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Chemical Challenge Tests on ISS Fire Cartridges

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Following a confirmed combustion event onboard the International Space Station (ISS), crew members will don Emergency Masks, each fitted with 2 ISS fire cartridge filters. As the crew member breathes through the filters, combustion products in the cabin air are either filtered or catalyzed by the fire cartridge media to minimize crew exposure to harmful levels of contaminants. Rigorous certification, acceptance, and surveillance programs for the fire cartridges ensure that each lot meets stringent performance requirements throughout the service life of the cartridges. In accordance with the Quality/Acceptance Test Plan, multiple fire cartridges from each lot undergo chemical challenge tests involving one or more chemicals at specified concentrations. These tests are conducted at specific temperatures, humidity levels, and gas flow rates intended to mimic the worst-case conditions for fire cartridge performance. These challenge tests are conducted by the Environmental Chemistry Laboratory at the NASA Lyndon B. Johnson Space Center. Many of the challenge tests focus on carbon monoxide (CO), but other gases include hydrogen cyanide (HCN), hydrogen chloride (HCl), cyclohexane, acrolein, ammonia (NH_3), and acetaldehyde. A fire cartridge is exposed to the test gas in a chamber at the specified conditions, and the outlet is monitored for breakthrough during the 2.5-hour test. This paper will briefly introduce fire cartridges and how they work and will then discuss details of the challenge gas delivery and exposure system, breakthrough monitoring methods, and discussion of issues that have arisen during the course of the test program. Although the focus of this paper will be on the challenge tests, a general summary of the performance of the fire cartridges will also be provided.

Nomenclature

CO = carbon monoxide
CO_2 = carbon dioxide
CSA-CP = Compound Specific Analyzer - Combustion Products
ΔP = pressure drop
EC = Crew and Thermal Systems Division
ECL = Environmental Chemistry Laboratory
GC/FID = gas chromatography/flame ionization detector
GC/MS = gas chromatography/mass spectrometry
HCl = hydrochloric acid
HCN = hydrogen cyanide
HM = Humidification Module

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ISS = International Space Station
LPM = liters per minute
mGSC = miniature grab sample container
N_2 = nitrogen gas
NH_3 = ammonia
PSMO = pressure systems management office
ppm = parts per million
RH = relative humidity
SMAC = Spaceflight Maximum Allowable Concentration
TPS = task performance sheet
VOC = volatile organic compound
ZA = zero air

I. Introduction

During a combustion event, a number of toxic gases and particulates are produced that could place people at risk of injury or death. In closed or semi-closed environments, such as spacecraft (e.g. the International Space Station [ISS], Gateway, or transfer vehicles) or submarines, these gases can prove to be far more serious than a similar event on land due to the cramped quarters, limited fire response resources, and limited evacuation opportunities.[1]

Both minor and major pyrolysis events occurred during the Mir and early Space Shuttle era.[2] While these resulted in limited toxicological effects, they showed the potential for combustion in spaceflight. A number of technology demonstrations have been performed to determine the species of interest and monitor the gases produced in combustion events;[1,3-5] however, having reliable countermeasures available to the crew is vital to their safety and increases their chance of surviving a potentially catastrophic event.

In the event of a fire on the ISS, the crew would follow fire suppression procedures, including the use of first response masks, before moving to a safe area in the spacecraft.[6] At the conclusion of the fire suppression, “smoke eater” systems, containing sorbents and catalysts to remove acid gases and carbon monoxide (CO) in the presence of high levels of humidity and carbon dioxide (CO_2), are used to return the spacecraft to contaminant levels well below the Spacecraft Maximum Allowable Concentration (SMAC) levels for the individual species.[7-10] In order to continue clean-up work to mitigate the effects of the combustion event before the general filtration is complete, the crew are able to don Emergency Masks to provide personal air filtration. Attached to the Emergency Mask is a Fire Cartridge, which aims to oxidize carbon monoxide (CO) and remove other chemical and particulate contaminants from the compromised air. CO oxidation is accomplished through the use of a catalyst consisting of gold nanoparticles supported on iron oxide (while generally considered inert, small gold nanoparticles are highly active for the low-temperature oxidation of CO to CO_2, among other reactions[11-13]). Removal of other combustion by-products, such as ammonia, particulates, and other trace contaminants is achieved through the use of a carbon layer and a polytetrafluoroethylene filter. The cartridges can easily be attached and detached from the Emergency Mask, making their implementation and replacement simple for crew members.

When new fire cartridge lots are manufactured, a rigorous regimen of qualification and acceptance testing, including physical and chemical testing, is conducted to verify that all specifications and requirements are met. Additionally, surveillance chemical-challenge tests are conducted periodically during the lifetime of the cartridges to ensure their efficacy has not significantly decreased. For all single-chemical flow bench testing, “the objective is to prove the functionality, size, and packaging of the universal carbon and CO catalyst beds.”[6] The data obtained from these tests provide valuable insight into the cartridge performance at specified conditions and allows for any degradation to be tracked.

II. Overview of the Testing Process

A. Approach

Prior to conducting any exposure testing, all test procedures are included in Task Performance Sheets (TPSs) and pre-approved by NASA/JSC Quality Engineering. Data generated from these tests are included in the TPSs, which, after completion, become official documents stored in the NASA/JSC Quality Assurance Record Center.

All chemical-challenge tests begin and end with measurements of the mass and pressure drop (ΔP) across the fire cartridge. Following the initial mass and ΔP measurements, the chemical challenge test is initiated. This testing includes a series of steps to verify that the exposure system meets specific test parameters prior to the installation of the fire cartridge. These parameters vary according to the specific chemical challenge test requirements and include the following:

- Total flow rate at test chamber outlet
- Relative humidity inside the test chamber
- Temperature inside the test chamber
- Challenge gas concentration

Gases used in the challenges include compressed gas sources of the specific chemical with zero air (ZA) and nitrogen diluents. Gas flows are controlled by mass flow controllers. Once the test specifications are achieved, the set points for all flows are recorded, and the challenge gas source is diverted from the exposure chamber. The fire cartridge is installed inside the exposure chamber and the flow rate (w/o challenge gas), temperature, and humidity conditions are re-established. The test begins when the challenge gas flow is diverted back into the test gas stream going into the test chamber. The test conditions are monitored during the 2.5-hour test. At the end of the test period, the challenge gas source is diverted from the exposure chamber, and the fire cartridge is removed. The challenge gas is re-introduced into the gas stream and the post-test gas concentration is measured at the chamber outlet to ensure that the average pre- and post-concentrations meet the test requirement, followed by a post-test mass and ΔP measurement. The test gas streams in all challenge tests are humidified at varying levels. Typically, the post-test mass is higher than the pre-test weight due to the adsorption of water inside the cartridge. Since large amounts of water may adversely affect the performance of the fire cartridge for subsequent tests, a post-test drying step includes flowing a dry air/N_2 mixture across the fire cartridge until the original pre-test mass is obtained.

The configuration of the exposure system for each of the different chemical challenge gases is dependent on the specific chemical, exposure requirements, and/or the sample collection or analytical method. There are 2 essentially identical air-tight acrylic test chambers used for testing. The chambers include several ports in the walls to allow for the insertion of temperature and humidity probes and for the connection of the inlet gas stream. The bayonet inlet/outlet assembly that connects to the fire cartridge is attached to the chamber lid. The exposure gas flowrate and challenge gas concentration are measured from the outlet tubing. **Figure 1** below shows one of the chambers with a non-flight Fire Cartridge and Vaisala humidity and temperature probe installed.

