

# Consideration of Open Loop Regenerable Carbon Dioxide and Humidity Removal Systems for Lunar Habitats

*James C. Knox*

*Amentum/Knox Analytical Solutions Inc., Lacey Springs, Alabama*

*Lyndsey Winslette and David Howard*

*Marshall Space Flight Center, Huntsville, Alabama*

## NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

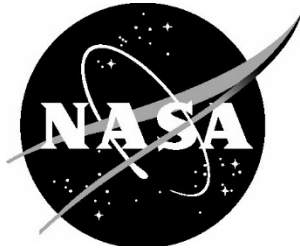
- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>



# Consideration of Open Loop Regenerable Carbon Dioxide and Humidity Removal Systems for Lunar Habitats

*James C. Knox*

*Amentum/Knox Analytical Solutions Inc., Lacey Springs, Alabama*

*Lyndsey Winslette and David Howard*

*Marshall Space Flight Center, Huntsville, Alabama*

National Aeronautics and  
Space Administration

Marshall Space Flight Center  
Huntsville, Alabama

---

July 2025

The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Available from:

NASA STI Program / Mail Stop 050  
NASA Langley Research Center  
Hampton, VA 23681-2199

# Technical Memorandum

## Consideration of Open Loop Regenerable Carbon Dioxide and Humidity Removal Systems for Lunar Habitats

As NASA moves towards the development of life support systems for Lunar Habitats, there has been a renewed interest in open-loop regenerable carbon dioxide (CO<sub>2</sub>) and humidity removal systems. These systems would eliminate the need for the resupply of consumables associated with non-regenerable lithium hydroxide-based (LiOH) CO<sub>2</sub> removal systems. This paper reviews flight-proven open-loop regenerable and non-regenerable CO<sub>2</sub> and humidity removal systems as well as emerging high maturity systems. A new trade study between a LiOH-based system and a Sorbent-Based Atmosphere Revitalization (SBAR) system for the initial Surface Habitat (SH) application is presented. Suitability for the specific SH mission characteristics, which includes long dormancy periods at low temperatures, is also considered.

### Acronyms and Nomenclature

|                   |   |                                                             |
|-------------------|---|-------------------------------------------------------------|
| 2BMS              | = | 2-Bed Molecular Sieve                                       |
| 4BMS              | = | 4-Bed Molecular Sieve                                       |
| CAMRAS            | = | CO <sub>2</sub> and Moisture Removal Amine Swing-bed System |
| CHC               | = | Carbon Dioxide and Humidity Control                         |
| CHX               | = | condensing heat exchanger                                   |
| CDRA              | = | Carbon Dioxide Removal Assembly                             |
| CO <sub>2</sub>   | = | carbon dioxide                                              |
| ECLSS             | = | Environmental Control and Life Support System               |
| ESM               | = | equivalent system mass                                      |
| EVA               | = | extravehicular activity                                     |
| FBCO <sub>2</sub> | = | Four-Bed Carbon Dioxide                                     |
| IVA               | = | intravehicular activity                                     |
| LiOH              | = | lithium hydroxide                                           |
| ISS               | = | International Space Station                                 |
| KPP               | = | key performance parameter                                   |
| NASA              | = | National Aeronautics and Space Administration               |
| ppCO <sub>2</sub> | = | partial pressure of CO <sub>2</sub>                         |
| SBAR              | = | Sorbent-Based Atmosphere Revitalization                     |
| SH                | = | Surface Habitat                                             |
| TRL               | = | technology readiness level                                  |

### I. Introduction

Crewed missions to the vicinity of and on the surface of the Moon are in various stages of planning and development. The duration of these missions will be very limited initially.<sup>1</sup> For example, the initial Surface Habitat, or SH, is planned to be manned for relatively short periods of 7 days initially, then as long as 28 days in later missions. The Multi-Purpose Habitation module is being designed as a potential initial SH by the Italian Space Agency.<sup>2</sup> A conceptual drawing of an initial SH is shown in Figure 1.

For missions of comparable durations as the initial SH, prior trade studies<sup>3,4</sup> have found that total mission mass is actually lower for open loop CO<sub>2</sub> and H<sub>2</sub>O removal technologies, that is, technologies which release CO<sub>2</sub> and H<sub>2</sub>O overboard rather than recycling as in closed loop technologies. The equipment mass to achieve recycling is greater than the required resupply mass of H<sub>2</sub>O or O<sub>2</sub>.

However, there is also an inner trade space when considering open loop CO<sub>2</sub> removal technologies, and that is between regenerable and non-regenerable approaches. In this paper, we will consider the specific CO<sub>2</sub> and H<sub>2</sub>O

removal needs of the initial SH module and assess the resource requirements of regenerable and non-regenerable approaches. Since some CO<sub>2</sub> removal technologies also remove H<sub>2</sub>O, we also consider the impacts on H<sub>2</sub>O removal resource requirements.

