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Evaluation of the Oxygen Concentrator Prototypes: Pressure Swing Adsorption Prototype and Electrochemical Prototype

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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

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1.0 Introduction

1.1 Purpose of the Technology Development

An oxygen concentrator is needed to provide enriched oxygen in support of medical contingency operations for future exploration human spaceflight programs [Watkins]. It would provide continuous oxygen to an ill or injured crew member in a closed cabin environment. Oxygen concentration technology is being pursued to concentrate oxygen from the ambient environment so oxygen as a consumable resource can be reduced. Because oxygen is a critical resource in manned spaceflight, using an oxygen concentrator to pull oxygen out of the ambient environment instead of using compressed oxygen can provide better optimization of resources. The overall goal of this project is to develop an oxygen concentrator module that minimizes the hardware mass, volume, and power footprint while still performing at the required clinical capabilities.

Should a medical event occur that requires patient oxygenation, the release of 100 percent oxygen into a small closed cabin environment can rapidly raise oxygen levels to the vehicles fire limit. The use of an oxygen concentrator to enrich oxygen from the ambient air and concentrate it to the point where it can be used for medical purposes means no oxygen is needed from the ultra-high purity (99.5+% O₂) oxygen reserve tanks. By not adding oxygen from compressed tanks to the cabin environment, oxygen levels can be kept below the vehicle fire limit thereby extending the duration of care provided to an oxygenated patient without environmental control system intervention to keep the cabin oxygen levels below the fire limits.

The oxygen concentrator will be a Food and Drug Administration (FDA) clearable device. A demonstration unit for the International Space Station (ISS) is planned to verify the technology and provide oxygen capability. For the ISS, the demonstration unit should not exceed 10 kg (approximately 22 lb), which is the soft stowage mass limit for launch on resupply vehicles for the ISS. The unit's size should allow for transport within the spacecraft to an ill crewmember. The user interface needs to be designed for ease of use by the local care provider and with consideration to the limited amount of training available to the astronaut corps for medical equipment and procedures.

1.2 Evaluation Criteria

This section lists the draft requirements for an oxygen concentrator for exploration missions. They will be referenced by number in the prototype test results evaluation. There are five main categories of requirements: atmosphere (oxygen and pressure), flow, timing, power, and other miscellaneous requirements. The first three have some quantitative requirements for which the prototypes can be directly evaluated. Other requirements were beyond the scope or technology readiness level (TRL) of the prototypes, and are included here for completeness.

1.2.1 Atmosphere (Oxygen and Pressure) Requirements

- 1.2.1.1 The OCM shall be capable of generating an oxygen concentration output of at least 50 percent oxygen on a minute average basis.

Rationale: This is the minimum oxygen concentration output coupled with the minimum flow rate described in requirement 1.2.2.2 needed to maintain the oxygen saturation of a crewmember during a medical contingency based on treatment protocols [Watkins].

- 1.2.1.2 The OCM shall be capable of generating an oxygen concentration output of over 90 percent oxygen on a minute average basis for critical cases.

Rationale: Nearly pure oxygen concentration will allow for increased care should the patient require more oxygen at the cost of increased power usage.

- 1.2.1.3 The OCM shall operate without increasing the overall partial pressure of oxygen in a closed cabin.

Rationale: Ensures that the medical oxygen needs can be supported for extended periods of time without exceeding the fire limit for cabin oxygen concentration. The OCM in and of itself will not be a source of oxygen. Its input and output oxygen mass balance should be a net of zero.

- 1.2.1.4 The OCM shall provide an output pressure of 55 to 60 psia regulated as needed as part of the delivery system.

Rationale: Provide at least some positive pressure when oxygen is being supplied to a patient using a mask. The system must maintain a pressure safe for patients and other medical equipment downstream of the output flow.

- 1.2.1.5 The OCM shall operate using ambient cabin air as the input gas supply.

Rationale: The system needs to meet the specified performance requirements without access to high pressure or preconditioned gases.

- 1.2.1.6 The OCM shall operate in the exploration ambient environments with the following characteristics [CxP 70024, Campbell, Conkin, Gerstenmaier]:

- A. Atmospheric temperature within the range of 18 °C (64.4 °F) to 27 °C (80.6 °F).
- B. Average relative humidity level over each 24-hour period between 25 and 75 percent.
- C. Average oxygen concentration of 21, 26.5, or 34 percent O₂ by volume, depending on total pressure.
- D. Internal pressure to operate within 7.5 and 15.0 psia.
- E. Partial pressure of oxygen in the internal atmosphere to operate within 2.69 and 3.44 psia.
- F. Partial pressure of carbon dioxide in the internal atmosphere to less than 0.100 psia average over any 1-hr time frame.

1.2.2 Flow Requirements

- 1.2.2.1 The OCM shall have a maximum output flow rate of at least 6 liters per minute.

Rationale: This is the maximum output flow rate coupled with the maximum oxygen concentration output described in requirement 1.2.1.2 needed to maintain the oxygen saturation of a crewmember during a medical contingency based on treatment protocols [Watkins].

- 1.2.2.2 The OCM shall have a minimum output flow rate of 2 liters per minute.
Rationale: This is the minimum output flow rate coupled with the minimum oxygen concentration output described in requirement 1.2.1.1 needed to maintain the oxygen saturation of a crewmember during a medical contingency based on treatment protocols [Watkins].
- 1.2.2.3 The OCM shall be able to provide on-demand oxygen flow to reduce power consumption for less critical cases.
Rationale: Any on-demand flow system senses the inhalation of the patient using a nasal cannula, and only provides flow during the actual inhalation. This decreases the duty cycle and reduces the power consumption of the unit.

1.2.3 Operational Time Requirements

- 1.2.3.1 The OCM shall operate within performance requirements within 2 min of startup. An indicator on the unit should indicate when it is operating at the set flow rate. “Performance requirements” are defined as the production of oxygen at the desired concentration and flow rate.
Rationale: Limits the amount of time after startup that patient oxygen saturation would have to be maintained using cabin air or an alternative oxygen supply.
- 1.2.3.2 The OCM shall operate within performance requirements after up to two years without significant maintenance required.
Rationale: Ensures the device shelf life supports the nature of the exploration mission and other space flight programs.
- 1.2.3.3 The OCM shall be able to support more than one non-concurrent medical contingency event within its certified operational life.
Rationale: The intent of this requirement is for the OCM to not be a single use device. The device can be used multiple times for non-concurrent medical events.
- 1.2.3.4 The OCM shall be capable of operating continuously for a minimum of 168 hr.
Rationale: This requirement stems from a potential medical contingency return from the lunar surface to recovery on Earth that has potential duration of seven days.

1.2.4 Power Requirements

- 1.2.4.1 The OCM shall support input power from 28 to 120 VDC.
Rationale: The system needs to support power input from various aircraft and spacecraft along the chain of care during a medical contingency. ISS currently uses 120 VDC, and the Constellation Orion vehicle is being designed to use 120 VDC. However, terrestrial transport aircraft typically use 28 VDC. Therefore, to maintain continuity of care, the OCM will need to support this range of power source voltages.
- 1.2.4.2 The OCM shall operate without exceeding a power draw of 360 W.
Rationale: The system needs to use external power supplies without exceeding the capacity of the host vehicles for power and subsequent heat rejection.

1.2.4.3 The OCM shall operate on internal battery power for at least 8 hr.
Rationale: The system needs to be able to continuously supply oxygen to the patient while being transferred from once host vehicle to another. Furthermore, following return to Earth, recovery by the recovery team could take up to 8 hr.

1.2.4.4 The OCM shall be able to switch between external and internal power while continuing to operate.
Rationale: The system needs to be able to continuously supply oxygen to the patient while being transferred from once host vehicle to another.

1.2.5 Miscellaneous Requirements

1.2.5.1 The OCM shall be portable between vehicles.
Rationale: The system needs to be easily removed from its primary use location and transported with the patient while being transferred from one vehicle to another.

1.2.5.2 The OCM shall provide removable inlet filters to filter smoke from a fire or fumes from a toxic spill, so the ambient cabin air is clean as it enters the device.
Rationale: The system needs to meet the specified performance requirements in emergency situations where the breathable atmosphere is contaminated.

1.2.5.3 The OCM shall provide closed loop oxygen ventilation capability for smoke inhalation and other medical conditions requiring oxygen.
Rationale: Automated oxygen ventilation control and monitoring is needed to allow crewmembers to focus on other patient care. The closed loop system needs to include a CO-oximeter for smoke inhalation as well as the normal pulse oximeter for oxygen saturation.

1.2.5.4 External monitoring and control capability with system parameters accessible in electronic form.
Rationale: Remote access to control and monitor system performance is needed to support computer control for remote care providers. The parameters should include power consumption, battery life and status, and the concentration and flow rate of the oxygen output, among others.

1.2.5.5 The OCM shall conform to military airworthiness requirements in MIL-HDBK-516B.
Rationale: In the event of a medical contingency during space flight, transport of the ill or injured crew member may require transfer to a definitive care facility via military aircraft.

1.2.5.6 The OCM shall conform to space flight certification requirements (SSP 41172 Revision AB).
Rationale: The OCM needs to be able to be certified for flight on the ISS and the associated transfer vehicles.

2.0 Experimental Setup

The Spacecraft Exploration Atmospheres Test Lab at NASA Glenn Research Center (Bldg. 77- Rm. 151) was used for the evaluation of the oxygen concentrator prototypes. The area of the lab used for the testing is shown in Figure 1, and includes the test chamber, a vacuum exhaust system, a gas supply rack, chiller, power supplies, and data acquisition system.

2.1 Lab Equipment

The test chamber is a 24- by 24- by 24- in. vacuum chamber with a cold plate at the floor level. Multiple flow and electrical feed-throughs provide access for the testing.

A chiller is used to provide temperature-conditioned water to the cold plate in the bottom of the chamber. This is used primarily for heat rejection to maintain the chamber temperature at near-ambient conditions. Saturated salts are used to control the initial humidity in the chamber.

The vacuum system is used to evacuate the chamber so it can be filled with the desired gas mixture. If the concentrator cannot withstand a hard vacuum, the chamber is partially evacuated and filled with the desired gas mixture repeatedly to obtain the desired ambient oxygen concentration and total pressure.

The chamber is filled from the gas supply rack, which contains different O₂-N₂ blends of 21 percent O₂, 30 percent O₂, and 34 percent O₂. In addition, a combustion products “dirty air” blend is present that contains 20 percent O₂, 1 percent CO₂ and 55 ppm of CO. Additional bottles of 95 percent O₂ and 100 percent N₂ are used to calibrate and purge the oxygen sensor before and after each test, respectively.

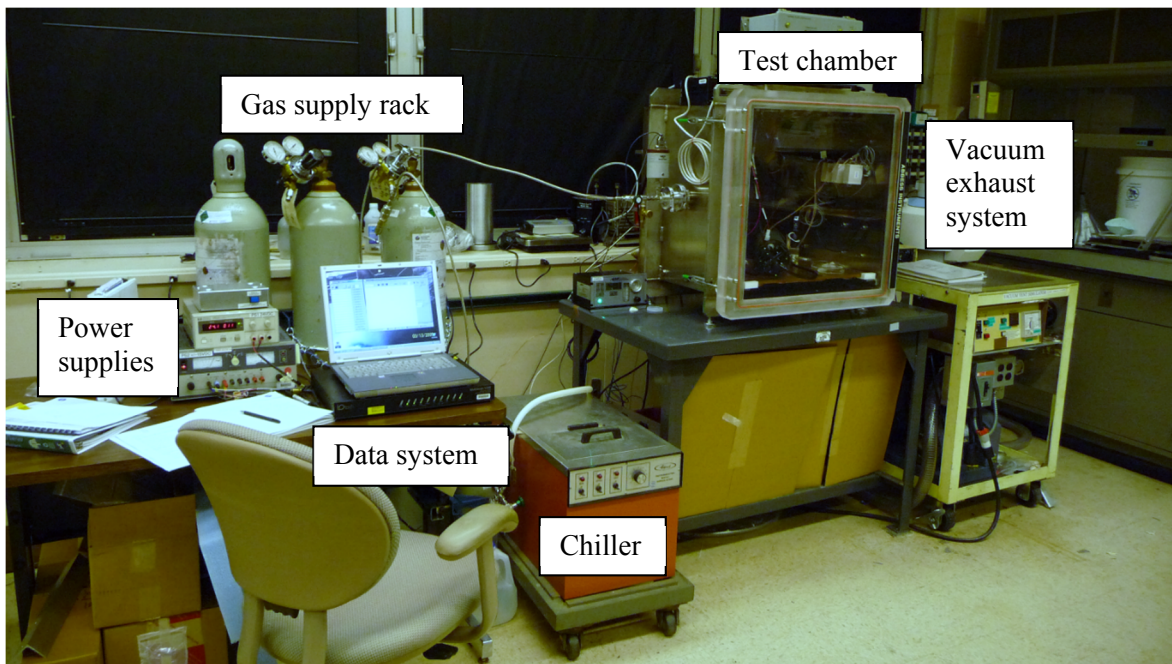


Figure 1.—The Spacecraft Exploration Atmospheres Test Lab at NASA Glenn Research Center.

