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Further Design and Initial AI&T of the Carbon Dioxide Removal System for SAM

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The Space Analog for the Moon and Mars (SAM) is an off-world habitat research facility dedicated to advancing Environmental Control & Life Support System and Biological Life Support Systems. The SAM Carbon Dioxide Removal Assembly is a physicochemical CO_2 removal system based on NASA's 4-Bed Carbon Dioxide scrubber architecture, with notable modifications. This paper presents an update on ICES-2025-141, offering design details and departures from the NASA scrubber design, as well as insight into the assembly, integration, and initial testing of the scrubber. Further logistical and scientific plans for the scrubber and ancillary assemblies are also discussed.

Acronyms and Nomenclature

AI&T	=	Assembly, Integration, and Testing
BLiSS	=	Bioregenerative Life Support Systems
CO_2	=	Carbon Dioxide
COTS	=	Commercial-Off-The-Shelf
EARL	=	Experimental Air Revitalization Laboratory
4BMS	=	Four bed Molecular Sieve
4BCO2	=	4-Bed Carbon Dioxide (scrubber)
m_{CO2}	=	Mass of CO_2
P	=	Pressure
ppm	=	parts-per-million
R_{CO2}	=	Specific Gas Constant for CO_2
RTD	=	Resistance Temperature Detector
SAM	=	Space Analog for the Moon and Mars
SCDRA	=	SAM Carbon Dioxide Removal Assembly
SCFM	=	Standard Cubic Feet per Minute
T	=	Temperature
V	=	Volume
VFD	=	Variable Frequency Drive
x_{CO2}	=	Mole fraction of CO_2

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I. Introduction

The Space Analog for the Moon and Mars (SAM) is a hi-fidelity, hermetically-sealed and pressurized research station composed of a variable volume, pressure regulation module ("lung"). Built around the Biosphere 2 Test Module (1987) that now serves as the controlled environment greenhouse, SAM added an engineering bay and crew quarters complete with kitchen, bath, and sleeping space for visiting teams. The habitat analog includes a fully functional airlock, as well as a mixture of manual and electric valves for pressure and flow control. Carbon dioxide (CO_2), oxygen, relative humidity, temperature, barometric pressure, and volatile organic compounds (VOCs) are monitored and regulated for the duration of research missions [1].

In ICES-2025-141 [2], our team implemented an analytical model that informed the optimal flow rate and path for a CO_2 removal system sized for four crew members. Since then, under a technology license with NASA, the SAM team has designed and built a CO_2 scrubber based on the current state-of-the-art Four Bed Molecular Sieve (4BMS) architecture currently operating on the International Space Station (ISS) [3]. The SAM Carbon Dioxide Removal Assembly (SCDRA, pronounced "Skee-Druh") has undergone subsystem verification tests and preliminary standalone demonstration tests, yielding positive results. SCDRA is demonstrated as a valuable piece of test infrastructure for future research into hybrid, bioregenerative and physicochemical life support systems.

II. CO_2 Scrubber Design

The design architecture and operation of SCDRA are similar to the existing 4BMS systems on the ISS as illustrated in Figures 1 and 2. It consists of two desiccant chambers filled with silica gel beads and two sorbent chambers filled with zeolite 13X that alternate adsorbing and desorbing moisture and CO_2, respectively. These are two symmetric configurations, the two half-cycles of a complete cycle.

The following describes the system operation at the start of a cycle. As shown in Figure 1, air enters through a previously regenerated desiccant bed 1 (D1), where moisture from the air stream is removed. The dehumidified air then enters the blower where it is pressurized. Next the heat exchanger (HX) removes the heat of adsorption and compression, cooling the air to roughly 10°C (50°F). The air continues on toward sorbent bed 2 (S2), which is virtually devoid of CO_2 and very hot at the beginning of a cycle. The in-bound air cools the sorbent bed such that it can adsorb CO_2, then CO_2 is removed from the air stream. The out-bound, hot, dry air moves through desiccant bed 2 (D2), which is loaded with moisture at this point, forcing the moisture from the bed back into the airstream. The air then leaves the system carrying the same total moisture as was input to the system over the previous half-cycle, but minimal CO_2.