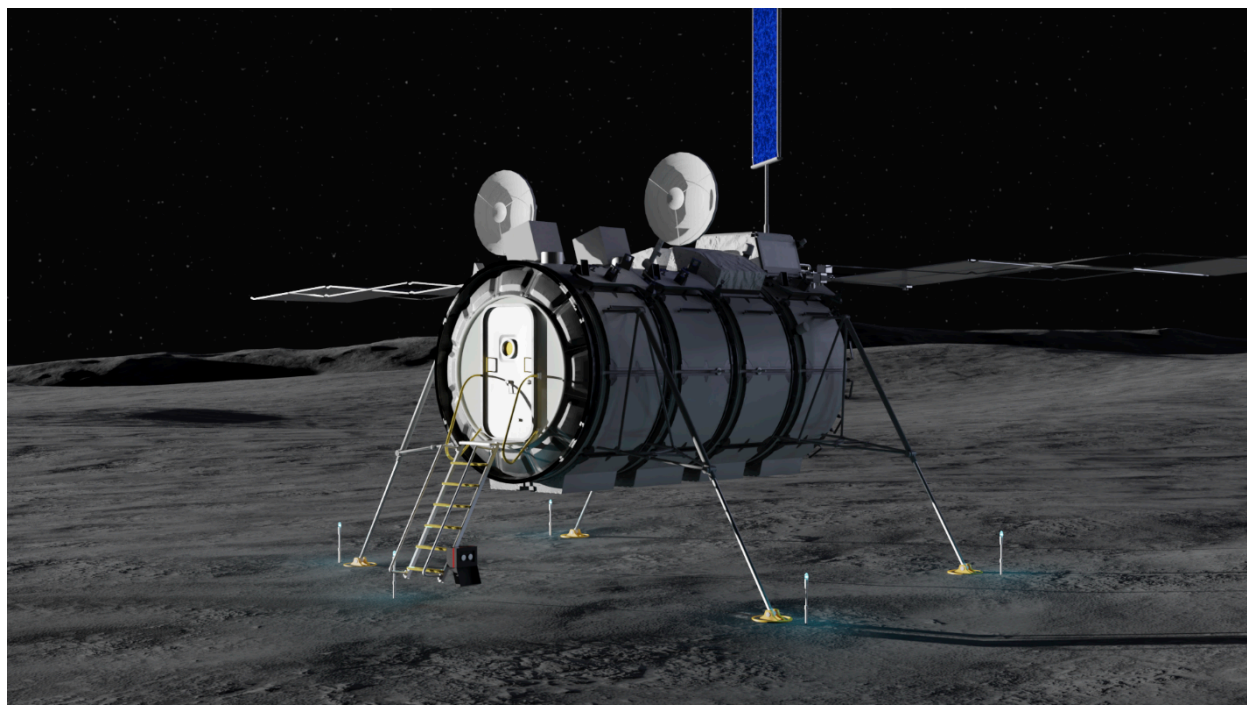


**Figure 1. Representative Initial Surface Habitat.<sup>1</sup>**

## **II. Initial Surface Habitat Mission Requirements**

The initial SH is one component of an overall mission of the Moon, wherein four crew members would land on the south pole of the Moon. Two crewmembers would deploy to a rover while the other two crewmembers would deploy to the initial SH module. Mission duration would initially be 7 days, then increase to 14 days, and finally increase to 28 days. Other requirements applicable to this study:

- 2 Crew for nominal case for up to 28 days
- 4 Crew for contingency case for up to 32 hours
- Intravehicular (IVA) activity includes an exercise period of 100 minutes total, with serial exercise assumed
- Initial SH cabin atmosphere is at 8.2 psia
- Initial SH must survive uncrewed lunar nights for up to 150 days
- Initial SH must maintain the 1-hr average CO<sub>2</sub> partial pressure below 3 mmHg
- Initial SH volume of 35 cubic meters

## **III. Open Loop CO<sub>2</sub> Removal Technologies**

### **A. Lithium Hydroxide (LiOH)**

For short duration missions, CO<sub>2</sub> removal has often been achieved with consumable LiOH. This is a historically proven method that was used as the primary CO<sub>2</sub> removal for Apollo and Space Shuttle missions. LiOH is also available for contingency backup on ISS, and used for commercial crew transport to ISS.<sup>5,6,7</sup>

Lithium Hydroxide requires approximately 1.75 kg of LiOH for each crewmember per day, though this can vary slightly depending on packaging, crew activity, LiOH form, etc.<sup>8</sup> Three examples of LiOH canisters are shown in Figure 2.

LiOH can be implemented in granules or sheets, represented by the Apollo/Shuttle and Dragon manifestations respectively. The radial flow packed beds used in the Shuttle are also used on the ISS as a backup system. Curtains have also been implemented for emergency responses on submarines and in mines.

LiOH is frequently used on short term missions due to the high CO<sub>2</sub> capacity of approximately (30 wt.%).<sup>9</sup> The LiOH canisters can be integrated into the ventilation system providing an opportunity to share air movers.

However, the single pass efficiency degrades over time, requiring crew time for staging of fresh and partially spent LiOH to maximize efficiency. Also, since LiOH is not regenerable, resupply mass becomes significant as mission length increases. As a result, for longer duration missions, non-consumable/regenerable systems are often preferred to minimize re-supply demands.

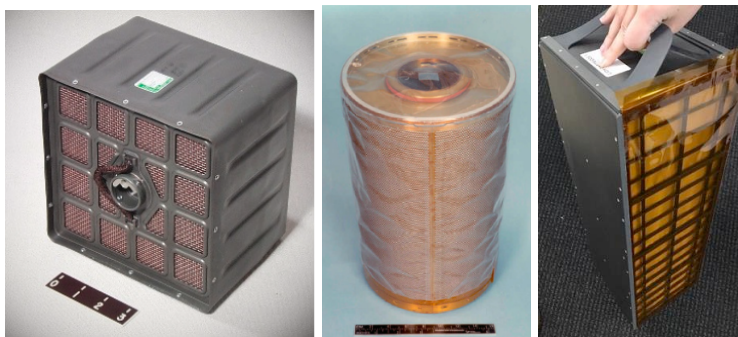


**Figure 2. Apollo<sup>5</sup>, Shuttle<sup>6</sup> and Dragon<sup>7</sup> LiOH Canisters (left to right)**

## B. Regenerable Pressure-Swing Sorption Systems

Three regenerable pressure-swing sorption systems are described in the next sections. Design considerations common to these systems are described below:

Each of these systems are dependent on space vacuum for regeneration and require high vacuum conductance in the vacuum vent lines.

Since cabin air from the interstitial spaces of the sorbent packed beds is dumped overboard with the CO<sub>2</sub> and H<sub>2</sub>O, makeup gas is required for these open loop pressure swing systems. This amount can be reduced by approximately half by equalizing the air pressure in the adsorbing bed with the bed at vacuum just prior to half cycle change.

### 1. Skylab 2-Bed Molecular Sieve System (2BMS)

The 2BMS architecture with zeolite sorbents was first flown on the Skylab space station.<sup>10</sup> It was the first regenerable open loop Environmental Control and Life Support System, venting CO<sub>2</sub> and H<sub>2</sub>O to space vacuum. This Skylab system provided partial humidity control as a condensing heat exchanger (CHX) was also used for complimentary humidity removal. Each Skylab bed was packed with 10.35 lbs of Linde 13X zeolite and 3.17 lb of 5A zeolite. The nominal operation consisted of 15 minute adsorption and 15 minute desorption half-cycles. The primary system operated without any hardware issues for three Skylab missions without any need to activate the backup system. The Skylab 2BMS system is shown in Figure 3.



**Figure 3. 2BMS CO<sub>2</sub> Removal System from Skylab**

As zeolites preferentially adsorb water vapor over CO<sub>2</sub>, periodic bakeout of the beds via internal heaters while exposed to space vacuum is required. Generally, 5-hour bakeouts were performed at the start of each Skylab mission.<sup>11</sup> Interestingly, no mid-mission bakeout was required during the longest (84 day) Skylab mission, even though the 2BMS had been qualified based on bakeouts at 28 day intervals.<sup>10</sup> The Skylab 2BMS demonstrated the flight (technology readiness level (TRL) of nine) success of this 2BMS approach giving confidence in the likelihood of success in actual flight of the next generation 2BMS described next.

## 2. Sorbent Based Atmosphere Revitalization

The Sorbent Based Atmosphere Revitalization (SBAR)<sup>12</sup> was developed as an Orion system risk mitigation technology. It is similar in architecture to the Skylab 2BMS system, but includes patented enhancements that improve efficiency, reduce size, and extend the period between thermal bakeouts.<sup>13</sup> It was developed by NASA to an approximate TRL of six. The Orion SBAR configuration would provide CO<sub>2</sub> and humidity control for up to 6 crew for the Orion mission without the need of a CHX. Eliminating the CHX significantly decreases the complexity of condensate control within the cabin and is advantageous when preparing for the significant dormant periods expected for Artemis lunar missions.