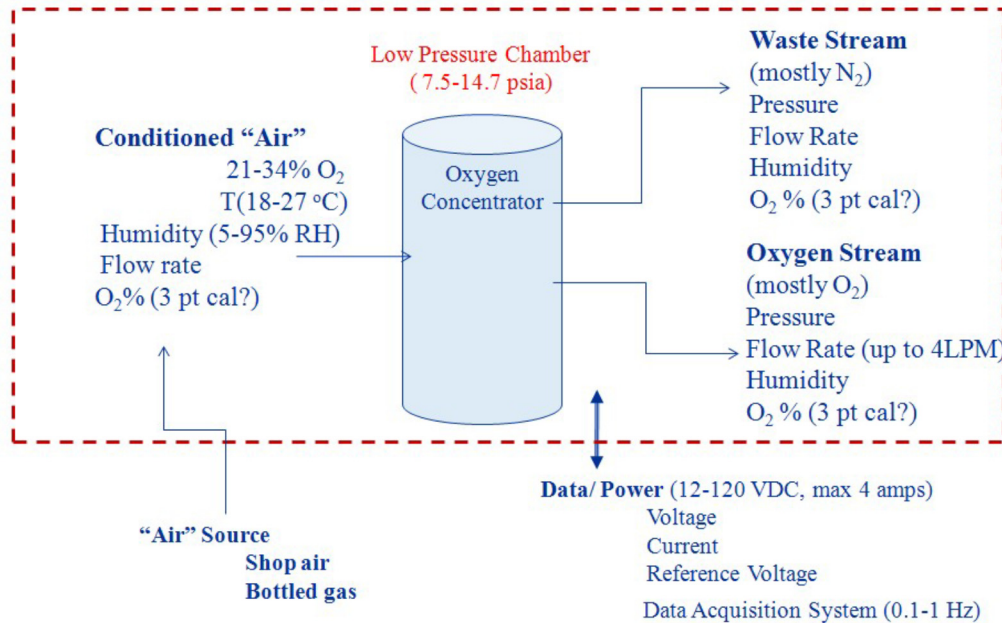


Figure 2.—Test apparatus concept.

A concept for the oxygen concentrator prototype evaluation test setup is shown in Figure 2. The oxygen concentrator is placed in the test chamber, draws in ambient atmosphere from the chamber, and separates the gases to a waste stream that is predominantly nitrogen, and a product stream which is predominantly oxygen. Each of the three flow streams is measured for pressure, flow rate, temperature, humidity, and the oxygen concentration of the product stream is also measured.

In addition, the voltage and current draw of the prototype was measured, and CO and CO₂ sensors were used in some tests that used a gas mixture with these contaminants present.

A full description of the flow systems, electrical systems, and sensors used can be found in Appendix A.

2.2 Test Procedure

Prior to each test, the prototype was prepared for the test. This included filling the liquid reservoir with deionized water for the electrochemical prototype, and checking the touchpad flow setting (liters per minute or lpm) for the PSA prototype. The electrochemical prototype had external software control, so the software was started and Ethernet connectivity was verified.

Saturated salts were installed in the chamber to control the initial humidity level in the chamber, if desired for the test point. The chamber was then sealed, and filled with the desired gas mixture at the desired pressure. The chiller was activated to control the cold plate temperature. The data system and power supplies were turned on and allowed to warm up for at least 1 hr prior to the start of the test.

The oxygen sensor was calibrated prior to each test point using a premixed supply of 95 percent O₂ in N₂ and then purged with 100 percent N₂ gas to provide an initial low oxygen reading so that the start of oxygen production could be detected accurately. Appendix B has the calibration for the pressure correction factor for the oxygen sensor, since the oxygen sensor is sensitive to the ambient pressure in the chamber.

The data system was set up to record data at 1 Hz for the desired test time. The data collection was started, and then the power was turned on to the prototype so that that the time from activation to oxygen production could be evaluated. To end a test, the prototype was powered down prior to data collection termination, to capture the power-down profile and timing.

After data collection was complete, the chamber was either evacuated to the fume hood or vented to atmosphere, depending on the gas being used. At the end of data collection for the day, the O₂ sensor was again flushed with 100 percent N₂ gas to prolong the electrochemical sensor life. The data was downloaded for analysis. The chiller was turned off, power systems and data systems powered down, and gas bottles resealed with regulators depressurized.

3.0 Pressure Swing Adsorption Prototype Evaluation

3.1 PSA Prototype Description

The National Space Biomedical Research Institute (NSBRI) prototype was developed under a 4 year grant, utilizing pressure swing adsorption technology (PSA) [Ritter, Bhadra, Ebner, Giesy, Lucas, Mehotra, Wang]. Pressure swing adsorption technology separates oxygen from the air using packed beds of zeolite sorbent that preferentially passes oxygen while adsorbing the nitrogen in the zeolite pores under elevated pressures. The prototype, built by Chart Industries, a partner in the NSBRI grant, was delivered to NASA Glenn Research Center in late 2013. The prototype is shown in Figure 3, installed in the test chamber.

The prototype measured approximately 14 in. long by 12 in. wide by 8 in. tall, and weighed less than 18 lb. The primary component of the system was a commercially available SeQual packed bed system, as shown in Figure 4.

Testing was performed under a range of varying chamber conditions including oxygen level, pressure (along the normoxic curve), temperature and relative humidity. Normoxic equivalent environments were chosen because oxygen transport across the alveoli in human lungs is dependent primarily on the partial pressure of O₂, preventing hypoxia. The flow rate of the prototype was varied during testing to demonstrate a variety of operational conditions. A premixed bottle with atmospheric contaminants was used to simulate the atmospheric conditions of smoke. This “dirty air” consisted of 20 percent O₂, 79 percent N₂, 1 percent CO₂ and 55 ppm CO.

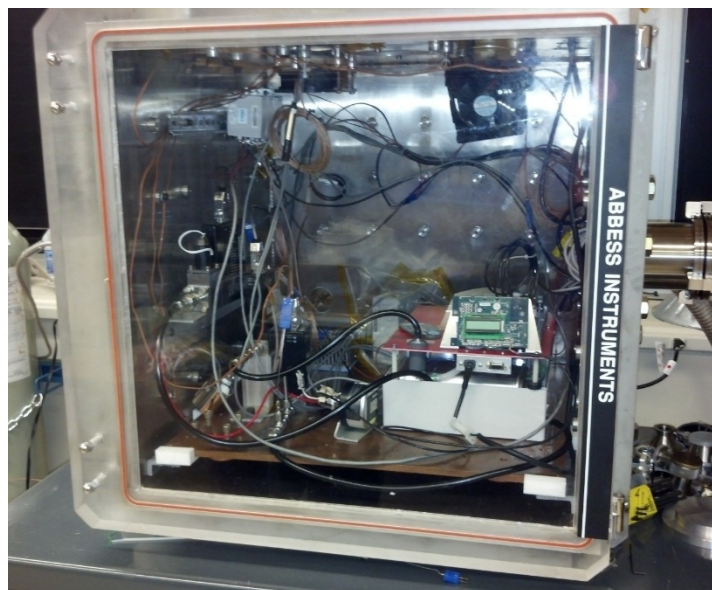


Figure 3.—Photograph of PSA prototype oxygen concentrator installed in the test chamber.



Figure 4.—Top left image shows packed bed module from SeQual, and bottom left image shows same packed bed (right) next to the compressor (left). Both sit on a bed of foam to provide vibration and noise dampening. Shown on the lower right is the exposed top circuitry and a display of the flow rate. The image on the top right shows the touchpad control on the prototype that toggled between off, 6, 3, 2, and 1 lpm.

TABLE 1.—SUMMARY OF ATMOSPHERIC CONDITIONS IN THE ENVIRONMENTAL CHAMBER.

Flow rate, lpm	Oxygen level, percent	Temperature, °C	Pressure, psia	Relative humidity, percent
1	21	20	8.2	37
2	30	28	10.2	78
3	34		14.7	83
6	Dirty air			
	Atmospheric air			

During all test conditions, the power consumption of the prototype was recorded, capturing device power profiles during plug-in, start-up (power on), steady-state operation, shutdown (power off) and unplugging the device. Data collected during the evaluation includes start-up time, power profile, shutdown time, steady-state outlet oxygen concentration, flow rate, relative humidity, temperature, pressure, O₂, CO, and CO₂ level.

Table 1 outlines the atmospheres tested for this prototype, including oxygen level, pressure, relative humidity and temperature. These atmospheres were selected to capture a variety of environmental conditions, from best case to worst case (see Appendix C for psychrometric chart).

The chamber was completely sealed during testing and was instrumented to capture a plethora of performance characteristics of the oxygen concentrator prototype. These data included pressure (chamber pressure, pressure out and O₂ pressure), humidity (chamber relative humidity, relative humidity out, O₂ relative humidity), temperature (chamber temperature, prototype touch temperature, O₂ temperature, temperature out and plate temperature), flow rate (flow rate in, flow rate out, and O₂ flow rate), voltage (system, prototype voltage and reference voltage), current draw, O₂ concentration levels, CO concentration levels, and CO₂ concentration levels. The plate temperature refers to a cold plate located at the floor of the chamber upon which the oxygen concentrator prototype sat. A photograph of the PSA prototype oxygen concentrator is shown in Figure 5.

The environmental chamber was completely sealed with the oxygen concentrator outlet going through the external oxygen sensor and then back into the chamber, so all air remained in the chamber. For each test point the power supplies, external data acquisition system and chiller were allowed to warm up for at least 1 hr prior to data collection. The oxygen sensor was calibrated prior to each test point using 95 percent O₂ and then purged with 100 percent N₂ gas so the initial level of oxygen was lowered. This was done to detect when the prototype started enriching the ambient oxygen in the environmental chamber. After calibration, a hard vacuum was pulled on the chamber (down to 0.5 Torr) to pull residual air and calibration gas out of the lines and chamber and then the chamber was filled with the appropriate gas. After 5 to 10 min, data collection was started, followed by plugging in and turning on the oxygen concentrator prototype to record the start-up power profile and timing. Data was then collected for 60 to 90 min followed by the power-down sequence (turning off and unplugging the prototype) prior to data collection ending, to capture the power-down profile and timing. After data collection was complete, the chamber was either evacuated to the fume hood or vented to atmosphere, depending on the gas being used. At the end of data collection for the day, the O₂ sensor was flushed with 100 percent N₂ gas and sealed to prolong sensor life.

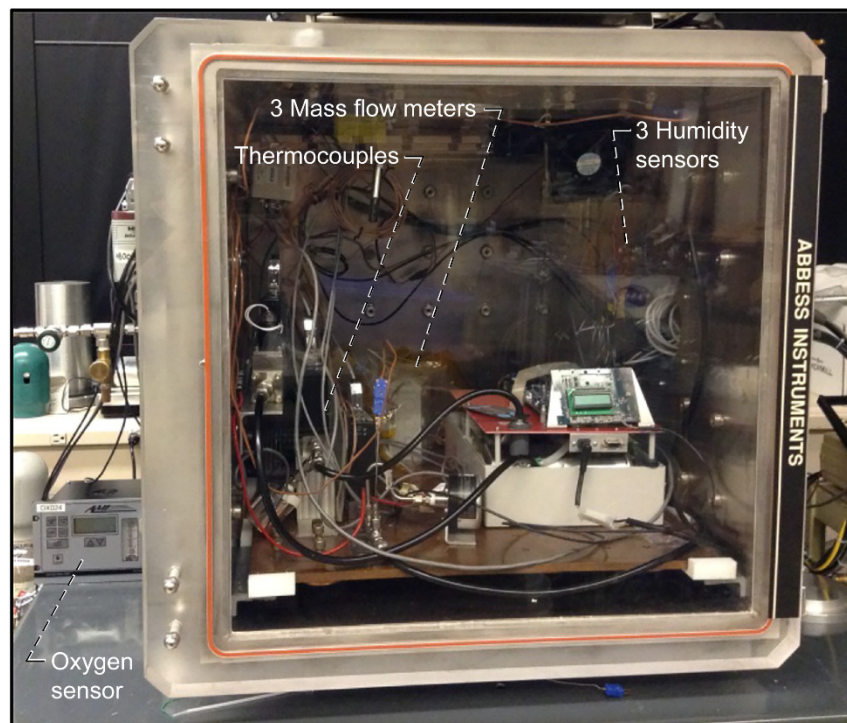


Figure 5.—Photograph of the environmental test chamber with the PSA prototype installed.

