost-to-repair-furnace/
[82] Home Adviser, https://www.homeadvisor.com/cost/heating-and-cooling/repair-a-furnace/, Average Furnace Repair Cost is $131 - $490 as of December 8, 2022.
[83] Consumer surplus is the difference between what consumers pay for a product or service and the price they're willing to pay. Producer surplus is the difference between the amount a producer benefits from producing a product and the market price.
[84] As of this document, electric heating was more expensive than natural gas and heating oil, but less expensive than propane, according to EIA's Winter Fuels Outlook, October 2022. https://www.eia.gov/outlooks/steo/report/winterfuels.php
[85] Staff used air conditioners because staff assesses it is a comparable inelastic, costly appliance.
[86] Taylor, Lester D., Houthakker, H.S., 2010. Consumer demand in the United States: Prices, income, and consumption behavior (3rd ed.). New York: Springer

Figure 2 and Figure 3 illustrate the slight decrease in demand on total sales of gas furnaces and boilers throughout the 30-year period study in reaction to the price increase.

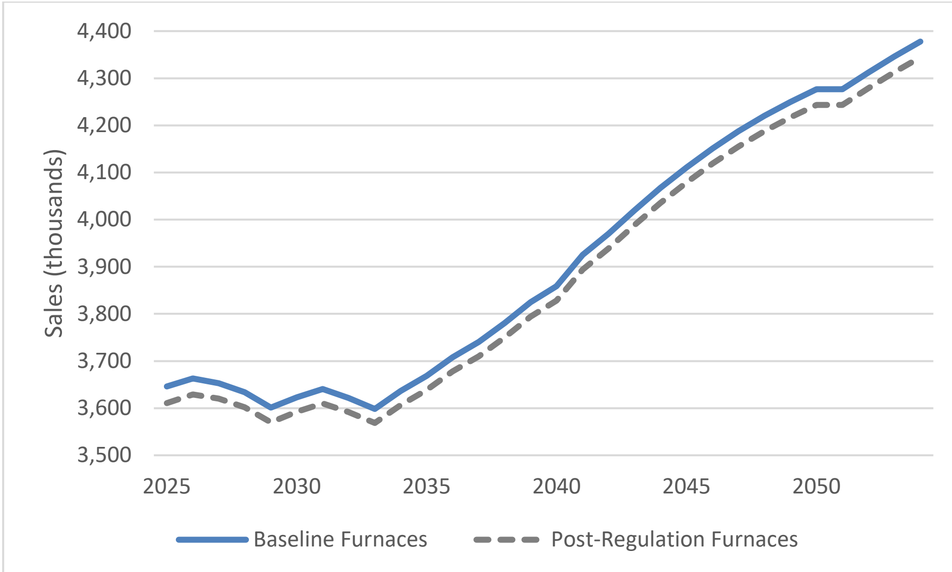

Figure 2: Shift in Sales for Gas Furnaces Due to the Draft Proposed Rule

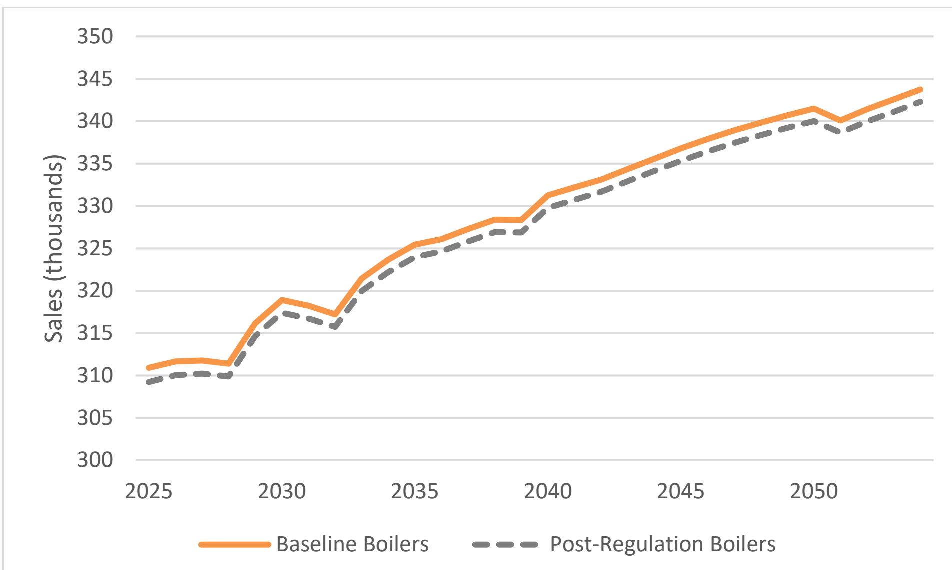

Figure 3: Shift in Sales for Gas Boilers Due to the Draft Proposed Rule

The figures show a small and consistent decrease in sales throughout the 30-year study period. In the baseline, the projected sales of all in-scope products of the rule are estimated to be 3.96 million in 2025 and expected grow to 4.72 million in 2054. When accounting for the market impact of increased prices, staff estimates projected sales of all in-scope products to 3.92 million in 2025 and expects it to grow to 4.69 million in 2054. This equates to about 33,000 less sales annually throughout the study period.

Staff calculates deadweight loss (DWL) by using the formula: DWL = ½ × Change in price × Change in quantity demanded. Staff applies this formula for each year in the 30-year study period.

3.5. 30-Year Cost Analysis

This section presents the aggregate costs for each category over the 30-year study period. A 30-year period guarantees at least one generation of gas furnaces and boilers that have product lives above 20 years and ensures the cost assessment accounts for the timing of various fixed and variable costs from the draft proposed rule.

3.5.1. 30-Year Cost of Installing CO Sensors and Shutoff Capabilities

In section 3.1, staff estimated the per-unit cost of installing CO sensors in new units to be $70.44 and $87.59 for gas furnaces and boilers, respectively. However, staff assesses that these costs would go down as manufacturers produce more iterations of these new gas furnaces and boilers models with CO sensors and shutoffs. To account for this, staff included a "learning curve" in this cost assessment to simulate the future efficiencies in production that would bring down costs. The learning curve reduces the per-unit costs by 5 percent every time the quantity of production doubles. This rate of cost reduction aligns with other repetitive electronics manufacturing industries.[87] Figure 4 shows the per unit cost of installation of CO sensor over the 30-year study period.

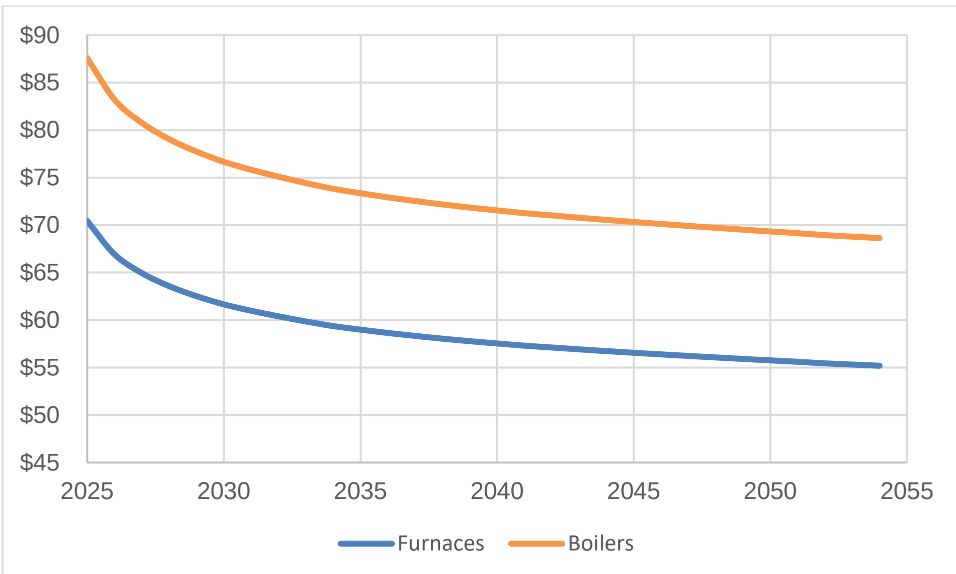

Figure 4: Installation Per Unit Costs with Learning Curve over 30 years

Staff multiplies these per unit costs by the number of gas furnaces and boilers sold throughout the 30-year study period. While manufacturers may produce more units than sold, staff assumes that since gas furnaces and boilers are expensive and expensive-to-transport goods, that manufacturers keep inventory low and thus sales are a good proxy for manufactured units. Staff

87 Learning Curve Calculator (archive.org)

multiplied unit costs with the post-regulatory forecasted sales (displayed in Figure 2 and Figure 3) to calculate CO sensor installation costs for each year in the study period.

Staff estimates that in the first year of the rule (2025), the undiscounted cost of installing CO sensors into gas furnaces and boilers would be $281.40 million,[88] and would be $263.28 million[89] in the last year of the rule (2054). Over 30 years, these costs aggregate to $7.55 billion undiscounted, $4.93 billion discounted at 3 percent, and $3.12 billion discounted at 7 percent.

3.5.2. 30-Year Conversion Cost

In section 3.2, staff estimated conversion costs, which are a fixed, one-time cost of $446.35 million in the first year of the rule (2025).

3.5.3. 30-Year Increased Maintenance Cost

In section 3.3, staff estimated per unit CO sensor replacement cost to be $159.23 and $15.80 for unplanned and planned replacements, respectively. Staff multiplies these per unit costs for each incidence where CO sensors need to be replaced or serviced.

Modeling for the timing of CO sensor replacement has many complexities. A sensor has a product life of 10 years, while the appliance it is attached to has product life of about double. Therefore, staff had to account for instances when CO sensors needed to be replaced and when the appliance needed to be replaced (which would include a new sensor). Additionally, staff had to distinguish a CO sensor that was replaced because it failed unexpectedly from one that was replaced during a routine inspection or maintenance because both have different labor costs. Given these complexities, staff used a simulation.

The sensor replacement simulation used a mixed Weibull distribution model. A Weibull distribution is a probability distribution used to model the likelihood of a product failure. It accounts for the small likelihood that products fail well before, or extend well beyond, its expected product life, but also that there is a higher likelihood that products will fail around the time of its expected product life. This simulation nests a Weibull distribution for the CO sensor lifetime within a wider Weibull distribution for the gas furnace or boiler lifetime subject to the following constraints:

1. Failed sensors are replaced over the life of the furnace or boiler;
2. Replacements are scaled by the probability that the furnace/boiler is still in-use;
3. Renter-occupied households regularly service gas furnaces and boilers and replace CO sensors after 5 years (i.e., planned replacement) unless the sensor failed before planned replacement; and
4. One-third of owner-occupied households regularly service gas furnaces and boilers and these owners replace CO sensors after 5 years (i.e., planned replacement) unless the sensor failed before the planned replacement.

If the sensor lifetime was less than the furnace lifetime, the simulation drew a second sensor lifetime and added it to the first, and so on until the furnace lifetime had been reached. The simulation ran 1 million of these simulated furnace lifetimes and normalized the results to obtain

[88] $281.40 million = $70.44 per furnace × 3.61 million furnaces sold in 2025 + $87.59 per boiler × 0.31 million boilers sold in 2025.
[89] $263.28 million = $55.19 per furnace × 4.34 million furnaces sold in 2054 + $68.63 per boiler × 0.34 million boilers sold in 2054.

the probabilities of planned and unplanned sensor replacements throughout the 30-year study period. Figure 5 illustrates the probabilities of a planned and unplanned replacement throughout the 30-year study period according to the simulation model.

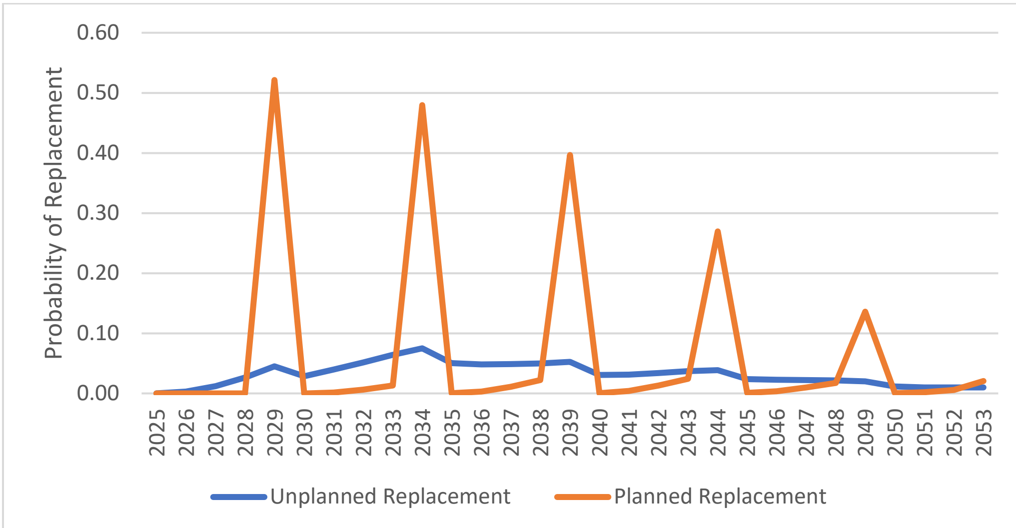

Figure 5: Expected CO sensor replacement schedule for a furnace purchased in 2025

In instances where the compliant gas furnaces and boiler shuts off because of a CO leak, the consumer will pay an average of $300 to service and repair their gas furnace or boiler. However, staff assumes the net cost of this is zero because gas furnaces and boilers in the baseline scenario of no regulation would also be replaced or repaired (along with potentially causing injury or death to consumers).

Staff sums the costs from unplanned CO sensor replacements and planned CO sensor replacements to estimate that there is no cost in the first year of the rule (2025) in increased maintenance, and in the last year of the rule (2054) there would be $755.99 million[90] in increased maintenance cost in undiscounted dollars. Over 30 years, these costs aggregate to $11.81 billion undiscounted, $6.42 billion discounted at 3 percent, and $3.09 billion discounted at 7 percent.

3.5.4. 30-Year Deadweight Loss

In section 3.4, staff presented the formula to calculate DWL in each year of the 30-year study period. Staff used the post-regulatory annual sales (displayed in Figure 2 and Figure 3) and the installation per-unit costs throughout the 30-year study period (Figure 4) in the DWL formula. Staff estimates that in the first year of the rule (2025), the undiscounted DWL would be $1.32 million,[91] and reach $0.97 million[92] in the last year of the rule (2054). Over 30 years, these costs aggregate to $29.66 million undiscounted, $19.65 million discounted at 3 percent, and $12.70 million discounted at 7 percent.