Figure 4 shows a schematic of the SBAR system. Virtually all H<sub>2</sub>O is removed in the first zeolite 13X layer. CO<sub>2</sub> is removed primarily in the second two layers consisting of 13X and 5A. The blue process air line is shown with a partial bypass of the second section. Since crew H<sub>2</sub>O loading is higher, the full flow is not required for the CO<sub>2</sub> removal section. Bypassing some of the flow extends the time period between thermal bakeouts. The red vacuum vent lines show three ports for vacuum venting. Using three ports has been shown to reduce overall bed pressure during desorption, resulting in more efficient desorption and thus greater adsorption on the subsequent half-cycle.

The SBAR system provides substantial improvements in mass, power, and volume compared to the Skylab CO<sub>2</sub> and H<sub>2</sub>O removal system. A conceptual flight design of the SBAR system, including a primary and backup 2BMS unit, is shown in Figure 5.

The SBAR concept is currently under further development under the Marshall Space Flight Center FY25 Technology Innovation and Development funding. The stated objectives of this effort are to further technical maturation of SBAR to a system that is more competitive for applications in short term missions, such as Gateway and Initial Surface Habitat, and obtain test data on the enhanced SBAR test unit to verify performance predictions and optimization of key performance parameters (KPPs). KPPs include operational lifetime, CO<sub>2</sub> and humidity removal rates, reliability, mass, power, and volume.

A key objective in the current effort is to enhance the SBAR design based on the design features developed for the successful 4BCO<sub>2</sub> Scrubber, including incorporation of the 4BCO<sub>2</sub> Scrubber internal bed heaters and other features. These features resulted in a 100 fold reduction in dust production rate for the 4BCO<sub>2</sub> Scrubber over the previous four-bed zeolite based system, the Carbon Dioxide Removal Assembly (CDRA), as discussed in Ref. 14.

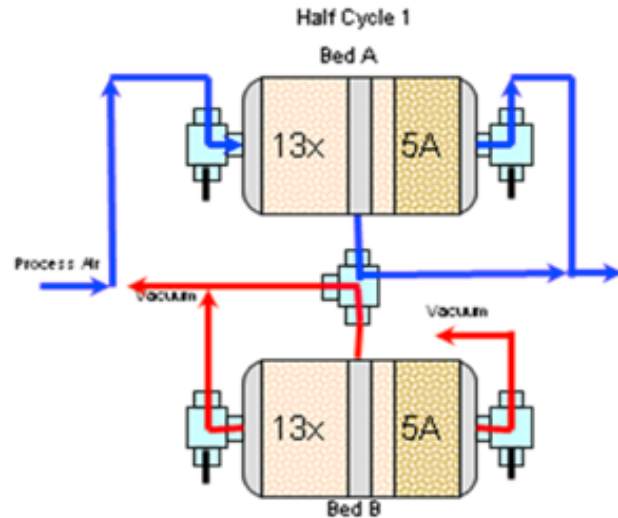


**Figure 4. Sorbent Based Atmosphere Revitalization System Schematic**

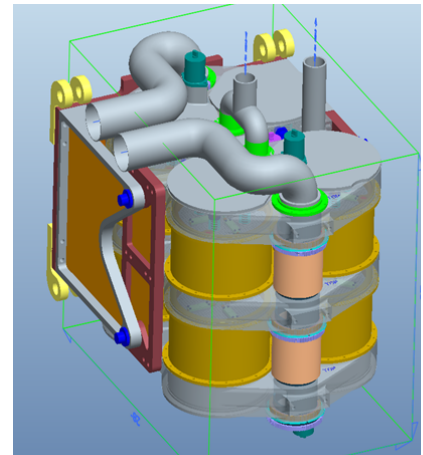


**Figure 5. Sorbent Based Atmosphere Revitalization (Flight Concept)**

### 3. Carbon Dioxide and Humidity Control Subassembly

The Carbon Dioxide and Humidity Control (CHC) Subassembly was developed for the Orion crew vehicle, where it is currently installed. The CHC is a two-bed, pressure swing amine system which vents CO<sub>2</sub> and H<sub>2</sub>O to space vacuum. An advantage of the amine absorbent is that CO<sub>2</sub> removal capacity is not degraded in the presence of water vapor. Prototypes of the CHC were called the CO<sub>2</sub> and Moisture Removal Amine Swing-bed System (CAMRAS), and were flown as a technology demonstration on ISS.<sup>15</sup> This version is shown in Figure 6. Three CHC are units installed in Orion. In nominal operation, two units are active while the third provides a backup system.

One of the considerations with the CHC is that amine off-gasses ammonia resulting in capacity loss over time. The off-gassed ammonia may also require a dedicated ammonia filter. Finally, the presence of ammonia, especially during periods of dormancy, may result in material compatibility issues.

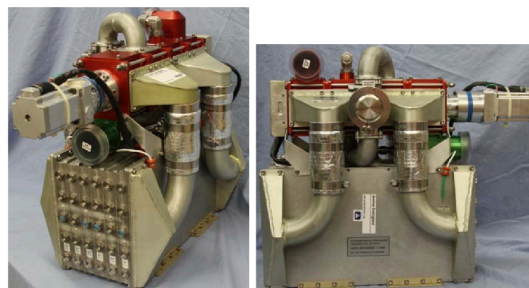


Figure 6. Amine Swingbed<sup>15</sup>

### 4. Resource Comparison for Regenerable Systems

In the initial phases of the Orion program the Orion capsule was to serve as an ISS Ferry, shuttling up to six crew up to and back from the ISS. During this time, studies were conducted to estimate the mass, power, and volume required for the three regenerable CO<sub>2</sub> and H<sub>2</sub>O removal systems described above.<sup>4,16</sup> Results for one representative case is shown in Figure 7. This case was for six crew and a cabin temperature of 80°F (note: higher temperatures result in high metabolic water production). Skylab estimates included both the 2BMS and the CHX since the CHX is not required for SBAR and CHC (aka CAMRAS).