3.2 PSA System Performance Relative to Requirements

3.2.1 Atmosphere (Oxygen and Pressure) Requirements

The PSA prototype was designed to provide variable levels of oxygen at four discrete flow rates: 1, 2, 3, or 6 lpm.

As indicated in Figure 6 the prototype generates about 45 percent oxygen at 6 lpm, 75 percent oxygen at 3 lpm, 85 percent oxygen at 2 lpm and approximately 90 percent oxygen at a flow rate of 1 lpm under these chamber conditions. This fulfills requirements 1.2.1.1 and 1.2.1.2. This also demonstrates the prototype meets requirement 1.2.1.5.

The prototype meets requirement 1.2.1.3 as demonstrated by the nearly constant pressure within the environmental chamber during operation (see Figure 7).

O₂ Concentration (14.7 psia, 20 °C, 21% O₂ Ambient)

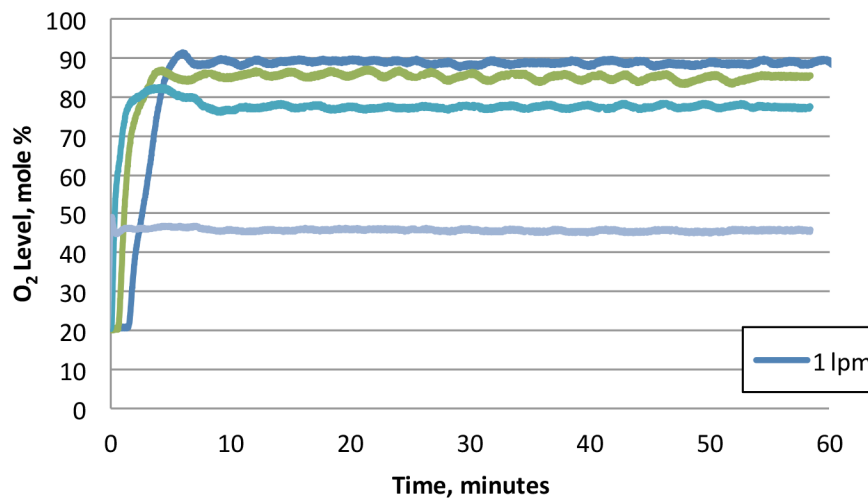


Figure 6.—Oxygen concentration at varying flow rates.

Chamber Pressure (14.7 psia, 20 °C, 21% O₂ Ambient)

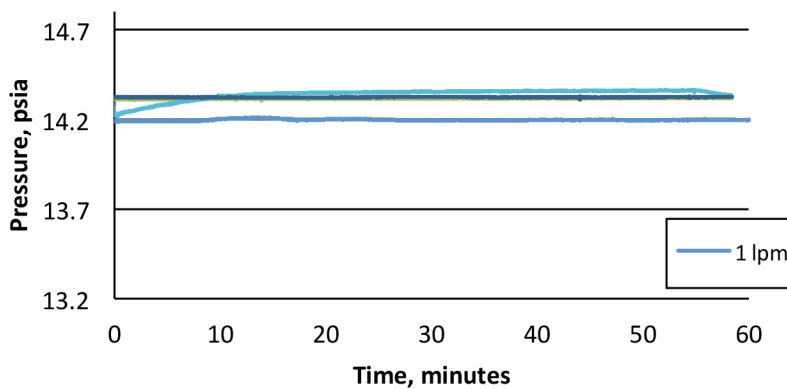


Figure 7.—Partial pressure of oxygen in a closed environment.

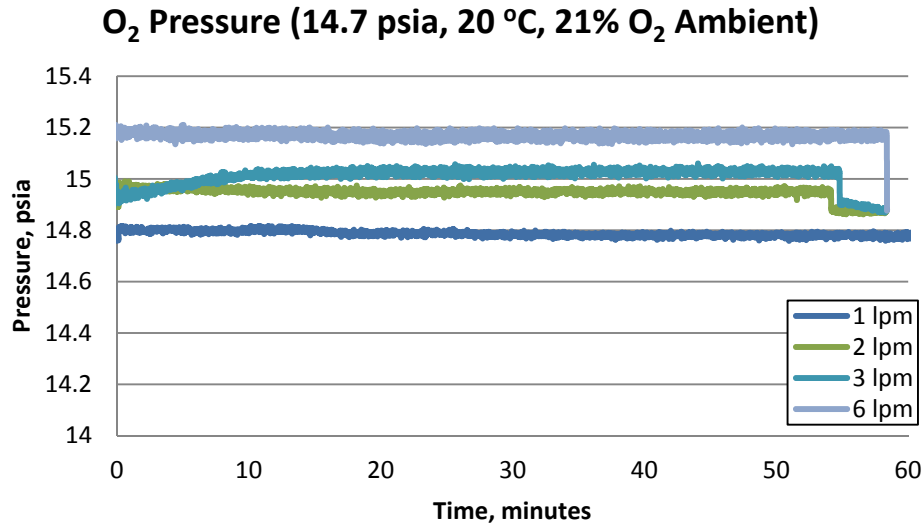


Figure 8.—Pressure of oxygen at varying flow rates.

The prototype was not tested against requirement 1.2.1.4. The pressure of the oxygen flowing directly back into the chamber is just slightly above ambient pressure (reference Figure 8).

The prototype was demonstrated in a variety of exploration ambient environments and therefore passes requirement 1.2.1.6. These data are shown in Figure 9 to Figure 14.

- A. Atmospheric temperature within the range of 18 to 27 °C. The prototype meets this requirement and is able to provide 45 to 50 percent oxygen at 20 and 28 °C (see Figure 9).
- B. Average relative humidity level over each 24-hr period between 25 to 75 percent, as shown in Figure 10. The prototype meets this requirement and is able to provide 45 to 50 percent oxygen at 37 percent relative humidity and 78 percent relative humidity at 20 °C and at 83 percent relative humidity at 28 °C. The PSA prototype meets this requirement and is able to provide oxygen at the 6 lpm flow rate, however the prototype does not perform optimally at high humidity levels (78 and 83 percent), as noted by the drop in flow rate of the N₂ outlet after 20 to 30 min of operation), possibly due to condensation in the mass flow meter. The N₂ flow is used in the prototype to reject heat and purge excess water, and the warm saturated gas cools and the water condenses in the lines. This is a limitation of the measuring system used, not necessarily of the prototype.
- C. Average ambient oxygen concentration of 21, 26.5, or 34 percent O₂ by volume. The prototype meets this requirement, as it is capable of putting out 45 percent O₂ with a chamber oxygen level of 21, and 60 and 67 percent O₂ with chamber oxygen levels of 30 and 34 percent (see Figure 11). Dry air bottles containing 21, 30 and 34 percent were used. The prototype meets this requirement, as it is capable of operating with 100 to 120 W of power at 21, 30, and 34 percent chamber oxygen levels (reference Figure 12).
- D. Internal pressure to operate within 7.5 to 15.0 psia. The prototype meets this requirement at 10.2 and 14.7 psia but does not at 8.2 psia (see Figure 13). This is a limitation of the PSA prototype, but not necessarily the inherent technology.

O₂ Concentration at Varying Chamber Temperature (14.7 psia, 6 lpm, 21% O₂)

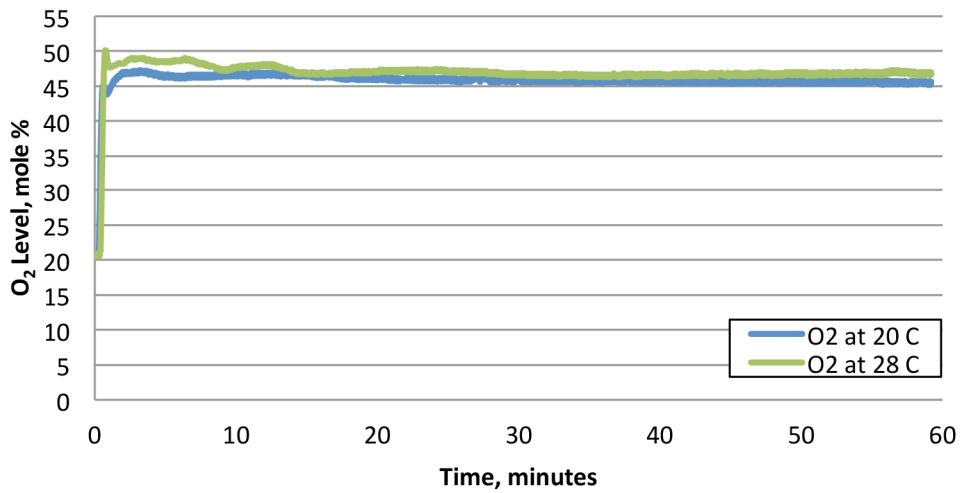


Figure 9.—Oxygen concentration with varying chamber temperatures at atmospheric pressure and oxygen levels.

O₂ Concentration at Varying Chamber Temperature and Humidity (14.7 psia, 6 lpm, 21% O₂)

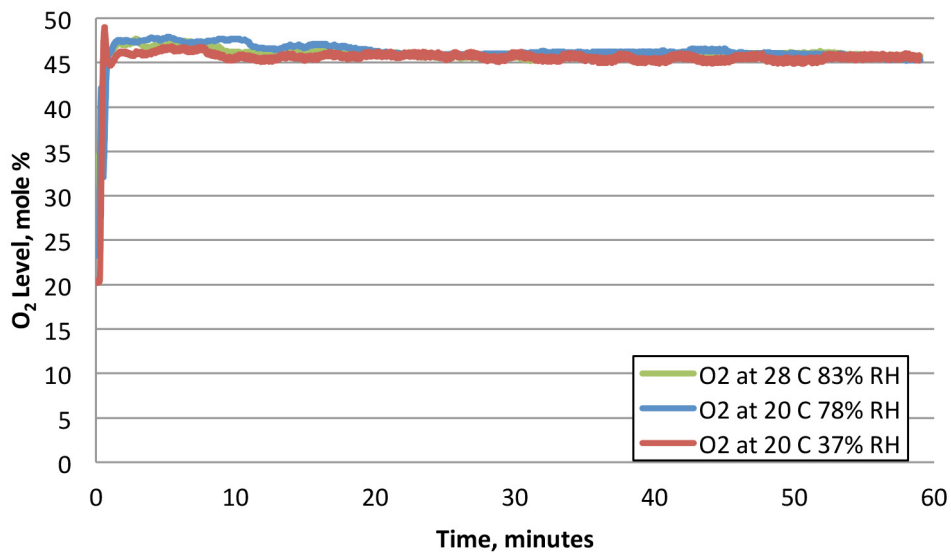


Figure 10.—Oxygen concentration at varying relative humidity levels and temperatures.