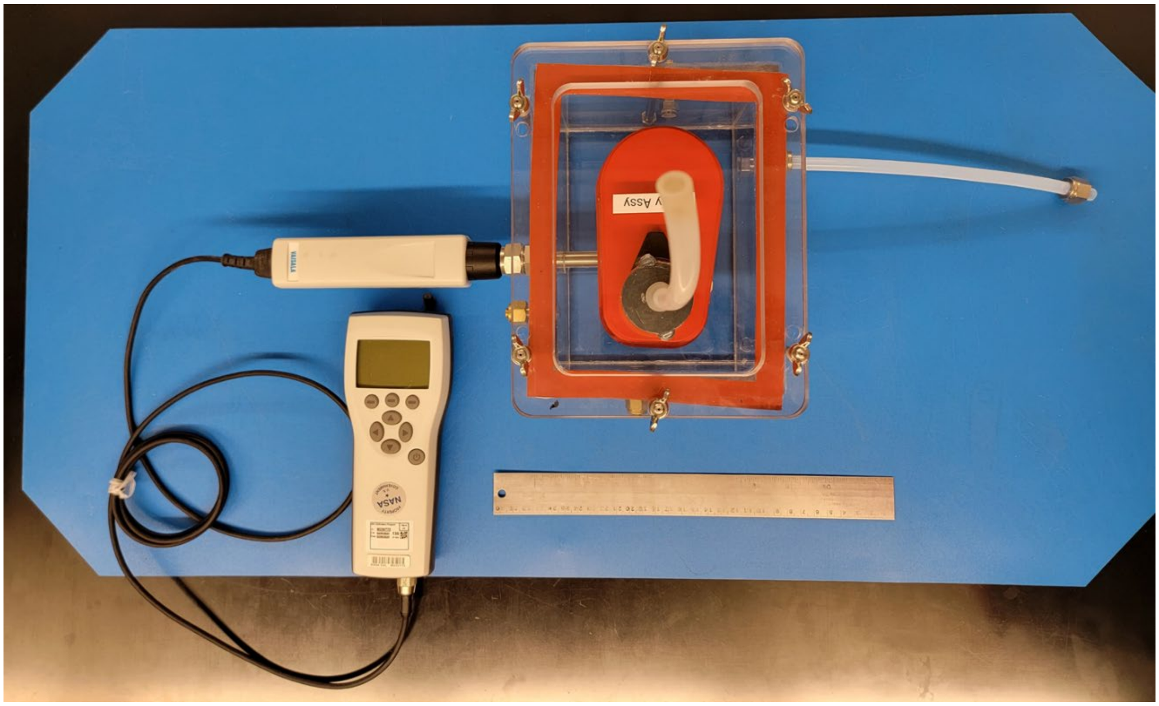

Figure 1: Test chamber with a fire cartridge and humidity probe installed

B. Equipment

On test days, both chambers are typically used: one for the differential pressure measurement and one for the chemical exposure test. A list of major equipment used in the chemical challenge tests and differential pressure measurements is provided in Table 1.

Table 1: List of Major Equipment Used in the Chemical Challenge Tests

Calibration	Description	Purpose/Test
JSC MSCL*-Calibrated Equipment	Alicat & Sierra Instruments mass flow controllers	Delivery of all gases used in the tests
	Vaisala Humidity & Temperature probes	Measurement of RH & temperature in test chambers
	Dwyer Digital Manometer or Short Airdata Multimeter	Measurement of ΔP across the fire cartridge
	Kin-Tek FlexStream Gas Standard Generator w/ Base and Humidity modules	Delivery of gas for ΔP measurement; provides and maintains humidity control for HCN, HCl, and NH_3 tests
	Bios DryCal flowmeters	Measurement of total chamber outlet flows
*Measurement Standards and Calibration Laboratory		
User Calibrated Equipment	Drager Xam-5600 real-time monitor	Measurement of CO and NH_3 concentrations
	Drager Xam-8000 real-time monitor	Measurement of cyclohexane concentration
	Industrial Scientific Compound Specific Analyzer- Combustion Products	Measurement of HCl and HCN concentrations
	Agilent Gas Chromatograph-Mass Spectrometer	Measurement of low-level (ppb) acrolein and acetaldehyde concentrations
	Agilent Gas Chromatograph-Flame Ionization Detector	Measurement of high-level (ppm) acrolein and acetaldehyde concentrations
Non-Calibrated Equipment	Thermo-Scientific water bath & bubbler	Introduction of water vapor into the test gas stream
	Thermo-Scientific chillers	Cooling of the dilutant gas stream
Other Equipment	Pressure systems for all compressed gases	Certified by PMSO
	Certified stock challenge compressed gases	Traceability

III. Fire Cartridge Test Stands

A. A Brief History

The ECL has worked with the EC/Crew and Thermal Systems Division for many years on fire cartridge performance testing. Initial fire cartridge support began in 2018 when the ECL analyzed 18 grab samples collected in an outside vendor's acrolein challenge test. In late 2018 and 2019, the ECL analyzed facility air samples collected in the fire cartridge manufacturer's production area, as well as samples in the JSC Receiving Inspection & Test Facility, EC3 Flight Hardware Processing Lab, and Space Food Systems Lab. These samples were collected to verify contaminant-free environments in which fire cartridges were being manufactured, inspected, or processed. In 2019, the EC3 fire cartridge project management contacted the ECL to inquire whether the ECL could perform the fire cartridge chemical challenge tests as stated in the quality/acceptance test plan. The ECL developed a plan to address the difficult exposure test requirements. In late 2019, the fire cartridge test program began at the ECL, and, by the end of 2022, approximately 120 tests and numerous engineering evaluations had been conducted by the Lab.

B. Pressure Drop

At the beginning and end of each chemical challenge test, the differential pressure is measured across the fire cartridge. **Figure 2** provides an image of the configuration for the differential pressure measurements. At a flowrate of approximately 21.8 liters per minute (LPM), the differential pressure across the chamber (lower pressure measured inside the chamber and higher pressure in the chamber outlet flow) is determined without the fire cartridge installed.

Once the fire cartridge is installed, the differential pressure is measured again. The difference between the 2 measurements is recorded as the ΔP across the fire cartridge. This information may be useful to verify the integrity of the internal layers of the fire cartridge over the duration of its test history and large differences in these measurements could be indicative of an internal issue. For example, reduced ΔP could suggest channeling, which could lead to decreased interaction between the catalyst and gas, while increased ΔP could be the result of a blockage.