[90] $424.68 million = $15.80 per furnace × 8.41 million sensors serviced in 2054 + $159.23 per boiler × 3.91 million sensors replaced in 2054.

[91] $1.32 million = $35.22 × 0.00972 ×3.65 million furnaces sold in 2025 + $43.79 × 0.00539 × 0.31 million boilers sold in 2025.

[92] $0.97 million = $27.60 × 0.00763 ×4.38 million furnaces sold in 2054 + $34.32 × 0.00423 × 0.34 million boilers sold in 2054.

3.5.5. 30-Year Total Cost of the Draft Proposed Rule

Staff added up all cost categories to determine the total cost of the draft proposed rule over the 30-year study period. Staff estimates that in the first year of the rule (2025), the total undiscounted cost would be $729.07 million,[93] and reach $1.02 *billion*[94] in the last year of the rule (2054). Over 30 years, these costs aggregate to $19.84 billion undiscounted, $11.80 billion discounted at 3 percent, and $6.65 billion discounted at 7 percent.

Over the 30-year study period, costs to install CO sensors and shutoff capabilities, and replacement costs, compose most of the costs – over 97 percent of total costs. Figure 6 illustrates the annual costs (non-cumulative) for both categories over the study period in undiscounted dollars. The graph shows installation costs remaining fairly stable throughout the 30 years, while replacement costs track the number of compliant products in-use and thus starts well below installation cost, but continuously rise at a fast pace and surpassing installation costs in 2035.

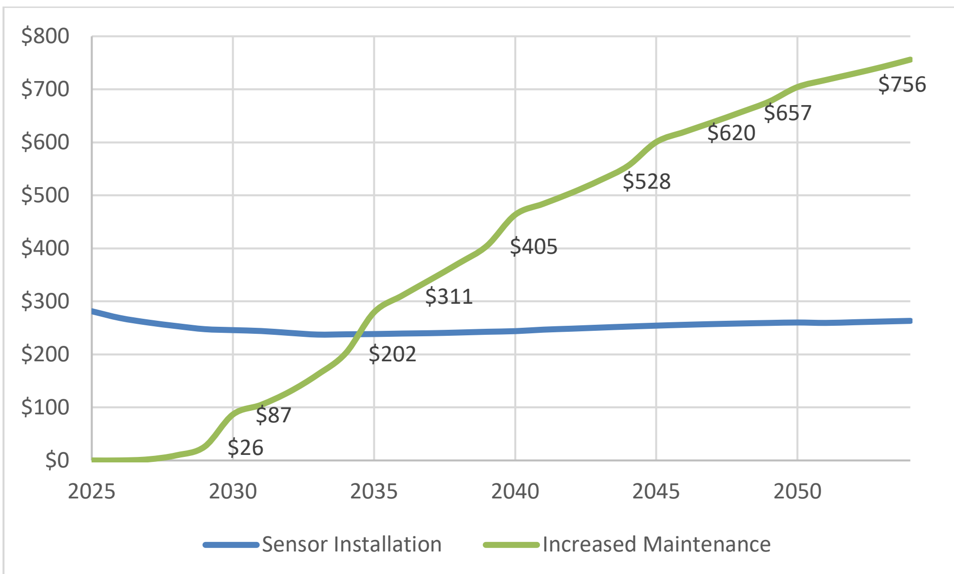

Figure 6: Significant Costs over the 30-Year Study Period

3.6. Annualized and Per Unit Cost of Draft Proposed Rule

This section converts the aggregate costs over the 30-year study period into annualized and per-unit outputs. An annualized output converts the aggregate costs over 30 years into a consistent annual amount while considering the time value of money. This metric is helpful when comparing the costs among different rules or policy alternatives that may have different timelines; or those that have similar timelines but costs for one are front-loaded while the other's maybe backloaded.[95] A per-product metric expresses the costs from the rule in one unit of product. This metric is helpful when assessing the impact in marginal terms; for example, comparing costs to

[93] $729.07 million = $281.41 million in CO sensor installation costs + $446.35 million in conversion costs + $0 replacement cost + $1.32 million in DWL.

[94] $1,020.24 million = $263.28 million in CO sensor installation costs + $0 million in conversion costs + $755.99 replacement cost + $0.97 million in DWL.

[95] The timing of costs along the period of study affects the present value of costs when considering the time value of money. Costs incurred several years into the future are discounted more heavily than costs realized in the short-term.

an increase in retail price. Staff presents both these metrics to convey a holistic perspective of the impact from this draft proposed rule.

The following table summarizes the cost of the draft proposed rule in annualized terms:

Table 4: Annualized Cost of the Draft Proposed Rule

Cost Categories	Annualized Costs ($M)		
	Undiscounted	3% Discount	7% Discount
Cost of CO Sensors and Shutoff	$251.73	$251.43	$251.81
Conversion Costs	$14.88	$22.11	$33.62
Increased Maintenance Costs	$393.64	$327.73	$249.30
Deadweight Loss	$0.99	$1.00	$1.02
Total Costs	**$661.24**	**$602.27**	**$535.75**

The following table summarizes the cost of the draft proposed rule in per unit[96] terms:

Table 5: Per Unit Cost of the Draft Proposed Rule

Cost Categories	Per Unit Costs ($)		
	Undiscounted	3% Discount	7% Discount
Cost of CO Sensors and Shutoff	$101.15	$66.01	$41.85
Conversion Costs	$5.98	$5.80	$5.59
Increased Maintenance Costs	$158.17	$86.04	$41.43
Deadweight Loss	$0.40	$0.26	$0.17
Total Costs	**$265.69**	**$158.11**	**$89.04**

4. Preliminary Regulatory Analysis: Benefits Assessment

Staff conducted the preliminary regulatory analysis from a societal perspective that considers significant costs and health outcomes (Gold et al., 1996; Haddix, Teutsch, and Corso, 2003; Neumann et al, 2016). Staff captured benefits by estimating the number of deaths and injuries that would be prevented by the draft proposed rule. Staff estimated the number of expected deaths and injuries prevented by the draft proposed rule for a 30-year study period and converted them into monetary terms – specifically, 2021 dollars – using the Value per Statistical Life (VSL) for deaths and CPSC's Injury Cost Model (ICM) for injuries.

Like the cost assessment, staff used a 30-year study period (2025-2054) to assess the benefits of the draft proposed rule. Staff then converted the aggregate benefits over the 30-year study period into annualized and per unit outputs. An annualized output converts the aggregate benefits over 30 years into a consistent annual amount while considering the time value of money. This metric is helpful when comparing the benefits among different rules or policy alternatives that may have

[96] Staff calculates per unit terms using this formula: (30-year total cost of the rule) ÷ (Sum of annual compliant units in use throughout 30-year study period) × 21.94 years for weight average product life for gas furnaces and boilers.

different timelines; or those that have similar timelines but benefits for one are front-loaded while the other's benefits have a latent effect.[97] A per unit metric expresses the benefits from the rule in one unit of product. This metric is helpful when assessing the impact in marginal terms; for example, comparing benefits to an increase in retail price or marginal increase in cost of production per-unit. Staff presents both these metrics to convey a holistic perspective of the impact from the draft proposed rule.

Finally, CPSC Engineering Sciences staff assesses that the draft proposed rule would be highly effective, between a 90 and 100 percent effective rate, in mitigating gas furnaces and boilers deaths and injuries. This is because the recommended mitigation requirement – installing a sensor and shut off device as a fail-safe system – would prevent CO levels from increasing to the point of causing deaths and injuries. Additionally, the control technology that would be used with CO sensors would prevent a gas furnace or boiler from fully operating – the appliance would cycle between on and off every 15 minutes when there is failed or malfunctioning CO sensor – which adds an additionally layer of safety. For the purpose of this analysis, staff chose the midpoint of the effective rate range, 95 percent, to estimate benefits from this draft proposed rule.

4.1. Deaths Related to Gas Furnaces and Boilers Hazards

Staff identified 108 deaths from gas furnace and boiler-related CO poisonings that occurred from 2014 through 2018 (Topping 2022). To forecast deaths into the future, staff used death rates per million gas furnaces or boilers with its forecast of compliant gas furnaces and boilers in-use throughout the study period. Staff assumed deaths would remain at the same average rate observed between 2014 to 2018: 0.37 deaths per million gas furnaces or boilers.

To estimate the societal costs of deaths, staff applied the VSL. VSL is an estimate used in benefit-cost analysis to place a value on reductions in the likelihood of premature deaths (OMB, 2003). The VSL does not place a value on individual lives, but rather, it represents an extrapolated estimate, based on the rate at which individuals trade money for small changes in mortality risk (OMB, 2003). This is a "willingness to pay" methodology which attempts to measure how much individuals are willing to pay for a small reduction in their own mortality risks, or how much additional compensation they would require to accept slightly higher mortality risks.

For this analysis, staff applied estimates of the VSL developed by the U.S. Department of Health and Human Services (HHS). The HHS estimate of the VSL when adjusted for inflation and growth in real income, consistent with HHS guidelines[98], is $12.29 million for 2022.[99] While staff keeps the VSL in 2022 dollars throughout the 30-year study period – like all monetized values in this analysis – it does allow the VSL to grow during this time to account for growth in real income in accordance with HHS guidelines. This is because VSL is a function of income. Staff applies the Congressional Budget Office's estimate of 0.80 percent for long-run income growth rate throughout the 30-year study period. This adjustment grows the VSL estimate to $12.59 million in 2025 to $15.86 million in 2054.

[97] The timing of benefits along the period of study affects the present value of benefits when considering the time value of money. Benefits realized several years into the future are discounted more heavily than benefits realized in the short-term.

[98] U.S. Health and Human Services, "Appendix D: Updating Value per Statistical Life (VSL) Estimates for Inflation and Changes in Real Income", Figure D.1., April 2021, https://aspe.hhs.gov/sites/default/files/2021-07/hhs-guidelines-appendix-d-vsl-update.pdf.

[99] Ibid. Original 2013 VSL estimate of $9.0 million was adjusted to 2022 using a factor of 1.256262 (292.655 ÷ 232.957, CPI-U indices for 2022 and 2013, Series Id: CUUR0000SA0) for inflation, and 1.087087 (362 ÷333, Weekly and hourly earnings data from the Current Population Survey Indices for 2022 and 2013, Series Id: LEU0252881600).

Staff uses the VSL estimates with the forecasted number of prevented deaths from the draft proposed rule throughout the 30-year study period to calculate benefits. First, staff calculates the number of prevented deaths by multiplying the death rate per gas furnace or boiler by the effective rate of the draft proposed rule and the number of compliant products in-use. Specifically, staff multiplies the number of products in-use for each year of the study period with the 95 percent effective rate, the 0.37 deaths per million products rate, and the VSL estimate for that year to calculate benefits from prevented deaths in that given year.

Staff used the forecast of the number of sales (displayed in Figure 2 and Figure 3) to estimate how many compliant products would be in-use in every year in the 30-year study period by applying a statistical distribution of product life rates.[100] Figure 7 displays the number of in-use compliant gas furnaces and boilers throughout the study period.

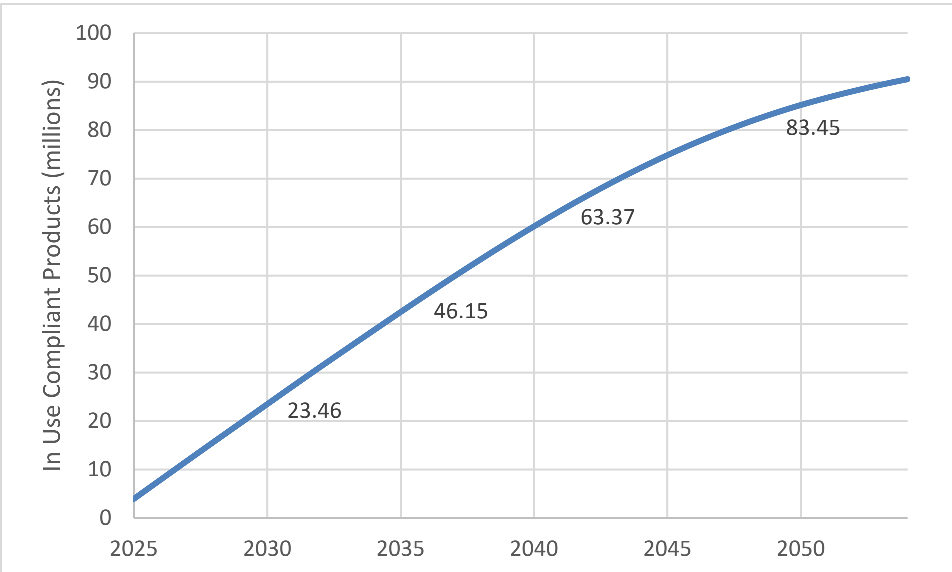

Figure 7: Compliant Products In-use Throughout 30-Year Study Period

Staff estimates that in the first year of the rule (2025), compliant gas furnaces and boilers would prevent an estimated 1.38 deaths and the undiscounted benefits would be $17.43 million;[101] in the last year of the study period (2054), compliant gas furnaces and boilers would prevent an estimated 31.96 deaths and benefits would reach $506.90 million[102]. Over 30 years, compliant gas furnaces and boilers would prevent an estimated 575.98 deaths and benefits would aggregate to $8.43 billion undiscounted, $4.75 billion discounted at 3 percent, and $2.44 billion discounted at 7 percent.

4.2. Injuries Related to Gas Furnaces and Boilers Hazards

[100] Staff used a Weibull distribution forecast product survival rates with a shape parameter of 22.90 and scale parameter of 3.37 for furnaces and 26.75 and 3.20 for boilers. These distribution parameters are consistent with a mean product duration of 21.6 years and 25.0 years for gas furnaces and boilers, respectively.

[101] $17.43 million = 3.92 million in use compliant products in 2025 × 95% effective rate × 0.372 deaths per million gas furnaces and boilers × $12.59 million.

[102] $506.90 million = 90.49 million in use compliant products in 2054 × 95% effective rate × 0.372 deaths per million gas furnaces and boilers × $15.86 million.

The Directorate for Epidemiology (EP) retrieved casualties reported through the National Electronic Injury Surveillance System (NEISS), a national probability sample of U.S. hospital emergency departments (ED). Staff used NEISS to identify 236 nonfatal injuries related to CO leakages from gas furnaces and boilers that occurred from 2014 through 2018. Of the 236 nonfatal injuries, 18 resulted in hospital admissions via the ED, and 218 were treated in the ED and released. Next, staff used these NEISS incidents and the ICM to extrapolate and generate national estimates for injuries from CO leakages from gas furnaces and boilers treated in the ED and other settings. The ICM estimated 30,587 aggregate nonfatal injuries from CO leakages from gas furnaces and boilers occurred from 2014 to 2018. The ICM estimates that from the 30,587 injuries, 22,817 were treated in an outpatient setting (e.g., doctor's office, or clinic), 7,358 resulted in ED treatment, 333 resulted in hospital admissions via the ED, and 79 resulted in direct hospital admissions.