At the same time sorbent bed 1 (S1), which is partially saturated with CO_2 from the previous half-cycle, is isolated, exposed to vacuum (the vacuum of space on ISS; a vacuum pump at SAM), and heated. This desorbs the CO_2 into a designated CO_2 exhaust line. The cycle then flips and each bed assumes the opposite role as shown in Figure 2. Airflow enters the freshly desorbed desiccant bed 2 (D2), continues into the freshly desorbed sorbent bed 1 (S1), then continues on to the now-loaded desiccant bed 1 (D1), while the loaded sorbent bed 2 (S2) is isolated and CO_2 is desorbed to vacuum.

Unlike a 4BMS designed for use in a spacecraft, the fundamental design philosophy of SCDRA emphasizes affordability, easy of fabrication, maintainability, and reuse in a test facility. It is not optimized for size, mass, or power consumption. The resulting design is a capable piece of test infrastructure, consisting of a combination of commercial off-the-shelf and custom fabricated components. It is not designed for flight.

SCDRA consists largely of two chamber stacks, shown in Figures 3 and 4. Each stack contains a desiccant and sorbent chamber, an instrumentation chamber (Figure 7) for air tap-off points and power/data connections, and a plenum chamber with a check valve assembly (Figure 4). There are also several valves to control airflow, a vacuum pump to simulate space vacuum, air re-pressurization valves (Figure 8) to slowly re-pressurize the chambers after vacuum to reduce zeolite attrition, a blower to move air through the system at the desired flow rate, and a heat exchanger connected to a custom coolant loop designed to cool the process airflow.

SCDRA also contains novel in-line desiccant heaters (Figure 6) located between the check valves and desiccant beds. These heaters are designed to increase airflow temperature before entering the desorbing desiccant bed to more efficiently desorb the moisture. This is intended to compensate for the partial thermal decoupling of the sorbent and desiccant beds in this design, improving system versatility and potentially increasing overall efficiency. The desiccant heater assembly has been integrated, but not yet fully tested, so will not be discussed further in this paper.

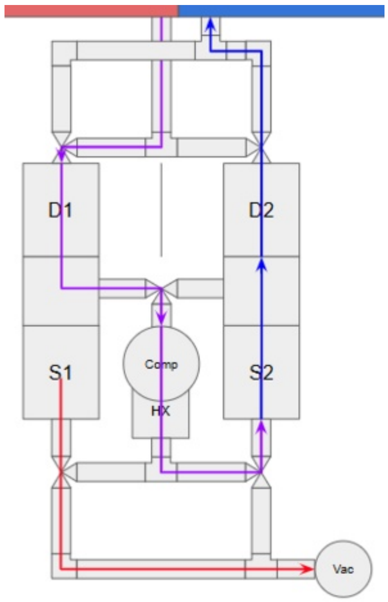

Figure 1. SCDRA Process Path, Half-Cycle 1.

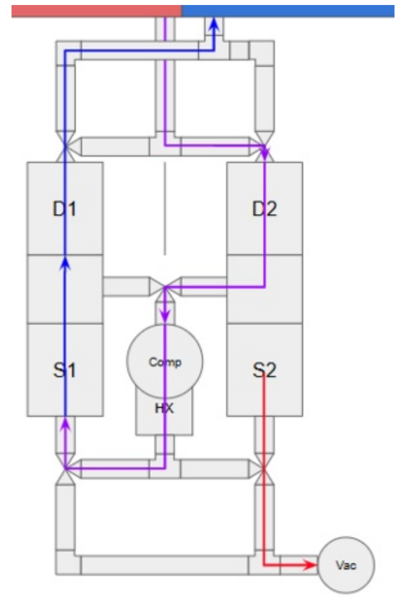

Figure 2. SCDRA Process Path, Half-Cycle 2.

Figure 3. Chamber Stack Assembly.