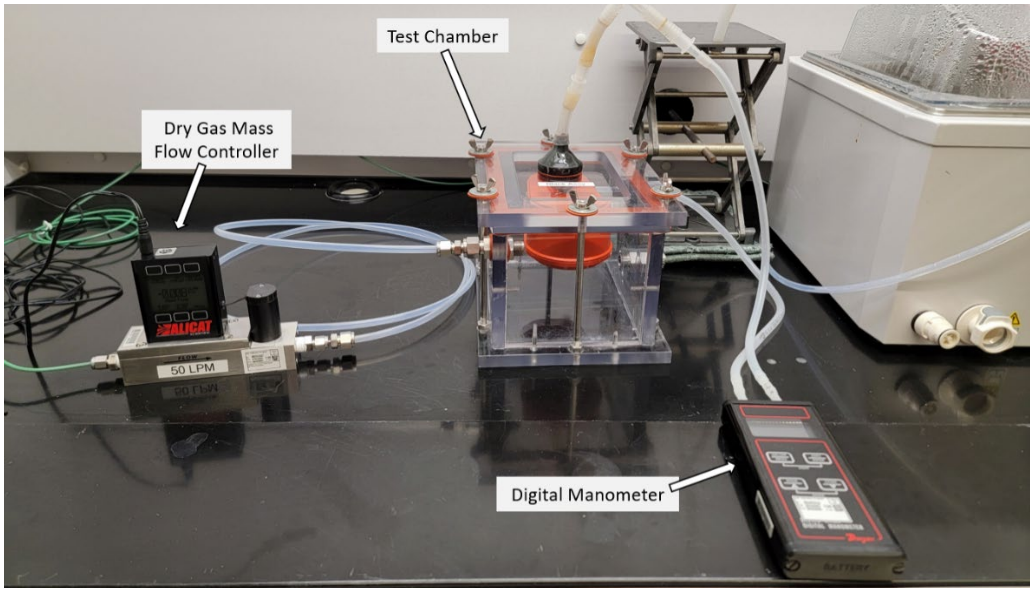

Figure 2: Configuration for Pressure Drop Measurement

C. Test Stands

In total, seven gases have been used to test fire cartridge performance: CO, NH_3, HCl, HCN, cyclohexane, acrolein, and acetaldehyde/CO combination. The Qualification/Acceptance test plan for new fire cartridge builds requires lot testing involving the exposure of a representative sample group to each of these chemicals. Since fire cartridges are given a long shelf life (approximately 5 years), an ongoing surveillance program is critical to monitor and verify that performance requirements are met for the projected life of the lot. The surveillance program involves challenging the surveillance units (determined with specified serial numbers) to a subset of the chemicals, primarily CO, HCN and cyclohexane.

Table 2: Challenge Test Exposure and Breakthrough Requirements

Challenge Gas	Exposure Concentration (ppm)	Temperature (^{o}C)	Relative Humidity (%)	Test Duration (min)	Peak Breakthrough (ppm)	Total Weighted Average (ppm)
CO (cold)	1000 ± 30	0 ± 3	85 ± 5	120 +2/-0	425	100
CO (ambient)	1000 ± 30	15.2 ± 1.5	85 ± 5	120 +2/-0	425	100
NH_3	100 ± 3	25 ± 3	20 ± 5	120 +2/-0	20	N/A
HCN	50 ± 1.5	25 ± 3	20 ± 5	120 +2/-0	5	N/A
HCl	50 ± 1.5	25 ± 3	20 ± 5	120 +2/-0	5	N/A
Cyclohexane	100 ± 3	25 ± 3	85 ± 5	120 +2/-0	10	N/A
Acrolein	5 ± 0.15	25 ± 3	85 ± 5	120 +2/-0	0.035	N/A
CO/Acetaldehyde	1000 ± 3 20 ± 1.5	2.8 ± 3	85 ± 5	120 +2/-0	425 6.0	100 N/A

*Test requirements are based on a 120-minute test. An additional 30-minute test period is for data-gathering purposes

The test conditions must meet specific requirements, including concentration, chamber temperature, relative humidity, flowrate, and test duration, as listed in **Table 2**. Breakthrough of the chemical, as measured in the chamber outlet gas stream, must meet peak breakthrough requirements. Specifically for CO, there is also a maximum time-weighted average requirement based on a 120 minute exposure period. Although the pass/fail requirements are based on the exposure period, the tests are conducted for an additional 30 minute data-gathering period at the request of the project engineer.

D. Generic Challenge Test Description

There are 2 basic test stand configurations for the challenge gases:

1. CO (cold & ambient), acrolein, cyclohexane and CO/acetaldehyde utilize the base configuration shown in the block diagram in **Figure 3**. This block diagram depicts the cold CO configuration specifically, though variations to this configuration include:
    - Acrolein and acetaldehyde tests incorporate a quick-disconnect T-fitting in the chamber outlet line for the collection of grab samples for subsequent analyses.
    - Cyclohexane tests utilize a Drager Xam-8000 photoionization sensor instead of a Drager Xam-5600 electrochemical sensor and the cooler with ice packs is not required.
    - The CO ambient test does not require the ice packs shown in the cooler.

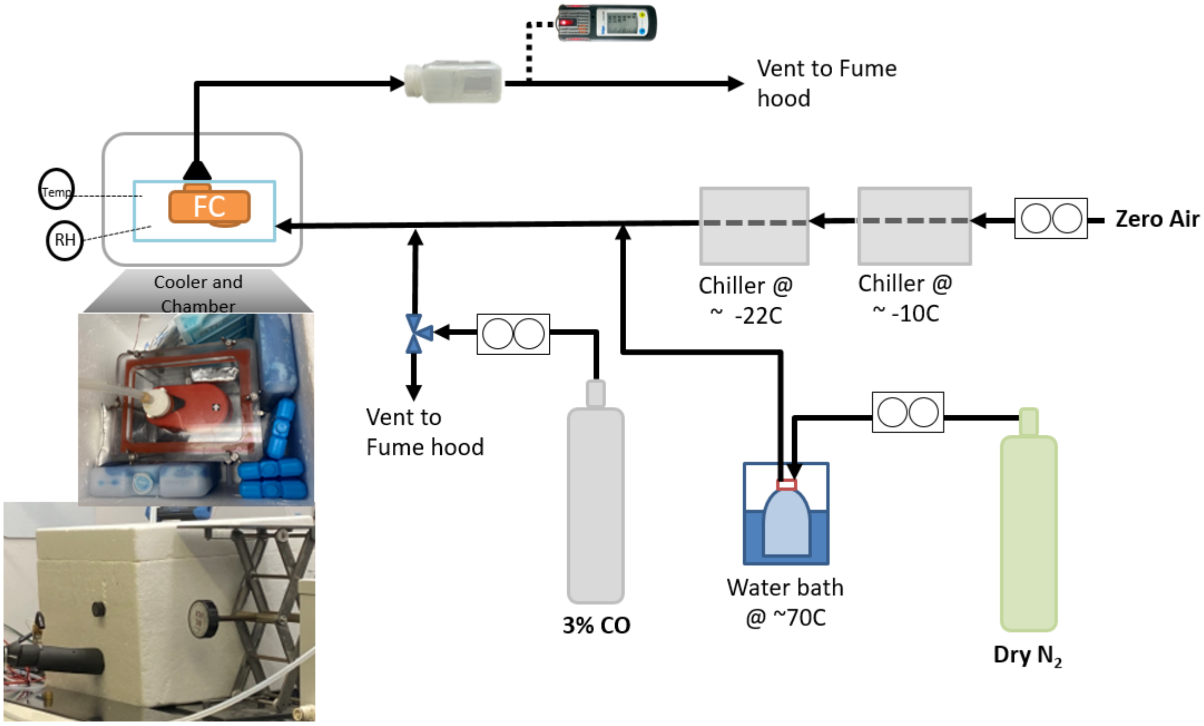

Figure 3: Block Diagram of CO Challenge Test Stand (Cold)

2. The acid (HCN, HCl) and base (NH_3) tests are conducted in a separate fume hood containing an identical exposure chamber. The chamber is fitted with a humidity probe that provides a sensor feedback loop to a Kin-Tek FlexStream Humidification Module (HM). The HM will change gas flow and pressure through the module to maintain a user-determined RH setpoint in the exposure chamber, while maintaining constant total flow from the FlexStream system. This system cannot be used for the very high RH requirements (85 ± 5%) in the CO, et al., challenge tests.

Data from the Drager units, Vaisala and Kin-Tek humidity and temperature probes, and Omega temperature datalogger are logged each minute for the duration of the 150-minute test period. Additionally, to prevent the loss of all data in the event of a datalogging issue, display readings from these instruments are manually recorded on the TPS every 5 minutes.

Total flow rate, as measured in the chamber outlet tubing, is recorded approximately every 20 minutes. These measurements are minimized during the test period and performed quickly, since it requires the removal of the real-time monitoring device from the outlet gas stream. All recorded and manually-collected data are gathered at the end of the test and compiled into a summary report.

