Continued Development of Multi-Gas Microsensor Array for the Exploration Portable Life Support System

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The Portable Life Support System (PLSS) of the Exploration Extravehicular Mobility Unit (xEMU) requires sensors capable of measuring the major constituents of the gas stream. These major constituents include oxygen, carbon dioxide, and water vapor. The sensors must operate across a wide range of flow and pressure conditions and introduce very low pressure drop in the ventilation loop. The sensors must operate with low power and occupy a small volume. This paper reports the fabrication and testing of a compact, low power, multi-parameter astronaut life support sensor (M-PALSS) prototypes. M-PALSS combines an array of low-power chemical sensors for oxygen (O_2), carbon dioxide (CO_2), water (H_2O) vapor, and pressure as well as sensors for potential trace contaminates of carbon monoxide (CO) and volatile organic compounds. NDIR and electrochemical CO_2 sensors are included. M-PALSS includes custom electronics to control the sensors and is packaged in a custom housing that meets the volume and shape requirements for service in the PLSS. M-PALSS prototype hardware has been developed and tested at relevant conditions for PLSS operation.

Nomenclature

CO_2	=	carbon dioxide
CO	=	carbon monoxide
COTS	=	commercial off-the-shelf
DMLS	=	Direct Metal Laser Sintering
EVA	=	Extravehicular Activity
H_2O	=	water
M-PALSS	=	Multi-Parameter Astronaut Life Support Sensor
NDIR	=	nondispersive infrared
O_2	=	oxygen
PCB	=	Printed Circuit Board
PLSS	=	Portable Life Support System
SMAC	=	Spacecraft Maximum Allowable Concentration
t_{90}	=	90% response time
TiO_2	=	titanium dioxide
VOC	=	volatile organic carbon
xEMU	=	Exploration Extravehicular Mobility Unit

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I. Introduction

Technology gaps regarding the current gas sensors used in the portable life support system (PLSS) have been identified during the design of the new Exploration Extravehicular Mobility Unit (xEMU). These gaps must be addressed to meet new exploration requirements. To ensure safe operation of the spacesuit there is a need to measure oxygen (O_2), carbon dioxide (CO_2), and water vapor (H_2O) in the gas stream. In addition to these major constituents of the gas stream, there is value in measuring some minor constituents. Specifically, additional sensing needs are driven in part by the need to determine if the gas is safe to breathe. The 24-hour Spacecraft Maximum Allowable Concentration (SMAC) limit is used as the minimum performance benchmark for sensors targeting these constituents. The current PLSS only includes nondispersive infrared (NDIR) sensors for CO_2 to ensure the carbon dioxide removal system is operating effectively. An added O_2 sensor can assist with knowing the exact concentration of oxygen during prebreathe and suit purge operations as the suit transitions from a nitrogen-oxygen mixture to purge oxygen at lowered pressure to help prevent Decompression Sickness (DCS).[8] The outer mold line of the current NDIR sensors is approximately 2.3 in. × 2.2 in. × 6.1 in. and consumes approximately 2 W during operation. Development of new components for the Portable Life Support System (PLSS) that meet targets of high performance, low mass, low power, and compact size will support exploration objectives.

This paper is a follow-on paper to ICES-2023-053 and reports the continued development of a compact, low power, multiparameter astronaut life support sensor (M-PALSS)[1]. The original M-PALSS was a rapid prototype and included solid-state electrochemical sensors for O_2 and CO_2 and commercial off-the-shelf (COTS) sensors for pressure and humidity. The updated M-PALSS which involves two generations of on-going development (GEN-1 and GEN-2) is described in this paper. The current generation of prototypes are integrating the new sensor types and redesigning electronics and mechanical features to provide a pathway to a flight qualified design. These new generations include the addition of a solid-state sensor for carbon monoxide (CO), an NDIR CO_2 sensor and updated electronics using circuit designs which can be implemented with components intended to meet ionizing radiation tolerance requirements.

The current M-PALSS GEN-1 prototype is shown in Figure 1. Incorporating the high Technology Readiness Level (TRL) level of NDIR CO_2 sensors for PLSS applications allows more flexible near-term integration path for the M-PALSS with current and future PLSS designs. Units with NDIR CO_2 and electrochemical O_2 or other sensors could be adopted as an incremental approach to mitigate technical risk. This approach also benefits from leveraging existing requirements directly applicable to NDIR based CO_2 sensing and mitigates risks associated with adoption of new CO_2 sensing technology. The incorporation of the CO_2 NDIR sensor in the GEN-1 serves a dual purpose. First, it serves as a reference measurement to compare with performance of the electrochemical CO_2 sensor. Second, the unit serves as a proof of concept that an NDIR system and solid-state sensors can be used together effectively in a compact package.

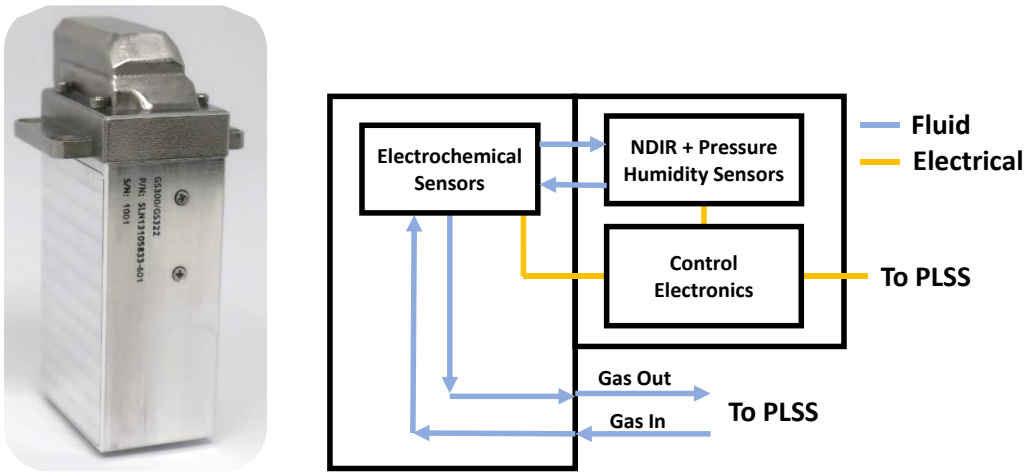

Figure 1. Multiparameter astronaut life support sensor for the PLSS.