The resource requirements for the Skylab 2BMS are significantly higher than either SBAR or CAMRAS. Mass, power, and volume reductions for SBAR vs. the Skylab 2BMS were estimated at approximately 600%, 300%, and 1700% respectively.<sup>11,17,18</sup> The values for the SBAR and CAMRAS systems are much closer, with the SBAR mass being slightly higher, but power and heat rejection requirements significantly lower due to the higher SBAR H<sub>2</sub>O removal efficiency (nearly 100%) and thus lower flow rate requirements. Equivalent System Mass (ESM) analyses for the ISS Ferry Mission as well as for Lunar Missions showed that the ESM values for SBAR and CAMRAS were very comparable and could be considered equivalent within the accuracy of these studies.<sup>4</sup>

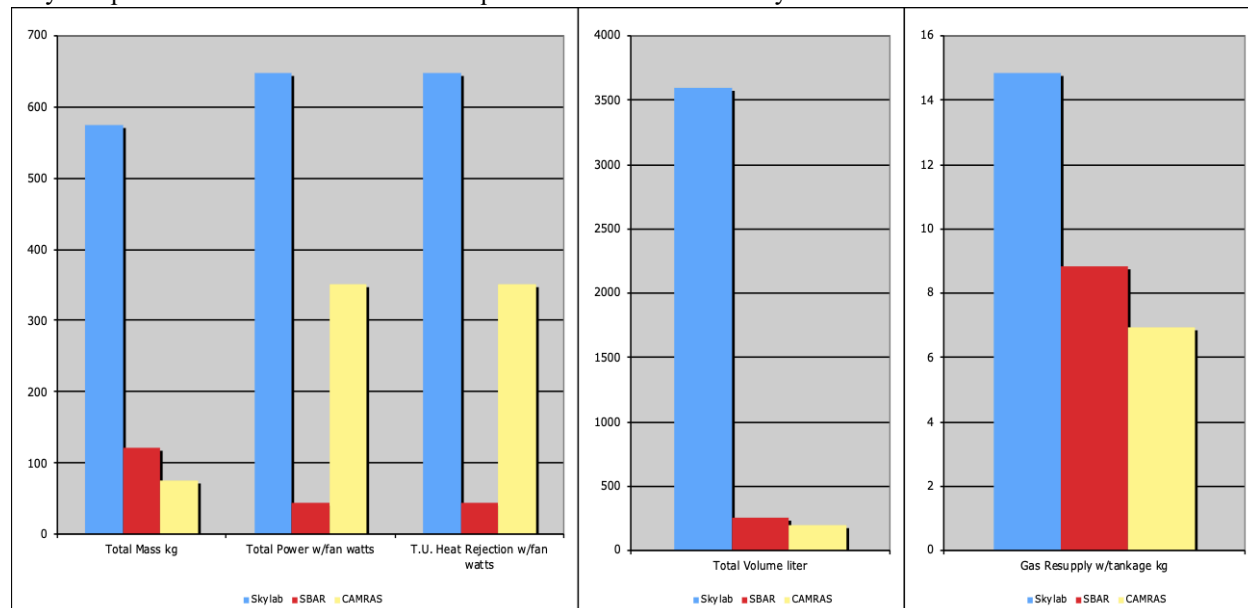


Figure 7. Resource Requirements for Orion ISS Ferry Mission<sup>11,17,18</sup>

The design considerations for LiOH, CHC, and SBAR are summarized in Table 1. Due to the high mass of the Skylab 2BMS system, it is not considered any further as a candidate in this assessment.

**Table 1. Design Considerations for Open Loop Systems**

| Technology                              | Vehicle Integration Considerations        | Pros                                                                       | Cons                                                                                |
|-----------------------------------------|-------------------------------------------|----------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Lithium Hydroxide                       | Integrates into ventilation system        | Longest flight pedigree (Apollo, Shuttle, ISS, Dragon, etc.)               | Mass and volume of non-regenerable cartridges becomes prohibitive for long missions |
|                                         |                                           | Simple design requires few components                                      | Crew interaction required to stage canisters due to efficiency degradation          |
|                                         |                                           |                                                                            | CO <sub>2</sub> removal only requiring additional H <sub>2</sub> O removal system   |
| Solid Amine Swingbed                    | Requires high vacuum conductance to space | Metabolic CO <sub>2</sub> and H <sub>2</sub> O removal                     | Amine material CO <sub>2</sub> capacity degrades over time                          |
|                                         | Ullage losses increase gas storage        | Water tolerance (no thermal regeneration required)                         | Ammonia off-gassing necessitates consumable NH <sub>4</sub> removal bed             |
|                                         |                                           | Flown on ISS (1000 hours), tested on Orion (on ground)                     | Ammonia buildup during dormant periods can lead to material issues                  |
| Sorbent Based Atmosphere Revitalization | Requires high vacuum conductance to space | Metabolic CO <sub>2</sub> and H <sub>2</sub> O removal                     | Gradual water buildup requires periodic thermal regeneration                        |
|                                         | Ullage losses increase gas storage        | Zeolite capacity does not degrade over time                                | System design must address zeolite dusting tendencies                               |
|                                         |                                           | H <sub>2</sub> O removal virtually 100% efficient requiring low flow rates | Ground testing only performed to date with non-flight hardware                      |

#### IV. Regenerable vs. Nonregenerable CO<sub>2</sub> Removal for Initial SH

In the following sections a new study is presented where the resource requirements for two different approaches, LiOH and SBAR, are compared for the CO<sub>2</sub> removal function for the Initial Surface Habitat.

##### A. Derived Initial SH Cabin CO<sub>2</sub> Requirements

The CO<sub>2</sub> performance correlation described in the next section is based on actual SBAR operations with a range of inlet conditions (CO<sub>2</sub> partial pressure, H<sub>2</sub>O vapor pressure, and flow rate). For each discrete test used to develop this correlation, however, the inlet conditions were held constant.

During a initial SH IVA day, variations in crew activity levels as specified in Ref. 19 will result in wide variations in cabin CO<sub>2</sub> partial pressure. Therefore, simulations of the initial SH transient ppCO<sub>2</sub> levels were developed in Matlab® based on mass balance equations. These simulations were used to find what daily average ppCO<sub>2</sub> level corresponds to a daily peak of 3 mmHg ppCO<sub>2</sub>. This is a slightly conservative case compared to the initial SH requirement (maintain the 1-hr average CO<sub>2</sub> partial pressure below 3 mmHg). For additional conservatism, one crewmember is assumed to be a 95<sup>th</sup> percentile person as specified in the Gateway requirements.<sup>20</sup> The daily average ppCO<sub>2</sub> levels for each scenario were then used as an input to the SBAR performance correlations.

##### 1. Nominal IVA Daily Profile

Two specific initial SH scenarios are considered in this analysis. The first is the Nominal IVA Daily Profile. In this case it is assumed that no EVA activities are performed for an extended period. This represents the worst case loading on the initial SH CO<sub>2</sub> removal system. Other requirements are shown in Section II, Initial Surface Habitat Mission Requirements. Figure 8 shows the CO<sub>2</sub> partial pressure profile for a nominal IVA day. Here the sleep period shows the lowest ppCO<sub>2</sub> levels, followed by the nominal activity period, followed by the serial exercise period. The average ppCO<sub>2</sub> was found to be 2.2 mmHg.

##### 2. Contingency Case Profile

The second initial SH profile considered was the contingency case, where 4 crew are housed in the initial SH for a period of 32 hours. For this case no exercise was assumed to reduce the load on the CO<sub>2</sub> removal system during a

contingency period. As shown in Figure 9, for this case the nominal awake period shows the highest ppCO<sub>2</sub> level and the sleep period the lowest level. The average ppCO<sub>2</sub> was found to be 2.8 mmHg.