To forecast these injuries into the future, staff used injury rates per million gas furnaces and boilers with its forecast of compliant gas furnaces and boilers in use throughout the 30-year study period. Staff assumed injuries would stay at the same rates observed between 2014 to 2018: 24.95 emergency department admissions per million gas furnaces or boilers in use, 0.27 direct hospital admissions per million gas furnaces or boilers in use, 1.13 hospital admissions via ED per million gas furnaces or boilers in use, and 77.37 doctor/clinic visits per million gas furnaces or boilers in use.

Staff estimated the societal costs of nonfatal injuries using the ICM. Societal cost components include medical costs, work losses, and the intangible costs associated with pain and suffering (Lawrence et al., 2018).

Medical costs include three categories of expenditures: (1) medical and hospital costs associated with treating the injured victim during the initial recovery period and in the long run, including the costs associated with corrective surgery, the treatment of chronic injuries, and rehabilitation services; (2) ancillary costs, such as costs for prescriptions, medical equipment, and ambulance transport; and (3) costs of health insurance claims processing. The ICM derives cost estimates for these expenditure categories from several national and state databases, including the Medical Expenditure Panel Survey (MEPS), the Nationwide Inpatient Sample of the Healthcare Cost and Utilization Project (HCUP-NIS), the Nationwide Emergency Department Sample (NEDS), the National Nursing Home Survey (NNHS), MarketScan® claims data, and a variety of other federal, state, and private databases.

Work loss estimates include: (1) the forgone earnings of the victim, including lost wage work and household work; (2) the forgone earnings of parents and visitors, including lost wage work and household work; (3) imputed long-term work losses of the victim that would be associated with permanent impairment; and (4) employer productivity losses, such as the costs incurred when employers spend time rearranging schedules or training replacement workers. The ICM bases these estimates on information from the MEPS, the Detailed Claim Information (a workers' compensation database) maintained by the National Council on Compensation Insurance, the National Health Interview Survey, the U.S. Bureau of Labor Statistics, and other sources.

The intangible costs of injury reflect the physical and emotional trauma of injury, as well as the mental anguish of victims and caregivers. Intangible costs are difficult to quantify because they do not represent products or resources traded in the marketplace. Nevertheless, they typically represent the largest component of injury cost and need to be accounted for in any benefit-cost analysis involving health outcomes (Rice et al., 1989; Haddix, Teutsch, and Corso, 2003; Cohen and Miller, 2003; Neumann et al, 2016). The ICM develops a monetary estimate of these intangible costs from jury awards for pain and suffering. Although these awards can vary widely on a case-by-case basis, studies have shown these are systematically related to several factors, including economic losses, the type and severity of injury, and the age of the victim (Viscusi, 1988; Rodgers, 1993; Cohen and Miller, 2003). The ICM derives these estimates from a regression analysis of jury awards in nonfatal product liability cases involving consumer products compiled by Jury Verdicts Research, Inc.

The ICM estimates that the costs (in 2022 dollars) associated with CO poisoning injuries are: $20,140 for injuries treated at the doctor's office/clinic, $24,035 for injuries treated at the emergency department, $281,142 for injuries direct hospital admissions, and $259,872 for injuries that result in hospital admission via ED.

To calculate the benefits of prevented injuries, staff multiplies the number of products in-use for each year of the study period (Figure 7) with the 95 percent effective rate, the vector of rates of injury type, and the vector of cost per type of injury, to calculate benefits from prevented injuries in that given year.

Staff estimates that in the first year of the rule (2025), compliant gas furnaces and boilers would prevent an estimated 386.22 injuries and the undiscounted benefits would be $9.41 million;[103] in the last year of the rule (2054), compliant gas furnaces and boilers would prevent an estimated 8,917 injuries and reach $217.20 million[104]. Over 30 years, compliant gas furnaces and boilers would prevent an estimated 160,699 injuries and benefits would aggregate to $3.91 billion undiscounted, $2.23 billion discounted at 3 percent, and $1.17 billion discounted at 7 percent.

4.3. Annualized and Per Unit Benefits of Draft Proposed Rule

This section converts the aggregate benefits over the 30-year study period into annualized and per-unit outputs. An annualized output converts the aggregate benefits over 30 years into a consistent annual amount while considering the time value of money. This metric is helpful when comparing the benefits among different rules or policy alternatives that may have different timelines; or those that have similar timelines but benefits for one are front-loaded while the other's maybe backloaded. A per-product metric expresses the benefits from the rule in one unit of product. This metric is helpful when assessing the impact in marginal terms; for example, comparing costs to an increase in retail price. Staff presents both these metrics to convey a holistic perspective of the impact from this draft proposed rule.

The following table summarizes the benefits of the draft proposed rule in annualized terms:

[103] $8.71 million = 3.92 million in use compliant products in 2025 × 95% effective rate × [(2.50×10^{-5} × $24,035) + ($2.67\times10^{-7}$ × $281,142) + ($1.13\times10^{-6}$ × $259,872) + ($7.74\times10^{-5}$ × $20,140)].

[104] $201.11 million = 90.49 million in use compliant products in 2054 × 95% effective rate × [(2.50×10^{-5} × $24,035) + ($2.67\times10^{-7}$ × $281,142) + ($1.13\times10^{-6}$ × $259,872) + ($7.74\times10^{-5}$ × $20,140)].

Table 6: Annualized Benefits of the Draft Proposed Rule

Prevented Casualties	Annualized Benefits ($M)		
	Undiscounted	3% Discount	7% Discount
Deaths	$281.13	$242.52	$196.56
Injuries	$130.48	$114.01	$94.03
Total Benefits	**$411.61**	**$356.52**	**$290.60**

The following table summarizes the cost of the draft proposed rule in per unit[105] terms:

Table 7: Per Unit Benefits of the Draft Proposed Rule

Prevented Casualties	Per Unit Benefits ($)		
	Undiscounted	3% Discount	7% Discount
Deaths	$112.96	$63.67	$32.67
Injuries	$52.43	$29.93	$15.63
Total Benefits	**$165.39**	**$93.60**	**$48.30**

5. Benefits and Cost Analysis

Staff compared estimated benefits and costs to assess the relation between benefits and costs of the draft proposed rule. Staff found that the costs of the rule outweighed the benefits by $64.51 per unit for an annualized net benefit of -$245.74 million, discounted at three percent.

Table 8 displays annualized metrics for both the benefits and costs of the draft proposed rule. The table displays both net benefits (difference between benefits and costs) and the benefit-cost ratio (benefits divided by costs) to assess the cost-benefit relationship.

Table 8: Annualized Net Benefits and B/C Ratio

	Benefits Compared to Costs		
Annualized Net Benefits ($M)	**Undiscounted**	**3% Discount**	**7% Discount**
Benefits	$411.61	$356.52	$290.60
Costs	$661.24	$602.27	$535.75
Net Benefits (Benefits – Costs)	($249.62)	($245.74)	($245.15)
B/C Ratio	0.62	0.59	0.54

Table 9 compares the benefits and costs on a per-unit basis, to add a marginal value perspective.

105 Staff calculates per unit terms using this formula: (30-year total benefits of the rule) ÷ (Sum of annual compliant units in use throughout 30-year study period) × 21.94 years for weighted average product life for gas furnaces and boilers

Table 9: Per-Unit Net Benefits and B/C Ratio

Per Unit Net Benefits ($)	Benefits Compared to Costs: Undiscounted	3% Discount	7% Discount
Benefits	$165.39	$93.60	$48.30
Costs	$265.69	$158.11	$89.04
Net Benefits (Benefits – Costs)	($100.30)	($64.51)	($40.74)
B/C Ratio	0.62	0.59	0.54

The net benefits on per-unit basis are -$64.51, discounted at 3 percent. Alternatively, this can be described as the draft proposed rule being a net cost of $64.51 per gas furnace or boiler, which represents about 3 percent of the average price of a gas furnace or boiler. Overall, for every $1 in cost of the draft proposed rule, there is a return of $0.59 in benefits from mitigated deaths and injuries.

5.1. Sensitivity Analysis

The benefits and costs of the draft proposed rule are estimates that depend upon a relatively high number of inputs and assumptions. The benefits, for instance, are dependent on the value of a statistical life, and the societal cost of the different type of injuries; the benefits per gas furnace or boiler are also influenced by the number of units in use and the expected lifecycle, among other considerations. The costs of the draft proposed are driven by the estimates about costs for manufacturers to make gas furnaces and boilers compliant, the number of units in use, as well as other market variables. Some of these inputs and assumptions have a significant impact on the outcome of the analysis, while others are less significant. In this section, staff examine the impact of using alternative values for some of the key inputs and assumptions of the analysis.

5.1.1. Lower CO Sensor Replacement Cost from Technological Innovation

A significant cost of implementing the draft proposed rule would be the cost to consumers to replace CO sensors in gas furnaces and boilers. Because CO sensors have a shorter product life (10 years) than gas furnaces and boilers (20-26 years), consumers would have to pay service costs to replace CO sensors at least once in the appliance's lifetime, and for some consumers more than once. Since service costs are overwhelmingly made up of labor costs, the learning curve cannot be applied for these costs and the high unit costs remain at the same value throughout the 30-year study period.

The cost-benefit analysis of the draft proposed rule assumes CO sensors continue to have shorter product lives than the appliance throughout the 30-year study period. However, technological innovation over 30 years could develop a CO sensor that has a longer product life and possibly one that is the same lifespan as the gas furnace or boiler; therefore, reducing or eliminating the replacement costs to consumers. For this sensitivity analysis, staff recalculates costs with the assumption that manufacturers develop a gas furnace and boiler with long-lasting CO sensors that eliminate the need for replacement. This sensitivity analysis assumes this technological change occurs 10 years after the draft proposed rule is implemented.

Under this assumption, all gas furnace or boiler produced on or after 2035 would have no CO sensor replacement costs associated with it. However, all gas furnaces and boilers manufactured before 2035 would continue to require CO sensor replacement costs even after the year 2035. When staff recalculates annualized sensor replacement costs, discounted at 3 percent, under the 10-year technological innovation assumption, the cost decreases from $184.37 million to $111.54 million. Figure 8 illustrates the impact of this assumption by showing that the sensor replacement costs begin to bend downward after 2039 due to newer gas furnaces and boilers no longer needed to have their sensors replaced. This is in stark contrast from Figure 6, where replacement costs continue to rise throughout the 30-year study period.

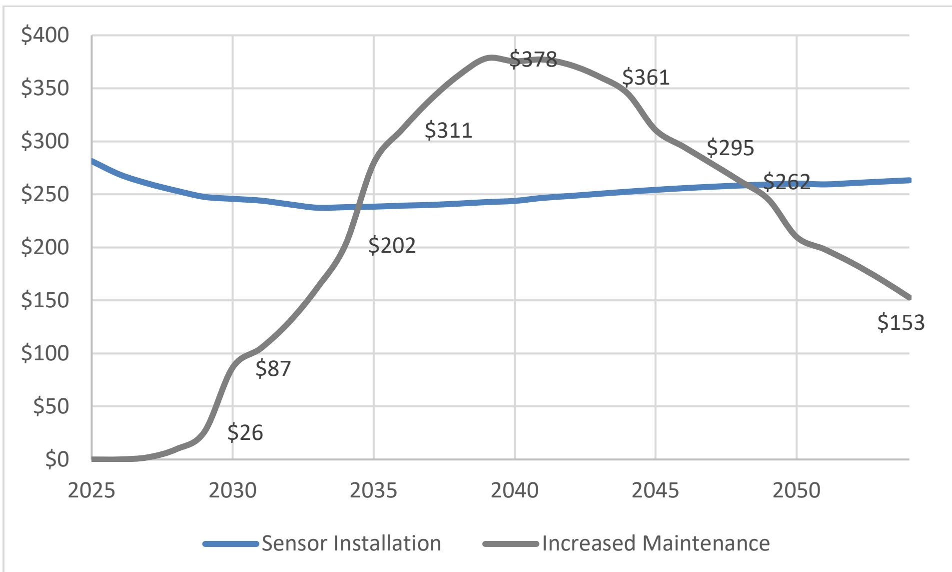

Figure 8: Sensitivity Analysis - Significant Costs over the 30-Year Study Period

Overall, total cost (sensor production, conversion, sensor replacement, and DWL) per unit, discounted at 3 percent, decreases from $158.11 per unit to $124.16 per unit.

5.1.2. Higher VSL for Children

In estimating the benefits associated with reduced mortality, staff applied an estimate of VSL of $10.5 million per premature death potentially averted by the draft proposed rule. Staff used a VSL estimate developed by the EPA.[106] The cost-benefit analysis did not distinguish between the VSL of children and adults.

Recent studies have suggested that the VSL for children could be higher than that for adults. Specifically, people might be willing to pay more to reduce the risk of premature death of children than to reduce the risk of premature death of adults. A review of the literature conducted for the CPSC suggested that the VSL for children could exceed that of adults by a factor of 1.2 to 3, with a midpoint of around 2 (IEc, 2018). Using the midpoint, the VSL for children would be $25.18

[106] EPA, "Mortality Risk Valuation", https://www.epa.gov/environmental-economics/mortality-risk-valuation

million per premature death averted in 2025, and grows to $31.72 million in 2054 due to the growth in real income.

Staff applied the children's VSL to 6 percent of deaths from CO poisoning from gas furnaces and boilers that are children (under 18 years old). When staff recalculates annualized benefits, discounted at 3 percent, it increases from $356.52 million to $371.08 million. Benefits per unit, discounted at 3 percent, increases from $93.60 per unit to $97.42 per unit.

5.1.3. Totality of Sensitivity Analyses

Staff recalculated costs and benefits with both assumptions of technological innovation for CO sensors and children's VSL to determine the totality of the impact. Table 10 displays metrics for benefits and costs from an annualized perspective.

Table 10: Sensitivity Analyses - Annualized Net Benefits and B/C Ratio

	Benefits Compared to Costs		
Annualized Net Benefits ($M)	**Undiscounted**	**3% Discount**	**7% Discount**
Benefits	$428.48	$371.08	$302.39
Costs	$485.30	$472.96	$454.79
Net Benefits (Benefits – Costs)	($56.82)	($101.88)	($152.40)
B/C Ratio	0.88	0.78	0.66

Under the totality of the sensitivity adjustments, annualized benefits, discounted at 3 percent, increase from $356.52 million to $371.08 million, while annualized costs, also discounted at 3 percent, decrease from $602.27 million to $472.96 million. The net effect of this is it increases net benefits from -$245.74 million to -$101.88 million, and the B/C ratio increased from 0.59 to 0.78 at a 3 percent discount rate.