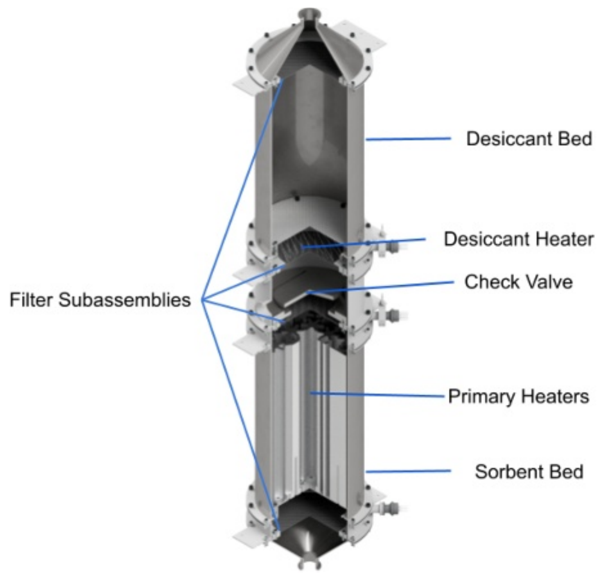

Figure 4. Chamber Stack ¾ Section Render.

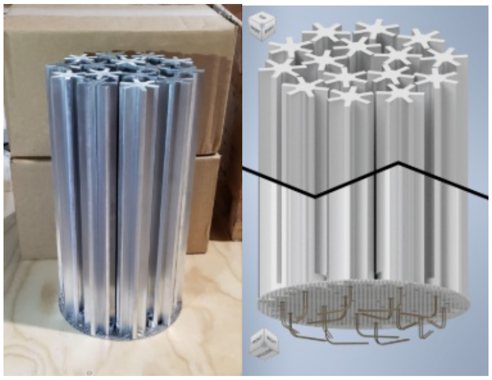

Figure 5. Primary Heater and Model .

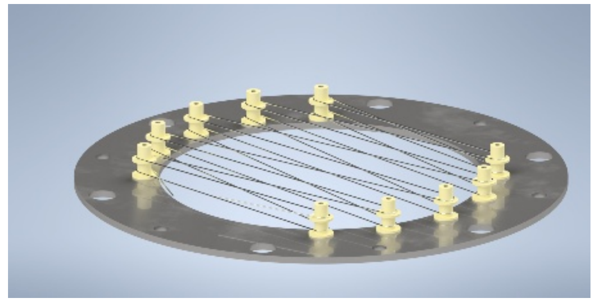

Figure 6. Desiccant Heater Render.

Figure 7. Instrumentation Chamber.

Figure 8. Re-pressurization Valve.

III. Assembly, Integration, and Subsystem-Level Testing

The SCDRA system, shown below in Figure 9, was assembled onto an 80-20 aluminum extrusion backplane to allow for versatility and adjustability. All subsystems were integrated using high-temperature silicone tubing and flexible vacuum bellows. Subsystems were assembled and tested on an incremental basis. The sorbent chambers underwent vacuum leak tests, with and without heating. The blower subsystem, controlled by a VFD (Variable Frequency Drive), underwent a validation of its capabilities by running the system at the desired flow rate of 25 SCFM. The coolant loop was tested to ensure it could circulate water at 4.4°C (40°F) and reduce airflow temperature from 65°C (150°F) to near 4°C (40°F). Sorbent heaters were tested to ensure they would distribute heat to the 13X zeolite media effectively (Figure 5). Initial subsystem tests were more qualitative than quantitative, with rigorous analysis planned once the system is fully automated.

Figure 9. SAM Carbon Dioxide Removal Assembly.

The primary heater assemblies were tested using an infrared camera (Figures 10,11,12) to visually confirm heat distribution through the sorbent chamber over time. The temperatures read by the infrared camera are only surface temperatures, indicative of trends and behaviors, not absolute temperature within the beds. RTDs inside the bed peaked at 196°C (387°F) during system-level testing.