The M-PALSS is designed to provide general situational awareness of the major constituents in the breathing loop of the PLSS. The required measurement accuracy is approximately 1 percent for O_2 percentage and relative humidity and 0.3 torr for CO_2 partial pressure. The device is intended to stream data at a rate of at least 1 Hz. CO_2 and O_2 data could be used for closed loop control of other systems such as CO_2 removal. These sensors are continuously powered

during extravehicular activity (EVA) and therefore their power consumption is a direct driver of battery capacity and mass. It is desirable to have a total sensor power consumption less than 2.5 W. The M-PALSS prototype development is focused on increasing chemical species measurements while staying under the power and mass limits of the existing CO_2 sensors.

II. Sensor Operating Principles

The M-PALSS includes solid-state electrochemical microsensors for O_2, CO_2, and CO, an NDIR sensor for CO_2, a capacitive humidity sensor, and piezoresistive pressure sensor. The operating principle of the O_2 and CO_2 sensors is described elsewhere.[1–5] The NDIR CO_2 sensor is a single pass optical cell design with an emitter and detector elements at opposite ends. The emitter and detector elements are isolated from the sensed gas by sapphire windows. The detector includes two thermopile elements with band pass filters of 3.9 µm and 4.23 µm to form channels for the reference light source intensity and CO_2 signal respectively. The CO_2 partial pressure is related to the ratio of the signal and reference channel and pressure and temperature of the gas of the optical cell. The ratio of the signal and reference channel is used to compensate for the effect of fluctuations in the infrared source intensity and other effects. The presence of water vapor in the sensed gas stream can affect the NDIR CO_2 measurement to the extent that water vapor absorbs infrared light at the wavelength corresponding to the CO_2 signal channel (4.23 µm). At this wavelength CO_2 absorption is significantly stronger than water vapor and the effect of water vapor is minimized. Changes in sensed gas total pressure affect the NDIR CO_2 measurement via pressure broadening of the absorption lines. In brief, pressure broadening is the name given to the phenomenon by which collisions between molecules perturb their energy states which results in variations in the energy required to transition between states. These variations result in a broadening of the spectral absorption lines used for the NDIR measurement.

III. Sensor Assembly Design and Construction

The M-PALSS sensor assembly is designed as a drop-in replacement for the existing NDIR CO_2 sensors. This approach supports the rapid development of a smaller and lighter prototype with enhanced sensing capability that consumes less power[1]. The prototype preserves existing interfaces for data, power, fluidic, and mechanical connection to the PLSS. The GEN-1 design conforms to the existing GS-300/G-322 PLSS CO_2 sensors mounting and electrical interfaces which will enable the unit to be used in the JSC PLSS test bed without modification. Mechanical connection to the PLSS is made by alignment with four 6-32 threaded holes. Fluidic connection is made via mating with two sensor fittings. Electrical connection is made with a 13-pin rectangular connector.

The M-PALSS is a modular system consisting of a sensor manifold, NDIR optical cell and electronics. Electrical connection is made between the sensors and electronics module via a board-to-board connector. The sensor manifold is designed for minimized dead space and low pressure drop. The sensor manifold shown in Figure 2 houses solid state chemical sensors for measuring O_2 and CO_2, and pressure and humidity sensors. Two sensor carriers with double O-ring seals are used to mount the sensors adjacent to the flow path. One sensor carrier contains both O_2 and CO_2 microsensors and the other carrier contains humidity and pressure sensors. The sensor carriers are backed by a plate that both mechanically loads the O-rings, preserving the seal, and provides the mechanical mounting interface between the Sensor Interconnect Printed Circuit Board (PCB) and the manifold. The sensor control PCB provides front end sensor signal conditioning, heater control, signal processing, power conditioning, and electronic interconnection to the PLSS. The mechanical design exceeds the required proof pressure of 15.9 psid and collapse pressure rating in excess of 15.2 psid.

The NDIR module is downstream of the electrochemical sensor module as shown in Figure 2. The flow inlet, outlet and optical cell were fabricated in a single part using Direct Metal Laser Sintering (DMLS). This 3D printing parts fabrication technique produces a fully dense 316L stainless steel part which meets ASTM F138. This approach eliminates multiple seals that would be required in a conventionally machined CNC part. The detailed design of the NDIR optical tube is shown in Figure 3.

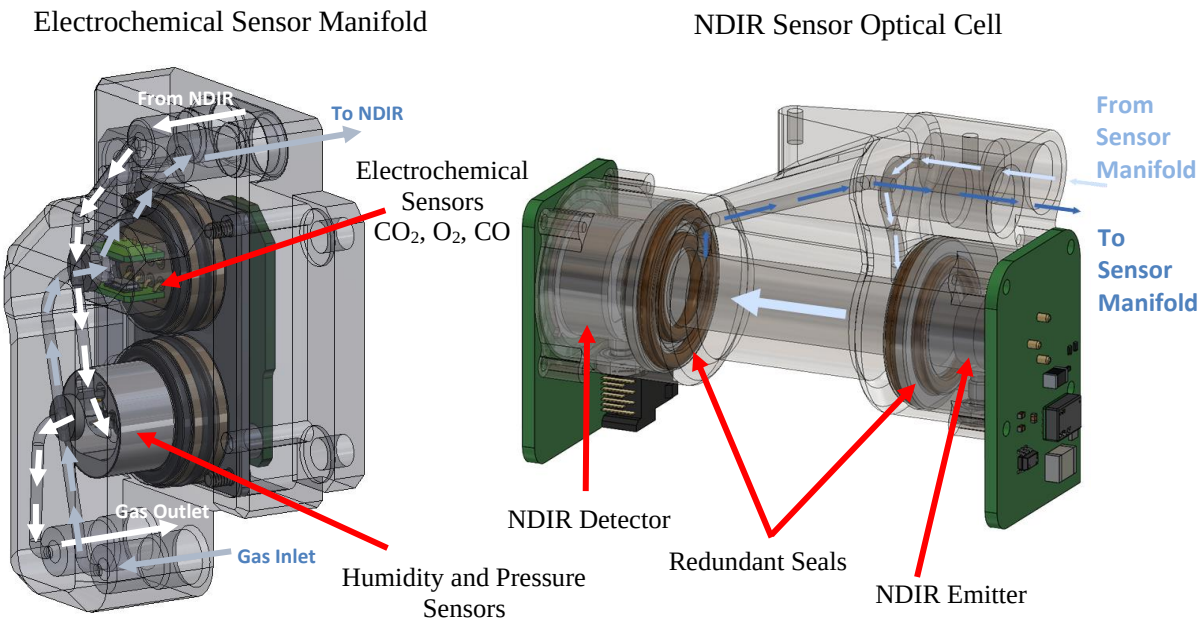

Figure 2. GEN-1 M-PALSS gas flow path.