O₂ Concentration for Varying Chamber O₂ Levels (6 lpm, 14.7 psia, 20 °C)

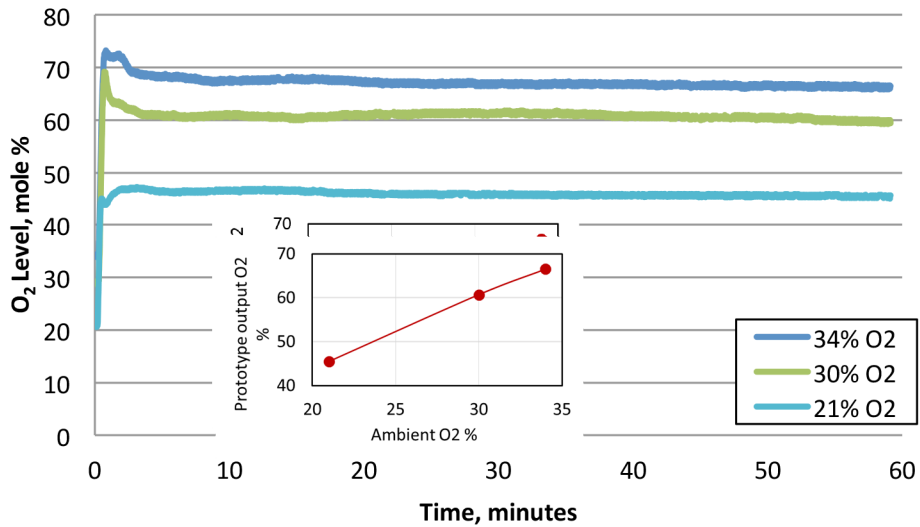


Figure 11.—Oxygen concentration at varying chamber oxygen levels. Inset shows the relationship between ambient oxygen concentration and prototype delivery oxygen concentration.

Power for Varying Chamber O₂ Levels (6 lpm, 14.7 psia, 20 °C)

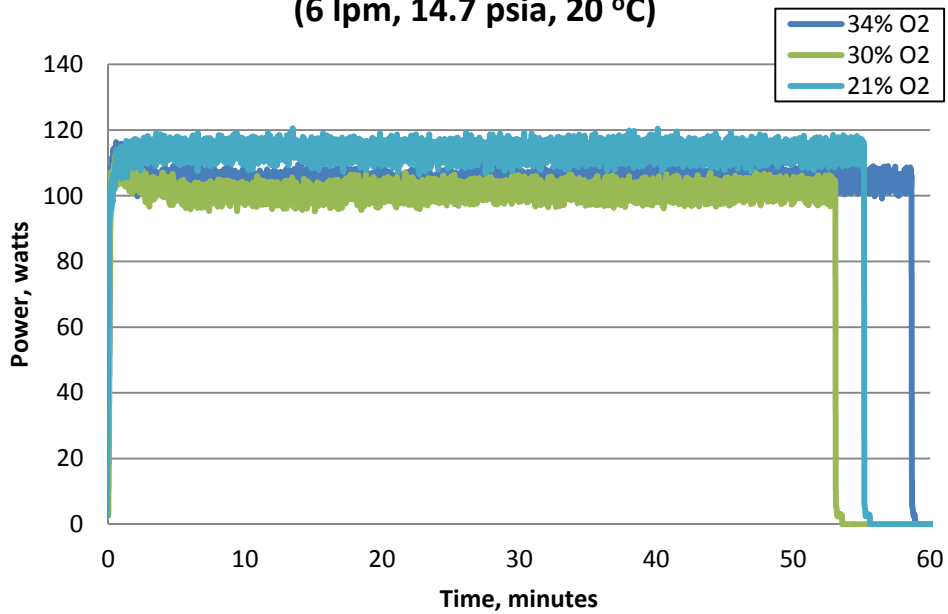


Figure 12.—Power requirements for varying chamber oxygen levels.

O₂ Flow Rates at Varying Pressures (6 lpm, 20 °C, 34% O₂)

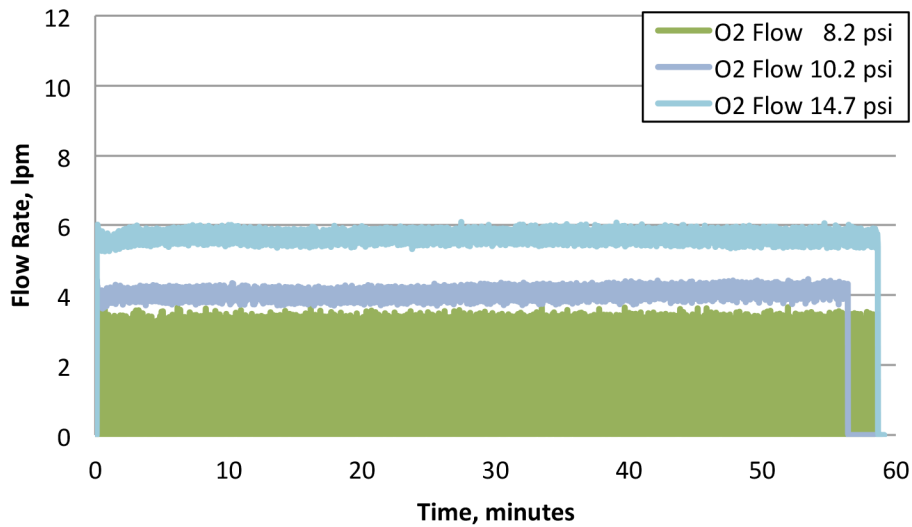


Figure 13.—Oxygen flow rates at varying pressure levels.

Flow Rate of O₂ (14.7 psia, 20 °C, 21% O₂ Ambient)

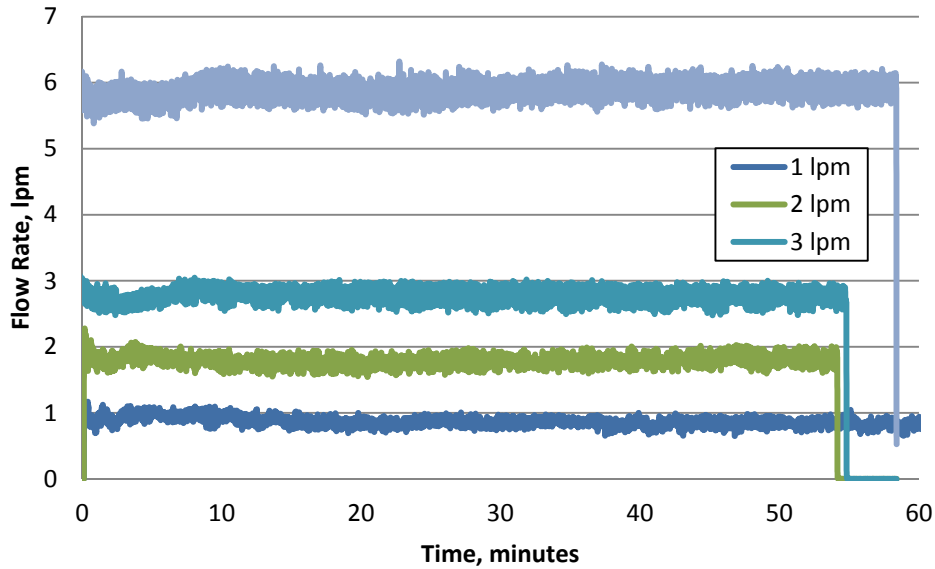


Figure 14.—Oxygen flow rate as compared to the flow rate set by the user on the prototype.

3.2.2 Flow Requirements

The prototype fulfills requirements 1.2.2.1 and 1.2.2.2 as it provides output flows from 1 to 6 lpm as shown in Figure 14. The prototype shows good correlation with the user-selected flow rate at atmospheric pressure (14.7 psia). The PSA was designed for on-demand flow as well as steady flow, and is capable of running in pulsed mode at rates of 16, 32, 48, 64, 80, and 96 mL, therefore it meets requirement 1.2.2.3.

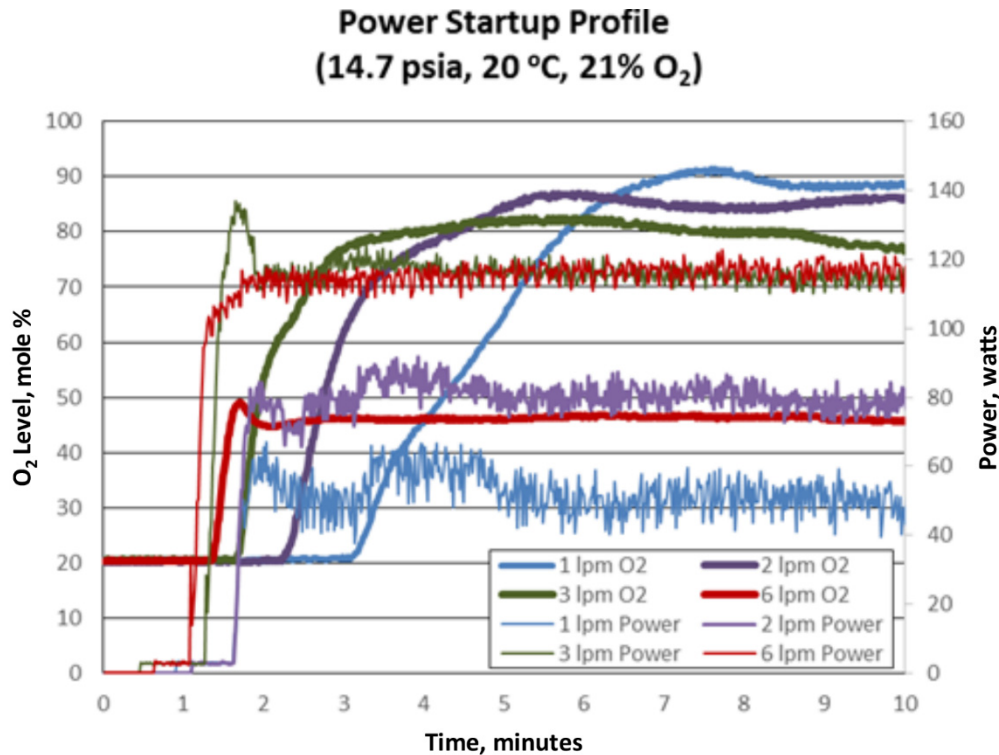


Figure 15.—Power profile during start-up.

3.2.3 Operational Time Requirements

The PSA prototype meets requirement 1.2.3.1, as shown in Figure 15. The slight jump up in power indicates the prototype was plugged-in, followed by the rapid increase in power after the prototype was turned on. The prototype was capable of reaching steady-state conditions within 2 min of being turned on. The prototype has an indicator displaying flow rate as shown in Figure 4. The prototype was run over a period of months and many test points, therefore it meets requirement 1.2.3.3. Requirement 1.2.3.2 was not evaluated. The PSA prototype was run continuously for 168 hr successfully and therefore meets requirement 1.2.3.4.

3.2.4 Power Requirements

The PSA prototype used a 120 VDC power supply and operated at less than 140 W of power, as shown in Figure 16 and Figure 17. It passes requirements 1.2.4.1 and 1.2.4.2.

The prototype requires the least amount of power to run at 1 lpm (about 60 W), followed by about 90 W at 2 lpm and the same level of power (about 120 W) for both the 3 and 6 lpm conditions. All flow conditions require less than 360 W.

The prototype requires less power at lower chamber pressures, as shown in Figure 17. At atmospheric pressure, the prototype needs about 110W of power to provide 6 lpm of oxygen with 34 percent ambient oxygen levels and a temperature of 20 °C. At 10.2 psia, the prototype requires about 55W of power and at 8.2 psia it requires about 40 W of power to produce 6 lpm of oxygen flow. The data collected at 8.2 psia corresponds with the data shown in Figure 13 where it does not produce the desired flow rate.

The PSA prototype did not have an internal battery, so it fails requirements 1.2.4.3 and 1.2.4.4 but the prototype could conceivably run on an appropriately sized battery.

Power Profile (14.7 psia, 20 °C, 21% O₂ Ambient)

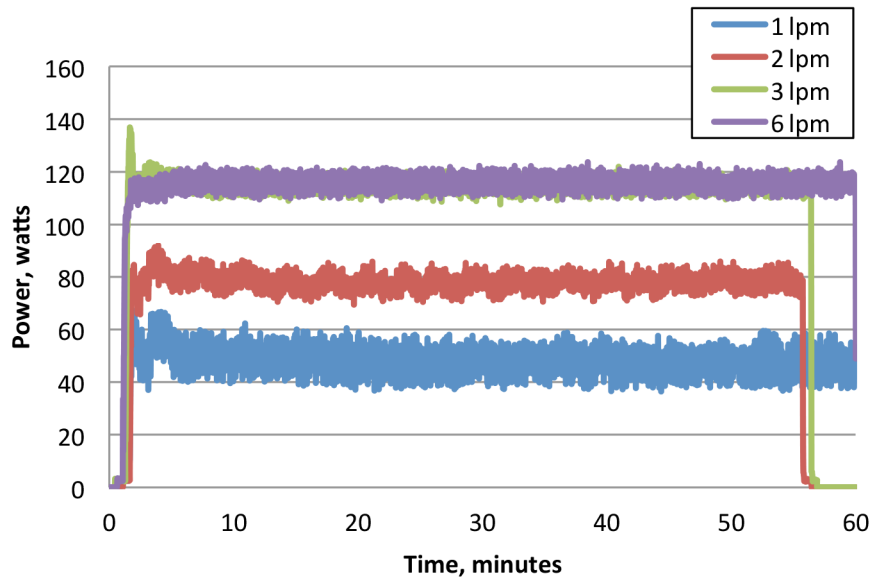


Figure 16.—Power profile during overall operation at varying flow rates.