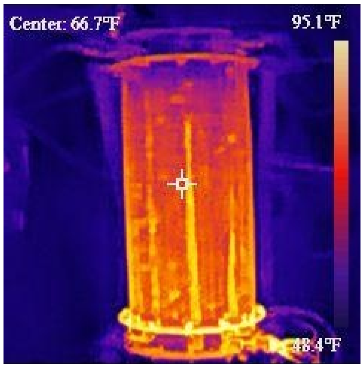

Figure 10. Sorbent Heater Thermal Image, 5 Min

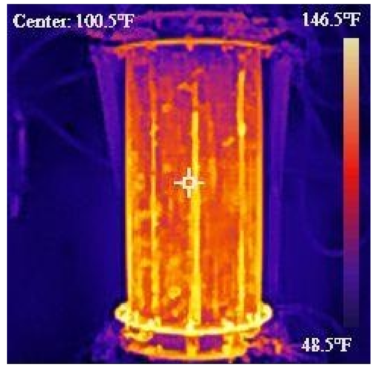

Figure 11. Sorbent Heater Thermal Image, 15 Min

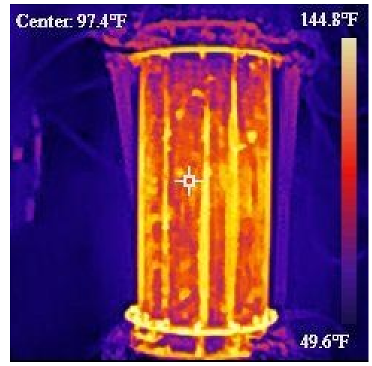

Figure 12. Sorbent Heater Thermal Image, 30 Min

IV. Initial System-Level Testing

A. Baseline Tests

The SCDRA is housed in a single-room external to the SAM habitat. This room, called the Experimental Air Revitalization Laboratory (EARL) was designed and built to not only house SCDRA but also permit independent researchers to conduct bench-top and in-line, human-in-the-loop testing of their own scrubbers at EARL. Heating and cooling of EARL is conducted by means of a mini-split heat pump that exchanges coolant fluid from an external condenser to internal heat exchanger and air handler. The internal air within the EARL is not exchanged with the internal air of the SAM habitat.

To analyze the effectiveness of SCDRA, EARL was effectively sealed using 10 mil plastic tarp and aluminum tape across the primary entrance. The secondary, rear door remained operable as the means for the human controller to enter and exit. CO_2 was injected from a liquid gas cylinder located outside of EARL, through a vinyl tube brought in through a port in the temporary, main entrance seal.

A leak rate of 54 ppm per hour, with the scrubber operator residing inside the EARL building, was measured by means of a 30-minute baseline test. This rate was applied to the SCDRA test, which operated under identical conditions except for SCDRA removing CO_2.

Heterogeneity of room air, or formation of pockets of CO_2, was minimized through application of a floor mount box fan to circulate and mix air, enabling a more homogenous gas mixture within the room.

B. SCDRA System Test

The SCDRA test involved the adsorption portion of the half-cycle in one sorbent bed, followed by the desorption portion in the same bed. This ensured that SCDRA was only removing or adding CO_2 for the duration of the test, not both at the same time as would be the case if both half cycles were operating at the same time. Note the vacuum pump discharges desorbed CO2 directly into the EARL atmosphere at this point. The system removed CO_2 for exactly one hour and then desorbed the same bed for the subsequent hour. The results from the full SCDRA test can be seen in Figure 13. The yellow markers indicate: (1) End of CO_2 injection; (2) End of settling period, beginning of adsorption half-cycle; (3) End of adsorption half-cycle; (4) Beginning of desorption half-cycle; (5) Conclusion of test. The total change in CO_2 concentration in the room, after adjusting for the room base leak rate of 54 ppm/hr found in the baseline tests, gave the adsorption and desorption rates of SCDRA shown in Table 1.

