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Development of a 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 development of a compact, low power, multi-parameter astronaut life support sensor (M-PALSS). M-PALSS consists of an array of low-power chemical microsensors for oxygen, carbon dioxide, water vapor, and pressure. 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.

Nomenclature

PLSS	=	Portable Life Support System
xEMU	=	Exploration Extravehicular Mobility Unit
E	=	potential
E^0	=	standard potential
R	=	ideal gas constant
T	=	temperature
F	=	Faraday's constant
P_{CO_2}	=	partial pressure of CO_2
$[O_2]$	=	oxygen proportion
k	=	oxygen sensor calibration coefficient
t_{90}	=	90% response time

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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 O_2, CO_2, and H_2O in the gas stream. However, the current PLSS only includes nondispersive infrared (NDIR) sensors for CO_2. The outer mold line of the current NDIR sensors is approximately 2.3 in. x 2.2 in. x 6.1 in. and consumes approximately 2 W during operation. Development of new components for the exploration Portable Life Support System (xPLSS) that meet targets of high performance, low mass, low power, and compact size will support exploration objectives.

This paper reports the development of a compact, low power, multiparameter astronaut life support sensor (M-PALSS). M-PALSS consists of an array of microsensors for O_2, CO_2, H_2O, and pressure. The O_2 and CO_2 sensors are solid-state electrochemical sensors. The H_2O and pressure sensors are commercial off-the-shelf (COTS) sensors that operate on capacitive and piezoresistive principles, respectively. The sensor signals are measured and digitized by integrated, low power electronics. The M-PALSS is shown in Figure 1.

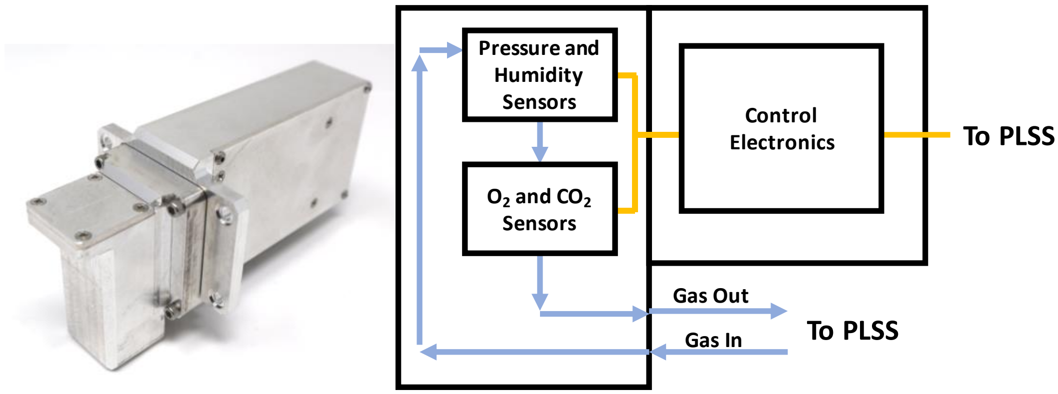

Figure 1. Multiparameter astronaut life support sensor for the xPLSS.

The M-PALSS is designed to provide general situational awareness of the major consitutuents in the breathing loop of the PLSS. The required measurement accuracy is approximately 1% for O_2 percentage and relative humidity and 0.3 torr for CO_2 partial pressure. 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 developed prototypes have a power consumption of approximately 1.8 W when powered from a 5 V supply.