Power at Varying Chamber Pressures (6 lpm, 20 °C, 34% O₂)

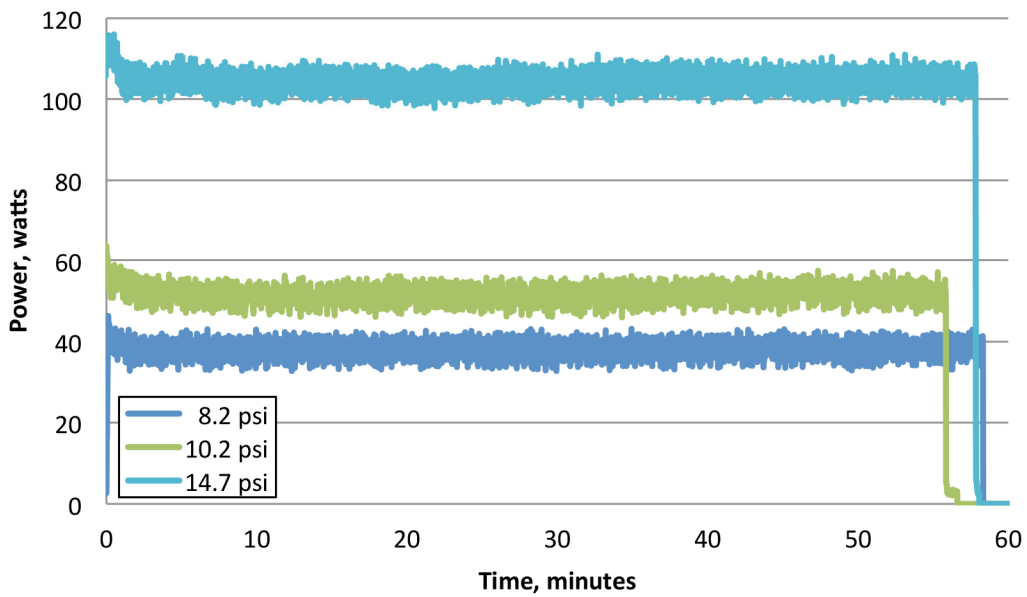


Figure 17.—Power demands at varying chamber pressures.

3.2.5 Miscellaneous Requirements

The PSA prototype is not portable in its current configuration due to the lack of an internal power source, so it fails requirement 1.2.5.1 although it could potentially meet this requirement with modifications to the prototype.

The prototype meets requirement 1.2.5.2, as it filters carbon dioxide and carbon monoxide (shown in Figure 18). There is a drastic reduction in CO and CO₂ levels in the first 10 min of operation. The level of CO₂ decreases to nearly that found in the Earth’s atmosphere (0.04 percent) at 20 °C and slightly more than that at 28 °C. It also thus meets the sub-requirement in 1.2.1.6 that the partial pressure of carbon dioxide in the internal atmosphere be less than 0.100 psia average over any 1-hr time frame.

The CO levels decrease to 10 to 15 ppm after 30 min of operation at both 20 and 28 °C, although this is higher than the trace amounts found in the atmospheric air of the United States (2 to 4 ppm). The prototype is able to output about 45 percent oxygen at both 20 and 28 °C using dirty air in the chamber as shown in Figure 19. The PSA prototype does not have closed loop ventilation capability, so it fails requirement 1.2.5.3. It does not have external monitoring and control capability, so fails 1.2.5.4 and is a low TRL device so it fails 1.2.5.5 and 1.2.5.6.

The oxygen concentrator module shall provide closed loop oxygen ventilation capability for smoke inhalation and other medical conditions requiring oxygen.

The prototype meets this requirement, as shown in Figure 19. It should be noted that the highest temperature tested using the dirty air mixture was 28 °C, which may not be reflective of the environment in close proximity to an actual fire. There may also be additional contaminants found in smoke that were not included in the “dirty air” mixture, which consisted of 20 percent O₂, 79 percent N₂, 1 percent CO₂ and 55 ppm CO.

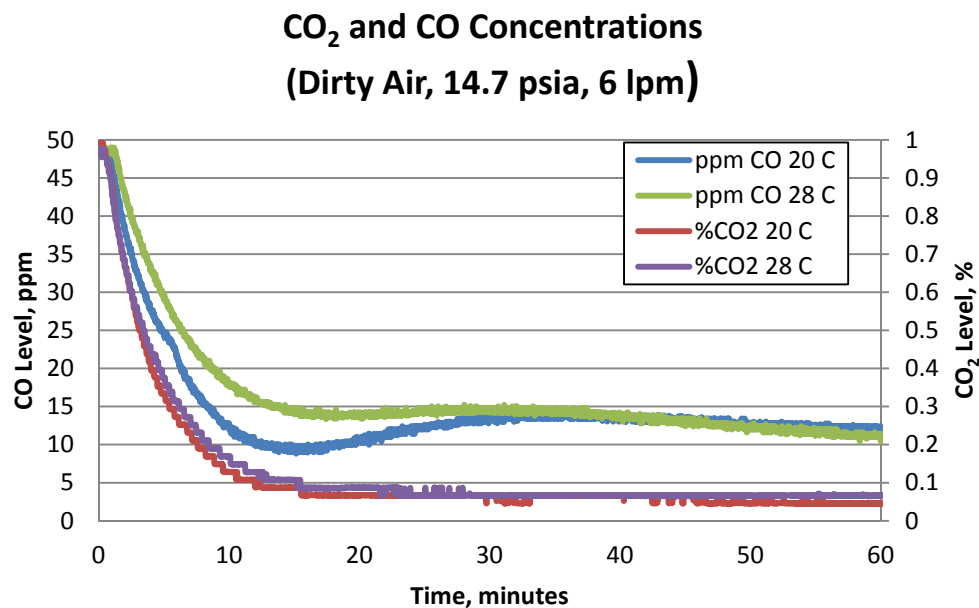


Figure 18.—Concentrations of carbon dioxide and carbon monoxide utilizing “dirty air” and varying temperatures.

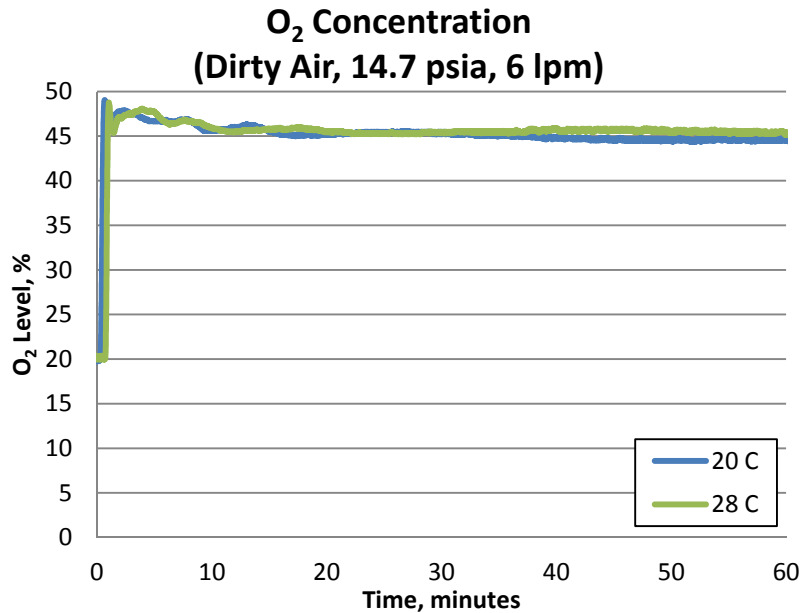


Figure 19.—Oxygen concentration using “dirty air” in the chamber.

4.0 Electrochemical Prototype Evaluation

4.1 Electrochemical Prototype Description

The electrochemical prototype, shown in Figure 20 and Figure 21 in the test chamber, was developed under a Phase II SBIR contract with Lynntech, Inc. [Cisar, Balasubramanian]. The prototype was delivered on September 6, 2012. It is an electrochemical stack that utilizes a cathode-air vapor feed, which was proposed on the premise that, unlike conventional electrochemical stacks, it did not require a liquid water feed. The prototype measured 16- by 16- by 16- in., and weighed approximately 70 lb.

The prototype’s interfaces include gas ports on the front of the prototype for O₂ out, Air in, and Return Air out. Also on the front is an Ethernet plug connection, and an on/off switch and power and alarm LED lights. The O₂ out and Return Air out lines had condensate collectors attached to catch condensate from these lines, which were supersaturated with water that otherwise condensed and collected on the floor of the test chamber. On the top of the prototype is a terminal strip for input power of 120 VDC, and a 50 oz water reservoir that was required to provide a liquid water feed to the device, since the contractor was unable to keep the stack from drying out without this liquid feed.

The test chamber was modified to include cooling fins on the cold plate, and a large recirculating fan in the chamber to improve heat rejection.

The prototype came with control software that allowed the user to select the delivery oxygen concentration and provided data on prototype performance. The system was run under a range of conditions, to evaluate its performance against the draft requirements listed in Section 1.2.

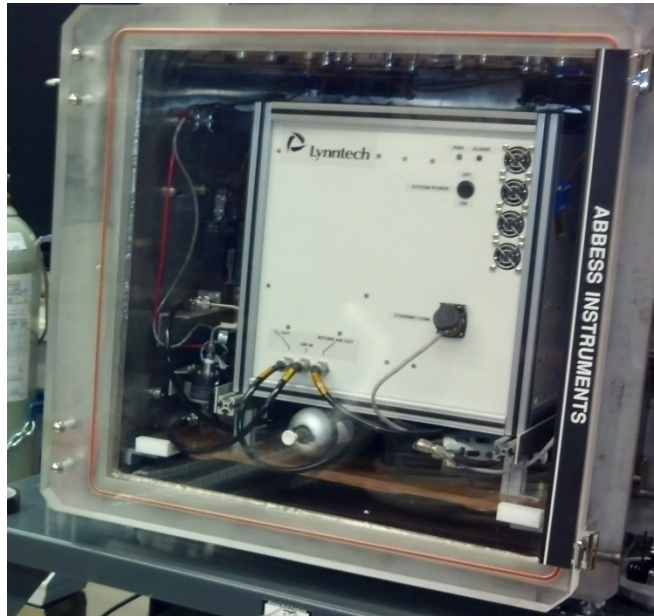


Figure 20.—Electrochemical prototype, inside the test chamber.



Figure 21.—Water reservoir for deionized water.

4.2 Electrochemical System Performance Relative to Requirements

4.2.1 Atmosphere (Oxygen and Pressure) Requirements

The electrochemical prototype was designed to provide 60 percent oxygen at 4 lpm. The delivered prototype provided a steady-state flow of 3.2 lpm of 72 percent oxygen when the set-point was 60 percent oxygen in the prototype software. The offset is possibly due to calibration differences in the internal prototype oxygen sensor and the lab oxygen sensor. This meets requirement 1.2.1.1 as shown in Figure 22.

The prototype software had a user selectable oxygen delivery concentration, so the prototype was cycled between 50 and 90 percent.

As shown in Figure 23, the prototype was able to generate oxygen concentration output of over 90 percent oxygen, thus meeting requirement 1.2.1.2. The prototype also did not increase the ambient oxygen in the chamber, thus meeting 1.2.1.3. The prototype was not tested to provide an output pressure significantly above ambient (~ 0.5 psia), and thus did not meet 1.2.1.4. The prototype uses ambient air, so passes 1.2.1.5. Lastly, the prototype was not designed to run at sub-atmospheric pressures, and thus did not meet 1.2.1.6.