As previously mentioned, humidity control for the HCN, HCl and NH_3 challenge tests is performed by the Kin-Tek FlexStream instrument. However, the high RH requirements for the remaining tests demand a different approach (see **Figure 3**). A N_2 gas stream, controlled by a mass flow controller, is directed through a bubbler filled with deionized water that is submerged in a heated water bath. The bubbler outlet flow tubing is connected to a T-fitting, located in the main test gas stream just before it enters the cooler. The RH inside the chamber is controlled by the flowrate through the bubbler. Small adjustments to the flowrate are often required to maintain an 85 ± 5% RH environment inside the chamber. This flow adds heat to the gas stream so the chiller temperatures (typically -10 and -22 ± 2° C) are set accordingly to maintain a chamber temperature within the specifications.

Key to maintaining the test environmental conditions within the allowable specifications is the management of the various input gas flows. Prior to installing a fire cartridge inside the chamber, the flowrates for the challenge test gas, diluent ZA, and bubbler N_2 are established such that the chamber environment and outlet challenge gas concentration meet the test specifications. At this point, all of the mass flow controller setpoints are recorded and a ratio of the test gas to the other gases is calculated (see below). Using a 3-way valve, the challenge gas input flow is re-directed away from the major test gas stream. Once the chamber is purged with the humidified ZA and bubbler gas streams, the fire cartridge is installed. The chamber temperature and humidity requirements are re-established, and the chamber outlet flow is verified to be approximately the specified outlet flow less the challenge gas input flow. The test begins when the 3-way valve is turned to direct the challenge input gas into the major test gas stream going into the chamber. It is common for small adjustments to be made to the input flows during the test but the ratio established before the test is maintained. For example, if the humidity must be lowered by reducing the bubbler flow, an increase of equal magnitude to the ZA flow is made so that the total is constant. However, if changes result in the sum of the ZA and bubbler setpoints being different, the ratio is used to calculate the necessary challenge gas input flow to maintain the same test gas concentration. The ratio is determined by the following calculation:

Test Gas Flow Set Point / (ZA+ Bubbler Flow Setpoints) = Test Gas Ratio

E. CO Test

CO is the most frequently employed test gas as it is largely used for the ground-based surveillance program for the cartridges on orbit. It can be performed using two different set-ups: cold (**Figure 4**) and ambient (**Figure 5**). These two test stands differ entirely by the requisite chamber temperature during the exposure test. The colder temperature is reached with the addition of a polystyrene chest that houses and insulates the test chamber. Ice packs line the space between the test chamber and the insulating chest to help further cool the chamber. Ice packs are arranged around the chamber inside of the cooler to allow for maximum cooling without disrupting the probes and tubing. For the ambient test, the chillers are still used to cool the ZA flow, but the chest and ice packs are not introduced unless required due to higher than typical temperatures inside the laboratory.

Measurement of the concentration of CO throughout the test is performed with a Drager Xam-5600 monitor. This monitor is user-calibrated every six months, and minor maintenance such as battery replacement is performed in-house. This monitor automatically records data in one-minute interval averaged values. The Vaisala humidity probe is used to monitor temperature and relative humidity conditions inside the test chamber, recording data in one-minute intervals during the entire exposure period.