II. Sensor Operating Principles

The M-PALSS sensors for O_2 and CO_2 are solid-state electrochemical microsensors. The CO_2 sensor is a potentiometric sensor consisting of a lithium phosphate electrolyte, a mixed lithium carbonate and barium carbonate working electrode, and a mixed lithium titanate and titania working electrode. This CO_2 sensor is an electrochemical cell summarized by:

$$O_2, CO_2, Au \mid Li_2CO_3\text{-}BaCO_3 \mid Li_3PO_4 \mid Li_2TiO_3\text{-}TiO_2 \mid Au, CO_2, O_2.$$

The potential measured between the working and reference electrode is expressed in Equation (**1**). Potentiometric CO_2 sensors based on Li_2CO_3 or $NaCO_3$ working electrodes present interference from the humidity in the sensed gas. The addition of $BaCO_3$ mitigates humidity interference.[1,2]

$$E = E^0 - \frac{RT}{2F} \ln (P_{CO_2}) \tag{1}$$

The O_2 sensor is an amperometric sensor consisting of a zirconia electrolyte, two platinum electrodes, and an O_2 diffusion barrier. A bias voltage is applied across the platinum electrodes and the resulting current is measured. The measured current is a function of the O_2 in the sensed gas as expressed in Equation (2).[3,4]

$$I = -k \ln(1 - [O_2]) \tag{2}$$

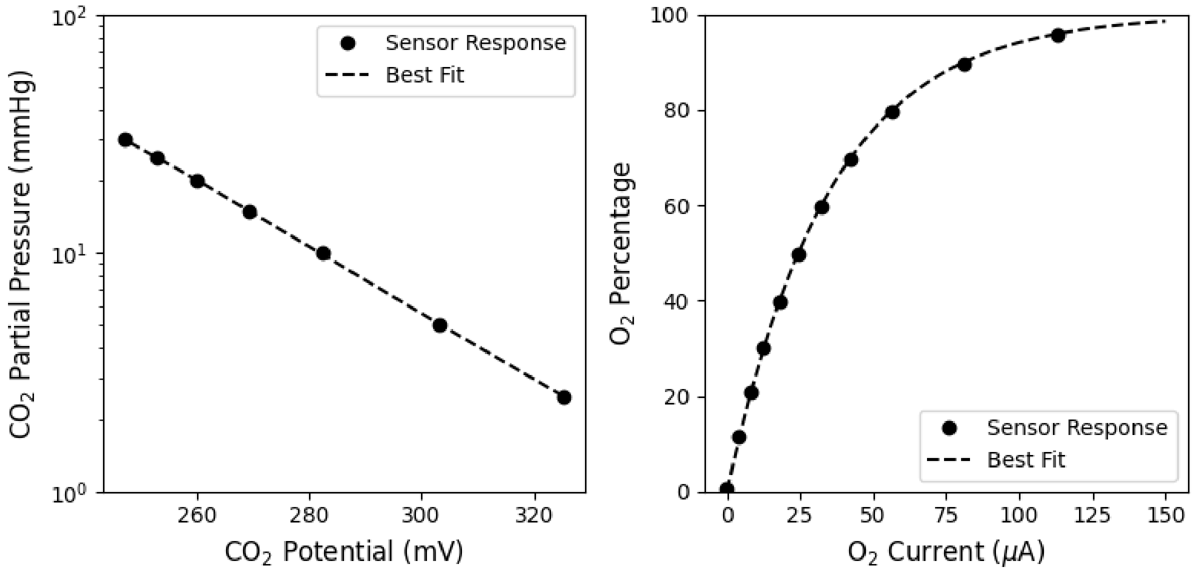

Figure 2. M-PALSS potentiometric CO_2 sensor and amperometic O_2 sensor calibration curves.

The term *k* is a calibration coefficient that consists of a group of terms that depend on sensor geometry and diffusivity in the O_2 diffusion barrier. Representative CO_2 and O_2 sensor calibration curves are shown in Figure 2. Additional details of sensor performance is provided in Section VI. In contrast to liquid electrolyte sensors and instrisically self-consuming electrochemical sensor technology the M-PALSS amperometric and potentiometric sensors offer long service life. Typical shelf life of sensors based on this technology is approximately 10 years or more. Typical operating life is on the order of thousands of hours.