Table 10 displays metrics for benefits and costs from a per-unit perspective.

Table 11: Sensitivity Analyses - Per-Unit Net Benefits and B/C Ratio

	Benefits Compared to Costs		
Per Unit Net Benefits ($)	**Undiscounted**	**3% Discount**	**7% Discount**
Benefits	$172.17	$97.42	$50.26
Costs	$195.00	$124.16	$75.59
Net Benefits (Benefits – Costs)	($22.83)	($26.75)	($25.33)
B/C Ratio	0.88	0.78	0.66

Under the totality of the sensitivity adjustments, per-unit benefits, discounted at 3 percent, increase from $93.60 to $97.42, while per-unit costs, also discounted at 3 percent, decrease from $158.11 to $124.16. The net effect of this is it increases net benefits from -$64.51 to -$26.75, and the B/C ratio increased from 0.59 to 0.78 at a 3 percent discount rate.

5.2. Unquantified Benefits and Costs

This section describes the benefits and costs that staff was not able to quantify but could potentially have a considerable impact on consumers. Staff seeks public comment, data, or information that could assist in quantifying these currently unquantified benefits and costs.

5.2.1. Unquantified Benefits

The cost-benefit analysis measured the cost to consumers using the increase in price, as well as the cost to consumers pushed out of the market by calculating deadweight loss. However, staff is unable to quantify the increase in utility to consumers from having safer gas furnaces and boilers. This utility is in addition to the reduced deaths and injuries and is essentially the sense of safety or reduction in anxiety in knowing that the hazard has now been mitigated.

Typically, intangible benefits, such as utility from an increase in safety, would be measured using a willingness-to-pay (WTP) study. However, a willingness-to-pay study is costly and can take months or years to complete, and unambiguous results are not guaranteed. Staff assumes that consumers would be willing to pay more for safer gas furnaces and boilers. In a relative case, a study found a positive WTP for auto safety devices such as airbags. While staff is certain that WTP would be positive for safer gas furnaces and boilers, the magnitude of WTP is unknown. But given a positive WTP, the exclusion of the utility from safer gas furnaces and boilers would mean the benefits estimate from the cost-benefit analysis is an underestimate.

5.2.2. Unquantified Costs

Section 3.3. of this Tab describes the methodology that staff used to calculate CO sensor replacement costs. The draft proposed rule establishes performance requirements that would lead to the installation of CO sensors in gas furnaces and boilers. Under this rule, gas furnaces and boilers would turn on and off in 15-minute cycles if they have a failed or malfunctioning CO sensor. This “short-cycling” would prevent the gas furnace or boiler from producing dangerous levels of CO, but not completely leave consumers without some heating in cases of emergencies or extreme cold. The gas furnace or boiler would continue to short-cycle until the CO sensor is replaced. Since the CO sensors have a shorter product life span than the gas furnace or boiler, nearly all consumers would experience this downgrade in functionality at one time from a failed CO sensor. The cost approach in Section 3.3. quantifies the cost to consumers of having to get a service technician to replace the CO sensor. However, staff did not quantify the inconvenience cost of having their furnace or boiler significantly disabled until a service technician can arrive.

Staff was unable to quantify the inconvenience cost of a gas furnace or boiler short cycling because of the variability in severity of the inconvenience and the difficulty of placing a value on inconvenience. First, inconvenience cost would vary widely depending on the time of the year and location. A gas furnace or boiler in Fargo, ND that short cycles in winter would have a higher inconvenience cost than if it short cycles in summer. Additionally, a gas furnace or boiler that short cycles in the sun belt of the United States may never have more than a *de minimis* inconvenience cost, while a prolonged period of short cycling in the upper Midwest could be significantly inconvenient. Second, staff did not find an established methodology to calculate inconvenience cost for a gas furnace or boiler.

Ultimately, staff was unable to quantify inconvenience cost because it did not have enough information to forecast the geographical distribution of compliant gas furnaces and boilers, nor did it have enough information on the severity of inconvenience or the expenses consumers would incur.

6. Staff Evaluation of the Voluntary Standard

Since 1993 CPSC staff has advocated for more effective voluntary standards for gas furnaces and boilers to protect consumers from CO hazards. In 2000, CPSC staff[107] proposed voluntary standard provisions that would require a furnace:

1. to shut down if the vent pipe became disconnected; and
2. to shut down if the vent pipe became totally or partially blocked; or
3. to have a means to prevent CO emissions from exceeding the standard limits once installed in the field; or
4. to have a means, once installed in the field, to shut down if CO emissions exceeded the standard limits.

In 2002, the ANSI Z21/83 Technical Committee (TC) established a working group (WG) to evaluate the feasibility of using CO and combustion sensor technology to implement CPSC staff's CO shutoff/response proposal. CPSC staff participated in that WG from 2002 through 2005. This WG was disbanded in 2005 out of a concern that there were no sensors commercially available that had the durability or longevity to operate within a gas furnace for the expected 20-year lifespan. CPSC staff conducted additional sensor testing from 2007 to 2008[108] to evaluate the ANSI ZS21/83 TC's concerns and address WG's concerns. The testing included the "Corrosion resistance criteria and test method"[109] from Annex G, ANSI Z21.47, *Standard for Gas-fired Central Furnaces* and was included in the Request for Proposals[110] and test criteria[111] that the Z21/83 CO Sensor Ad Hoc Working Group adopted to evaluate sensor performance and that gas furnace and boiler manufacturers use to evaluate how well metallic heat exchangers and venting components withstand corrosive attack during the lifespan of the appliance. Because the industry uses these test criteria to qualify heat exchangers that pass the testing for a 20-year service life, the criteria were also used as a means to assess the sensors being tested for a 20-year life. At the time of test, staff found that the sensors survived the conditions under test.

In 2012, staff provided the ANSI Z21/83 TC an updated review of CO-related IDIs involving gas furnaces and boilers.[112] In 2014, CPSC issued a request for information, and staff hosted a forum to gather more information on the availability and feasibility of CO and combustion sensors for use in gas furnaces and boilers. In 2015, CPSC staff proposed that updated CO shutoff/response[113] provisions be added to the voluntary standards for gas furnaces, boilers, wall furnaces, and floor furnaces.

In 2015, the Z21/83 TC established another WG to evaluate CPSC staff's new proposal. CPSC staff participated in that WG (2016 through 2019) by identifying Japanese and European

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[107] Jordan, R., CO shutoff/response proposal letter Canadian Standards Association International, CPSC. November 2000.
[108] Jordan, R., Evaluation of the Durability and Longevity of Chemical Sensors In-Situ for Carbon Monoxide Shutdown of Gas Furnaces, CPSC. September 2012
[109] Annex G, ANSI Z21.47, Standard for Gas-fired Central furnaces.
[110] Letter from the Chairman, Ad Hoc Working Group on CO/Combustion Sensors to the Chairman of the Z21/83 Committee conveying request for proposals, dated November 4, 2004.
[111] Request For Proposals To Conduct Test And Evaluation Of CO/Combustion Sensors For In-Situ Deployment In Residential, Vented Gas Furnaces
[112] Jordan, R., Updated Review of In-Depth Investigations Associated with Carbon Monoxide Poisoning and "Modern" Gas Furnaces and Boilers. CPSC. September 2012.
[113] Jordan, R. Updated CO shutoff proposal letters (3 total) to the ANSI/CSA Technical Subcommittees for gas-fired central furnaces, boilers, and wall/floor furnaces. CPSC. September 2015.

standards and related technologies that could be used as benchmarks to implement the CPSC staff's proposals and providing redacted CO-related incident reports involving gas furnaces and boilers.[114] However, the WG disbanded in 2019 without proposing any revisions to the voluntary standard that would adequately mitigate the CO hazard.

As of the publication of this document, there are no existing U.S. voluntary standards addressing the hazard of CO exposure from leakage of elevated levels of CO from gas furnaces or boilers. Additionally, because no standard or portion of a standard was submitted to the Commission under subsection (a)(5) of the CPSA, no voluntary standard is included as a performance standard in the proposed rule.

7. Alternatives to the Draft Proposed Rule

Staff considered four alternatives to the draft proposed rule: 1) continue to work and advocate for change through the voluntary standards process, 2) rely on the use of residential CO alarms, 3) continue to conduct education and information campaigns, and 4) take no action. Each alternative is discussed in detail below.

7.1. Continue to work and advocate for change through the voluntary standards process

CPSC has been engaged with the Standards Development Organizations (SDO) for more than 20 years in the Agency's attempt to mitigate preventable deaths and injuries from CO production from gas furnaces and boilers. Section 6 highlights CPSC participation in the voluntary standard development of ANSI Z21.47, Z21.13, and Z21.86. Despite staff's encouraging industry to adopt a standard that adequately addresses the hazard, industry has not adopted such a standard in over 20 years, and thus consumers continue to fall victim to preventable fatalities and injuries. For these reasons, staff does not recommend this alternative.

7.2. Rely on the use of residential CO alarms

Gas furnace and boiler manufacturers have expressed their views that increased education about, and adoption of, CO alarms would adequately address the hazard. CPSC has long promoted CO alarm adoption, but CO fatalities and injuries from gas furnaces and boilers remain high. CPSC staff concludes that increased CO alarm adoption would not be sufficient to mitigate the hazard for several reasons. Primarily, the evidence of continued CO fatalities and injuries from gas furnaces demonstrate that CO alarm adoption and proper use are insufficient to address the hazard, and also, residential CO alarms may malfunction due to battery failure, poor maintenance, manufacturer defect, age, incorrect installation or defects. A CO alarm would not shut down an appliance producing a dangerous amount of CO and the occupant would have to properly recognize what to do when it alarms, and a malfunctioning CO alarm with a failed battery or other cause would fail to warn the occupants of the danger. Furthermore, states have increasingly required CO alarms in homes[115] over the last two decades since the Agency studied them, but CPSC has not seen a significant decline in CO injuries and fatalities.[116] For these reasons, staff does not recommend this alternative.

7.3. Continue to conduct education and information campaigns

[114] Redacted CO IDIs (79 IDIs) involving gas furnaces and boilers emailed to the Z21/83 Cross Functional Working Group for Carbon Monoxide Detector Sensors for Gas Appliances. CPSC. Emailed to Working Group between October 2016 and February 2017.

[115] iPropertyMangement, "Carbon Monoxide and Smoke Detector Laws", https://ipropertymanagement.com/laws/carbon-monoxide-smoke-detectors

[116] The Agency is currently updating its national study on smoke alarm and CO alarm usage.

Staff considered the merits of conducting education and information campaigns. Existing CPSC education and information campaigns on fire and smoke (CO) hazards and CPSC advocacy on smoke and CO alarm adoption could increase the presence of CO detectors in homes but have been in place for decades with injuries and deaths from CO poisoning continuing to be a significant problem. The efforts CPSC staff and others have done through education and advocacy of CO alarm adoption may have even attenuated a potential increase in fatalities and injuries over the years. However, CO fatalities and injuries for gas furnaces and boilers remain high and without a significant and large downward trend in incidents, this will likely be the case for the foreseeable future. Staff concludes that education and information campaigns have not and would not adequately address the hazard in the absence of a performance standard which would adequately address the hazard. For these reasons, staff does not recommend this alternative.

7.4. Rely on Recalls

The Commission could seek voluntary or mandatory recalls of gas furnaces and boilers that present a substantial product hazard. With this alternative, manufacturers could continue producing noncompliant products without incurring any additional costs to modify or test for compliance with the proposed rule. Furthermore, recalls only apply to an individual manufacturer and product, but do not extend to similar hazardous products. Recalls also occur only after consumers have purchased and used such products with possible resulting deaths or injuries due to exposure to the hazard. Additionally, recalls can only address products that are already on the market but do not directly prevent unsafe products from entering the market. Staff are not aware of any recent recalls of gas furnaces and boilers. In the absence of a rule, hazardous gas furnaces and boilers will continue to see sales of several million units annually and the stock of hazardous products will continue to grow. Additionally, a recall for such a large appliance may prove challenging. While detached gas furnaces and boilers could be easily recalled, installed gas furnace and boiler recalls would be disruptive and costly. Firms also have incentives to mitigate the impact of a recall due their costly nature (i.e., providing consumers with a free appliance and potential reputational costs) where a mandatory standard would ensure a consistent standard and be more widely enforced. Firms also have incentives for avoiding recalls from hidden hazards such as the cost providing consumers with a free appliance and potential reputational costs.

8. References

Bhattachara, S., Lawrence, B., Miller, T.R, Zaloshnja, E., Jones, P.R., 2012. Ratios for Computing Medically Treated Injury Incidence and Its Standard Error from NEISS Data (Contract CPSC-D-05-0006, Task Order 8). Calverton, MD: Pacific Institute for Research and Evaluation, (Aug 2012).

Consumer Product Safety Commission, 2000. The National Electronic Injury Surveillance System: A tool for researchers. Bethesda, MD: U.S. Consumer product Safety Commission. Available at: https://www.cpsc.gov/s3fs-public/pdfs/blk_media_2000d015.pdf

Consumer Product Safety Commission, 2019, “Performance Requirements for Residential Gas Furnaces and Boilers”, Tab B, pp. 67, FR 2019-17512.

Freedonia Group, 2017. Heating Equipment Market in the US. Cleveland, OH

Gold, Marthe R., Siegel, Joanna E., Russell, Louise B., Weinstein, Milton C., 1996. Cost-effectiveness in health and medicine. New York: Oxford University Press.

Haddix, Anne C., Teutsch, Steven M., Corso, Phaedra S., 2003. Prevention effectiveness: A guide to decision and economic evaluation (2nd ed.). New York: Oxford University Press.

Lawrence, BA, Miller, TR, Waejrer, GM, Spicer, RS, Cohen, MA, Zamula, WW, 2018. The Consumer Product Safety Commission's Revised Injury Cost Model. Maryland: Pacific Institute for Research and Evaluation (PIRE). (February, 2018). Available at: https://www.cpsc.gov/s3fs-public/ICM-2018-Documentation.pdf?YWuW4Jn0eb2hExeA0z68B64cv6LlUYoE

Miller et al., 2000. The Consumer Product Safety Commission revised injury cost model. Calberton, MD: Public Services Research Institute. Available at https://www.cpsc.gov/s3fs-public/pdfs/Revised-Injury-Cost-Model-120100.pdf

Guidehouse, Review of Combustion Control and Carbon Monoxide Sensors in Europe and Japan, 2021, prepared for US Consumer Product Safety Commission, Bethesda, MD

Industrial Economics, "Valuing Reductions in Fatal Risks to Children", January 2018, Cambridge, MA.