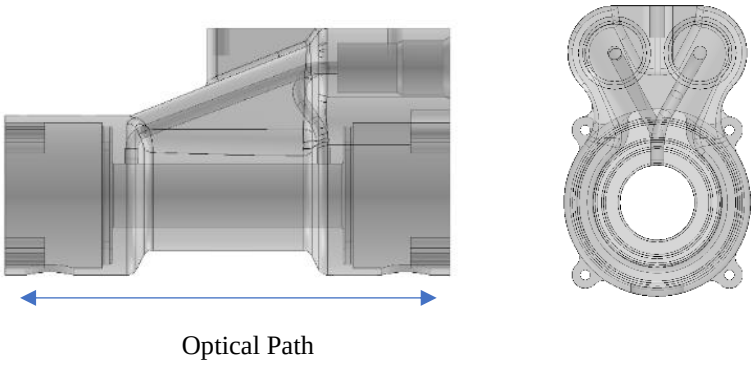

Figure 3. Direct Metal Laser Sintering (DMLS) NDIR tube design.

The DMLS process allows complex geometries and flow paths as seen in Figure 3 that would be difficult or impossible to produce with traditional machining methods. These complex geometries support both potentially improved sensor performance (time response) by reducing dead volume and reducing total unit mass. The GEN-1 development activities identified the need for controlled surface finishing processes to ensure adequate performance of sealing surfaces. Both mechanical polishing and electropolishing techniques have been used. While the electropolished finished resulted in an overall smoother surface it had limited effectiveness in the as-designed complex internal geometry. This limitation is driven by the ability to place a cathode close enough to the internal geometry to yield sufficient electrical current for the electropolishing process. Example of the surface finishes achieved with the DMLS NDIR tube are shown in Figure 4. To ensure good sealing, GEN-2 3D printed builds are also pursuing CNC post machining for O-ring grooves and sealing surfaces.

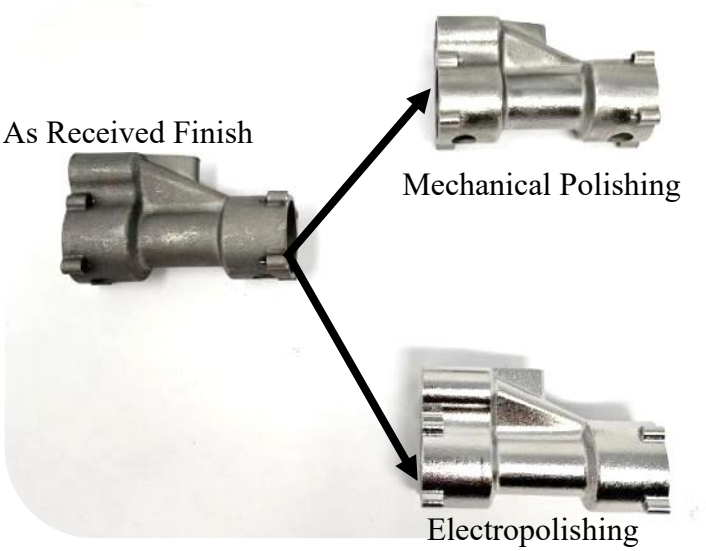

Figure 4. M-PALSS prototype DMLS parts surface finish.

M-PALSS GEN-1 assembly overview is shown in Figure 5. The design enables individual components to be leak checked at the subassembly level. The interconnection between the electrochemical sensor module and the NDIR module provides location for a hydrophobic Teflon membrane if needed to meet water intrusion requirements and pressure drop under 0.02 in water with 150 ccm of flow at reduced pressure.

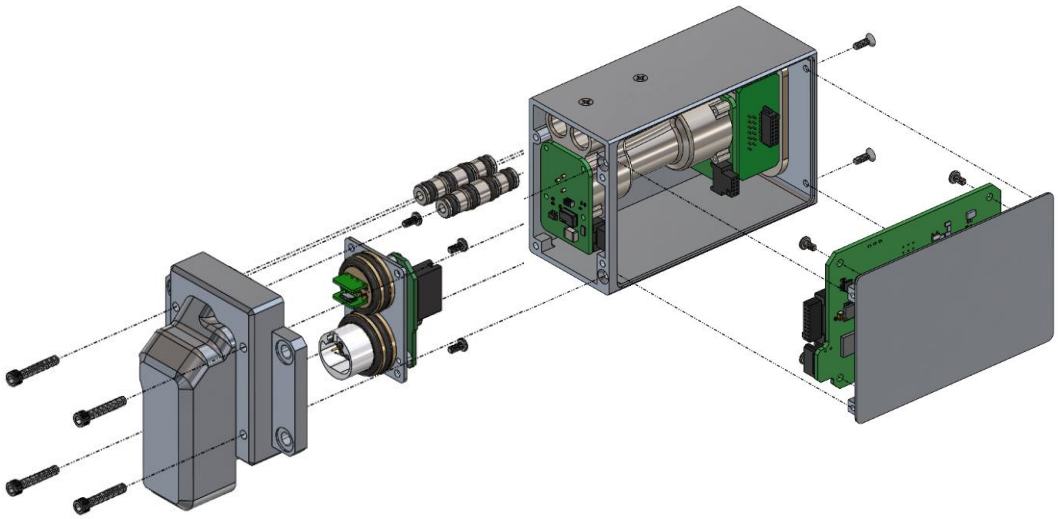

Figure 5. GEN-1 M-PALSS assembly overview.