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. The prototype preserves existing interfaces for data, power, fluidic and mechanical connection to the PLSS. The M-PALSS mechanical, fluidic, and electrical interfaces are shown in Figure 3. Mechanical connection to the PLSS is made by alignment with 4x 6-32 threaded holes. Fluidic connection is made via mating with 2x sensor fittings. Electrical connection is made with a 13-pin rectangular connector.

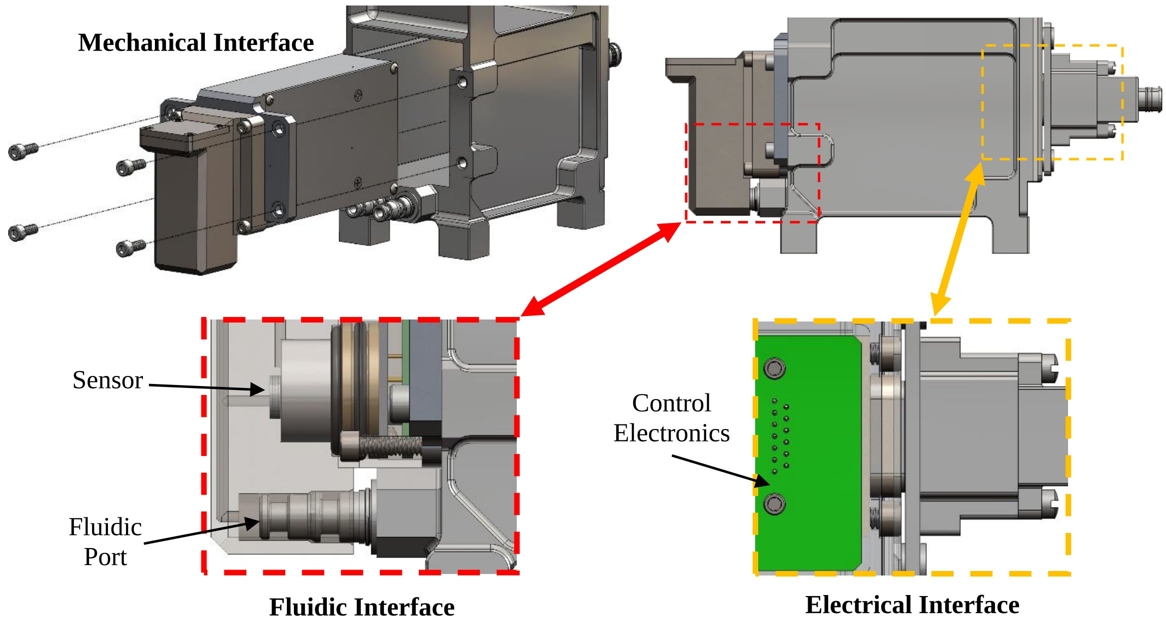

Figure 3. M-PALSS mechanical, fluidic, and electrical interfaces.

The M-PALSS is a two component modular system consisting of a sensor manifold and an electronics module. Electrical connection is made between the sensor manifold and electronics module via a board-to-board connector. The sensor manifold is designed for minimized deadspace and low pressure drop. Low pressure drop in the flow manifold is intended to preserve the capability to control gas flow through the sensor manifold by appropriately sizing inlet and outlet orifices. If pressure drop in the sensor manifold is too large then the flow rate cannot be controlled through orifice sizing. The pressure drop is approximately 0.1 inches of H_2O at 100 sccm flow rate at 14.7 psia. This pressure drop does not include inlet and outlet flow restricting orifices. A detailed view of the sensor manifold is shown in Figure 4.