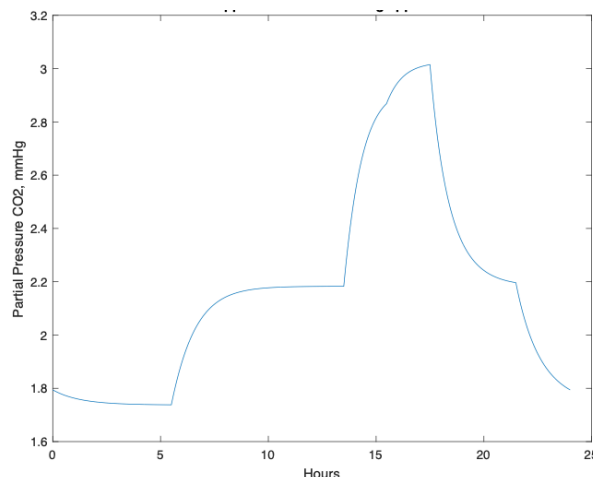


**Figure 8. CO<sub>2</sub> Partial Pressure for a Nominal IVA Day with Average ppCO<sub>2</sub> of 2.2 mmHg**

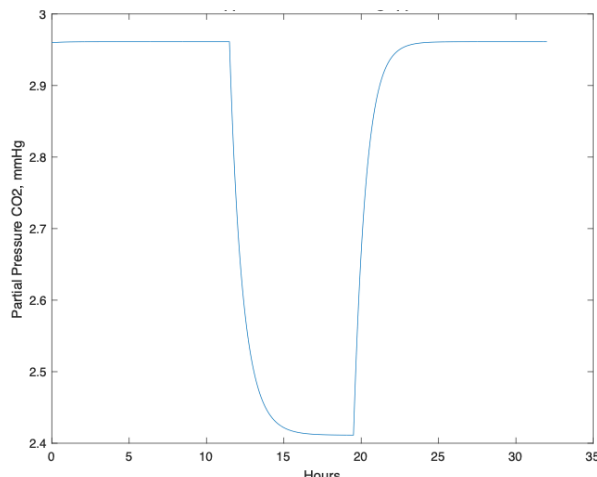


**Figure 9. CO<sub>2</sub> Partial Pressure for a Contingency Case Profile with Average ppCO<sub>2</sub> of 2.8 mmHg**

## B. SBAR CO<sub>2</sub> Performance Correlation

Different versions of the SBAR system were tested extensively from 2006 to 2014 under a wide range of inlet conditions. For the majority of these tests, the inlet conditions were held constant over the multi-day duration of the tests. This approach gave a clear understanding of how quickly the H<sub>2</sub>O vapor was permeating the zeolite, which is observed by a decreasing CO<sub>2</sub> removal rate. Also, the resulting data, specifically CO<sub>2</sub> removal rates at elapsed operational days, provided direct input to the SBAR CO<sub>2</sub> performance correlation.

The CO<sub>2</sub> removal rate for a typical test is illustrated in Figure 10 by the dark green line, which shows a high CO<sub>2</sub> removal rate initially then slowly decreases over 8.5 days. This test was conducted with the high conductance test article, which is described below.

The required removal rate for a 4-person crew (4.16 kg/day) is shown by the light green horizontal line. If the two lines meet, the SBAR will no longer be able to maintain control of the cabin ppCO<sub>2</sub> below a specified value, thus requiring off-line thermal regeneration. For this case thermal regeneration was not required until somewhat after 8.5 days of operation.

Figure 10 also provides the vacuum levels at the four locations called out in Figure 11. The impact of tubing, bends, and expansion into the plenums is reflected in the observed pressure increases from the trunk line to the bed plenums.

For the test results shown in Figure 10, the test article shown in Figure 11 was used. This test article was designed to maximize vacuum conductance with off-the-shelf components, and to enable conductance sensitivity testing. Vacuum conductance was adjusted by adding orifice plates near the valves and in the trunk line.

More extensive testing was conducted with an earlier test article shown in Figure 12. The data from this test article, as well as an earlier single bed test article, is shown in Figure 13. This plot also shows correlated data for the low vacuum conductance CO<sub>2</sub> removal performance. This correlation was developed to determine the CO<sub>2</sub> removal performance of an SBAR system as a function of the inlet CO<sub>2</sub> partial pressure, humidity, and flow rate, as well as the elapsed time since thermal regeneration, sorbent volume, and cycle time.