IV. Sensor Electronics

The GEN-1 prototype electronics consist of a main sensor control board, dedicated boards for NDIR detector signal transduction and emitter drive, and interconnect boards for connection with the PLSS and solid-state sensing elements. The electronics integrate the sensor control and signal acquisition functionality onto a single printed circuit board compared to the earlier version of the M-PALSS. The NDIR module includes dedicated electronics boards for the emitter and detector. The electronics acquire raw signals from the solid-state sensors for O_2, CO_2, pressure, and humidity in addition to the NDIR CO_2 raw signal. The signals are converted to engineering units by the firmware

running on the microcontroller and reported to the PLSS via RS-485. The electronics run off a single +12V power input.

The sensor control board control performs power conditioning, sensor temperature control, data digitization, and communication. The heater drive circuits modulate the electrochemical sensor heater power according to the control signal received from the control board. The sensor control board transduces the raw signals of the electrochemical, NDIR, humidity, and pressure sensors and prepares the signals for digitization. Separate NDIR emitter and detector boards are used in NDIR CO_2 sensor on opposite end of the optical cell to control emitter power and to precondition detector and reference channel signal. The M-PALSS electronics block diagram is shown in Figure 6. GEN-1 incorporates electronics with a transition path to radiation compliant electronics to be use in GEN-2 prototoype.

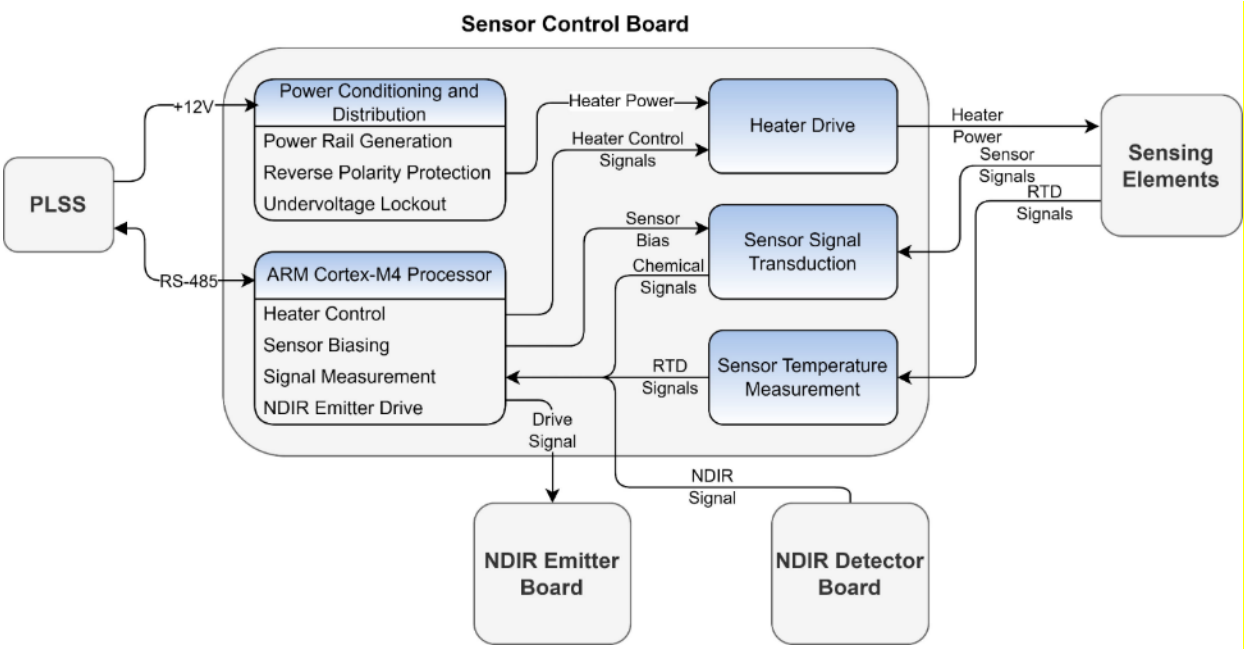

Figure 6. M-PALSS GEN-1 electronics block diagram.

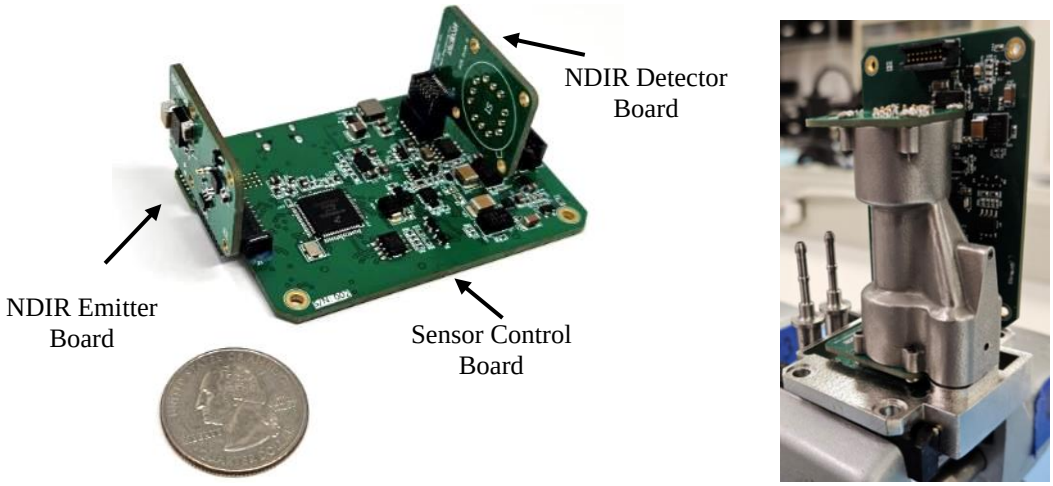

Figure 7. M-PALSS GEN-1 sensor control and NDIR electronics.

V. Sensor Performance

M-PALSS sensor response characterization across a wide range of conditions based on PLSS operating requirements indicate suitable performance to support the use case of general situational awareness monitoring. Sensor testing was conducted using an array of mass flow controllers and a Bronkhorst VDM-100 vapor delivery system (for gas stream humidification) and dry scroll vacuum pump to produce sensed gas mixtures over a range of pressure from 2 to 28 psia and dew points from 30°F to 100°F as shown in Figure 8. Thermal cycle testing is performed with the sensor in temperature-controlled chambers with independent control of the pressure of the sensor gas stream.