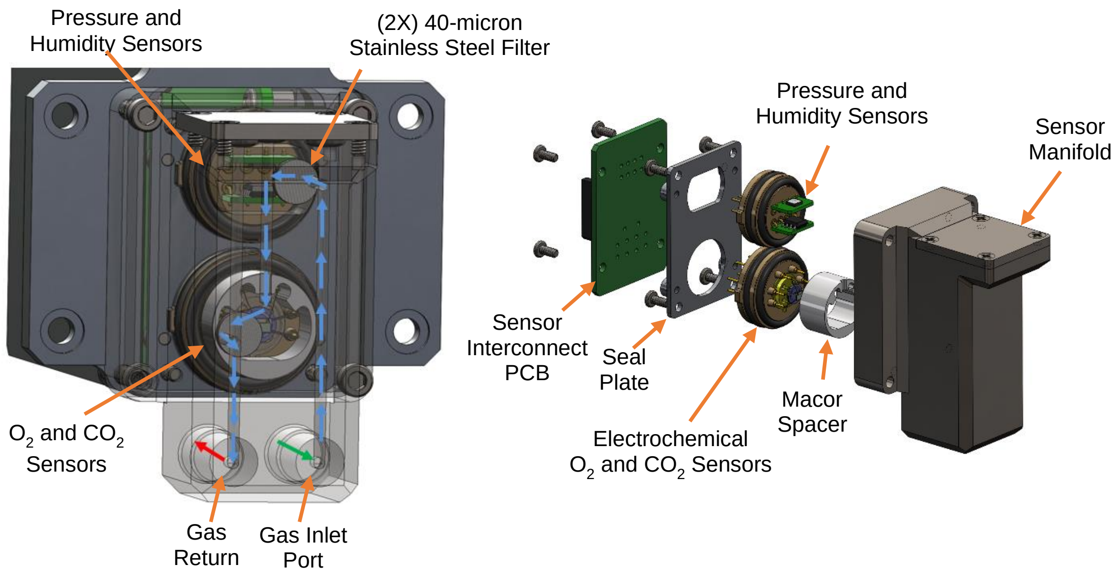

Figure 4. M-PALSS sensor module and sensed gas flow path.

IV. Sensor Electronics

The M-PALSS electronics module consists of three 1.5 in. x 1.5 in. boards and an enclosure. The control and power board handle power conditioning, sensor temperature control, data digitization, and communication. The heater drive board modulates the sensor heater power according to the control signal received from the control board. The signal board transduces the raw signals of the O_2 and CO_2 sensors and prepares the signals for digitization on the control board. The M-PALSS electronics block diagram is shown in Figure 5.