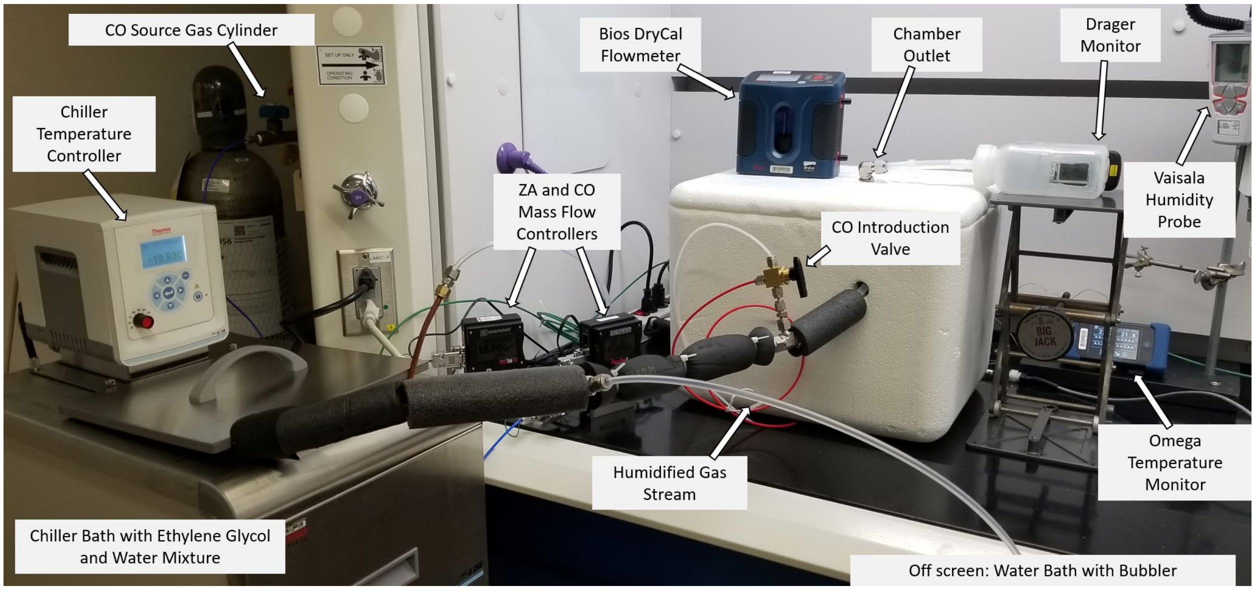

Figure 4: CO Cold Exposure Test Set-Up

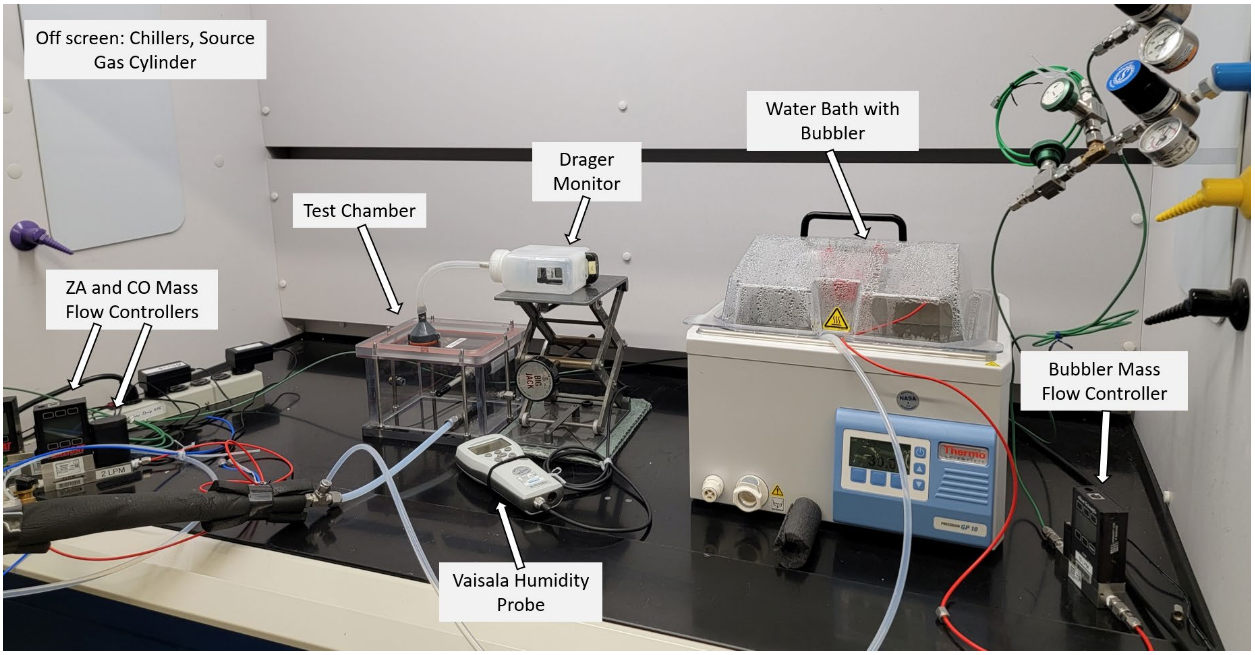

Figure 5: CO Ambient Exposure Test Set-Up

F. NH_3, HCN, and HCl Tests

NH_3, HCN, and HCl testing utilizes the Kin-Tek FlexStream system for temperature and humidity control due to the moderate test requirements: 25 ± 3°C and 20 ± 5% RH. As previously mentioned, the FlexStream system includes a humidity and temperature probe installed in the wall of the exposure chamber, providing a feedback loop for humidity control. The FlexStream also provides data logging of the humidity and temperature. The FlexStream is limited in the total output flow it can provide, so additional diluent (N_2) is added to the gas stream at a T-fitting. Identical to the CO system, the stock challenge gas is added to the gas stream using a 3-way valve. A thermocouple installed in the chamber and an Omega temperature recorder provides a second method for recording chamber temperature.

The NH_3 concentration is monitored and recorded using a Drager Xam-5600 fitted with an NH_3 electrochemical sensor. HCN and HCl concentrations are measured with a Compound-Specific Analyzer for Combustion Products (CSA-CP), which also uses electrochemical sensors. Data are recorded in one-minute intervals by the CSA-CP. See **Figures 6 and 7** for images of these test set-ups.

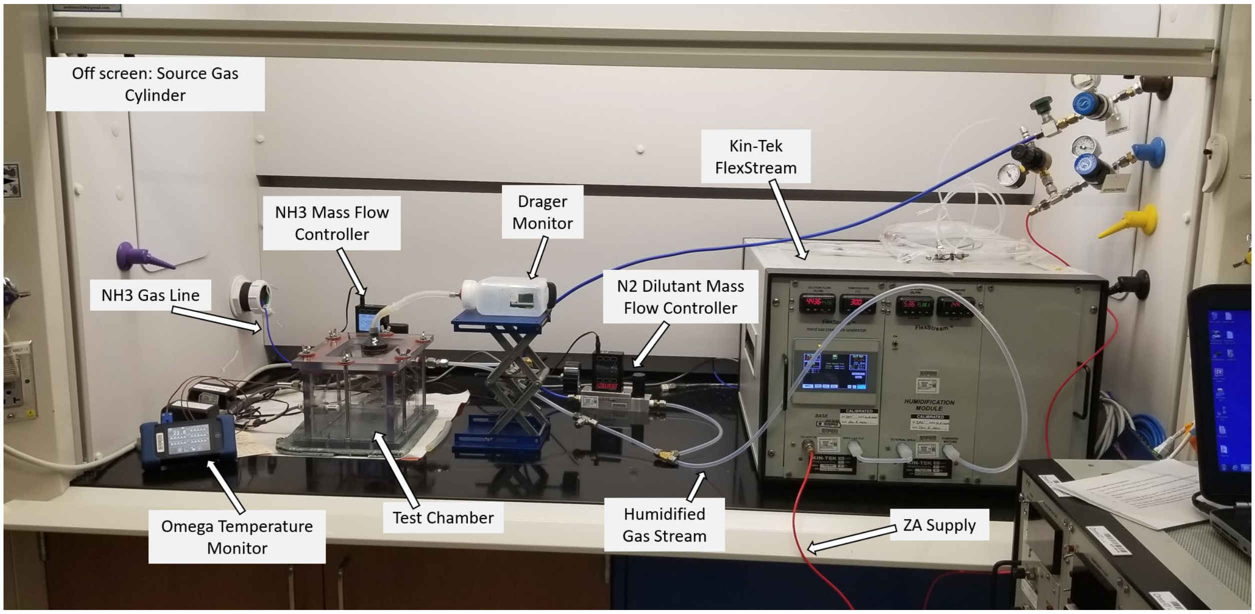

Figure 6: NH_3 Exposure Test Set-Up

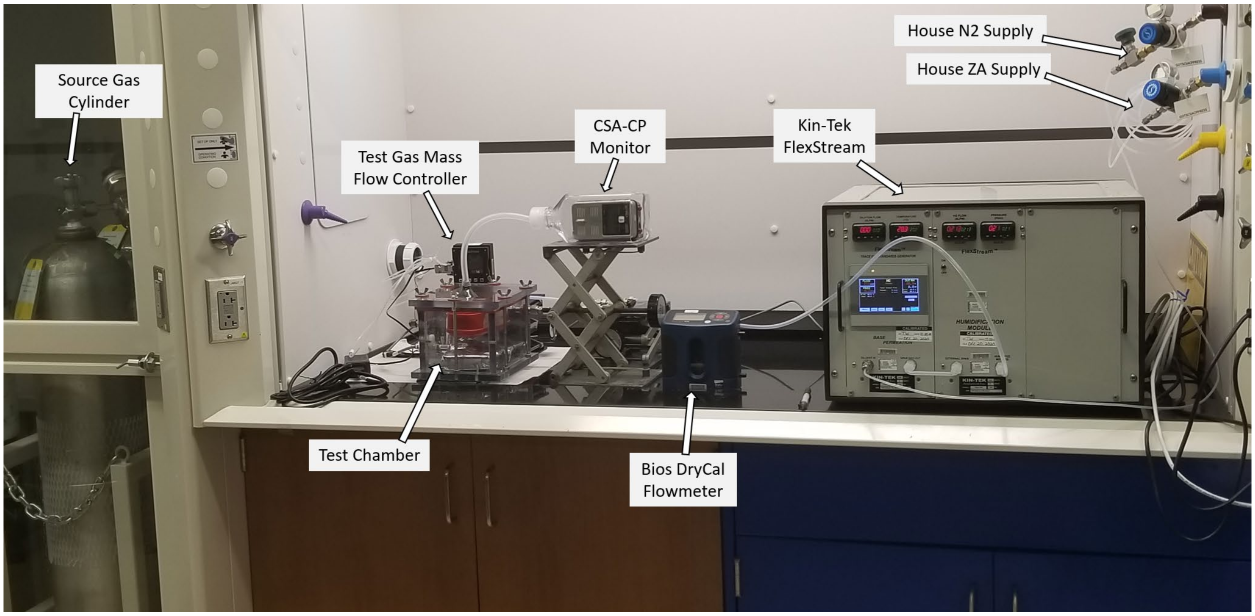

Figure 7: HCN and/or HCl Exposure Test Set-Up

G. Cyclohexane Test

The cyclohexane test stand is the only one that uses the Drager Xam-8000 for continuous monitoring. The photoionization sensor in the Xam-8000 is user-calibrated for this measurement. Due to its high humidity requirements, this test necessitates the use of the same test stand as the ambient temperature CO test. **Figure 8** provides an image of this set-up.