Navigant Consulting and Lawrence Berkeley National Laboratory, "Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment - Residential Furnaces ", 2015, Prepared for the U.S. Department of Energy, Washington, DC 20585, url: https://www.regulations.gov/document/EERE-2014-BT-STD-0031-0217

Navigant Consulting and Lawrence Berkeley National Laboratory, "Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment - Residential Boilers", 2015, Prepared for the U.S. Department of Energy, Washington, DC 20585, url: https://www.regulations.gov/document/EERE-2012-BT-STD-0047-0036

Department of Energy, "Energy Conservation Program for Consumer Products: Energy Conservation Standards for Residential Furnaces; Notice of proposed rulemaking and announcement of public meeting", 2015, 80 FR 13119, url: https://www.regulations.gov/document/EERE-2014-BT-STD-0031-0032

Department of Energy, "Energy Conservation Program for Consumer Products: Energy Conservation Standards for Residential Boilers; Notice of proposed rulemaking and announcement of public meeting", 2015, 80 FR 17222, url: https://www.regulations.gov/docket/EERE-2012-BT-STD-0047

Neumann, Peter J., Sanders, Gillian D., Russell, Louise B., Siegel, Joanna E., Ganiats, Theodore G., 2016. Cost-effectiveness in health and medicine: Second Edition. New York: Oxford University Press.

OMB, 2003. Circular A-4: Regulatory analysis. Washington, DC: Office of Management and Budget. Available at: https://www.transportation.gov/sites/dot.gov/files/docs/OMB%20Circular%20No.%20A-4.pdf

Residential Energy Consumption Survey for 2015. Published 2018, Energy Information Administration. Washington, DC 20585

Rice, Dorothy P., MacKenzie, Ellen J., and Associates, 1989. Cost of injury in the United States: A report to Congress. San Francisco, CA: Institute for Health & Aging, University of California and Injury Prevention Center, The Johns Hopkins University.

Rodgers, Gregory B., 1993. Estimating jury compensation for pain and suffering in product liability cases involving nonfatal personal injury. Journal of Forensic Economics 6(3), 251-262.

Schroeder, Tom, and Ault, Kimberly, 2001. The NEISS sample (design and implementation) 1997 to present. Bethesda, MD: U.S. Consumer product Safety Commission. Available at: http://www.cpsc.gov//PageFiles/106617/2001d011-6b6.pdf

Topping, J., 2022. Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products 2019 Annual Estimates. U.S. Consumer Product Safety Commission, Bethesda MD (September, 2022).

Viscusi, W. Kip, 1988. The determinants of the disposition of product liability cases: Systematic compensation or capricious awards? International Review of Law and Economics, 8, 203-220.

TAB E: Memorandum from the Directorate for Economic Analysis – Initial Regulatory Flexibility Analysis

United States
Consumer Product Safety Commission

Memorandum

TO: Ron Jordan, Project Manager, Division of Mechanical Engineering, Directorate for Engineering Sciences

DATE: September 20, 2023

THROUGH: Alex Moscoso, Associate Executive Director, Directorate for Economic Analysis

FROM: Bretford Griffin, Economist, Directorate for Economic Analysis

SUBJECT: Analysis for Performance Requirements for Gas Furnaces and Boilers, Initial Regulatory Flexibility Analysis

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Background

Whenever an agency publishes a notice of proposed rulemaking (NPR), Section 603 of the Regulatory Flexibility Act (RFA), 5 USC 601–612, requires agencies to prepare an initial regulatory flexibility analysis (IRFA) unless the head of the agency certifies that the rule will not have a significant economic impact on a substantial number of small entities. The IRFA or a summary of it must be published in the Federal Register with the proposed rule. Under Section 603(b) of the RFA, each IRFA must address:

1. a description of why action by the agency is being considered;
2. a succinct statement of the objectives of, and legal basis for, the proposed rule
3. a description of and, where feasible, an estimate of the number of small entities to which the proposed rule will apply;
4. a description of the projected reporting, recordkeeping, and other compliance requirements of the proposed rule, including an estimate of the classes of small entities which will be subject to the requirement and the type of professional skills necessary for preparation of the report or record; and
5. an identification to the extent practicable, of all relevant Federal rules which may duplicate, overlap, or conflict with the proposed rule.

The IRFA must also describe any significant alternatives to the proposed rule that would accomplish the stated objectives and that minimize any significant economic impact on small entities.

Discussion

A. Reason for Agency Action

The intent of this rulemaking is to reduce deaths and injuries resulting from carbon monoxide (CO) leaks from gas furnaces and boilers. Staff identified an average of 21 fatalities every year caused by lethal amounts of CO resulting in poisoning. There are, on average, 6,895 non-fatal CO injuries every year that are likely cause by gas furnaces and boilers. This action seeks to address these injuries, both fatal and non-fatal, by establishing mandatory performance standard requiring gas furnaces and boilers to shut off or modulate when CO levels reach specified amounts for a certain duration (TAB B).

B. Objectives and Legal Basis for the Rule

To address the risk of injury associated with CO production and leakage from residential gas furnaces and boilers, the Commission is considering developing a mandatory safety standard. This standard is promulgated under the authority of the Consumer Product Safety Act (CPSA). 15 U.S.C. 2051-2089. To issue a mandatory standard under section 7, the Commission must follow the procedural and substantive requirements in section 9 of the CPSA. Id. 2056(a).

C. Small Entities to Which the Rule Will Apply

The proposed rule would apply to all manufacturers and importers of gas furnaces and gas boilers including gas wall and floor furnaces. Staff is aware of as many as 70 firms manufacturing gas furnaces and boilers for the U.S. market. When accounting for subsidiaries and multiple brands provided by the same company, staff identified 20 parent firms.

Staff assesses that firms affected by the draft proposed fall under the NAICS code for “Heating Equipment (except Warm Air Furnaces) Manufacturing” (NAICS 333414) and “Air Conditioning and Warm Air Heating Equipment and Commercial and Industrial Refrigeration Equipment Manufacturing” (NAICS 333415). The SBA employer size thresholds for 333414 and 333415 are 500 employees and 1,250 employees respectively. Using these guidelines, staff identified two small manufacturers of gas furnaces, three small manufactures of residential gas boilers, and one importer of gas furnaces that may fall within the scope the rule.[117] Staff requests comment on additional manufacturers and importers of gas furnaces and boilers that may meet the SBA definition of a small business.

D. Compliance, Reporting, and Record Keeping Requirements of Proposed Rule

The proposed rule would establish a performance requirement for gas furnaces and boilers that would require the appliance to shut off or modulate when CO levels reach specified amounts for a certain duration (TAB B).

In accordance with Section 14 of the CPSA, manufacturers would have to issue a General Certificate of Conformity (GCC) for each gas furnace or boiler model, certifying that the model complies with the performance requirement. According to Section 14 of CPSA, GCCs must be based on a test of each product or a reasonable testing program; and GCCs must be provided to all distributors or retailers of the product. The manufacturer would have to comply with 16 CFR

[117] CPSC used the firms enumerated in its Regulatory Analysis (Tab D), Department of Energy’s Technical Support Documents on residential furnaces and boilers (2015 and 2022) and used Dun and Bradstreet and internet search to identify suppliers that may manufacture or import products that fall within the scope of the rule.

part 1110 concerning the content of the GCC, retention of the associated records, and any other applicable requirement.

E. Federal Rules that May Duplicate, Overlap, or Conflict with the Proposed Rule

At the time of this document, no other Federal rules duplicate, overlap, or conflict with the proposed rule.

F. Potential Impact on Small Entities

One purpose of the IRFA is to evaluate the impact of a regulatory action to small entities and to determine whether that impact is economically significant. Although the SBA allows considerable flexibility in determining "economically significant," staff typically uses one percent of gross revenue as the threshold for determining "economically significant." When staff cannot demonstrate that the impact is lower than one percent of gross revenue, staff prepares an initial regulatory flexibility analysis.[118]

1. Impact on Small Manufacturers

The preliminary regulatory analysis (Tab D) discusses costs more fully. Based on that analysis, to achieve compliance with the proposed rule's performance requirements, small domestic manufacturers would incur costs from: (1) the increased variable costs of producing furnaces and boilers with CO sensors and shutoff capabilities; and (2) the one-time conversion costs of redesigning and modifying factory operations for installing CO sensors.

Installing CO Sensors and Shutoff Capabilities

Installing CO sensors and shutoff capabilities in a gas furnace or boiler is a variable cost that is attached to each unit produced. To determine the average units shipped for each small businesses, staff uses industry data that shows the largest 10 firms comprise no more than 83.3 percent of the heating equipment market (Freedonia, 2017). The remaining 16.7 percent of the market accounts for an estimated $1.08 billion in sales from 597,860 units shipped from industry total of $6.52 billion in sales from 3.58 million units shipped. That corresponds to an estimated average of 119,572 units shipped for each of the five small manufacturers in Section C, and average revenue of $181.47 million per year for small suppliers ($1.08 billion / 6), which includes the five manufacturers and the small importer.

Staff used a Guidehouse study (Guidehouse, 2021) to find that the cost to manufacturers (without any markup included) at an annual production level of 119,572 yields an average incremental

[118] The one percent of gross revenue threshold is cited as example criteria by the SBA and is commonly used by agencies in determining economic significance (see U.S. Small Business Administration, Office of Advocacy. *A Guide for Government Agencies: How to Comply with the Regulatory Flexibility Act and Implementing the President's Small Business Agenda and Executive Order 13272*. May 2012, pp 18-20. http://www.sba.gov/sites/default/files/rfaguide_0512_0.pdf)

cost of $66.47 per unit.[119] This is expected to cost an annual total of $7.95 million ($66.47 × 119,572) for each small firm.

Conversion Costs

DOE's findings from its 2015 Rules on Gas Residential Furnaces and Boilers (80 FR 13120 and 80 FR 17222) found an industry cost of $413.28 million (inflated to 2021 dollars).[120] This would suggest a maximum conversion cost for small firms of $69.02 million (16.7 percent × $413.28 million) or $13.80 million per firm among the small five manufacturers.

In summary staff identified five gas furnace and boiler manufacturers which meet SBA size standards for small businesses. Staff estimated per unit and overall fixed conversion costs to each manufacturer to be $21.75 million ($7.95 million CO sensor installation costs + $13.80 million in conversion costs). Staff found this initial cost to comply with the draft proposed rule exceeds the estimated one percent of annual revenue of $10.80 million ($1.08 billion × 10%) for all five firms. Therefore, staff expects the economic impact on these five small gas furnace and boiler manufacturers to be significant.

2. Impact on Small Importers

Staff identified one small importer of products that would be within the scope of the standard. Importers may pass on testing responsibility and GCC creation to the foreign manufacturers and then issue the resulting certificate. Changes in production costs and certification costs incurred by suppliers from the standard could be passed on to the importers, which they in turn are likely to pass onto consumers given the relative demand inelasticity of heating appliances. For this reason, staff does not believe that the draft proposed rule will have a significant impact on small importers.

Staff recommends seeking public comment on information on importers of gas furnaces and gas boilers, specifically how many are imported, how many different models each importer sells, and what technologies those models are currently using (atmospheric venting, condensing, non-condensing, premix power burners, etc.)? Staff also seeks public comment on information regarding to what degree supplying firms tend to pass on increases in production and regulatory costs to importers. To what extent is the ability to pass on these costs limited by the ease with which importers can switch suppliers or substitute to alternative products such as electrical furnaces and boilers?

Conclusion

Staff identified five manufacturers that meet the SBA criteria to be considered small firms. For all five firms, the estimated costs from the draft proposed rule exceed one percent of annual

[119] Weighted average between retail price increase from gas furnaces ($65.22) and boilers ($81.10) for the first year impact of the rule.

[120] Conversion costs were calculated in 2013 dollars and now reported in 2020 dollars adjusted for 2013-2020 inflation using the Consumer Price Index-Urban.

revenue. Staff assesses that the draft proposed rule would have a significant economic impact on these five firms.

Staff found one importer of foreign manufactured products that meets the SBA criteria to be considered small and requests additional information on small importers. A small importer whose supplier exits the market or does not provide the importer a GCC could experience a significant adverse economic impact. For this one small importer, the cost of compliance including certification testing would not exceed one percent of annual revenue. Therefore, staff assesses the rule will not have a significant economic impact on gas furnace and boiler importers.

Staff welcomes public comments on this IRFA. Small businesses that believe they would be affected by the proposed rule are encouraged to submit comments. The comments should be specific and describe the potential impact, magnitude, and alternatives that could reduce the impact of the proposed rule on small businesses.

G. Alternatives for Reducing the Adverse Impact on Small Businesses

Staff considered four alternatives to the draft proposed rule: (1) Continue to work and advocate for change through the voluntary standards process, (2) rely on the use of residential CO alarms, (3) education and information campaigns, and (4) take no action. Staff does not recommend these alternatives for the reasons stated in Tab D.

References

Freedonia Group, 2017. Heating Equipment Market in the US. Cleveland, OH

Navigant Consulting and Lawrence Berkeley National Laboratory, “Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment - Residential Furnaces ”, 2015, Prepared for the U.S. Department of Energy, Washington, DC 20585, url: https://www.regulations.gov/document/EERE-2014-BT-STD-0031-0217

Navigant Consulting and Lawrence Berkeley National Laboratory, “Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment - Residential Boilers”, 2015, Prepared for the U.S. Department of Energy, Washington, DC 20585, url: https://www.regulations.gov/document/EERE-2012-BT-STD-0047-0036

Navigant Consulting and Lawrence Berkeley National Laboratory, “Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment - Residential Boilers”, 2022, Prepared for the U.S. Department of Energy, Washington, DC 20585, url: https://www.regulations.gov/document/EERE-2014-BT-STD-0031-0320

TAB F: Memorandum from the Directorate for Health Sciences – Health Effects of CO exposure from Gas Furnaces and Boilers

United States
Consumer Product Safety Commission
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Memorandum

TO:	Ronald Jordan, Project Manager Division of Mechanical and Combustion Engineering Directorate for Engineering Sciences	**DATE:** September 20, 2023
THROUGH:	Stefanie Marques, Ph.D., Director, Division of Pharmacology and Physiology Assessment, Directorate of Health Sciences	
FROM:	Lin Wang, M.D. Ph.D. Physiologist | Division of Pharmacology and Physiology Assessment	
SUBJECT:	Health Effects of CO Exposure from Gas Furnaces and Boilers - Gas Appliance CO Sensor Project	

The purpose of this memorandum is to discuss the health and safety risks associated with carbon monoxide (CO) poisoning that were not addressed in the previous voluntary standards for portable generators, gas furnaces, gas boilers, gas wall furnaces, and gas floor furnaces. This is a part of a staff NPR briefing package to follow the advance notice of proposed rulemaking (ANPR) published in the *Federal Register* (84 FR 42847) to address the risk of injury and death associated with CO production and leakage from residential gas furnaces and boilers. The staff from the U.S. Consumer Product Safety Commission (CPSC) Division of Pharmacology and Physiology Assessment in the Directorate for Health Sciences describes the pathophysiology, symptoms and clinical treatments of CO poisoning. Examples from the select CPSC In-Depth Investigation (IDI) and Injury or Potential Injury Incident (IPII) reports are included to illustrate the severity and imperceptible nature of CO poisoning.