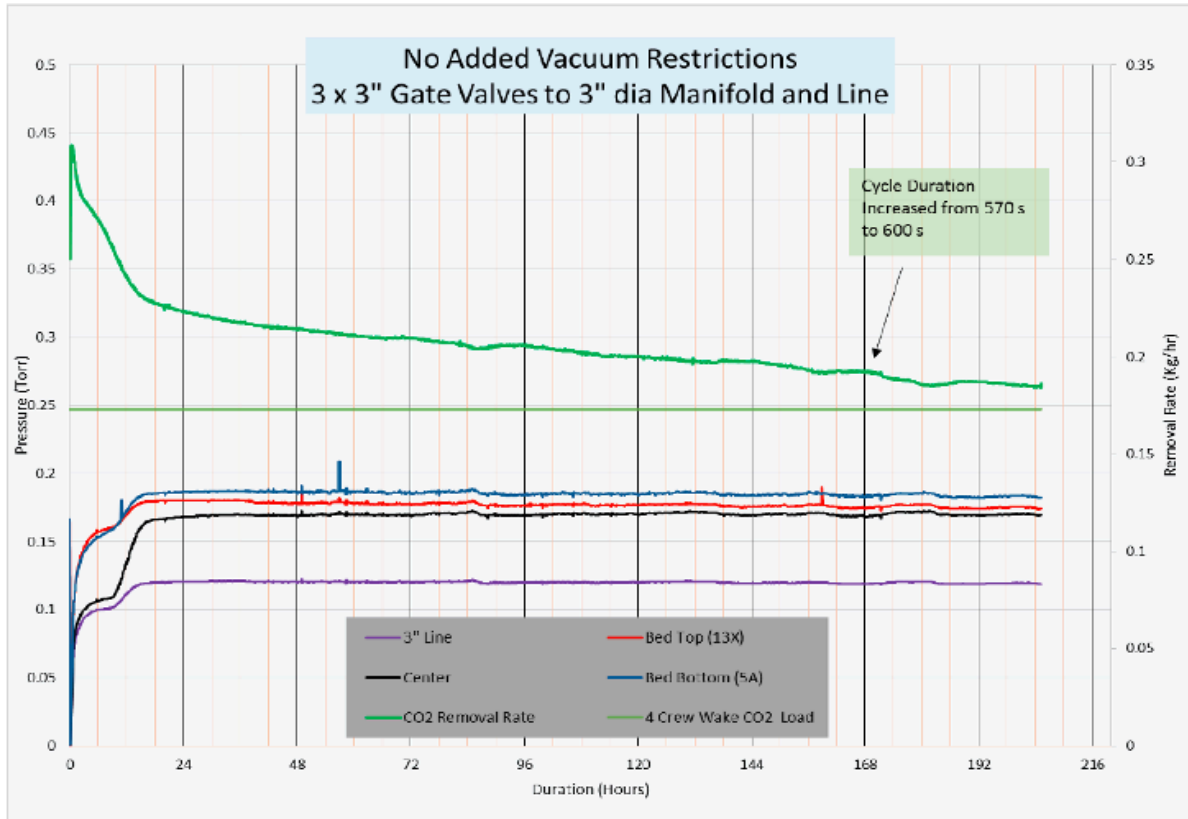


Figure 10. High Conductance SBAR Test Results

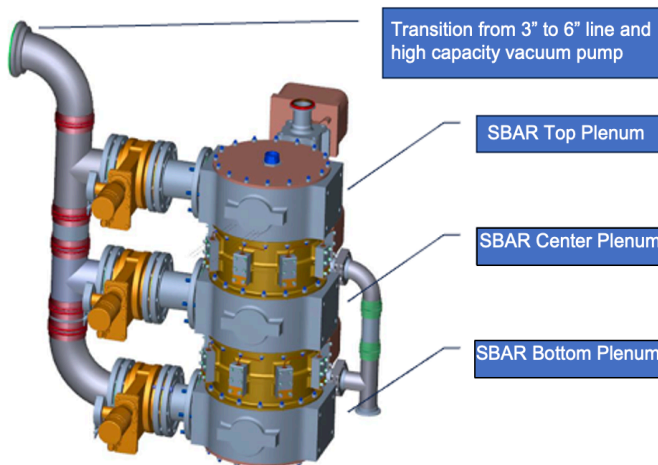


Figure 11. SBAR High Vacuum Conductance Test Article

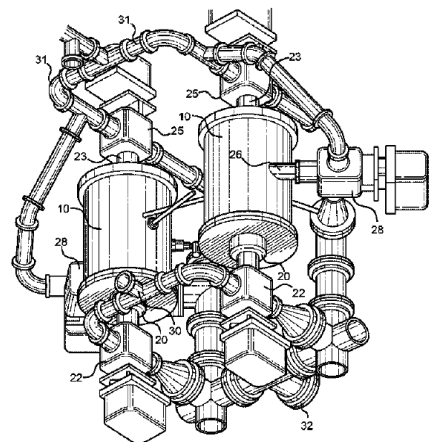


Figure 12. SBAR Low Conductance Test Article

As seen in the plot, the correlation fits the test data very well for lower removal rates and elapsed times. The lower removal rates correspond to an inlet ppCO<sub>2</sub> of 3 mmHg, which is slightly higher than the initial SH mission requirement. The test data for higher removal rates in this plot was for inlet conditions of 5 and 7 mmHg.

A comparison between test data with low and high vacuum conductance is shown in Figure 14. Here the low conductance data is in green, purple, and black, with inlet CO<sub>2</sub> partial pressure was set to 3, 5, and 7 mmHg respectively, and bed sorbent volume of 8.9 liters. The high conductance data is in red, with inlet CO<sub>2</sub> partial pressure set to 4 mmHg and bed sorbent volume of 6.7 liters. Symbols represent the test data values.

These test results show that the high conductance test article achieved equivalent CO<sub>2</sub> removal rates with 75% of the sorbent and similar inlet CO<sub>2</sub> flow rates. However, to achieve high conductance, larger and heavier lines are

required. As the SBAR design matures, trade studies will be needed to weigh the pros and cons of a high conductance approach.