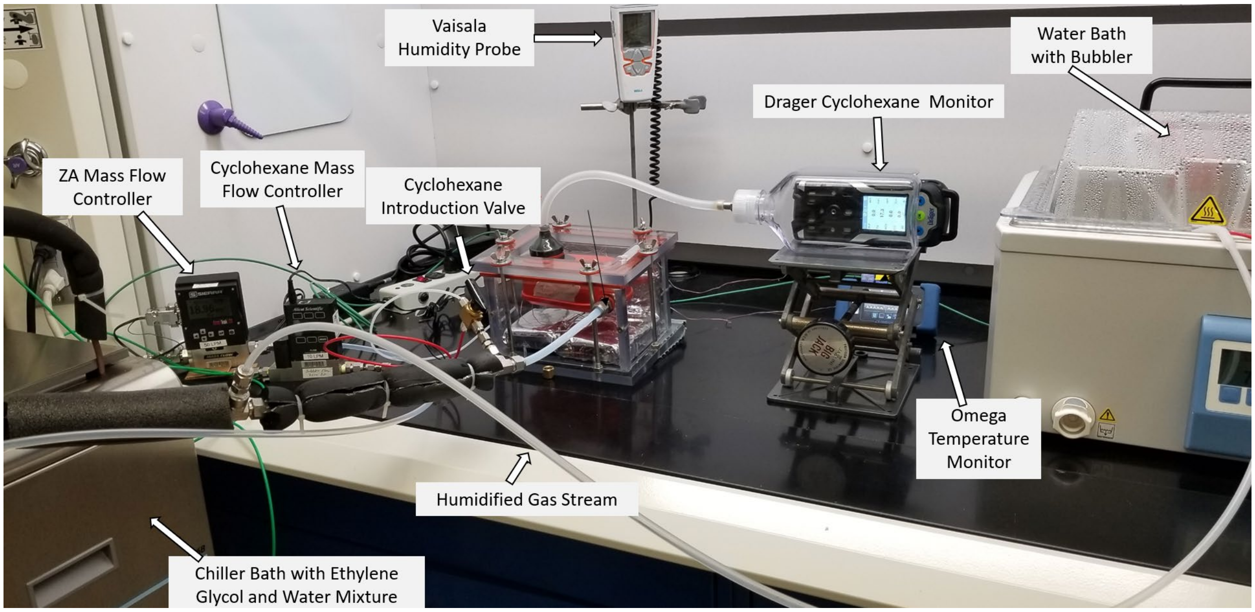

Figure 8: Cyclohexane Exposure Test Set-Up

H. Acrolein and CO/Acetaldehyde Tests

Real-time monitoring of acrolein and acetaldehyde is not available. For these analytes, grab samples are collected from the chamber outlet line every 15 minutes for the duration of the tests. Humidity requirements for both tests are high, and, therefore, the test set-up is similar to the CO-only configuration. The acrolein test is conducted at room temperature, so a cooler with ice packs is not needed. However, due to Orion program requirements, the CO/acetaldehyde test is conducted at 2.8 ± 3°C and must utilize a cooler and ice packs.

The collection of grab samples is made possible by adding an Entech female quick-disconnect to a T-fitting in the chamber outlet tubing. Entech 200 cc evacuated canisters, fitted with male quick disconnects, are used to collect the grab samples. Typically, a day or two prior to the exposure test, a trial run, without a fire cartridge installed, is conducted to confirm the proper flows needed to achieve the required concentration. Samples are collected and analyzed by gas chromatography with a flame ionization detector (GC/FID). Flows are adjusted, if necessary, and a sample is collected again. This process continues until the concentration in the chamber outlet meets the test requirement. On test day, the challenge gas concentration and other test requirements are confirmed again before the fire cartridge is installed into the test chamber. Grab samples are collected approximately every 15 minutes for the duration of the test. These samples are analyzed by gas chromatography/mass spectrometry (GC/MS), which provides a much lower reporting limit (0.003 ppm). Like all challenge tests, after the fire cartridge is removed from the chamber, the stock challenge gas is re-introduced into the chamber and the post-test gas concentration is measured. The average of the pre- and post-test concentrations is the reported exposure concentration for the test.

The combined CO/acetaldehyde gas test is an Orion program test requirement. This test requires the use of two 3-way valves for the 2 stock challenge gases. Like acrolein, the pre- and post-test gas concentrations of acetaldehyde are confirmed by GC/FID, and GC/MS is used for grab samples collected during the exposure period. CO is measured continuously during the test. **Figures 9 and 10** provide images of each set-up.