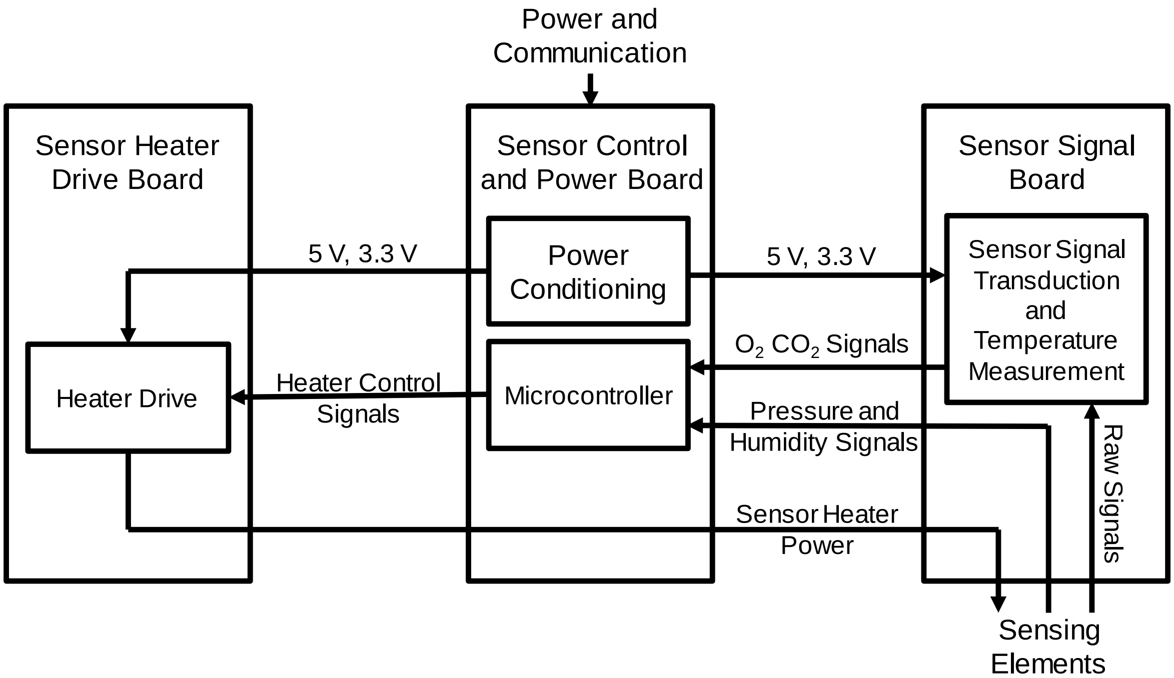

Figure 5. M-PALSS multi-board electronics architecture.

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 humidifier to produce sensed gas mixtures on demand. Operation in the PLSS requires that sensors operate over a wide range of humidity and pressure conditions. The sensed gas stream is prepared using a mixing system represented by the schematic shown in Figure 6.

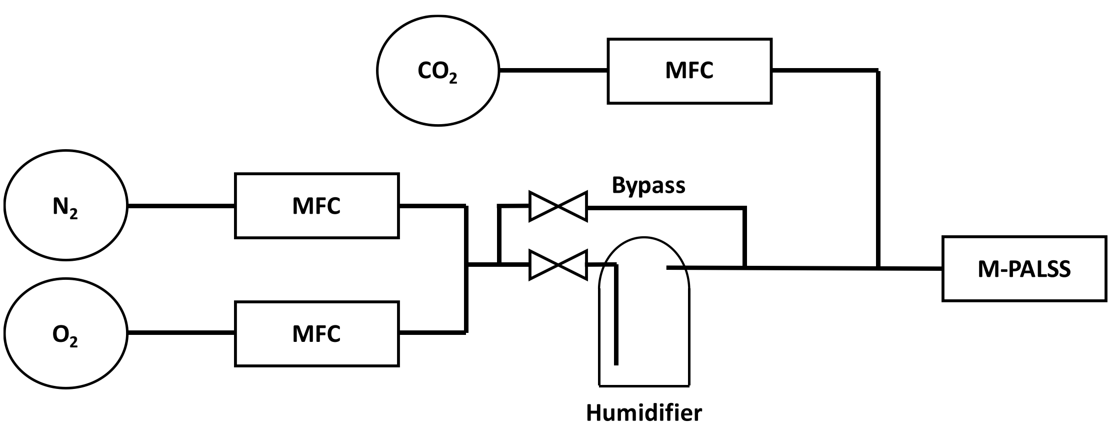

Figure 6. Gas mixing and humidification schematic.

In the first step, pure and dry O_2 and N_2 streams are mixed to the O_2 percentage annotated in Figure 6a. In the second step, the mixed gas stream is split into two streams using proportional valves. One of these gas streams is passed through a bubbler to achieve approximately 100% relative humidity and other gas stream runs through the bubbler bypass. The wet stream is then recombined with the dry stream. The recombined gas stream is then delivered to the M-PALSS unit as the sensed gas stream. The humidity of the final sensed gas stream is controlled by adjusting the relative flow rates through the bubbler and the bubbler bypass. Representative M-PALSS O_2 sensor performance at 14.7 psia is summarized in Figure 7.