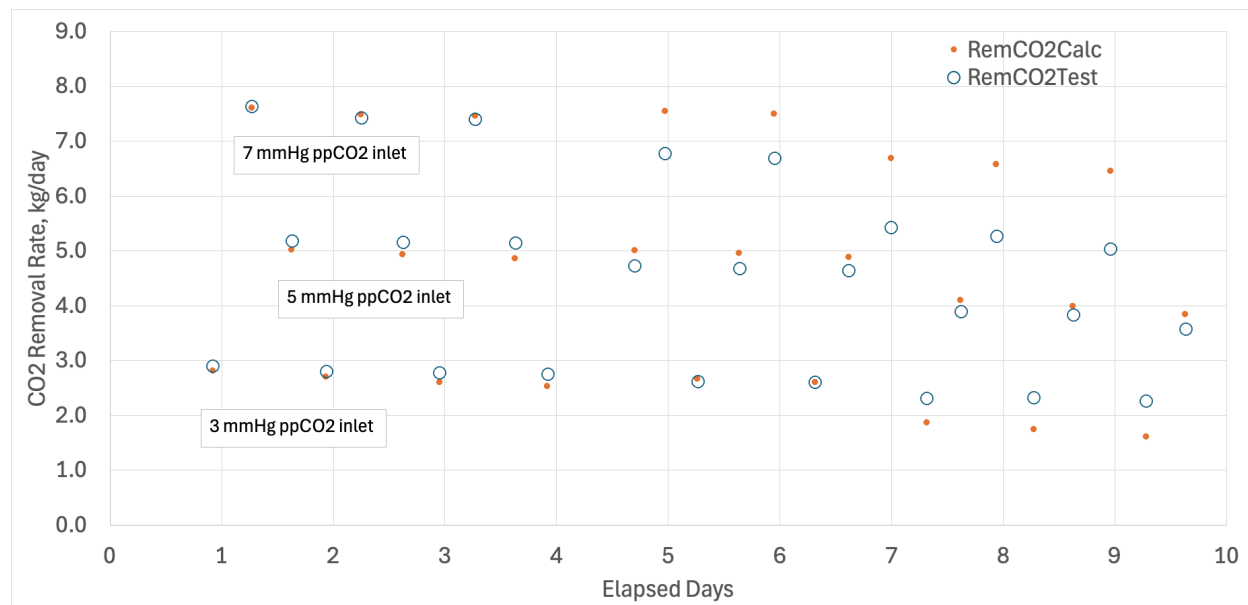


**Figure 13. Low Conductance Test Results vs. Correlation**

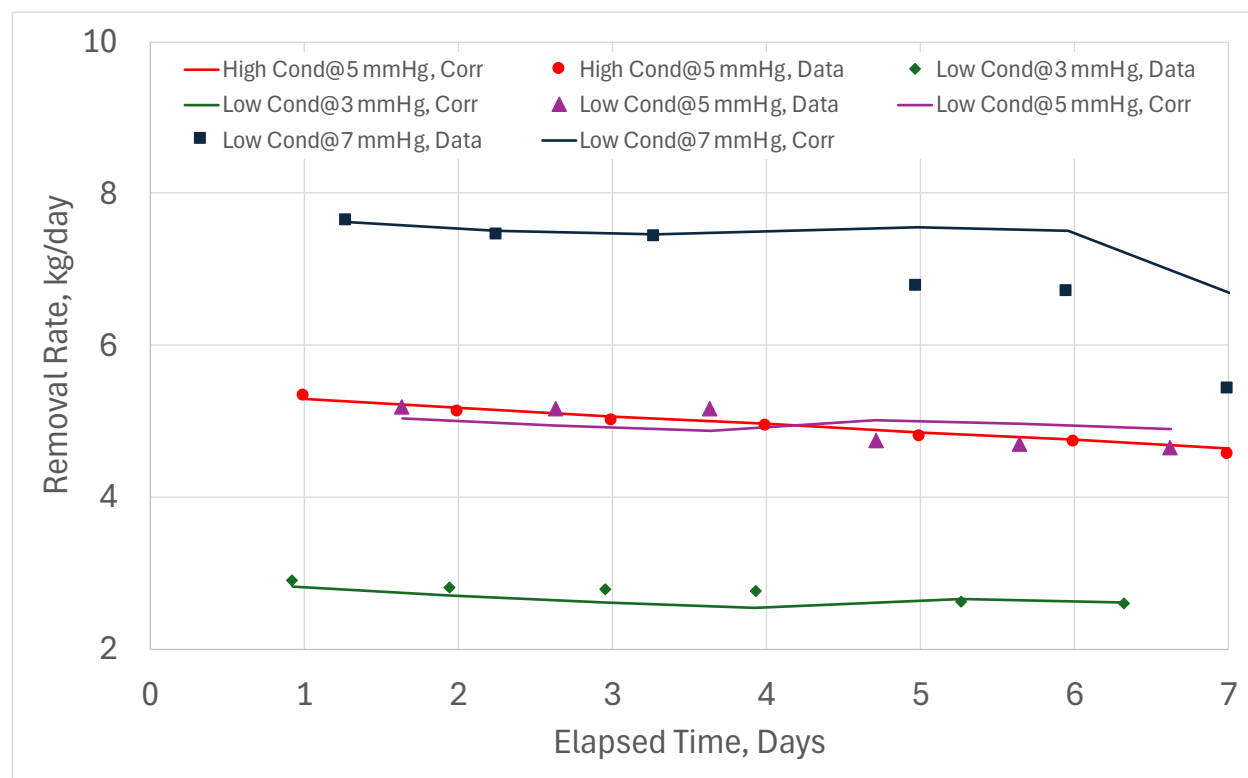


**Figure 14. Comparison of High and Low Conductance SBAR Test Data vs. Correlation**

### C. SBAR Design Optimization

To optimize the overall resource requirements of SBAR, the performance correlation was augmented in a MATLAB® routine with calculations for gas losses, canister and tubing mass, blower and valve power, and overall

volume requirements. This algorithm evaluates total system mass, power, and volume for user specified inlet conditions over a user specified range of sorbent volumes and cycle times.

The results for a representative parametric study is shown in Figure 15. Here the minimum system mass of 129 kg was found for a system with bed sorbent volume of 14 liters and half-cycle time of 11 minutes. As low half-cycle times result in high gas losses, a sharp mass increase is evident at the lowest half-cycle times.

For comparison, for the same case with high conductance, the minimum system mass is 108 kg with a sorbent volume of 10 liters and half-cycle time of 9 minutes.

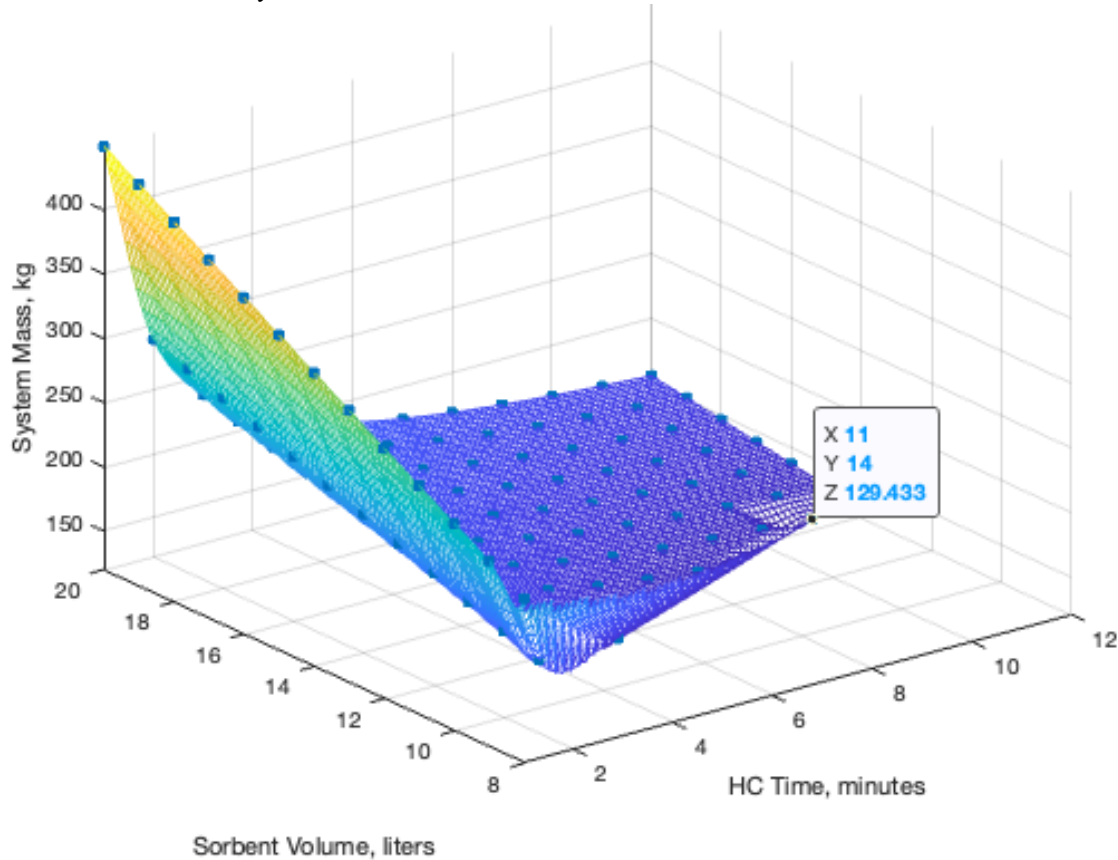


**Figure 15. Mass Optimization for 28 Day Mission with Low Vacuum Conductance**

Overall resource requirements for a nominal mission (2 crew for 28 days) and contingency mission (4 crew for 32 hours) are shown in Figure 16. These figures compare the mass, volume, and power requirements for low and high vacuum conductance cases, including specific values for gas losses and sorbent volume.