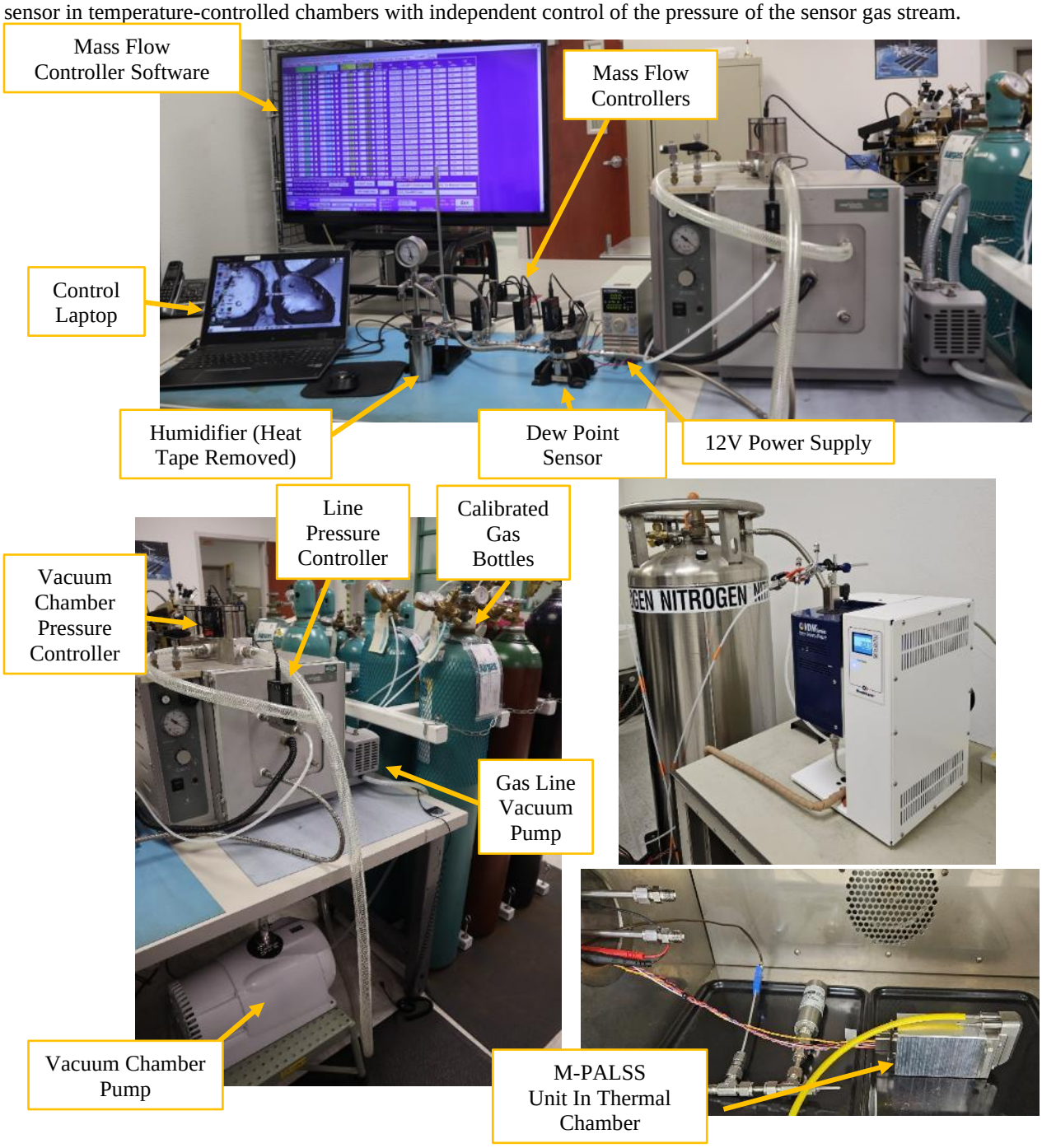

Figure 8. Reduced pressure and thermal testing system.

Representative M-PALSS O_2 sensor performance at 3.5 psia is summarized in Figure 9. Deviations in O_2 sensor current at high O_2 percentage are observed in the raw data in Figure 9. These deviations are caused by dilution of the sensed gas stream by introduction of humidity. This dilution is accounted for in the calibration plot shown in Figure 9. The M-PALSS O_2 sensor 90 percent response time (t_{90}) is approximately 3 s.

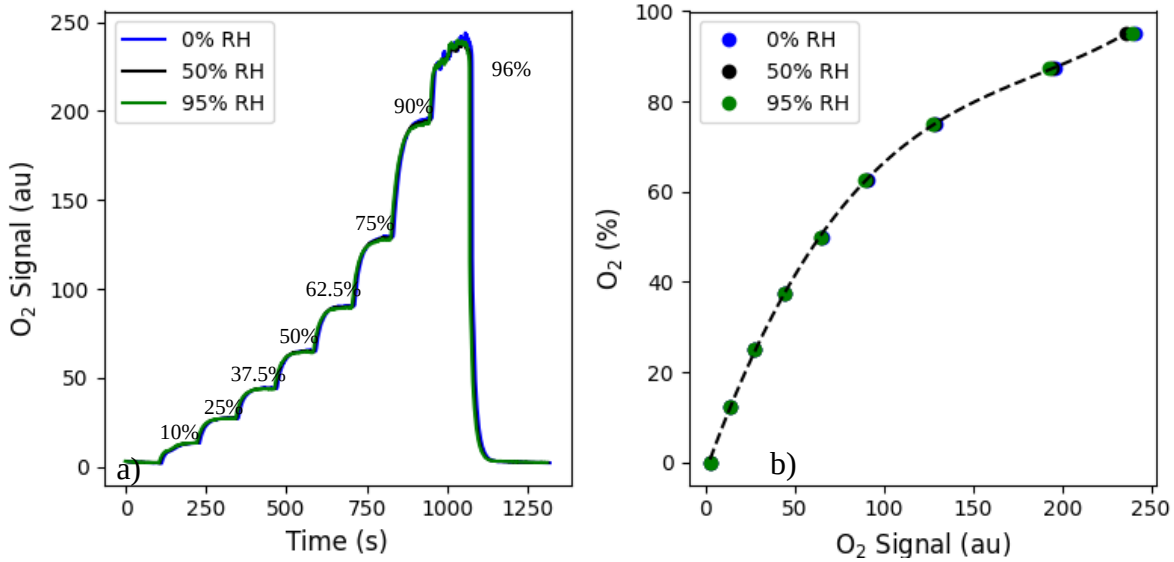

Figure 9. M-PALSS O_2 sensor performance at 3.5 psia for various operational dewpoints, a), and steady-state calibration data, b). The annotated percentages in a) are O_2 percentages prior to humidification. The gas mixture is balance nitrogen.