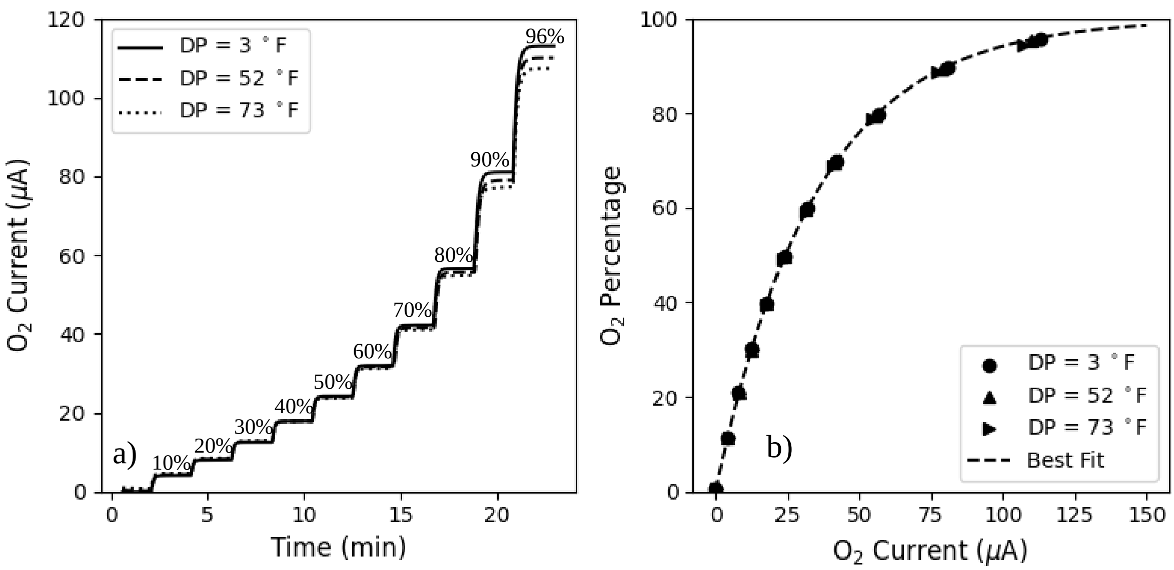

Figure 7. M-PALSS O_2 sensor performance at 14.7 psia for various operational dewpoints, a), and steady-state calibration data, b). The annotated percentages in a) are O_2 percentages prior to humidification. The gas mixture is balance N_2.

Deviations in O_2 sensor current at high O_2 percentage are observed in the raw data in Figure 7a. 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 7b. The M-PALSS O_2 sensor t_{90} response time is approximately 3 s.

Representative M-PALSS CO_2 sensor performance at 14.7 psia is shown in Figure 8. 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 12 s.