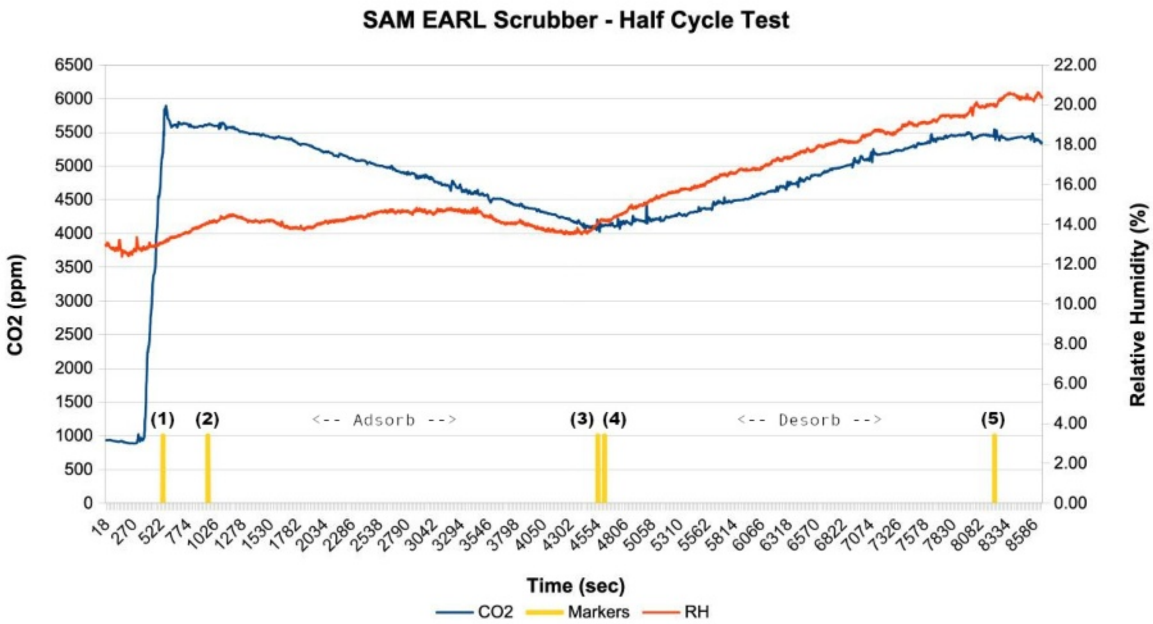

Figure 13. SAM EARL Scrubber - Half-Cycle Test.

Table 1. Half-Cycle Test Results.

Adsorb			Desorb		
Initial CO_2	Final CO_2	Adsorption Rate	Initial CO_2	Final CO_2	Desorption Rate
5610 ppm	4150 ppm	1406 ppm/hr	4121 ppm	5493 ppm	1426 ppm/hr

V. Results and Discussion

By manipulating the Ideal Gas Law (Equation 1), to the form shown in Equation 2, the mass of CO2 adsorbed or desorbed can be calculated given the ambient pressure, volume and temperature of the room, the specific gas constant of CO2, and the change in CO2 concentration over a time period. The constants used are shown in Table 2.

$$P \cdot V = \frac{m_{CO2}}{x_{CO2}} \cdot R_{CO2} \cdot T \tag{1}$$

$$\Delta m_{CO2} = \frac{P \cdot V}{R_{CO2} \cdot T} \cdot \frac{\Delta x_{CO2}}{\Delta t} \tag{2}$$

Table 2. Modified Ideal Gas Law Constants.

P [Pa]	V [m^3]	R_{CO2} [J/(kg*K)]	T [k]
88,400	74.5	188.9	293

Table 3. CO_2 Removal Rate Summary.

	$\frac{\Delta x_{CO2}}{\Delta t}$ [ppm_{CO2}/hr]	$\frac{\Delta x_{CO2}}{\Delta t}$ [mol_{CO2}/(mol_{air}*hr)]	Δm_{CO2} [kg CO_2 / hr]	$\Delta \dot{m}_{CO2}$ [kg CO_2 / day]
Adsorbing	1406	0.001406	0.167	4.01
Desorbing	1426	0.001426	0.170	4.08

The target CO_2 removal rate for SCDRA is 4.5 kg/day given 5000 ppm ambient CO_2. The results shown in Table 3 indicate a slight shortfall of this target. There are a number of confounding factors that result in a difference from test to future removal rates: (1) Incomplete desorption of sorbent beds prior to test, (2) incomplete desorption of desiccant beds prior to test, (3) lower flow rate than nominal, and (4) single half-cycle test, rather than averaged multi-cycle tests.