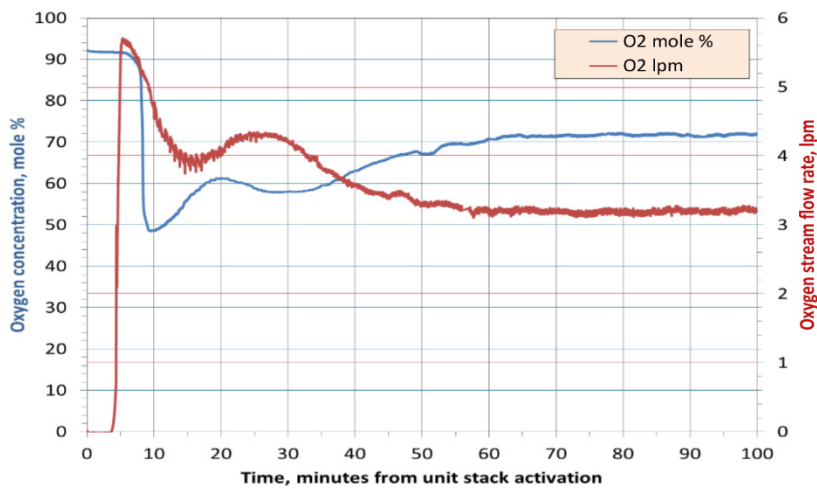


Figure 22.—Electrochemical prototype oxygen flow and concentration with time for a set point of 60 percent O₂.

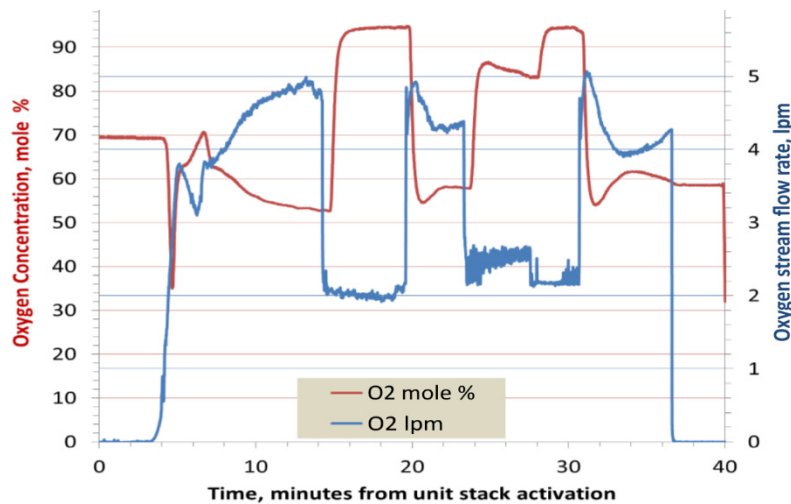


Figure 23.—Electrochemical prototype toggled between 50 and 90 percent oxygen.

4.2.2 Flow Requirements

The electrochemical prototype was designed for 4 lpm oxygen flow at 60 percent oxygen, and thus does not meet 1.2.2.1. It does meet 1.2.2.2 for 2 lpm, as shown in Figure 22. It was not designed for on-demand flow, so does not meet 1.2.2.3.

4.2.3 Operational Time Requirements

The electrochemical prototype took over 4 min to begin to produce adequate oxygen after initial power on and auto-sequence startup via the software, as shown in Figure 24. It does not meet 1.2.3.1.

The electrochemical prototype suffered a significant failure during testing that required significant maintenance, and so it failed 1.2.3.2. The water reservoir unexpectedly ran dry during a 3 hr low humidity air test, and in reviewing the data, it appears that the internal water feed rate had increased from previous tests of 1.4 to 3.5 ml/min, thus draining the water reservoir at over twice the expected rate. Prior to that failure, a number of tests had been performed, so the prototype passes 1.2.3.3.

The electrochemical prototype was deemed to be not able to operate continuously over a 7 day period, 1.2.3.4, due to the lack of adequate heat rejection in the design, which allowed the exterior of the prototype to heat up beyond touch temperature limits, while simultaneously needing to remove and refill the water reservoir many times during the 7 day operation. In addition, the water condensate collectors on the O₂ out and Return Air out would similarly need to be drained multiple times during that 7 days.

4.2.4 Power Requirements

The electrochemical prototype used a 120 VDC power supply, and operated at 600+ W of power, as shown in Figure 24. It passes 1.2.4.1 but fails 1.2.4.2 due to the greater than 360 W power draw.

The prototype did not have an internal battery, and no reasonable size battery would be able to sustain that power level for 8 hr, so the prototype fails both 1.2.4.4 and 1.2.4.5.

4.2.5 Miscellaneous Requirements

The electrochemical prototype is determined to be not portable due to its weight, lack of an internal power source, and need for high power and heat rejection, so it fails 1.2.5.1.

It does not have inlet filters to protect the prototype against smoke or toxic fumes, and it uses inlet air directly to mix with the oxygen generated to produce concentrations less than 100 percent, so it fails 1.2.4.2.

It does not have closed loop ventilation capability, so it fails 1.2.5.3.

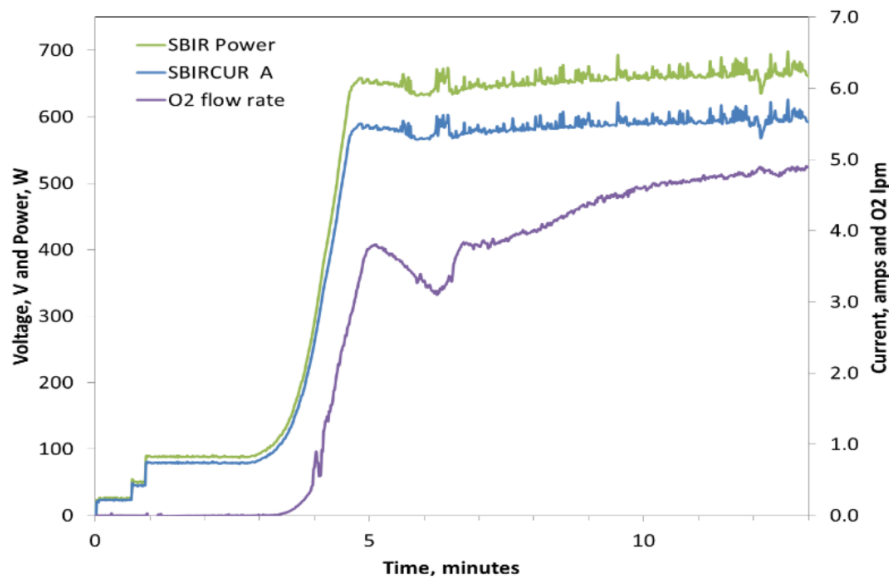


Figure 24.—Startup time for electrochemical prototype, showing power, current, and oxygen flow.

The prototype does have external monitoring and control capability using the provided software, so it passes 1.2.5.4.

The prototype is a low TRL, so fails 1.2.5.5 and 1.2.5.6.

5.0 Discussion and Conclusion

5.1 Prototype Evaluation Summary Table

Both prototypes met some of the requirements, but not all of them, since these are prototype units and not high TRL. Table 2 has a summary of the evaluation results presented here. Based on these results, of the two prototypes, the PSA technology meets significantly more of the requirements.

TABLE 2.—PROTOTYPE EVALUATION SUMMARY

Requirement	PSA Prototype	Electrochemical Prototype
1.2.1 Atmosphere		
1.2.1.1 50% O ₂ min	Yes	Yes
1.2.1.2 90% O ₂	Yes	Yes
1.2.1.3 ambient PPO ₂ not enriched	Yes	Yes
1.2.1.4 50+ psia**	N/A	N/A
1.2.1.5 Use cabin air	Yes	Yes
1.2.1.6 Exploration atmospheres	Yes	No
1.2.2 Flow		
1.2.2.1 6 lpm maximum	Yes	No
1.2.2.2 2 lpm minimum	Yes	Yes
1.2.2.3 On demand operation	Yes	No
1.2.3 Timing		
1.2.3.1 2 min startup	Yes	No
1.2.3.2 2 years**	N/A	N/A
1.2.3.3 Repeated use	Yes	Yes
1.2.3.4 7 day op	Yes	No
1.2.4 Power		
1.2.4.1 28-120 VDC	Yes	Yes
1.2.4.2 < 360 W	Yes	No
1.2.4.3 8 hour battery	No	No
1.2.4.4 Switch power during ops	No	No
1.2.5 Misc.		
1.2.5.1 Portable	No	No
1.2.5.2 Filter smoke/fumes	Yes	No
1.2.5.3 Closed loop control*	No	No
1.2.5.4 External monitor/control	No	Yes
1.2.5.5 Military airworthiness*	No	No
1.2.5.6 Spaceflight certification*	No	No
Summary	14/23 Pass	8/23 Pass

* The prototypes were not designed for closed loop ventilation capability, since these requirements were added after the awards were issued. In addition, the TRL level of the prototypes was not expected to meet air worthiness or flight certification requirements.

** We did not attach the oxygen output to a ventilator, so we did not test for the delivery pressure requirement. We did not test the prototype for 2 years. Those requirements are included for completeness, and since both prototypes were developed in parallel, both are judged against the same criteria fairly.

5.2 PSA Prototype Discussion

Overall, the PSA prototype met the majority of the requirements, with a few notable exceptions. These exceptions included:

1. The OCM shall provide an output pressure of 55 to 60 psia regulated as needed as part of the delivery system (reference Figure 8). We did not test this capability.
2. Internal pressure to operate within 7.5 to 15.0 psia (reference Figure 13). Specifically, the prototype does not function properly at an environmental chamber pressure of 8.2 psia as it does not produce the desired flow rates, although it is still able to output acceptable oxygen levels (see Figure 25). The appropriate conversion factors to correct the oxygen sensor for the pressure dependence were applied (reference Appendix B for chart).
3. Average relative humidity level over each 24-hr period between 25 to 75 percent. Although the prototype meets the requirement to function within a 25 to 75 percent relative humidity range and is able to provide oxygen at the 6 lpm flow rate, the prototype is unable to perform optimally at the high humidity levels (78 and 83 percent), which may result in overheating or other damage for long operations.
4. During operation, there was a small temperature and pressure increase over time in the chamber due to the power use of the prototype (refer to Figure 7 and Figure 26 for pressure and temperature changes, respectively). This is reflective of the heat up time of the prototype.

In conclusion, the NASA Exploration Medical Capability element should continue to pursue pressure swing adsorption technology for medical applications with an understanding of limitations of the technology as related to low pressure and high relative humidity environments. The PSA prototype oxygen concentrator performed admirably in a variety of environmental chamber conditions, several of which pushed the limits of the PSA technology itself. The data collected on the PSA prototype presented in this report can be compared to other prototype oxygen concentrators as well as commercial units and evaluated against the flight requirements for an oxygen concentrator.

5.3 Electrochemical Prototype Discussion

The electrochemical technology has issues that make it difficult to implement in an exploration mission scenario. The primary issues are the very high power draw and associated heat rejection for the prototype. The supply of deionized water to the prototype, and the collection of excess water from the product stream and return air lines will complicate the design to accommodate microgravity fluid handling. The prototype is not currently designed to operate at exploration atmospheres, and it is unclear if the technology will support lower pressure operations, which will exacerbate heat rejection and condensation in the exhaust lines.

The prototype was not designed to have inlet filters since that requirement was added after the award.

O₂ Concentration for Varying Pressures (6 lpm, 20 °C, 34% O₂)

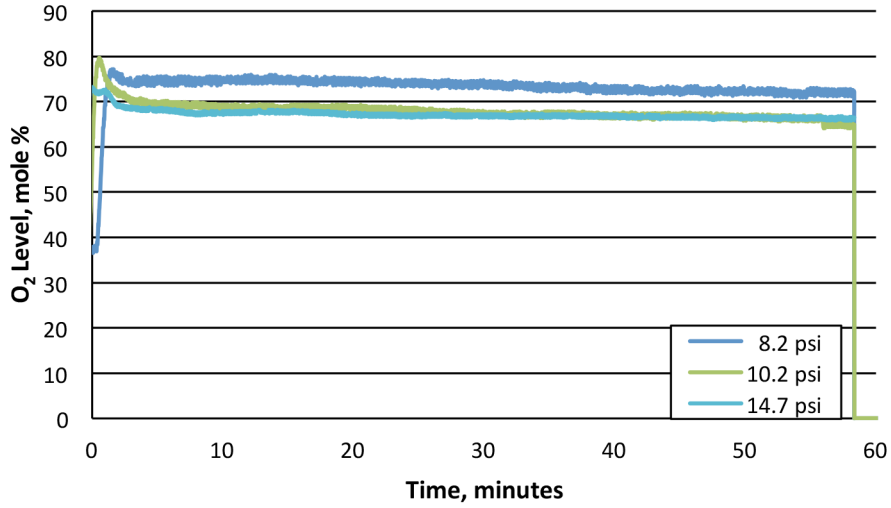


Figure 25.—Oxygen concentration at varying pressure levels.