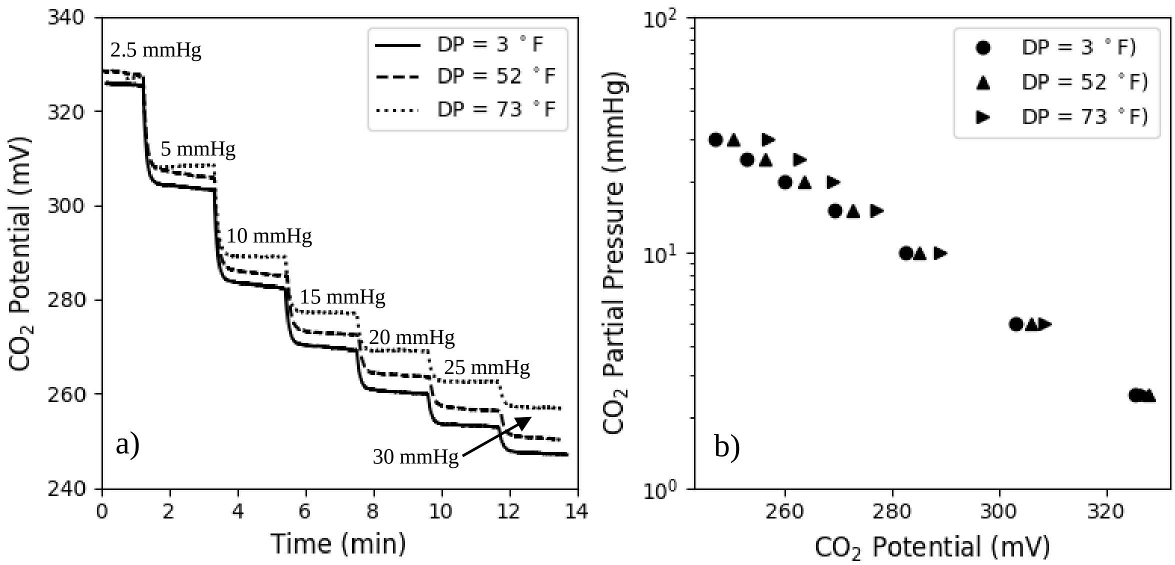

Figure 8. M-PALSS CO_2 sensor performance at 14.7 psia for various operational dew points, a), and steady-state calibration data, b). The background gas mixture is 21% O_2 balance N_2.

A small amount of humidity interference is seen in Figure 8a and the calibration plot in Figure 8b. 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. The measurement uncertainties for the M-PALSS O_2 and CO_2 measurements are shown in Figure 9.

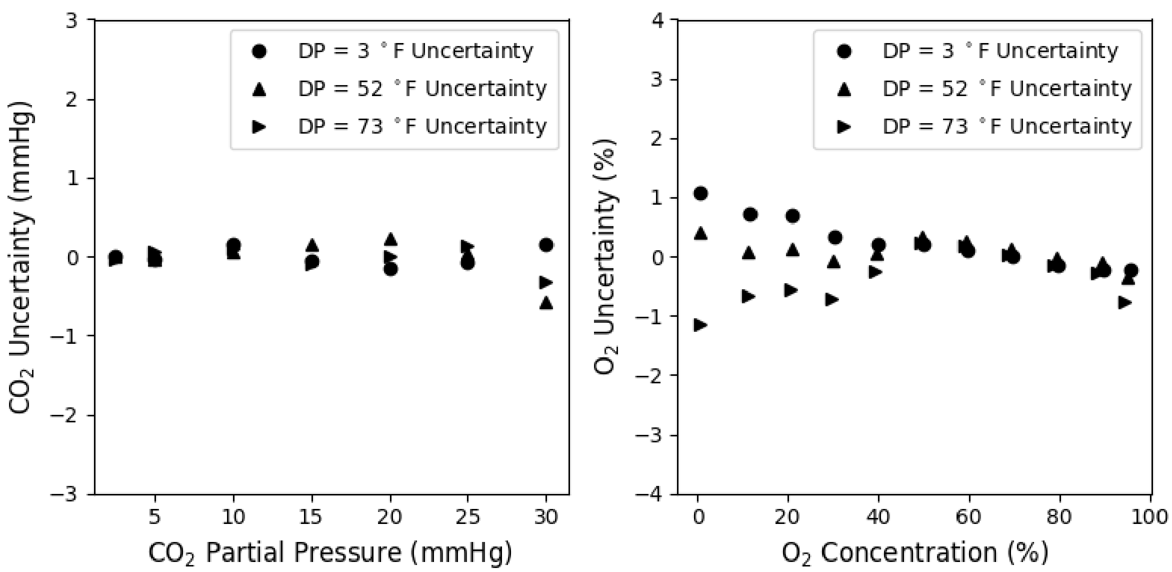

Figure 9. M-PALSS CO_2 sensor measurement uncertainty a) and O_2 sensor measurement uncertainty b). CO_2 measurement uncertainty includes humidity compensation.

VI. Conclusion and Future Work

This work summarizes the development of a multi-parameter astronaut life support sensor (M-PALSS) suitable to provide situational awareness of the breathing gas in the PLSS during extravehicular activities. The M-PALSS is a two component modular system. The electronics module houses the sensor control and signal transduction circuitry. The sensor module houses the CO_2, O_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%. 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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