Nominally, the sorbent chambers would be desorbed completely before long-term operation of the system began. This SCDRA test was conducted without the full bake-out period as required for the media to reach their nominal state of desaturation. This would result in higher CO_2 uptake, and warrants consideration for future tests.

This SCDRA test was also run without fully desorbed desiccant beds, resulting in a higher likelihood of moisture breakthrough into the sorbent beds. Zeolite 13X will preferentially adsorb water vapor in place of CO_2 when exposed to both (ICES-2018-3) [4]. As a result, preloaded desiccant beds are likely to reduce CO_2 capture efficiency, suggesting that a complete desiccant bake-out period would result in improved future performance.

SCDRA is designed for a nominal airflow rate of 25 SCFM. Due to the nature of the system, airflow rate is a primary limiting factor in the CO_2 capture rate. This SCDRA test was run at 22.3 SCFM. It is estimated that if run at 25 SCFM, the CO_2 capture rate likely would have increased proportionally.

On the other hand, a single half-cycle test does not suffer from switch-over inefficiencies like valve turning time or holdup CO_2 - a known cause of efficiency loss where Zeolite 13X in the desiccant bed captures some CO_2 and then releases it back into the cabin air on the next half-cycle, instead of venting it (ICES-2021-313) [5]. If an average CO_2 capture rate was measured over several half-cycles, including downtime for valve turning and being subject to holdup CO_2, the capture rate would likely have decreased.

It is unclear whether the total CO_2 capture rate will increase or decrease - and by how much - once these factors are taken into account. Fortunately, the design requirement of 4.5 kgCO_2/day is a conservative one; SCDRA can support up to three crew members indefinitely, which is sufficient for all near-term goals. Regardless, SCDRA testing will continue, and each of these confounding factors will be rectified.

VI. Conclusion

The SAM team has designed, built, and conducted subsystem validation tests and preliminary system-level performance tests of the Four Bed Molecular Sieve CO_2 removal system installed in the facility. At this current time, with the first order design and assembly, the system may underperform compared to its intended design specifications. However, it is immediately capable of removing CO_2 at an adequate rate to be used for the intended purpose of human-in-the-loop sealed missions and experiments at SAM, with one to three crew members. Future modifications and upgrades should enable the intended removal of CO_2 generated by a fourth crew member.

The 4BCO2 scrubber will be operated as a stand-alone unit, and in parallel with the existing, plant-based bioregeneration system housed in the controlled environment, for a hybrid physicochemical / bioregeneration solution to CO_2 scrubbing.

Since the automated system was not yet ready for operational control, all tests to date were conducted by means of the manual controls. Once the fully automated controls are programmed, experimenting with several variables including maximum temperature of the desiccant heater, speed of the VFD blower, and timing between half-cycle change-overs will be conducted and may result in higher overall performance.

SCDRA is scheduled to be integrated into the SAM habitat facility by the close of 2026, allowing for human-in-the-loop tests in a fully sealed and positively pressurized habitation space. Future applications for SCDRA include experiments comparing bioregenerative life support system and hybrid, parallel system operation; on-site comparison with guest scrubbers; and integration with in-line, post processing of CO_2 for capture, storage, and use in photo-bioreactors.

Acknowledgments

We thank NASA Marshall for approving the license of the scrubber patent, and Thierry Carriere and Patrick Pasadilla of Paragon Space Development Corporation for their support and guidance bringing the final components into place. Thanks goes to Dr. Joaquin Ruiz, Executive Director and John Adams, Deputy Director for Biosphere 2 for the continued support in the development of SAM since 2019, and for sharing our vision through the years of design and construction towards producing high quality results in a world-class facility. We share a great deal of gratitude to the pioneers in the field of study, from the 1950s forward, and to ICES. We have been privileged to spend the last eight years providing an arena in which to explore, receive valuable feedback, and present science that will help take our species to the Moon, to Mars, and beyond.