Introduction

CO is an odorless, colorless and tasteless gas at room temperature and atmospheric pressure and is often called a silent killer due to the imperceptible nature of CO poisoning (1). The affected individuals often quickly become unconscious and unable to escape from CO exposure. This is particularly relevant to the case of a malfunctioned large gas appliance such as a furnace and boiler whereby a large volume of CO is generated and leaked into the living space in short time, causing irreparable or lethal consequence. Mitigation of CO production at the combustion source would greatly reduce risk of CO exposure to consumers. Accordingly, in this NPR briefing package CPSC staff proposes changes to existing voluntary standards that incorporate combustion sensors to monitor and mitigate the CO production of subject products by either modulation of their performance or product shutoff. Here we review our current knowledge of CO toxicity, with an emphasis on its etiology, pathophysiology and hazardous health outcomes.

Prevalence, Etiology and Risk Factors

CO poisoning is a major public health hazard. According to the Centers for Disease Control and Preventions (CDC), 430 people die in the U.S. each year and approximately 50,000 people visit the emergency department each year due to accidental CO poisoning. For the 10-year period from 1979 to 1988, 56,133 deaths were reported from CO poisoning in the U.S., with 25,889 being suicides and 30,244 as accidental deaths (2). By analyzing the CDC's Wide-ranging ONline Data for Epidemiologic Research (WONDER) database, one study found 24,890 CO poisoning deaths in the United States from 1999 to 2014, averaging 1,555 per year (3). CO poisoning is likely underdiagnosed or misdiagnosed because the symptoms can present in varied ways and are similar to those of many flu-like illnesses.

CO is produced by the incomplete combustion of carbon-containing fuels, such as coal, gas, charcoal and oil. Potential CO sources inside home include gas-powered portable generators, gas stoves, gas heaters and gas boilers and cars running idle in garages that are poorly ventilated. CO binds to hemoglobin in the blood to form carboxyhemoglobin (COHb). The outcome of CO toxicity is dependent on the extent of CO exposure, the resulting COHb level in the blood and the COHb-independent factors. General medical condition of the individual including comorbidities also greatly affects the outcome of CO poisoning. CO exposure is determined by the ambient CO concentration (often measured as parts per million, ppm, 10^{-6}), the duration of exposure, and the breathing rate of the individual that is usually determined by the activity level (e.g., sedentary and exercise). Mathematical models have been developed to estimate the COHb levels in blood and other compartments as a result of CO exposure and endogenous CO production (7-12).

Natural background levels of CO in the outdoor environment range from 0.009 to 0.2 ppm. In urban traffic areas, the 8 hour mean CO concentrations can rise to 17.5 ppm and exposure to this level for prolonged time could result in COHb level rising to 3%. Exposure to CO at as little as 10 ppm can increase COHb levels to 2%. A variety of guidelines for CO toxicity have been issued by many domestic and foreign agencies, including those from the National Research Council (NRC) Committee on Acute Exposure Guideline Levels (13), National Institute for Occupational Safety and Health (NIOSH) (14), Occupational Safety and Health Administration (OSHA, 29 CFR 1910.1000 Z-1), National Aeronautics and Space Administration (15,16), Department of Defense (MIL-STD-3050), Federal Aviation Administration (14 CFR Part 25.831), and World Health Organization (1).

The standards in these guidelines are generally comparable but they have different focus. For example, the NRC Committee on Acute Exposure Guideline Levels (AEGL) classified CO exposure using three COHb levels and their associated symptoms (13). In AEGL-1, the level of COHb is indistinguishable from the endogenous COHb level and such exposures do not cause harm in the general population but may render the vulnerable populations more susceptible to their existing conditions. The AEGL-2 is the exposure that induce COHb levels to and above 4% and causes individuals with cardiovascular disease to readily experience chest pain and arrythmias. AEGL-3 is exposure inducing COHb levels rising to and above 40% and causing more severe conditions such as myocardial infarction and stillbirths in both susceptible populations and the general public.

Notably, NASA reasoned that exposure to a maximum CO concentration of 425 ppm for 1 hour in spacecraft, which would lead to a 15% COHb level, was acceptable, due to the enhanced physical condition of astronauts and the nature of NASA mission objectives. On the other hand, the World Health Organization warns that chronic exposure to CO of levels greater than 6 ppm can be toxic. National Comfort Institute, an organization that aims to promote the performance of heaters and other home appliances, compiled an integrated list of various CO exposures, the associated risks and actions required to mitigate the risks (Table 1). At 400 ppm, healthy adults will have headaches within 1-2 hours and is life threatening after 3 hours. For reference, UL listed CO alarms must alarm within 15 minutes in a 400 ppm environment.

Table 1 CO Exposure Level, Risk and Action

1-4 ppm	Normal levels in human tissues produced by body.
3-7 ppm	14% increase in the rate of admission in hospitals of non-elderly for asthma (17).
5-6 ppm	Significant risk of low birth rate if exposed during last trimester (18).
5 ppm	1st visual display on NSI 3000 Low Level CO Monitor.
9 ppm	ASHRAE standard for allowable spillage from vented appliances, indoors, for 8 hours exposure daily. EPA standard for outdoors for 8 hours and a maximum 3 times per year (Clean Air Act).
10 ppm	Outdoor level of CO found associated with a significant increase in heart disease deaths and hospital admissions for congestive heart failure. (JAMA) lst ambient level occupants should be notified-NCI Protocol.
15-20 ppm	First level World Health Organization lists as causing impaired performance, decrease in exercise time and vigilance. 1st Alarm level for NSI 3000 Low Level CO Monitor-5 minutes.
25 ppm	Maximum allowable in a Parking Garage (International Mechanical Code).
27 ppm	21% increase in cardiorespiratory complaints (19).
30 ppm	Earliest onset of exercise-induced angina (World Health Organization). 1st visual display on UL2034 approved CO Alarm-Must not alarm before 30 days.
35 ppm	US NIOSH recommended 8 hour maximum workplace exposure. EPA standard for outdoors for 1 hour and a maximum of 1 time per year. Many fire departments wear breathing apparatus before entering 2nd ambient level. Occupants should be notified and space ventilated. 2nd Alarm level for NSI 3000 Low Level Monitor-5 minutes.
50 ppm	US OSHA recommended 8 hour maximum workplace exposure Maximum NCI level for unvented appliances.
70 ppm	1st Alarm level of UL2034 approved CO Alarms - 2-4 hours 3rd Alarm level for NSI 3000 – 30 seconds NSI 3000 Low Level Monitor cannot be silenced by reset button.
100 ppm	Maximum NCI CO level during run cycle in all vented appliances (stable) Maximum NCI CO for all oil appliances.
200 ppm	First listed level (established in 1930) healthy adults will have symptoms-headaches, nausea NIOSH & OSHA recommend evacuation of workplace Maximum "Air Free" CO for vented water heater and unvented heaters (ANSI Z21) UL approved alarms must sound between 30 – 60 minutes (NSI 3000 – 30 seconds).
400 ppm	Healthy adults will have headaches within 1-2 hours. Life threatening after 3 hours Maximum "Air Free" CO in all vented heating appliances (ANSI Z21) Maximum EPA levels for industrial flue exhaust UL Alarms must alarm within 15 minutes (NSI 3000 – 30 seconds) Maximum recommended light-off CO for all appliances – NCI (except oil).
800 ppm	Healthy adults will have nausea, dizziness, convulsions within 45 minutes. Unconscious within 2 hours then Death (established in 1930). Maximum "Air Free" CO for unvented gas ovens (ANSI Z21) 800 ppm+ Death in less than one hour.
2000 ppm	EPA standard for new vehicle emissions.
3000 ppm	Typical emissions from propane lift trucks, gasoline powered tools etc.
4000 ppm	Lethal concentration for exposure of 30 minutes (20).

People who are at greater risk from CO poisoning include those with underlying medical conditions or comorbidities such as cardiovascular disease, coronary heart disease, respiratory disorder and anemia, pregnant women and their fetus, infants, and elderly people (21). In people with coronary heart disease, blood COHb levels of 4.5% or higher induced anginal pain and arrhythmia during exercise. In people with anemia, the oxygen-carrying capacity of the blood is already compromised and therefore they will be more sensitive to the toxic effects of CO. Elderly people are at greater risk because of existing heart and/or respiratory conditions, and because of a reduced compensatory response to hypoxic situations. Pregnant women's risks are greater, because they have a higher rate of endogenous CO production from both the mother and the fetus as well as higher ventilation rates. Fetus, infants and developing children all have greater risks due to higher demand of oxygen consumption and the toxic effects of CO can have a lasting effect on their nervous system and development.

Pathophysiology of CO Toxicity

Mechanistically, CO toxicity is dependent on its reactivity to the transition metals of the target proteins. The three major CO targets are hemoglobin (Hb), myoglobin (Mb) and the mitochondrial cytochrome c oxidase (COX), which together are responsible for the transport, storage and consumption of oxygen in our body. CO binds to the ferrous (Fe^{2+}) heme group in these proteins. CO exposure occurs when the condition of a subject product leads to 1) incomplete combustion of fuel and production of excess CO and 2) leakage of CO into the living space. Inhalation of CO and the subsequent diffusion of CO into the blood can lead to adverse or deadly health outcomes, i.e., CO poisoning.

Carboxyhemoglobin

The principal function of Hb is to transport oxygen in the blood from the lungs to tissues throughout the body. CO binds to Hb, forming COHb with an affinity 200 to 300 times higher than oxygen and thus greatly reduces the oxygen carrying capacity of Hb (22-24). Besides competitive displacement of oxygen, CO binding to Hb also stabilizes the quaternary state of Hb, which increases the binding affinity of remaining oxygen to other sites of the Hb tetramer and thus further decreases the oxygen delivery capacity of Hb in the tissues (24,25). Collectively, CO exposure induces the anemia-like, hypoxic outcomes (26).

Generally, CO poisoning occurs when the blood levels of COHb rise over 10%. CO poisoning can be divided into three categories based on the COHb levels: 1) mild CO poisoning with COHb level at 10% but without the typical symptoms of CO poisoning; 2) moderate CO poisoning with COHb level of 10-25% and mild symptoms of CO poisoning (e.g. headache, lethargy and nausea); 3) severe CO poisoning with COHb level rising over 25% and severe CO poisoning symptoms (e.g. loss of consciousness or cardiac ischemia or both). Previous work by HSPP staff suggests that it may be possible to survive CO poisoning with the peak COHb below 40%, while the risk of mortality markedly increases with peak COHb levels exceeding 40% (27). Despite common recording of the COHb levels of CO-poisoning victims, these readings often occur after removal from the CO source. Thus the measured COHB levels do not correlate with outcomes (28). In fact, the blood COHb levels are only correlated with the neurological injuries in acute CO poisoning (21). Clearly, factors independent of COHb also contribute to CO toxicity. In addition, vulnerable populations such as pregnant women and their fetus, infants, the elderly, and the people with comorbidities are more sensitive to hypoxia, despite exhibiting low or normal levels of blood COHb.

CO can also be produced inside the body as a product of heme degradation, and this reaction is catalyzed by two isoforms of heme oxygenases (HOs), the inducible HO-1 and the constitutive HO-2 (24). Accordingly, a baseline level of COHb of 0.4-1% is found in the blood of healthy individuals (29), whereas the levels of up to 5% can be seen in the individuals living in busy urban settings (30). The blood levels of COHb are much higher in tobacco smokers, and healthy heavy smokers can tolerate COHb levels up to 15% without toxic CO effects, which probably reflects adaptation after long-term exposure (31). However, heavy smokers do experience headaches and dizziness, symptoms consistent with CO poisoning (32). Exogenous CO exposure can increase local heme levels, which in turn stimulate local CO production via HO-1. For example, the CO levels in rat brain tissue can remain elevated up to 2 hours after the animal is removed from CO exposure (33).

Clinical Manifestations

The symptoms of CO poisoning can be non-specific and variable among individuals, and include headache, fatigue, malaise, “trouble thinking”, confusion, nausea, dizziness, visual disturbances, chest pain, shortness of breath, loss of consciousness, and seizures (54-56). The classical signs of CO poisoning such as cherry-red lips, peripheral cyanosis, and retinal hemorrhage are rare (21). In people with co-morbidities, shortness of breath or chest pain can be seen.

People with severe CO poisoning can become critically ill and eventually die. Characteristics associated with CO-induced mortality include lower pH values (less than 7.2), fire as a source of CO, loss of consciousness, high COHb levels, and need for endotracheal intubation during hyperbaric oxygen therapy (28). CO poisoning induces rapid and profound cardiovascular effects. Up to one-third of patients with moderate to severe CO poisoning present with myocardial injury, and higher levels of COHb are associated with both acute and long-term development of myocardial infarction (57). This is particularly the case in the patients with underlying coronary artery disease (58). In CO poisoning, the decreased oxygen delivery and increased O_2 demand are initially compensated by increased cardiac output and oxygen extraction, but the compensatory mechanisms are eventually overwhelmed, resulting in cardiovascular collapse (59). Numerous mechanisms account for the cardiac injuries induced by CO poisoning, including reduction in ATP levels, the increased NO level and the compromised function of Mb (59,60).

CO at toxic levels can increase thrombosis, which is likely due to CO binding to the heme group in fibrinogen and the subsequent platelet activation (58). Environmental air pollution studies showed that CO and other air pollutants increased the risk for arterial and venous thrombosis, coronary vasoconstriction and development of arrhythmia (61,62) . Survivors of CO poisoning can suffer neurocognitive sequelae related to brain injury (63,64). Importantly, the severity of the initial symptoms of CO poisoning does not correlate with the development of long-term neurological symptoms (65). Long-term neurological issues include impaired memory, cognitive dysfunction, depression, anxiety, and/or vestibular and motor deficits (47,63,66). Furthermore, the incidence of each symptom seems to vary. For example, after CO poisoning, 40% of the people experience depression, anxiety, and cognitive dysfunction (47,66), 19% experience cognitive deficits (67) and 68.6% experience intellectual disturbances (68).