Chamber Temperature (14.7 psia, 20 °C, 21% O₂ Ambient)

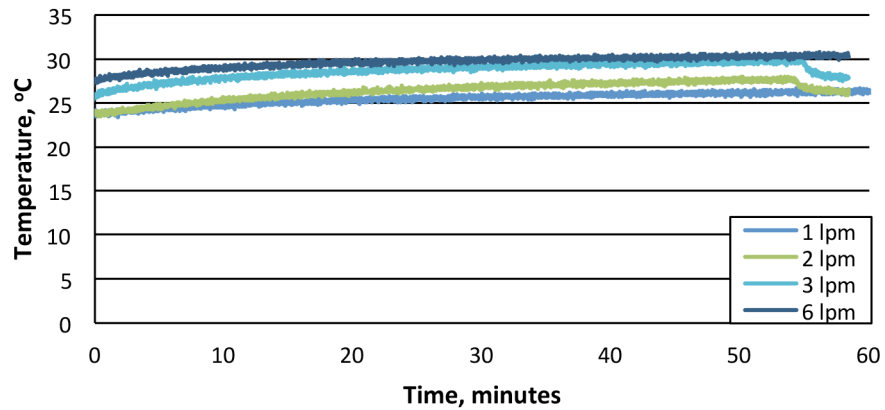
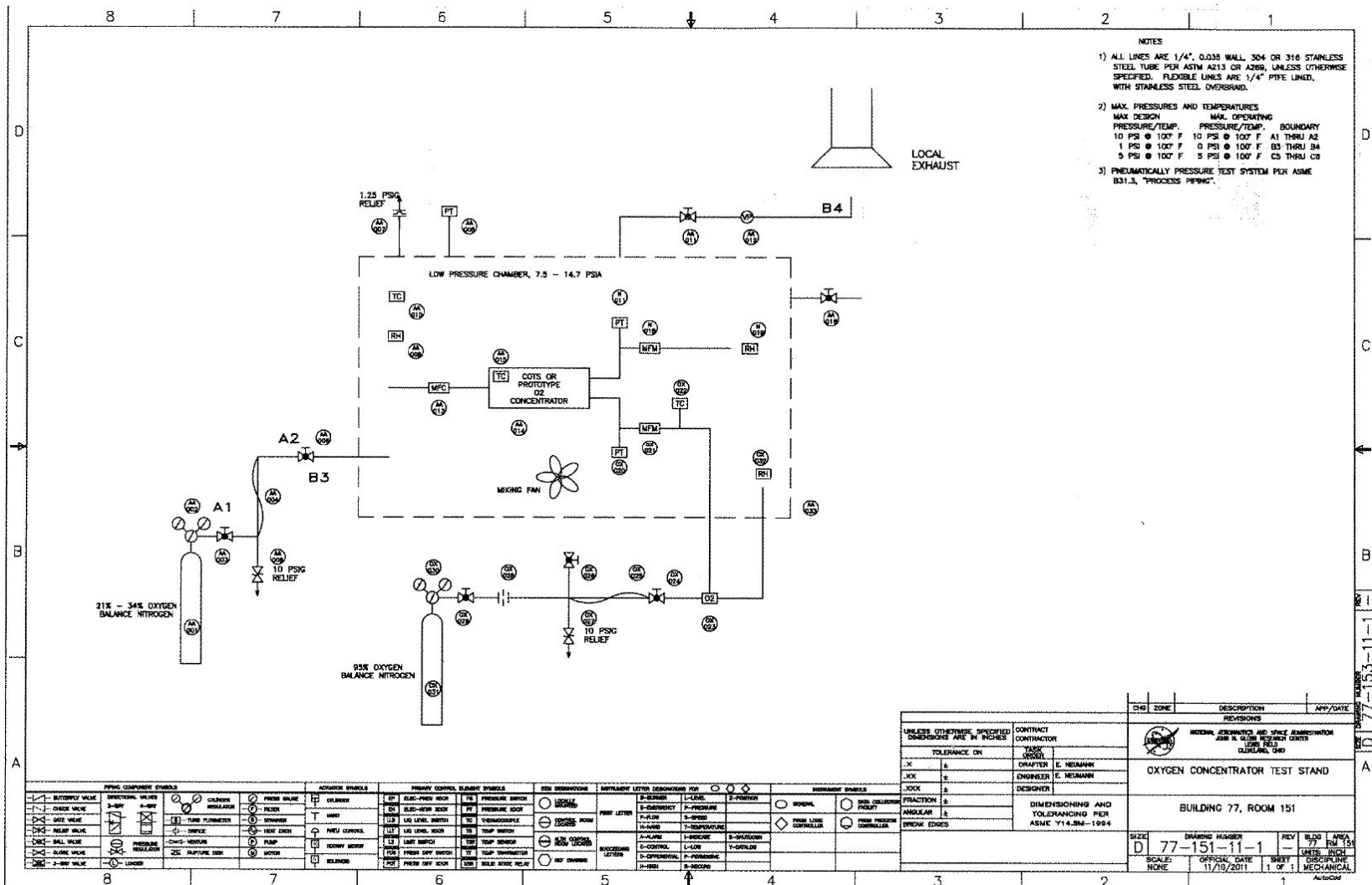


Figure 26.—Chamber temperature at varying flow rates.

Appendix A.—Electrical Schematics, Flow Schematics, and Data Acquisition Setup



OXYGEN CONCENTRATOR TESTBED, 77, 151

FLOW COMPONENT LISTING

ITEM NO.	DESCRIPTION	MFG	MODEL NUMBER	CONNECT SIZE	WORKING PRESSURE	REMARKS
AA001	COMMERCIAL GAS CYLINDER			CGA 296	3000 PSIG	O2/N2 MIXTURE TO 34% O2
AA002	CYLINDER REGULATOR	MATHESON	8-296	1/4 NPT	3000 PSIG	Cv = 0.02
AA003	NEEDLE VALVE	MATHESON	100S	1/4 NPTM	3000 PSIG	Cv = 0.41
AA004	FLEXIBLE HOSE	SWAGELOK	SS-4BHT-120	1/4 TUBE	3000 PSIG	FH1438
AA005	RELIEF VALVE	KUNKLE	542-C01-NM0010	1/2 NPT	200 PSIG	10 psig, 47 SCFM
AA006	NEEDLE VALVE	SWAGELOK	SS-4L	1/4 TUBE	1000 PSIG	Cv = 0.128
AA007	RELIEF VALVE	PROTECTOSEAL	7802H	2" PIPE FLANGE	4 PSIG	20 OZ/SQ IN RELIEF
AA008	PRESSURE TRANSDUCER	MKS	627A13TAC	1/2 TUBE	30 PSIG	0 - 1000 TORR RANGE
AA009	RELATIVE HUMIDITY SENSOR	VIASALA	HMM100			
AA010	THERMOCOUPLE	OMEGA				TYPE T
AA011	GLOBE VALVE	KURT LESKER	SA150MVQF	NW40	15 PSI	VACUUM ISOLATION VALVE
AA012	VACUUM PUMP	WELCH	1397B-01	NW50		
AA013	MASS FLOW CONTROLLER	MKS	1559A0050L-SV	1/2 TUBE	100 PSIG	0 - 50 SLM
AA014	OXYGEN CONCENTRATOR	VARIOUS				
AA015	THERMOCOUPLE	OMEGA				TYPE T
AA016	GLOBE VALVE	NOSHOCK	152-FFB-P1	1/4 NPT	3000 PSIG	Cv = 0.42
N017	PRESSURE TRANSDUCER	SETRA	239	1/8 NPT	15" WC	
N018	MASS FLOW METER	MKS	179A01324CS3BM	1/4 TUBE	150 PSIG	0 - 20 SLM
N019	RELATIVE HUMIDITY SENSOR	VIASALA	HMM100			
OX020	PRESSURE TRANSDUCER	SETRA	239	1/8 NPT	15" WC	
OX021	MASS FLOW METER	MKS	179A01353CS3BM	1/4 TUBE	150 PSIG	0 - 5 SLM
OX022	THERMOCOUPLE	OMEGA				TYPE T
OX023	OXYGEN SENSOR	AMI	201RS	1/4 TUBE	30 PSIG	
OX024	GLOBE VALVE	SWAGELOK	SS-4H	1/4 TUBE	1000 PSIG	Cv = 0.28
OX025	FLEXIBLE HOSE	SWAGELOK	SS-4BHT-72	1/4 TUBE	3000 PSIG	FH1435
OX026	GLOBE VALVE	SWAGELOK	SS-4H	1/4 TUBE	1000 PSIG	Cv = 0.28
OX027	RELIEF VALVE	KUNKLE	542-C01-NM0010	1/2 NPT	200 PSIG	10 psig, 47 SCFM
OX028	ORIFICE	O'KEEFE CONTROLS	E-37-SS	1/4 NPT	3000 PSIG	Cv = 0.031
OX029	NEEDLE VALVE	MATHESON	LMT4374B	1/4 NPT/1/4 TUBE	3500 PSIG	Cv = 0.16
OX030	CYLINDER REGULATOR	MATHESON	3810-540	1/4 NPT	3000 PSIG	Cv = 0.05
OX031	COMMERCIAL GAS CYLINDER			CGA 540	3000 PSIG	95% O2
OX032	RELATIVE HUMIDITY SENSOR	VIASALA	HMM100			0-1000 PSIG RANGE, Cv = 0.06
AA033	VACUUM CHAMBER	ABBESS	AL24	MULTIPLE	0-30" VAC	24" X 24" CUBE