Representative M-PALSS CO_2 sensor performance at 3.5 psia is shown in Figure 10. The sensed gas stream is mixed in the same manner as for the O_2 sensor performance testing with the addition of CO_2 being mixed into the humidified gas stream. The CO_2 gas stream is added after humidification to avoid absorption of CO_2 into the water in the bubbler. The M-PALSS CO_2 sensor t_{90} response time is approximately 10 to 12 s.

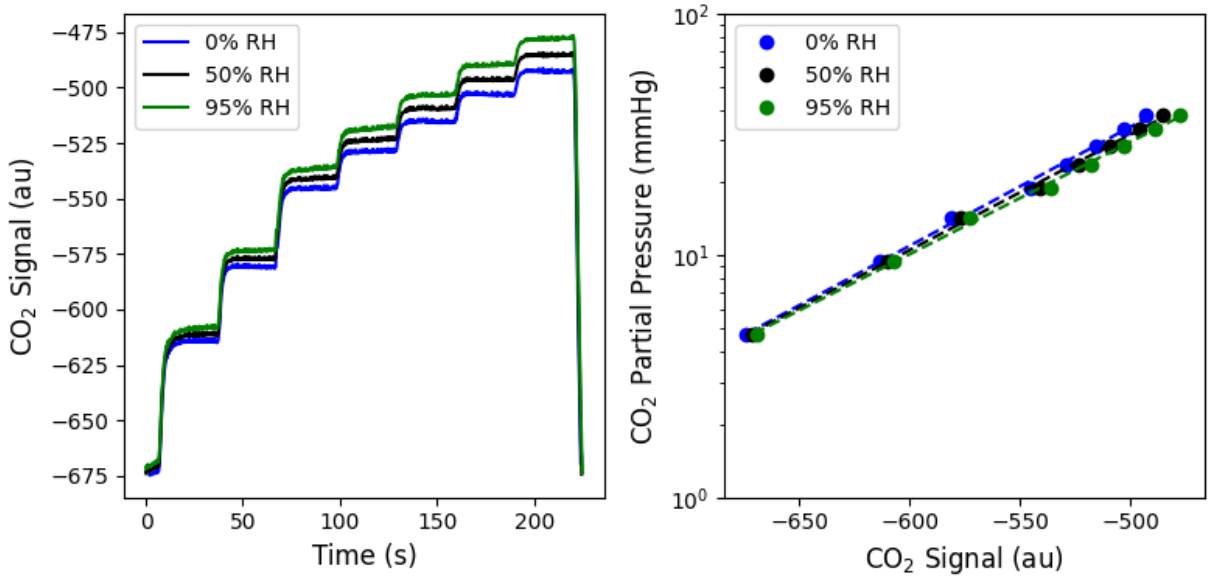

Figure 10. M-PALSS electrochemical CO_2 sensor performance.

A small amount of humidity interference is seen in Figure 10. This humidity interference is attributed to water adsorption on the sensor working electrode. This humidity interference is addressed by leveraging the independent humidity measurement on M-PALSS. The CO_2 sensor calibration coefficients are treated as linear function of the measured humidity. The humidity dependence is determined empirically by testing of the full range of interest for the application. In this way a humidity compensated CO_2 measurement reduces the measurement uncertainty to an acceptable range for the use-case of situational awareness monitoring in the PLSS.

A key improvement achieved in the GEN-1 has included verification of an improved bias control signal transduction circuit which improves the performance of the O_2 sensor in high (90 percent and greater) concentration range. The improved bias control ensures constant bias to the sensor regardless of the level of signal current. Previously, the sensor bias voltage was a function of sensor signal current which resulted in limited sensitivity at high O_2 concentrations where the sensor current signals are highest. The enhanced sensitivity the high range typical of most PLSS operating conditions is shown in Figure 11.

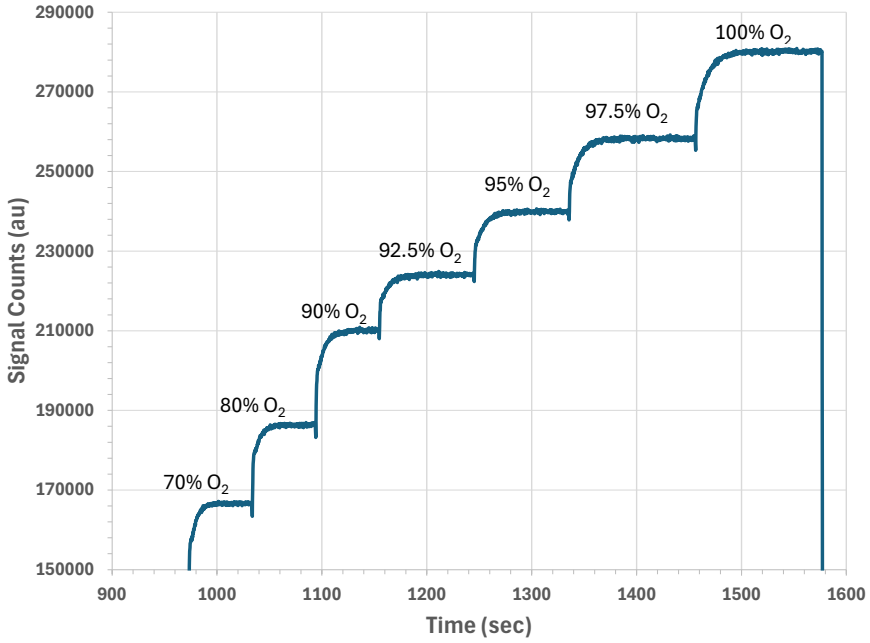

Figure 11. Improved O_2 sensor sensitivity in high concentration range.