Generally, there are two types of neurocognitive sequelae: 1) persistent neurological sequelae whereby injuries such as poor concentration and memory problems persist through their life even after people recover from the initial symptoms of CO poisoning; and 2) delayed neurological sequelae, whereby the symptoms including cognitive changes, personality changes, incontinence, psychosis, and Parkinsonism develop between 2 and 240 days after exposure. Fortunately, 50–75% of people with delayed neurological sequelae recover within 1 year. Up to a third of survivors from severe CO poisoning experience delayed neurological sequelae.

Notably, chronic exposure to low-level CO can also lead to neurological and cognitive deficits that do not resolve after removal from the CO source. The pathological mechanisms that lead to neurological damages in spite of nearly normal levels of blood COHb are not fully understood (47,69). Chronic exposure to subclinical or low levels of CO can cause memory loss, cognitive dysfunction, and other neurological impairments, and these neurological impairments are particularly relevant for fetus, infants and developing children (69). Additional health outcomes from chronic exposure to subclinical or low levels of CO include headache, malaise, respiratory difficulty, disorientation and chest pain, which are common in adults (69,71).

Prognosis

Prognosis data for people who are injured but do not immediately die from CO poisoning are rather inconclusive (21). A poor outcome is generally predicted by lengthy CO exposure, loss of consciousness, and advanced age. In addition, hypotension and cardiac arrest are risk factors associated with greater incidence of permanent disability and death. After acute CO poisoning, the organs most sensitive to hypoxia, i.e. the brain and heart, are mostly affected. The prognosis for CO poisoning patients who are resuscitated after experiencing cardiac arrest is generally poor.

Oxygen Treatment

Current oxygen therapies for CO poisoning include normobaric oxygen (NBO_2) and hyperbaric oxygen (HBO_2), which operate at 1 and 2.5–3 atmospheric pressure, respectively (72). NBO_2 and HBO_2

remove CO at a faster rate from the blood by increasing the partial pressure of oxygen, which increases the dissociation rate of CO from Hb (31,63,73). While NBO_2 reduces the half-life of COHb from 320 minutes in room air to 74 minutes, HBO_2 further reduces the half-life of COHb to 20-42 minutes (74,75). HBO_2 therapy has also been demonstrated to reverse CO-induced inflammation and mitochondrial toxicity (49,76). There have been several clinical studies evaluating the benefit of HBO_2 versus NBO_2 (25,77,78). Systemic review and meta-analysis of several randomized trials failed to show an overall benefit of HBO_2 therapy (21,79). Nonetheless, one study that measured 1-year outcome showed a significant improvement in long-term neurocognitive dysfunction after HBO_2 treatment (77).

CO poisoning IDIs

The following reports involved malfunctioning gas furnaces or gas boilers. They are to illustrate the varying degree of severity in CO poisoning and the almost identically imperceptible nature such as loss of consciousness and inability to escape in severe CO poisoning. The injuries and death in these reports reinforce staff's recommendation that CO sensors should be installed in large gas appliances in order to effectively mitigate consumers' risks.

Fatal and non-fatal injuries

IDI 180221HFE0002

According to a fire and rescue report, a 61-year-old male (YOM) died and a 57-year-old female (YOF) suffered from headache and nausea following CO exposure in a single family home under renovation. The fire department detected between 40 ppm and 300 ppm CO in the home. A police report indicated that personnel from the gas service provider determined an improperly vented natural gas furnace as the cause of the CO buildup in the house.

IDI 180328HCC3656

According to sheriff and fire and rescue reports, a 68 YOF was found dead and a 68 YOM was found unconscious next to vomit in their home. Fire department personnel measured CO levels between 280 and 354 ppm in the home. The male was treated for two hours in a hyperbaric chamber. During the preceding week, the basement was flooded due to a malfunction of the back flow preventer in the home gas boiler. A service provider repaired the boiler and an insurance company facilitated third-party flood remediation services, which installed fans implicated in the redirection of the boiler exhaust into the home thus leading to a buildup of CO. Consistent with this, one responding sheriff's officer also felt lightheaded after investigating the source of the CO and providing first aid to the 68 YOF.

IDI 181221HCC1133

A state police report describes the death of a 10 YOM and CO poisoning of two adults and of another 10 YOM in a one-story residential building. Elevated CO levels were detected by the fire department and all the involved individuals were reported to have vomited. A gas furnace with a buildup of a thick, black substance was implicated as the source of CO buildup.

IDI 191024HCC3070

This case describes the death of a 47 YOF and the hospitalization of her 52-year-old husband following exposure to elevated CO levels in a single-family residence. A death investigation summary from a university medical center included in the IDI indicates that CO toxicity as the cause of death for the 47 YOF. In addition, her postmortem examination revealed a COHb level of 47%, and atherosclerotic cardiovascular disease, diabetes mellitus, and obesity were identified as comorbidities. A natural gas wall furnace was implicated as the source of excess CO.

IDI 100415HBB3573

Approximately two weeks after the improper installation of filter panels into a furnace, seven people at an assisted care facility experienced effects linked to CO poisoning. One 48 YOF died with a COHb of 43.7% measured in blood collected from the aorta during autopsy procedures. CO levels of 68 ppm and 40 ppm were measured in the assisted care facility following ~30 minutes of ventilation conducted by EMS personnel.

Non-fatal incidents with at least one high severity victim

IDI 170302HCC3536

According to an emergency services report, several people experienced loss of consciousness and vomiting after exposure to elevated CO levels due to the malfunction of a snow melt boiler in a two-story duplex. One adult was treated with HBO therapy. Both the fire department and a plumber detected up to 2000 ppm CO at the residence.

IDI 170508HCC1840

According to a Fire Department report, an adult female contact Emergency Medical Service (EMS) upon feeling sick for 2 hours after arriving home. The female was unable to rouse the male co-occupant of the home who had ostensibly been in the residence for several hours prior to her arrival. The fire department detected CO levels in the residence ranging from 700 ppm to over 1000 ppm. The male also exhibited a COHb level of 42% on the scene where an intravenous delivery of fluid was provided. Both the male and female were transported to medical facilities for treatment. According to medical records, the male demonstrated a COHb level of 17.6% and he received HBO therapy. A CPSC interviewed with the male later implicated a malfunctioned exhaust vent from a propane gas boiler as the source of excess CO. The male experienced no lingering effects from the incident.

Survival non-fatal with no severity victim

IDI 181127CFE0001

Fire department detected over 1000 ppm of CO in a single family home due to a furnace malfunction and four occupants ranging from 10 to 43 years of age experienced headache, dizziness, loss of consciousness and vomiting. The occupants were treated on scene with supplemental oxygen and transported to the hospital, and no additional complications were reported.

IDI 190225HFE0003

A malfunctioning furnace was discovered as the cause of CO buildup in a single-family home where a 67 YOF, a 11 YOF, and an 8 YOF were found with a recent history of illness. A furnace technician detected 220 ppm CO on the first floor of the residence and evacuated the occupants who were treated at the hospital with oxygen. All the affected people were reported to have fully recovered.

IDI 190308HFE0001

A family of four including two adults and two children experienced fatigue, nausea, headache, and dizziness for about one week before contacting emergency services. A female adult from the family was almost 3 months pregnant. The fire department detected approximately 320 ppm CO in the family's residence, which was later confirmed by the gas company and likely due to a furnace malfunction. Family members were treated with supplemental oxygen at the scene and transported to the hospital where COHb levels were measured and hypobaric oxygen (HBO) therapy was provided. Due to the adult female's inability to perform pressure equalization maneuvers for the ear, a myringotomy to pierce the tympanic membrane (ear drum) was performed prior to HBO therapy. The family was reported to have fully recovered.

IDI 100212CNE0140

Approximately 40 YOF and three sons were found unconscious following apparent CO poisoning. EMS was contacted by the mother before she lost consciousness while attempting to escape the threat and rescue her sons. The loss of consciousness was preceded by various symptoms including vomiting and headache among the involved individuals. EMS measured a CO level of 195 ppm. All the involved individuals appeared to have fully recovered. The female and her 6-year-old son were treated with HBO therapy. Female indicated an earache that may be associated with the HBO therapy.

IDI 100302HNE0174

A 47 YOM and a 52 YOF were apparently subdued (lost consciousness) by elevated CO levels that were later measured to be 380 ppm. Associated blood COHb levels measured at 50%. Male did not respond immediately to EMS but female did respond appropriately. The male responded appropriately after recovery during initial EMS care procedures. Their dog also became unconscious due to CO. The IDI indicates they were both treated by HBO at OSU. A faulty heat exchanger in gas furnace was implicated. The male indicated being lightheaded and dizzy upon waking up in the middle of the night.

Reference

1. Penney, D., Benignus, V., Kephalopoulos, S., Kotzias, D., Kleinman, M., and Verrier, A. . (2010) Carbon monoxide. in *WHO Guidelines for Indoor Air Quality: Selected Pollutants*, Geneva. pp

2. Cobb, N., and Etzel, R. A. (1991) Unintentional carbon monoxide-related deaths in the United States, 1979 through 1988. *JAMA* 266, 659-663

3. Hampson, N. B. (2016) U.S. Mortality Due to Carbon Monoxide Poisoning, 1999-2014. Accidental and Intentional Deaths. *Ann Am Thorac Soc* 13, 1768-1774

4. (1981) Carbon monoxide, an old enemy forgot. *Lancet* 2, 75-76

5. Mott, J. A., Wolfe, M. I., Alverson, C. J., Macdonald, S. C., Bailey, C. R., Ball, L. B., Moorman, J. E., Somers, J. H., Mannino, D. M., and Redd, S. C. (2002) National vehicle emissions policies and practices and declining US carbon monoxide-related mortality. *JAMA* 288, 988-995

6. Nager, E. C., and O'Connor, R. E. (1998) Carbon monoxide poisoning from spray paint inhalation. *Acad Emerg Med* 5, 84-86

7. Coburn, R. F., Forster, R. E., and Kane, P. B. (1965) Considerations of the physiological variables that determine the blood carboxyhemoglobin concentration in man. *J Clin Invest* 44, 1899-1910

8. Peterson, J. E., and Stewart, R. D. (1975) Predicting the carboxyhemoglobin levels resulting from carbon monoxide exposures. *J Appl Physiol* 39, 633-638

9. Andersen, M. E., Clewell, H. J., 3rd, Gargas, M. L., MacNaughton, M. G., Reitz, R. H., Nolan, R. J., and McKenna, M. J. (1991) Physiologically based pharmacokinetic modeling with dichloromethane, its metabolite, carbon monoxide, and blood carboxyhemoglobin in rats and humans. *Toxicol Appl Pharmacol* 108, 14-27

10. Benignus, V. A., and Annau, Z. (1994) Carboxyhemoglobin formation due to carbon monoxide exposure in rats. *Toxicol Appl Pharmacol* 128, 151-157

11. Tyuma, I., Ueda, Y., Imaizumi, K., and Kosaka, H. (1981) Prediction of the

carbonmonoxyhemoglobin levels during and after carbon monoxide exposures in various animal species. *Jpn J Physiol* 31, 131-143

12. Bruce, E. N., and Bruce, M. C. (2003) A multicompartment model of carboxyhemoglobin and carboxymyoglobin responses to inhalation of carbon monoxide. *J Appl Physiol (1985)* 95, 1235-1247

13. (2010). in *Acute Exposure Guideline Levels for Selected Airborne Chemicals: Volume 8*, Washington (DC). pp

14. National Institute for Occupational Safety and Health. (2007) NIOSH pocket guide to chemical hazards. in *DHHS (NIOSH) publication no 2005-149*, U.S. Dept. of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health,, Cincinnati, Ohio

15. Khan-Mayberry, N. N. (2008) Carbon monoxide - Spacecraft maximum allowable concentrations for selected airborne contaminants. (Administration, N. A. a. S. ed.

16. National Research Council (U.S.). Subcommittee on Spacecraft Maximum Allowable Concentrations. (1996) *Spacecraft maximum allowable concentrations for selected airborne contaminants*, National Academy Press, Washington, D.C.

17. Sheppard, L., Levy, D., Norris, G., Larson, T. V., and Koenig, J. Q. (1999) Effects of ambient air pollution on nonelderly asthma hospital admissions in Seattle, Washington, 1987-1994. *Epidemiology* 10, 23-30

18. Ritz, B., and Yu, F. (1999) The effect of ambient carbon monoxide on low birth weight among children born in southern California between 1989 and 1993. *Environ Health Perspect* 107, 17-25

19. Kurt, T. L., Mogielnicki, R. P., and Chandler, J. E. (1978) Association of the frequency of acute cardiorespiratory complaints with ambient levels of carbon monoxide. *Chest* 74, 10-14

20. Lefaux, R. (1968) *Practical toxicology of plastics*, CRC Press

21. Smollin, C., and Olson, K. (2010) Carbon monoxide poisoning (acute). *BMJ Clin Evid* 2010

22. Palmeri, R., and Gupta, V. (2022) Carboxyhemoglobin Toxicity. in *StatPearls*, Treasure Island (FL). pp

23. Patel, S., Jose, A., and Mohiuddin, S. S. (2022) Physiology, Oxygen Transport And Carbon Dioxide Dissociation Curve. in *StatPearls*, Treasure Island (FL). pp

24. Wu, L., and Wang, R. (2005) Carbon monoxide: endogenous production, physiological functions, and pharmacological applications. *Pharmacol Rev* 57, 585-630

25. Rose, J. J., Wang, L., Xu, Q., McTiernan, C. F., Shiva, S., Tejero, J., and Gladwin, M. T. (2017) Carbon Monoxide Poisoning: Pathogenesis, Management, and Future Directions of Therapy. *Am J Respir Crit Care Med* 195, 596-606

26. EPA. (2010) Integrated science assessment for carbon monoxide.

27. Emmerich, S. J., Polidoro, B., Brookman, M. J., Buyer, J., and Hnatov, M. (2019) Simulation and Analysis Plan to Evaluate the Impact of CO Mitigation Requirements for Portable Generators. (Commerce, U. D. o., and Technology, N. I. o. S. a. eds.)