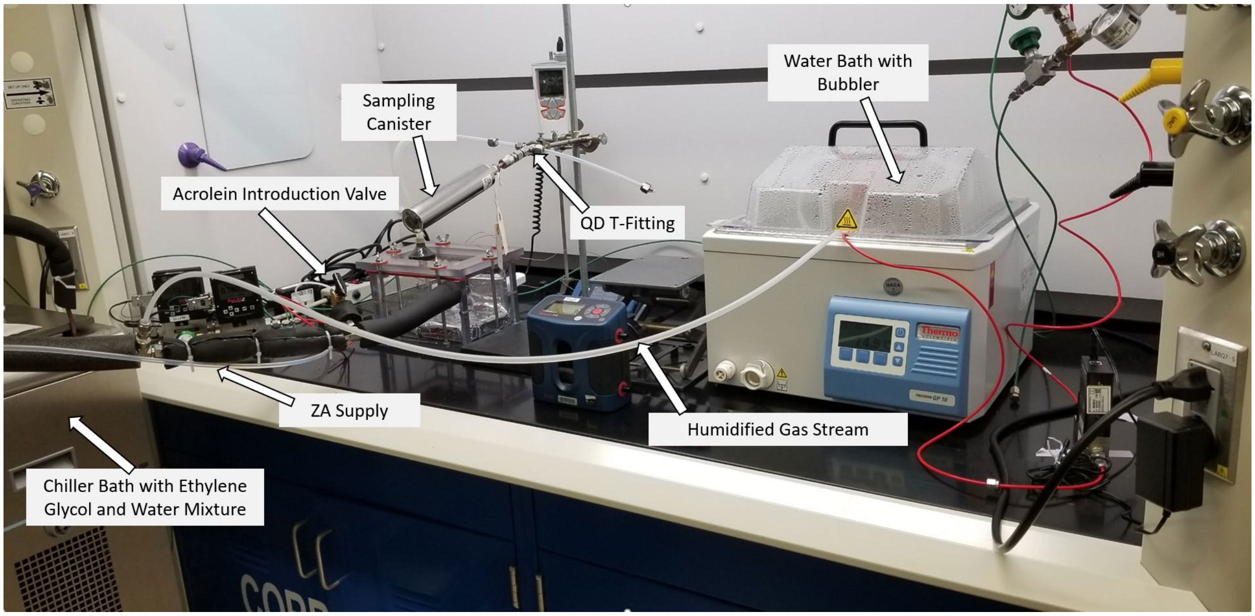

Figure 9: Acrolein Exposure Test Set-Up

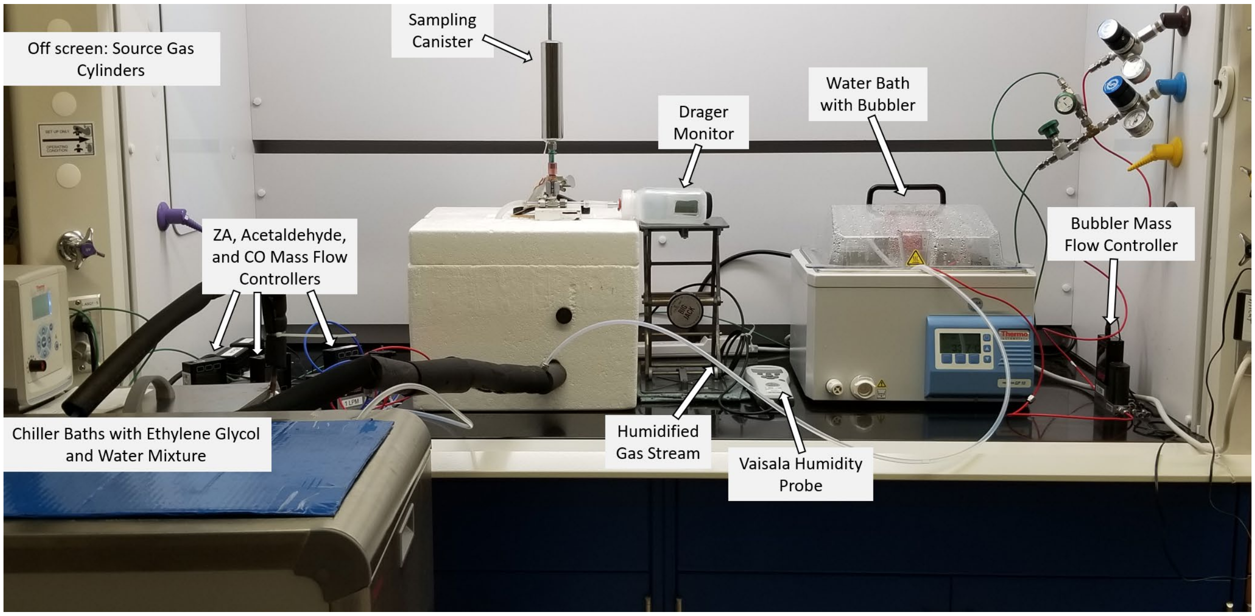

Figure 10: Combined CO/Acetaldehyde Exposure Test Set-Up

IV. Results Summary

A. CO Data

There has been no significant breakthrough of HCN, HCl, NH_3, cyclohexane, acrolein, or acetaldehyde observed since testing began in 2020. **Table 3** summarizes the total weighted averages of previous acceptance testing completed using these non-CO gases. The fire cartridges are very effective at removing these gases, owing to their layers of activated carbon. However, breakthrough of CO occurs during essentially all CO tests. Comparing the results of CO-cold vs CO-ambient tests, the colder temperature decreases the efficiency of the catalytic oxidation of CO to CO_2. This can be seen through higher breakthrough concentrations from a cold test versus an ambient test, even when testing the same cartridge on two separate occasions. The graph below (**Figure 11**) shows such results for a previously-tested fire cartridge during cold and ambient CO challenge tests conducted about 5 weeks apart.

Table 3: Results of a sample set of different cartridges tested using non-CO gases

Cartridge	Test Gas	Date Testing Performed	Total Weighted Average (ppm)*	Breakhtrough Requirement (ppm)
Fire Cartridge A	HCN	12/15/2021	<0.3	≤ 5
Fire Cartridge B	HCl	12/22/2021	<0.4	≤ 5
Fire Cartridge C	Cyclohexane	12/30/2021	<1	≤ 10
Fire Cartridge D	NH3	1/25/2022	<3	≤ 20
Fire Cartridge E	HCN	5/31/2022	<0.3	≤ 5
Fire Cartridge F	Cyclohexane	6/16/2022	<1	≤ 10
Fire Cartridge G	Cyclohexane	7/21/2022	<1	≤ 10

*Some average results are recorded as a less than value due to the detecting limits of the monitors used during testing

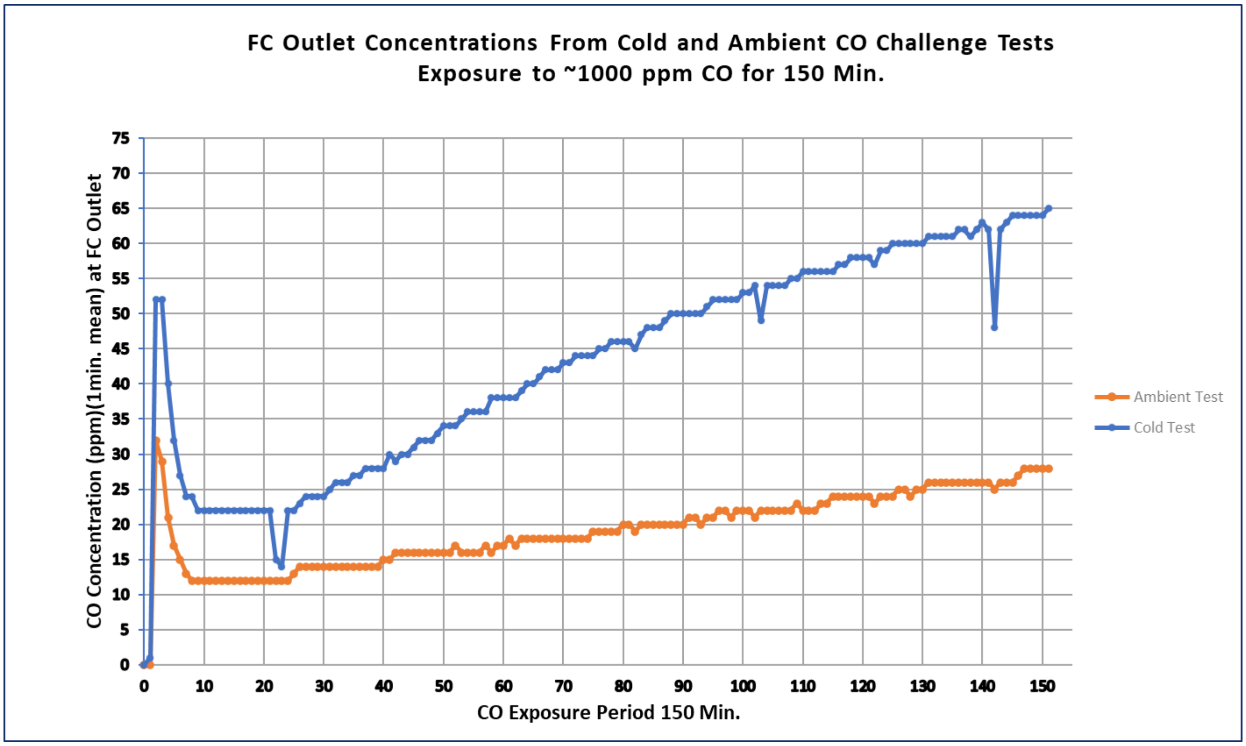

Figure 11: Breakthrough Curve for Cold and Ambient CO Challenge Test

The CO breakthrough concentration graph above is very characteristic of all CO challenges; typically a high spike is seen at initial gas exposure, followed by a rapid decline to a lower concentration that is held for 15-30 minutes. Finally, a slow, steady rise in concentration occurs, reaching near the initial spike concentration at the beginning of the test. The initial spike is thought to be the result of the catalyst bed being momentarily cooler at the beginning of the test and, thus, less efficient. In early tests conducted at the outside laboratory, this spike was attributed to turbulence in the test chamber on test initiation. The catalytic reaction is exothermic, resulting in a greater efficiency once the catalyst bed increases in temperature due to the reaction. Although speculative, the long steady increase in the breakthrough concentration may be due to a buildup of water in the catalyst bed.

The initial CO breakthrough requirement prior to the latest revision of Quality/Acceptance Test Plan Rev. F (Nov 2021) was a not-to-exceed peak value of 50-ppm CO for the 120-minute test period.[3,4] This value, when compared to NASA's Spaceflight Maximum Acceptable Concentration (SMAC) for CO was highly conservative, and occasional tests did result in a fire cartridge failing to meet this requirement. After much consultation with the NASA medical and toxicology community, the breakthrough requirement was changed to a peak maximum of 425 ppm (SMAC for a 1-hour, off-nominal situation) and a time-weighted average concentration of 100 ppm (NASA 24-hour SMAC; 120-minute exposure)[5,6]. There have been no failures since this requirement was changed in November 2021.

Figure 12 below graphs two cold and one ambient CO challenge tests of one specific cartridge serial number over a period of approximately 9 months. This cartridge has been tested every 3 months to monitor the performance of the catalyst over time. It can be seen that as time and repeated usage increases, the performance of the catalyst decreases in the cold setting. However, once the cartridge is tested at ambient conditions, performance is recovered.