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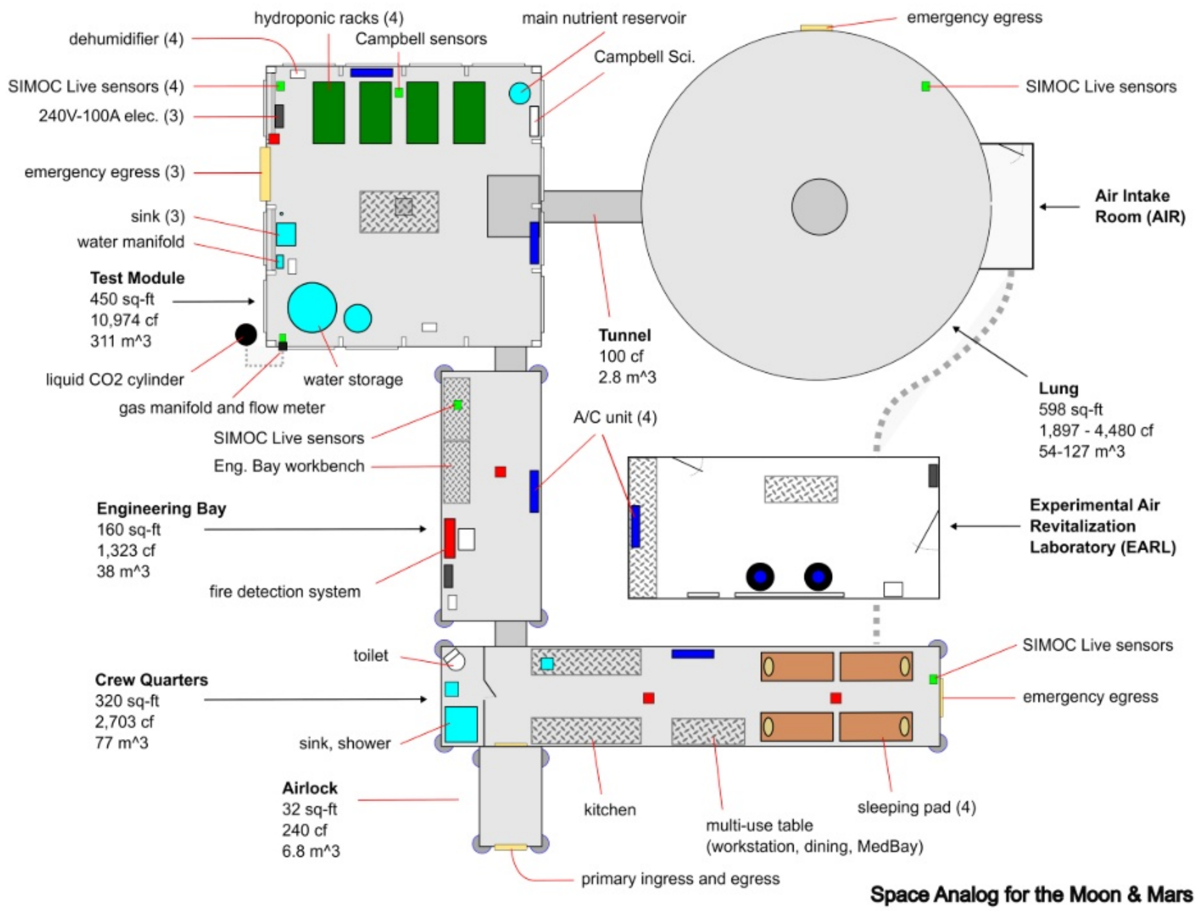
Appendix



The floorplan of the Space Analog for the Moon & Mars with Air Intake Room, Lung, Test Module, Engineering Bay, Crew Quarters and airlock, and the Experimental Air Revitalization Laboratory which houses the 4-bed CO_2 scrubber. SAM AIR and EARL are not a continuation of the pressure vessel.