28. Hampson, N. B., and Hauff, N. M. (2008) Risk factors for short-term mortality from carbon monoxide poisoning treated with hyperbaric oxygen. *Crit Care Med* 36, 2523-2527

29. Piantadosi, C. A. (2002) Biological chemistry of carbon monoxide. *Antioxid Redox Signal* 4, 259-270

30. Cooper, K. R., and Alberti, R. R. (1984) Effect of kerosene heater emissions on indoor air quality and pulmonary function. *Am Rev Respir Dis* 129, 629-631

31. Ernst, A., and Zibrak, J. D. (1998) Carbon monoxide poisoning. *N Engl J Med* 339, 1603-1608

32. Sen, S., Peltz, C., Beard, J., and Zeno, B. (2010) Recurrent carbon monoxide poisoning from cigarette smoking. *Am J Med Sci* 340, 427-428

33. Cronje, F. J., Carraway, M. S., Freiberger, J. J., Suliman, H. B., and Piantadosi, C. A. (2004) Carbon monoxide actuates O(2)-limited heme degradation in the rat brain. *Free Radic Biol Med* 37, 1802-1812

34. Vanek, T., and Kohli, A. (2022) Biochemistry, Myoglobin. in *StatPearls*, Treasure Island (FL). pp

35. Ahmad, M., Wolberg, A., and Kahwaji, C. I. (2022) Biochemistry, Electron Transport Chain. in *StatPearls*, Treasure Island (FL). pp

36. Sangalli, B. C., and Bidanset, J. H. (1990) A review of carboxymyoglobin formation: a major mechanism of carbon monoxide toxicity. *Vet Hum Toxicol* 32, 449-453

37. Alonso, J. R., Cardellach, F., Lopez, S., Casademont, J., and Miro, O. (2003) Carbon monoxide specifically inhibits cytochrome c oxidase of human mitochondrial respiratory chain. *Pharmacol Toxicol* 93, 142-146

38. Lo Iacono, L., Boczkowski, J., Zini, R., Salouage, I., Berdeaux, A., Motterlini, R., and Morin, D. (2011) A carbon monoxide-releasing molecule (CORM-3) uncouples mitochondrial respiration and modulates the production of reactive oxygen species. *Free Radic Biol Med* 50, 1556-1564

39. Weber, R. E., and Vinogradov, S. N. (2001) Nonvertebrate hemoglobins: functions and molecular adaptations. *Physiol Rev* 81, 569-628

40. Goldbaum, L. R., Ramirez, R. G., and Absalon, K. B. (1975) What is the mechanism of carbon monoxide toxicity? *Aviat Space Environ Med* 46, 1289-1291

41. Gilles-Gonzalez, M. A., and Gonzalez, G. (2005) Heme-based sensors: defining characteristics, recent developments, and regulatory hypotheses. *J Inorg Biochem* 99, 1-22

42. Sun, J., Hoshino, H., Takaku, K., Nakajima, O., Muto, A., Suzuki, H., Tashiro, S., Takahashi, S., Shibahara, S., Alam, J., Taketo, M. M., Yamamoto, M., and Igarashi, K. (2002) Hemoprotein Bach1 regulates enhancer availability of heme oxygenase-1 gene. *EMBO J* 21, 5216-5224

43. Meyer, G., Andre, L., Kleindienst, A., Singh, F., Tanguy, S., Richard, S., Obert, P., Boucher, F., Jover, B., Cazorla, O., and Reboul, C. (2015) Carbon monoxide increases inducible NOS expression that mediates CO-induced myocardial damage during ischemia-reperfusion. *Am J Physiol Heart Circ Physiol* 308, H759-767

44. Thom, S. R., Ohnishi, S. T., and Ischiropoulos, H. (1994) Nitric oxide released by platelets inhibits neutrophil B2 integrin function following acute carbon monoxide poisoning. *Toxicol Appl Pharmacol* 128, 105-110

45. Thom, S. R., Bhopale, V. M., Han, S. T., Clark, J. M., and Hardy, K. R. (2006) Intravascular neutrophil activation due to carbon monoxide poisoning. *Am J Respir Crit Care Med* 174, 1239-1248

46. Thom, S. R., Xu, Y. A., and Ischiropoulos, H. (1997) Vascular endothelial cells generate peroxynitrite in response to carbon monoxide exposure. *Chem Res Toxicol* 10, 1023-1031

47. Weaver, L. K. (2009) Clinical practice. Carbon monoxide poisoning. *N Engl J Med* 360, 1217-1225

48. Kuroda, H., Fujihara, K., Kushimoto, S., and Aoki, M. (2015) Novel clinical grading of delayed neurologic sequelae after carbon monoxide poisoning and factors associated with outcome.

Neurotoxicology 48, 35-43

49. Thom, S. R., Bhopale, V. M., and Fisher, D. (2006) Hyperbaric oxygen reduces delayed immune-mediated neuropathology in experimental carbon monoxide toxicity. *Toxicol Appl Pharmacol* 213, 152-159

50. Doyle, K. P., Simon, R. P., and Stenzel-Poore, M. P. (2008) Mechanisms of ischemic brain damage. *Neuropharmacology* 55, 310-318

51. Geocadin, R. G., Koenig, M. A., Jia, X., Stevens, R. D., and Peberdy, M. A. (2008) Management of brain injury after resuscitation from cardiac arrest. *Neurol Clin* 26, 487-506, ix

52. Kim, I., Xu, W., and Reed, J. C. (2008) Cell death and endoplasmic reticulum stress: disease relevance and therapeutic opportunities. *Nat Rev Drug Discov* 7, 1013-1030

53. Piantadosi, C. A., Zhang, J., Levin, E. D., Folz, R. J., and Schmechel, D. E. (1997) Apoptosis and delayed neuronal damage after carbon monoxide poisoning in the rat. *Exp Neurol* 147, 103-114

54. Burney, R. E., Wu, S. C., and Nemiroff, M. J. (1982) Mass carbon monoxide poisoning: clinical effects and results of treatment in 184 victims. *Ann Emerg Med* 11, 394-399

55. Centers for Disease, C., and Prevention. (1995) Unintentional carbon monoxide poisonings in residential settings--Connecticut, November 1993-March 1994. *MMWR Morb Mortal Wkly Rep* 44, 765-767

56. Kirkpatrick, J. N. (1987) Occult carbon monoxide poisoning. *West J Med* 146, 52-56

57. Kaya, H., Coskun, A., Beton, O., Zorlu, A., Kurt, R., Yucel, H., Gunes, H., and Yilmaz, M. B. (2016) COHgb levels predict the long-term development of acute myocardial infarction in CO poisoning. *Am J Emerg Med* 34, 840-844

58. Dziewierz, A., Ciszowski, K., Gawlikowski, T., Rakowski, T., Kleczynski, P., Surdacki, A., and Dudek, D. (2013) Primary angioplasty in patient with ST-segment elevation myocardial infarction in the setting of intentional carbon monoxide poisoning. *J Emerg Med* 45, 831-834

59. Smithline, H. A., Ward, K. R., Chiulli, D. A., Blake, H. C., and Rivers, E. P. (2003) Whole body oxygen consumption and critical oxygen delivery in response to prolonged and severe carbon monoxide poisoning. *Resuscitation* 56, 97-104

60. Lippi, G., Rastelli, G., Meschi, T., Borghi, L., and Cervellin, G. (2012) Pathophysiology, clinics, diagnosis and treatment of heart involvement in carbon monoxide poisoning. *Clin Biochem* 45, 1278-1285

61. Andre, L., Boissiere, J., Reboul, C., Perrier, R., Zalvidea, S., Meyer, G., Thireau, J., Tanguy, S., Bideaux, P., Hayot, M., Boucher, F., Obert, P., Cazorla, O., and Richard, S. (2010) Carbon monoxide pollution promotes cardiac remodeling and ventricular arrhythmia in healthy rats. *Am J Respir Crit Care Med* 181, 587-595

62. Macmillan, C. S., Wildsmith, J. A., and Hamilton, W. F. (2001) Reversible increase in QT dispersion during carbon monoxide poisoning. *Acta Anaesthesiol Scand* 45, 396-397

63. Hampson, N. B., Piantadosi, C. A., Thom, S. R., and Weaver, L. K. (2012) Practice recommendations in the diagnosis, management, and prevention of carbon monoxide poisoning. *Am J Respir Crit Care Med* 186, 1095-1101

64. Ning, K., Zhou, Y. Y., Zhang, N., Sun, X. J., Liu, W. W., and Han, C. H. (2020) Neurocognitive sequelae after carbon monoxide poisoning and hyperbaric oxygen therapy. *Med Gas Res* 10, 30-36

65. Chambers, C. A., Hopkins, R. O., Weaver, L. K., and Key, C. (2008) Cognitive and affective outcomes of more severe compared to less severe carbon monoxide poisoning. *Brain Inj* 22, 387-395

66. Vieregge, P., Klostermann, W., Blumm, R. G., and Borgis, K. J. (1989) Carbon monoxide

poisoning: clinical, neurophysiological, and brain imaging observations in acute disease and follow-up. *J Neurol* 236, 478-481

67. Hsiao, C. L., Kuo, H. C., and Huang, C. C. (2004) Delayed encephalopathy after carbon monoxide intoxication--long-term prognosis and correlation of clinical manifestations and neuroimages. *Acta Neurol Taiwan* 13, 64-70

68. Mimura, K., Harada, M., Sumiyoshi, S., Tohya, G., Takagi, M., Fujita, E., Takata, A., and Tatetsu, S. (1999) [Long-term follow-up study on sequelae of carbon monoxide poisoning; serial investigation 33 years after poisoning]. *Seishin Shinkeigaku Zasshi* 101, 592-618

69. Townsend, C. L., and Maynard, R. L. (2002) Effects on health of prolonged exposure to low concentrations of carbon monoxide. *Occup Environ Med* 59, 708-711

70. Ryter, S. W., Alam, J., and Choi, A. M. (2006) Heme oxygenase-1/carbon monoxide: from basic science to therapeutic applications. *Physiol Rev* 86, 583-650

71. Penney, D. G. (2008) Chronic carbon monoxide poisoning: a case series. in *Carbon Monoxide Poisoning* (Penney, D. G. ed.), CRC Press, Boca Raton, FL. pp 551-567

72. Weaver, L. K. (2014) Hyperbaric oxygen therapy for carbon monoxide poisoning. *Undersea Hyperb Med* 41, 339-354

73. Weaver, L. K., Howe, S., Hopkins, R., and Chan, K. J. (2000) Carboxyhemoglobin half-life in carbon monoxide-poisoned patients treated with 100% oxygen at atmospheric pressure. *Chest* 117, 801-808

74. Pace, N., Strajman, E., and Walker, E. L. (1950) Acceleration of carbon monoxide elimination in man by high pressure oxygen. *Science* 111, 652-654

75. Sasaki, T. (1975) On half-clearance time of carbon monoxide hemoglobin in blood during hyperbaric oxygen therapy (OHP). *Bull Tokyo Med Dent Univ* 22, 63-77

76. Garrabou, G., Inoriza, J. M., Moren, C., Oliu, G., Miro, O., Marti, M. J., and Cardellach, F. (2011) Mitochondrial injury in human acute carbon monoxide poisoning: the effect of oxygen treatment. *J Environ Sci Health C Environ Carcinog Ecotoxicol Rev* 29, 32-51

77. Weaver, L. K., Hopkins, R. O., Chan, K. J., Churchill, S., Elliott, C. G., Clemmer, T. P., Orme, J. F., Jr., Thomas, F. O., and Morris, A. H. (2002) Hyperbaric oxygen for acute carbon monoxide poisoning. *N Engl J Med* 347, 1057-1067

78. Raphael, J. C., Elkharrat, D., Jars-Guincestre, M. C., Chastang, C., Chasles, V., Vercken, J. B., and Gajdos, P. (1989) Trial of normobaric and hyperbaric oxygen for acute carbon monoxide intoxication. *Lancet* 2, 414-419

79. Buckley, N. A., Juurlink, D. N., Isbister, G., Bennett, M. H., and Lavonas, E. J. (2011) Hyperbaric oxygen for carbon monoxide poisoning. *Cochrane Database Syst Rev*, CD002041

80. Hampson, N. B., and Weaver, L. K. (2011) Residential carbon monoxide alarm use: opportunities for poisoning prevention. *J Environ Health* 73, 30-33

81. Commission, U. S. C. P. a. S. (2011) *Carbon Monoxide*,

82. Prevention, C. f. D. C. a. (2011) *Carbon monoxide poisoning prevention guidance*,

TAB G: Memorandum from the Office of Compliance and Field Operations

United States
Consumer Product Safety Commission

Memorandum

TO: Ronald Jordan, Mechanical Engineer
Division of Mechanical and Combustion Engineering
Directorate for Engineering Sciences

DATE: September 20,2023

THROUGH:

FROM: Blake Rose, Division Director
Resources Management and Fast Track Recalls
Office of Compliance and Field Operations

SUBJECT: Recalls Involving CO Risks Associated with Gas Furnaces, Boilers, Wall Furnaces and Floor Furnaces

BACKGROUND:

To support rulemaking to address CO risks associated with gas furnaces, boilers, wall furnaces and floor furnaces, the Office of Compliance and Field Operations staff prepared this memorandum that provides relevant CPSC recall data over the last 10 years.

RECALL HISTORY:

Recall Date	Product	Hazard	Defect	# of Units	Incidents/Injuries/Deaths	Remedy
June 30, 2022	Residential atmospheric gas-fired boilers	Carbon Monoxide Poisoning	Malfunctioning blocked vent temperature switch	545	None	Repair
June 18, 2020	Condensing residential boilers	Carbon Monoxide Poisoning	Flue grommet can deteriorate and dislodge during use	34,300	7 incidents/two nonfatal injuries	Repair
July 28, 2020	Condensing gas boilers	Carbon Monoxide Poisoning	Vent adapter not securely attached	63,000	3 incidents/1 death	Repair
April 25, 2019	Boilers	Carbon Monoxide Poisoning	Heat exchanger back plate can corrode and leak	2,900	None	Repair
December 20, 2018	Condensing tankless water heaters and combination boilers	Carbon Monoxide Poisoning	Natural gas to propane conversion kit can cause unit to produce excessive CO	3,400	None	Replacement conversion kit
May 15, 2018	Residential and commercial boilers	Carbon Monoxide Poisoning	Grommet seal can dislodge during use	16,000	3 incidents/no injuries	Repair
February 25, 2016	Gas boilers	Carbon Monoxide Poisoning	Boiler can overheat and emit gases into the venting system	165	10 incidents/no injuries	Repair
January 9, 2014	Gas-fired hot water boilers	Carbon Monoxide Poisoning	Air pressure switch can fail to shut down burners if vent system becomes blocked	191	None	Repair
December 3, 2013	Gas-fired hot water boilers	Carbon Monoxide Poisoning	Air pressure switch can fail to shut down burners if vent system becomes blocked	2,200	None	Repair