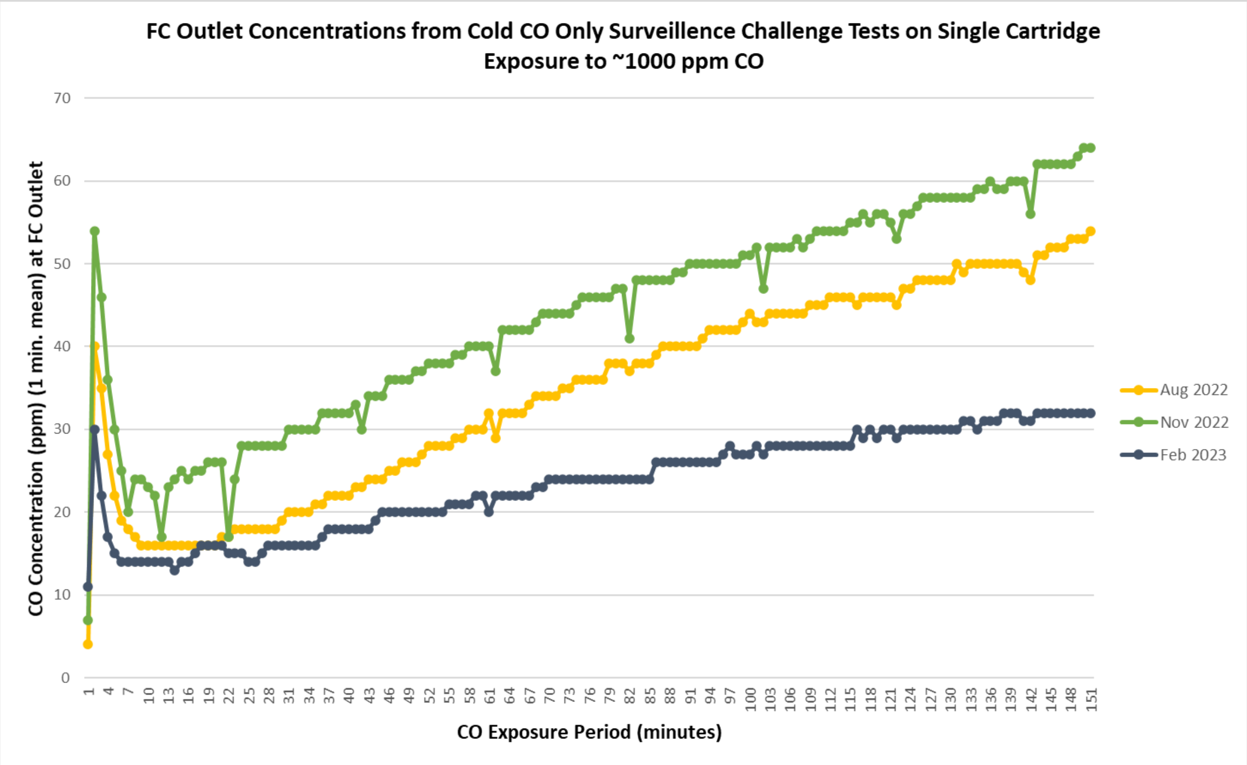

Figure 12: Graph depicting periodic surveillence CO only testing results for a single fire cartridge

V. Lessons Learned

Many observations have been made over the years while conducting these tests, and several patterns have emerged. There have also been some experiences that have helped shape the test stands, which led to better ways to prepare for the unexpected.

In general, low temperature and high humidity conditions have been the most difficult to meet and tend to require the most flow changes during exposure tests. For lower humidity configurations, the Kin-Tek Gas Standard Generator does a great job of maintaining humidity set points with the aid of a probe that completes a feedback loop to the system.

Many tests are performed using this equipment each year, and the next several years anticipate over forty completed tests annually. This causes wear and tear on much of the frequently-used equipment. The bayonet fittings that affix the fire cartridge to the interior of the test chamber have broken, as seen in **Figure 13**, due to repeated coupling and uncoupling. Gaskets have warped from repeated twisting and untwisting. Even the printed fitting that attaches to the outlet of the test chamber has failed, as seen in **Figure 14**. These failures have prompted the addition of inspection steps to the TPSs. These inspections are conducted by NASA Quality representatives and include the bayonet fittings and fire cartridge before and after each test.

Figure 13: Broken bayonet fitting on one of the lids of a test chamber

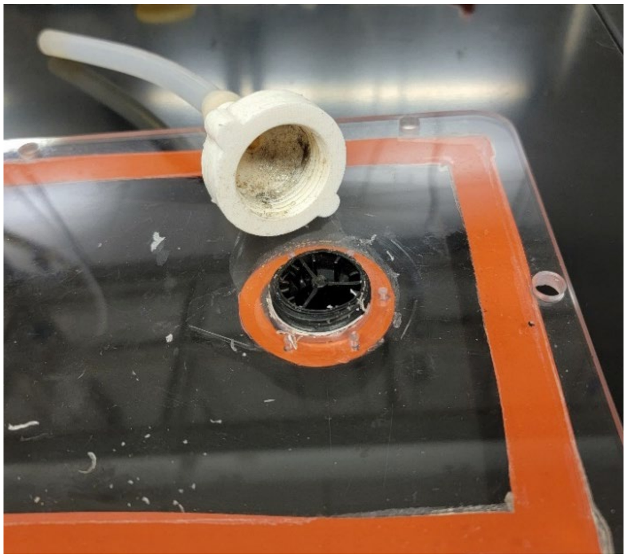

Figure 14: Broken connection to the outlet of a test chamber

The fire cartridges gain weight during the 150-minute high-humidity test. There has been in excess of 12 grams gained during an exposure test. The accumulation of water may impact the efficacy of the catalyst that performs the CO oxidation reaction. This prompted a post-test drying step, initiated in November 2020, which involved a dry purge of the fire cartridge until the original weight was obtained. Though this step can add anywhere from 30 minutes to 2 hours, it is vital for maintaining testing integrity for each cartridge. Once the tested cartridge has been dried to its original pre-testing weight, it is vacuum sealed in a mylar pouch until the next surveillance testing occurs, typically 3 to 6 months later.

Water freezing in the main insulated gas delivery line occurred several times. This caused a severe restriction of the gas flow and high back pressure in the system, which, in turn, resulted in the bubbler lid popping out. This problem was solved by moving the T-fitting, where the bubbler line connects to the main ZA flow, closer to the chamber. The initial configuration had the bubbler line entering closer to the chiller. The modified configuration allowed the water condensate to drain into the chamber without sufficient time to freeze in the line.

Differential pressure measurements across the fire cartridge were initiated in early 2020. Until November 2020, these measurements did not account for the ΔP (background) of the chamber without the fire cartridge installed. Consequently, the reported ΔP measurements during this period were biased high.

VI. Future Work

For the duration of the ISS and Orion programs, new fire cartridges will continue to be manufactured. Through rigorous qualification/acceptance testing and periodic surveillance test programs, testing of a representative sample of fire cartridges will ensure that performance requirements continue to be met. Testing has been tentatively scheduled out to 2026 with possible increases in testing throughout the next several years. Fiscal year 2023 currently has 41 scheduled tests, a majority of which are CO surveillance.

Several future tests are being discussed that may include considerably higher CO challenge concentrations at higher humidity and temperature. These new tests may require modified configurations and equipment.

Continued improvements to the test stand are also anticipated. Back-up systems will be put in place to alleviate any potential work stoppages, allowing for the tight testing schedule to be maintained. There is also interest in allowing the test performer some relief from monitoring the test stand so rigorously by introducing a remote monitoring system. Such a system could allow the tester the freedom to keep up with other responsibilities while maintaining a close eye on the testing at hand.

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