There have been concerns of sensor drift over time with other sensors in the field, especially regarding electrochemical sensors. A plan is in development for setting up long term multi-year testing to evaluate long term sensor stability.

The NDIR CO_2 sensor requires pressure compensation to correct for pressure broadening over the operating range from 3.5 to 25 psia. The compensation factor is a function of both pressure and carbon dioxide partial pressure. A simple correction factor based solely on pressure is inadequate to achieve accuracy requirements. The real-time compensation algorithm is based on a reference pressure calibration and then recalculating the fitting coefficients as a function of both pressure and reference CO_2 partial pressure. This algorithm has been incorporated into the firmware and tested. Figure 12 show the raw NDIR test data (markers) and the calibration curve fits generated by the algorithm over the full operating pressure range.

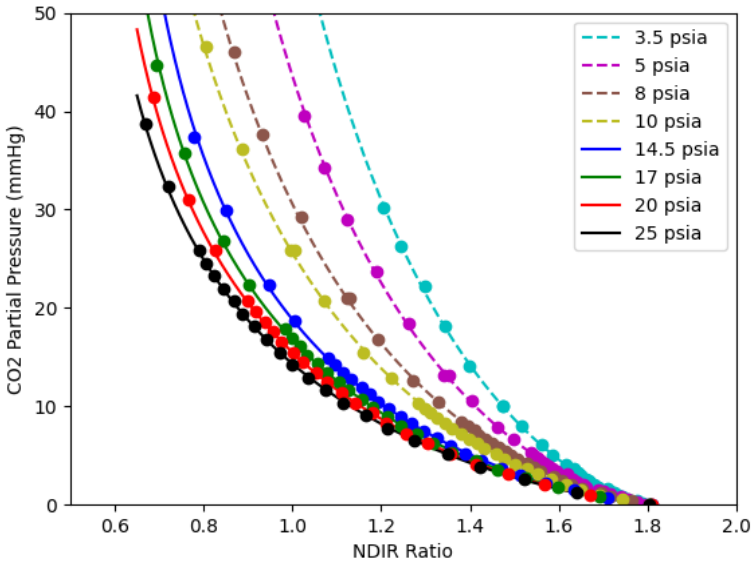

Figure 12. Raw NDIR data and algorithm fits.

Figure 13 shows a typical test profile used for testing units over a range of O_2 and CO_2 partial pressures. This profile can be run at specific pressures set by the test stand pressure controller and with different levels of humidity in the gas stream.

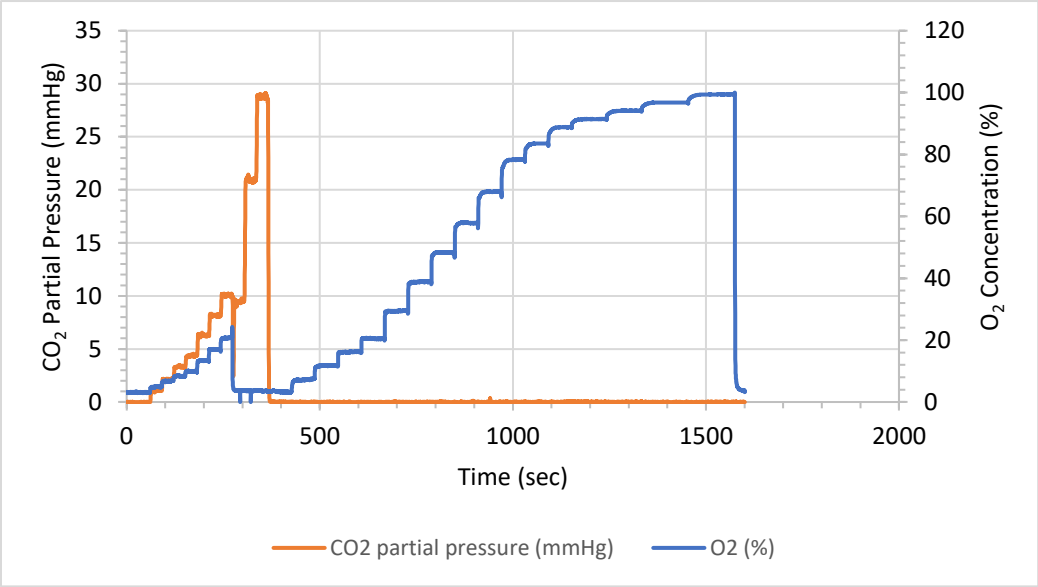

Figure 13. O_2 and CO_2 sensor response profile used at different pressure and humidity levels.

VI. Enhanced Sensing Capability for Next Generation M-PALSS

The next generation of M-PALSS is underway which is transitioning the electronics to part types which can meet NASA ionizing environment conditions.[6] Sensors for additional chemical species are being assessed for integration into the Generation 2 prototype. Development of enhanced sensing capability offers the potential to monitor the performance of other components such as the Rapid Cycle Amine system. Additionally, if PLSS developers have access to suitable measurement systems certain design choices may be enabled. For example, a continuous temperature or pressure swing adsorption process for the removal of trace contaminants may be desirable. This removal system

could eliminate the need for activated charcoal as a logistic consumable but requires enhanced measurement capabilities.

Additional chemical measurements can improve the general situational awareness of the minor constituents of the breathing gas stream. Specifically, the sensing requirements are driven by the need to determine if the gas is safe to breathe. The 24-hour SMAC limit is used as the minimum performance benchmark for candidate sensors targeting these constituents[7]. The candidate sensors are under evaluation for future M-PALSS integration to detect in the range of the 24-hour SMAC limits for species of high interest listed in Table 1.

Table 1. M-PALSS candidate minor constituent gas sensing targets.