Sensor and Data Acquisition Information

CH#	Parameter	Range	Serial/Tag #	Calibration Date	Calibration Due Date	Description	Sensor	Supply Voltage	Power Required	Signal Range	Data System Range	Data System Unit	Scaling Input	Scalar	Offset	Notes
1	AB008	1000 torr	M624356	1/9/2014	1/9/2015	Chamber pressure	MKS 626A-13TAD	+/-15VDC	75mA	0-10VDC	10V	PSIA	V	1.93368	0.000	-
2	AB009	0-100% RH	M704092	1/14/2014	1/14/2015	Chamber humidity sensor	Vaisala HMM100	15-35VDC	6mA	0-10VDC	10V	%RH	V	10.00000	0.000	
3	AB010	Type T	N.A.	Not In Cal	N.A.	Chamber air temperature	Thermocouple	N.A.	N.A.	-	T	°C	N.A.	N.A.	N.A.	Type T Feedthrough TC1
4	AB013	50 SLM	M602772	1/17/2014	1/17/2015	Oxygen concentrator input flow rate	MKS 1559A	+/-15VDC	450mA	0-5VDC	10V	SLM	V	10.00000	0.000	Not In Calibration
5	AB015	Type T	N.A.	Not In Cal	N.A.	Oxygen concentrator temperature	Stick on Thermocouple	N.A.	N.A.	-	T	°C	N.A.	N.A.	N.A.	Type T Feedthrough TC2
6	N017	20000 SCCM	M707079	1/17/2014	1/17/2015	Oxygen concentrator exhaust flow rate	MKS 179A	+/-15VDC	150mA	0-5VDC	10V	SLM	V	4.00000	0.000	Factory Calibrated
7	N018	25PSIA	M603885	1/6/2014	1/6/2015	Oxygen concentrator exhaust pressure	Setra 204	24VDC	10mA	0-5VDC	10V	PSIA	V	5.00000	0.000	-
8	N019	0-100% RH	M704093	1/14/2014	1/14/2015	Oxygen concentrator exhaust relative humidity	Vaisala HMM100	15-35VDC	6mA	0-10VDC	10V	%RH	V	10.00000	0.000	
9	OX020	5000 SCCM	M707080	1/17/2014	1/17/2015	Oxygen concentrator oxygen output flow rate	MKS 179A	+/-15VDC	150mA	0-5VDC	10V	SLM	V	1.00000	0.000	-
10	OX021	0-100% RH	M704094	1/14/2014	1/14/2015	Oxygen concentrator oxygen output relative humidity	Vaisala HMM100	15-35VDC	6mA	0-10VDC	10V	%RH	V	10.00000	0.000	
11	OX022	25PSIA	M608759	1/6/2014	7/6/2014	Oxygen concentrator oxygen output pressure	Setra 204	24VDC	10mA	0-5VDC	10V	PSIA	V	5.00000	0.000	
12	OX023	Type T	N.A.	Not In Cal	N.A.	Oxygen concentrator oxygen output temperature	Thermocouple	N.A.	N.A.	-	T	°C	N.A.	N.A.	N.A.	Type T Feedthrough TC3
13	OX024	0-100%	110722-13	Not In Cal	N.A.	Oxygen concentrator oxygen output percent oxygen	AMI 201RSM	115VAC	10W	1.86-9.30VDC	10V	%O2	V	13.44086	-25.000	New From The Factory (4-20mA signal with 465 Ohm resistor to convert to voltage. 0%=>1.86V / 100%=>9.30V
14	Current	10A	N.A.	Not In Cal	N.A.	Oxygen Concentrator Supply Current	Shunt	N.A.	N.A.	0-50mV	100mV	A	mV	0.20000	0.000	Shunt (50mV = 10A)
15	Voltage	30VDC	N.A.	Not in Cal	N.A.	Oxygen Concentrator Supply Voltage	Voltage Divider	N.A.	N.A.	0-10VDC	10V	V	V	2.99400	0.000	Resistor Voltage Divider (1.000KOhm in series with 1.994KOhm)
16	N025	Type T	N.A.	Not In Cal	N.A.	Oxygen concentrator exhaust temperature	Thermocouple	N.A.	N.A.	-	T	°C	N.A.	N.A.	N.A.	Type T Feedthrough TC4
17	Spare															Check TC Calibration Before Using TC's on this channel
18	SBIRVOLT	0-200 V	M203544	7/17/2012	7/16/2013	SBIR Oxygen Concentrator Supply Voltage	Power Supply	N.A.	N.A.	0-5VDC	5V	V	V	40.00000	0.000	Voltage Signal From Power Supply
19	SBIRCUR	0-17 A	M203544	7/17/2012	7/16/2013	SBIR Oxygen Concentrator Supply Current	Power Supply	N.A.	N.A.	0-5VDC	5V	A	V	3.40000	0.000	Current Signal From Power Supply
20	OX025	0-200 PPM	132CS1B0511	7/29/2013	N.A.	Oxygen concentrator oxygen output CO detector	CO Detector	24VDC	50mA	0-10VDC	10V	PPM	V	20.00000	0.000	
21	OX026	0-5 %CO2	42260	Not In Cal	N.A.	Oxygen concentrator oxygen output CO2 detector	CO2 Detector	+15VDC	3.5mW	0-3.3VDC	5V	%CO2	V	1.51515	0.000	See Note 1 Below Table
22	CO2V	3.3VDC	N.A.	Not In Cal	N.A.	CO2 detector OX016 supply voltage	Voltage Measurement	N.A.	N.A.	0-5VDC	5V	V	V	1.00000	0.000	See Note 1 Below Table
23	PLTTEMP	Type K	N.A.	Not In Cal	N.A.	Chamber Plate Temperature	Thermocouple	N.A.	N.A.	-	K	°C	N.A.	N.A.	N.A.	Type K Feedthrough TC1 (Moved from Ch. 17)
24	Spare															
			M700418	2/11/2014	2/11/2015	Data System										
			M709837	2/11/2014	2/11/2015	Data System										

Notes: 1) The %CO2 measurement, channel OX026, is actually scaled from 0 to the the supply voltage equates to 0 to 5% CO2. However the data system is only capable of scaling a fixed value. Because of this the nominal value of 3.3V was chosen for the supply voltage so the data system is setup for 0 to 3.3V equates to 0 to 5% CO2. To correct for this channel CO2V measures the supply voltage going to the CO2 detector. This can be used to calculate a correction factor in post processing of the data if desired.

Appendix B.—Calibration for Ambient Pressure Correction of Oxygen Sensor

The oxygen sensor used is also a function of the ambient pressure in the chamber, so a calibration was conducted to correct for the internal pressure of the chamber. Two different gases were used for the calibration, and the overall correlation can be used to correct the reading at any given pressure to give an accurate reflection of the oxygen concentration. The calibration is shown in Figure B1.

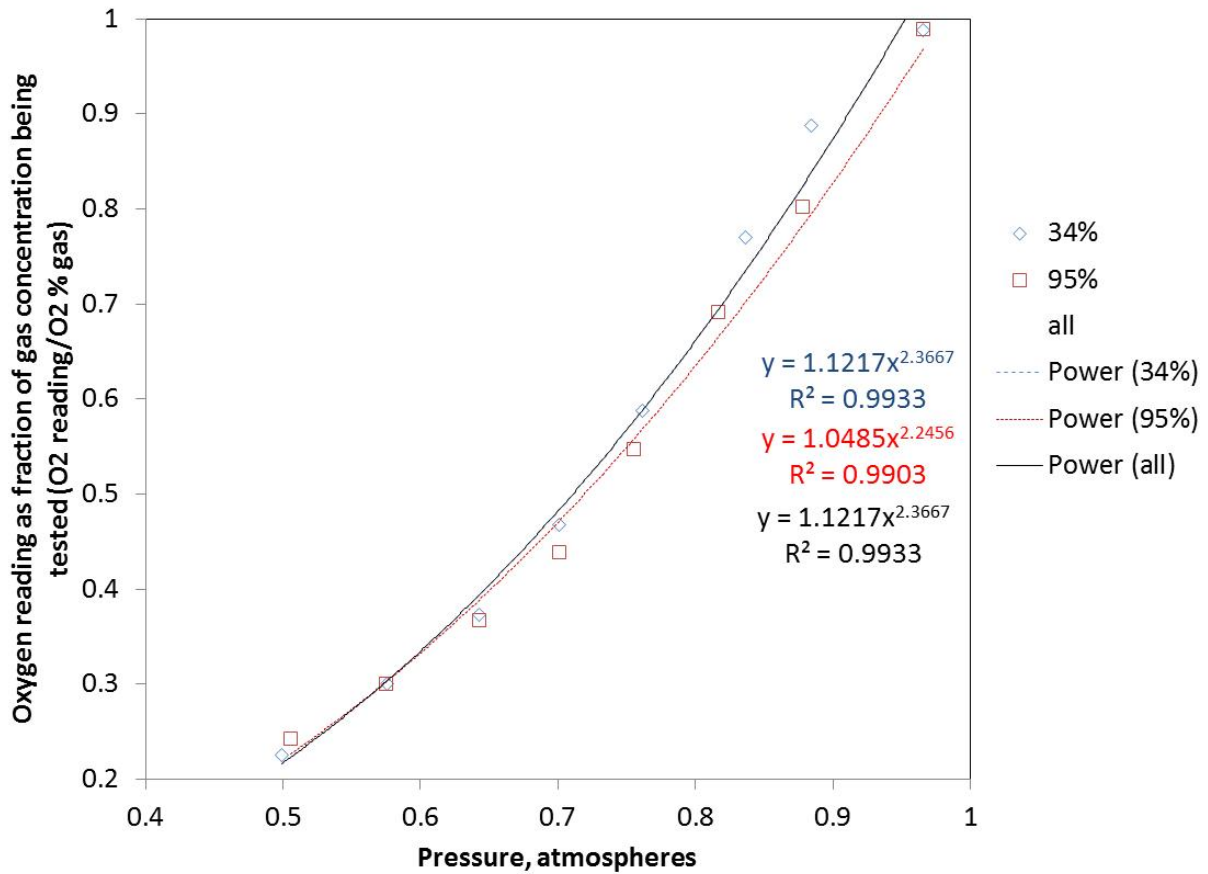


Figure B1.—Oxygen sensor calibration for different chamber pressures.

Appendix C.—Planned Test Matrix for Variable Atmospheres

TABLE C1.—O₂-PRESSURE VARIATIONS: AMBIENT TEMPERATURE (~22 °C AND ~50% RH)
DIAGONAL IS NORMOXIC

O ₂ (%)	21%	30%	34%
Pressure (psia)	14.7	14.7	14.7
	10.2	10.3	
	8.2		9.1

TABLE C2.—TEMPERATURE AND RH VARIATIONS (SEE FIGURE B1 ALSO): (21% O₂, 14.7 PSIA)
DIAGONAL IS CONSTANT MASS OF WATER PER MASS OF AIR

Temperature (°C)	18	22	27
RH	70%	5%	
	50%	50%	50%
		95%	40%

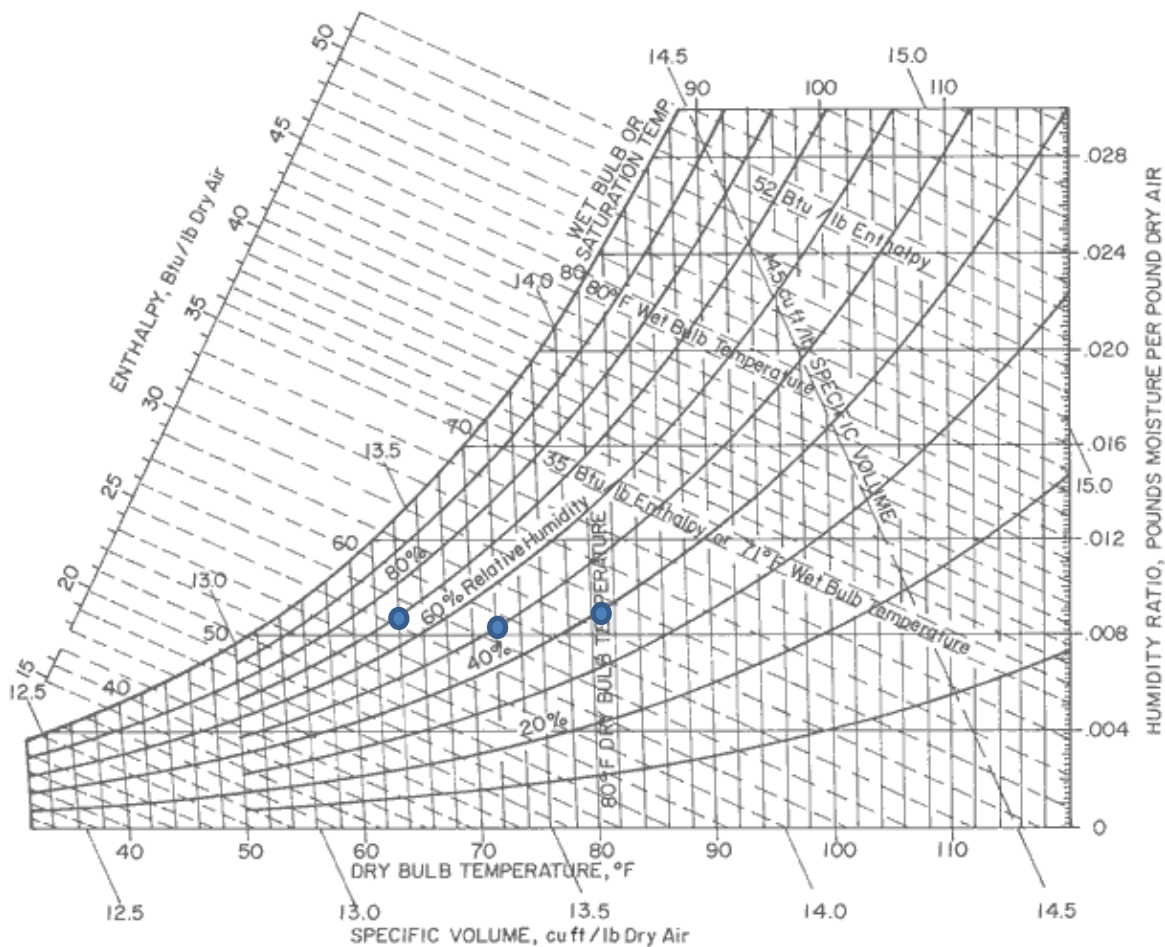


Figure C1.—Psychrometric Chart with diagonal test conditions from Table C2 with approximately constant pounds moisture per pound of dry air indicated.

Available saturated salt solutions, resulting RH% at 25 °C

6.4 percent	Lithium Bromide hydrate
38.2 percent	Sodium Iodide dihydrate
52.9 percent	Magnesium Nitrate hexahydrate
68.9 percent	Potassium Iodide
93.6 percent	Potassium Nitrate

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