Chemical	24 Hour SMAC Limit (ppm)
Ammonia	20
Carbon Monoxide	100
Formaldehyde	0.5
Methanethiol	(10 to 20)*

*Expected value based on OSHA limits

A thick film type CO sensor type developed previously by Makel Engineering for CO monitoring in aerospace life support systems is being adapted to integration into the PLSS. The CO sensor is a chemiresistor based on titanium dioxide (TiO_2) with additives to increase stability and CO adsorption and has been used in applications to monitor pilot breathing gas. TiO_2 is a wide band gap semiconductor. At temperatures on the order of 500°C a film of TiO_2 has an electrical resistance that is a function of its chemical environment. O_2 undergoes dissociative adsorption on the TiO_2 surface and is reduced to O^-. The reduction reaction reduces the charge carrier density and therefore the conductivity of the TiO_2 film. CO also adsorbs on the metal oxide surface and reacts with adsorbed O^- to form CO_2 and release the trapped electron resulting in the density of charge carriers (and the conductivity) increasing. Therefore, the resistance of the CO sensor depends on both the partial pressure of CO and the partial pressure of O_2. The use of an independent O_2 measurement to correct and isolate the effect of CO on the resistance of the sensor results in a selective measurement. The effect of other reducing species is mitigated by doping the TiO_2 will with additives that promote CO adsorption. Figure 14 shows CO sensor response to pulses of 5 ppm and 10 ppm at pressures ranging from 15.3 to 3.5 psia. The data contains only an ideal gas law type pressure correction.

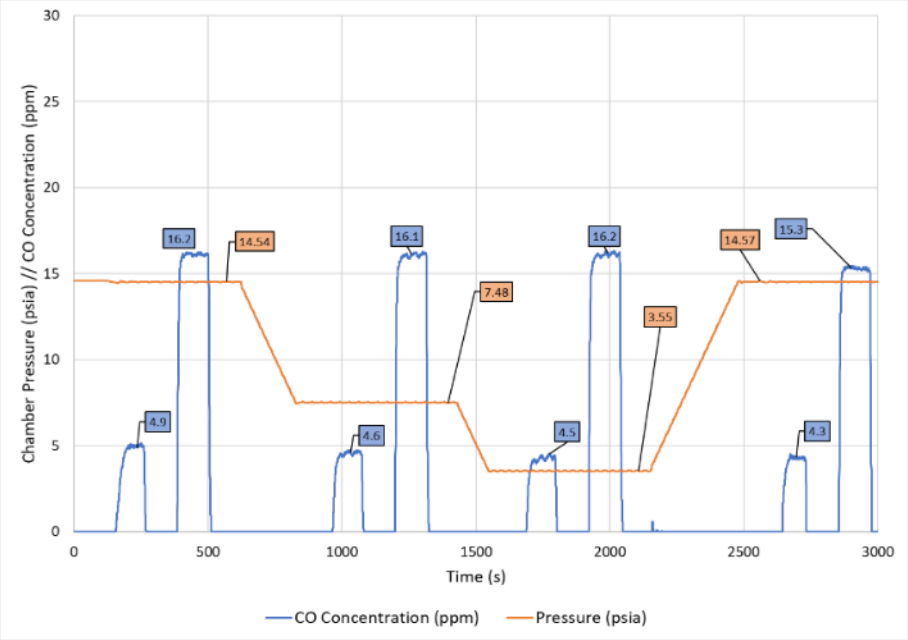

Figure 14. CO sensor test data with 5 ppm and 15 ppm pulses at reduced pressure.

Additional broadband trace volatile organic carbon (VOC) detection is being evaluated using photoionization detection. A traditional approach to selective sensing (one target species to one sensor relationship) is often suitable for major constituents of a sensed gas stream and some minor constituents, it can encounter challenges when applied

to higher and higher numbers of minor constituents. One of the primary challenges facing this traditional approach is flexibility. When all the minor constituents of interest are not known, or their sensing requirements may change in the future the traditional one sensor to one target approach has limitations in terms of size and complexity of the sensor array. An alternative approach involves a sensor that can detect a particular class of targets. A photoionization measurement of VOCs offers an alternative route to the objective of providing general situational awareness. This method would not selectively determine the concentration of formaldehyde, methanethiol, or total VOCs but give a metric of total VOCs in the breathing gas stream that can be used to provide useful information about the performance of relevant systems such as a pressure or temperature swing adsorption system. Breadboard testing of photoionization detection with methanethiol has been conducted using a dilute concentration for methanethiol generated with KINTEK 491 vapor generator using a calibrated gas permeation tube. Successful test results for Photoionization Detector control response are shown in Figure 15 for concentration of 2 ppm to 0.5 ppm at 14.7 psia. The signal response is linear, and the likely minimum detection limit is likely to be in the 100 to 200 ppb range. There is a wide range of exposure limits for the VOCs that can be detected with a photoionization detector. Exposure limits for methanethiol range from 0.5 ppm to 10 ppm depending on duration. This exposure limit range is typical for many of the compounds of interest.

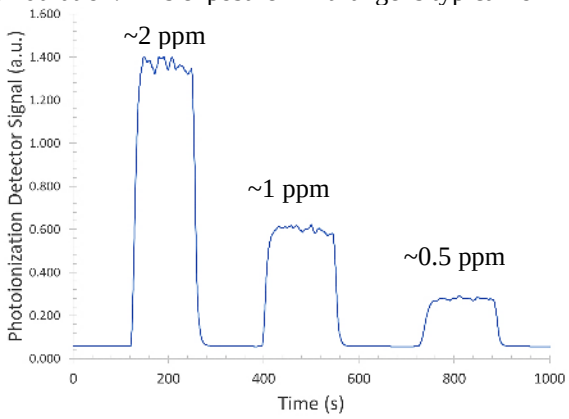

Figure 15. Photoionization detection of trace concentrations of methanethiol in O_2 background.

VII. Conclusion and Future Work

This work summarizes the continued development of a M-PALSS suitable to provide situational awareness of the breathing gas in the PLSS during extravehicular activities. The M-PALSS is a modular system which integrates multiple sensor types into compact form factor. The electronics module houses the sensor control and signal transduction circuitry. The sensor module houses the electrochemical CO_2, O_2, CO, NDIR CO_2, pressure, and humidity sensors and is designed to introduce very low pressure drop into the breathing loop. The CO_2 sensor measurement uncertainty is approximately ±0.3 mmHg and the O_2 sensor measurement uncertainty is approximately ±1 percent. The next generation of M-PALSS development will focus on meeting all the requirements for spaceflight and integration with the PLSS.

Acknowledgments

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