From these charts, it is evident that the contingency case has a higher power requirement due to higher flow rates for the 4-crew loading, but minimal gas losses due to short mission duration. This assumes a single SBAR system is operational for the contingency case. If single fault failure is acceptable during the contingency case, having two SBAR systems would reduce both the power requirement and required sorbent mass.

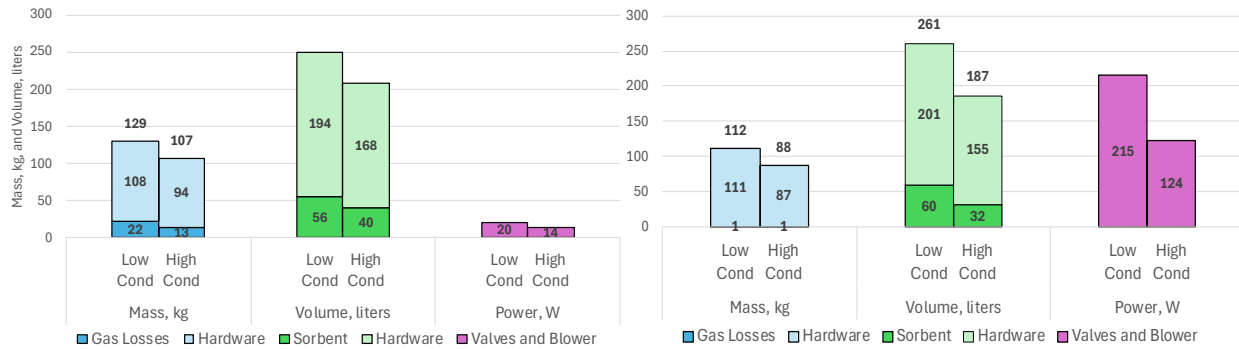


**Figure 16. SBAR Resource Requirements for 28 Mission with Thermal Regeneration at 7 Days (left) and for 32 Hour Contingency Mission with 4 Crew and Thermal Regeneration after 32 Hours: 1 SBAR 2-Bed System Operational (right)**

#### D. SBAR/LiOH Resource Comparison

The nominal mission resource requirements were revised for the larger sorbent volume required for the contingency mission; the resulting requirements are shown in Figure 17. These values will be used to compare the SBAR requirements with LiOH requirements. The following ground rules and assumptions apply:

- Currently using sizing requirement based on low conductance/contingency case for trades (pending assessment of high conductance mass penalty)
- Total sorbent volume of 60 liters (4 beds)
- Half-cycle time of 13 minutes (40 minutes for high conductance case)
- Gas losses include tankage in mass calculation (though not in volume calculation at present)

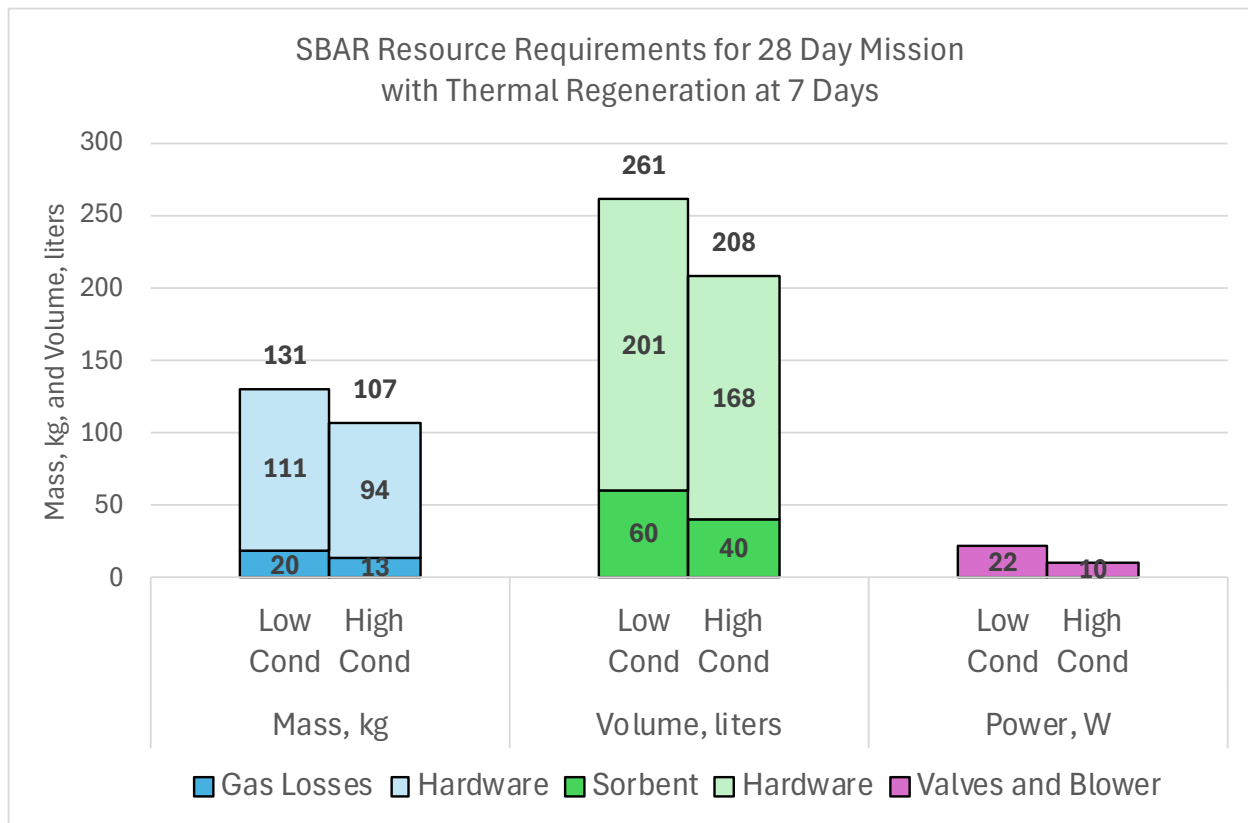


**Figure 17. Revised SBAR Sizing for Initial Surface Habitat Nominal Mission**

To compare the SBAR mass requirements with the logistics mass required to employ LiOH, the additional assumptions and restrictions apply:

- 2 days of contingency LiOH is included in the SBAR swingbed consumables
- Spares mass and other system impacts not yet quantified
- Initial SH mass reduction for H<sub>2</sub>O removal system elimination not considered

An assessment of the SBAR hardware and logistics mass given these assumptions is shown in Figure 18. As shown, replacing LiOH with an SBAR swingbed system saves approximately 97 kg of consumable mass per 28 day initial SH mission. This assessment would become more favorable if elimination of a H<sub>2</sub>O removal system is considered, and if program requirements allowed for the backup SBAR system to provide single fault tolerance.

For the current requirements, the break-even point (where it becomes advantageous to use SBAR over LiOH) occurs on the second 28 day initial SH mission. From that point forward, almost 100 kg of consumable mass would be saved per mission by using an SBAR system vs. LiOH.

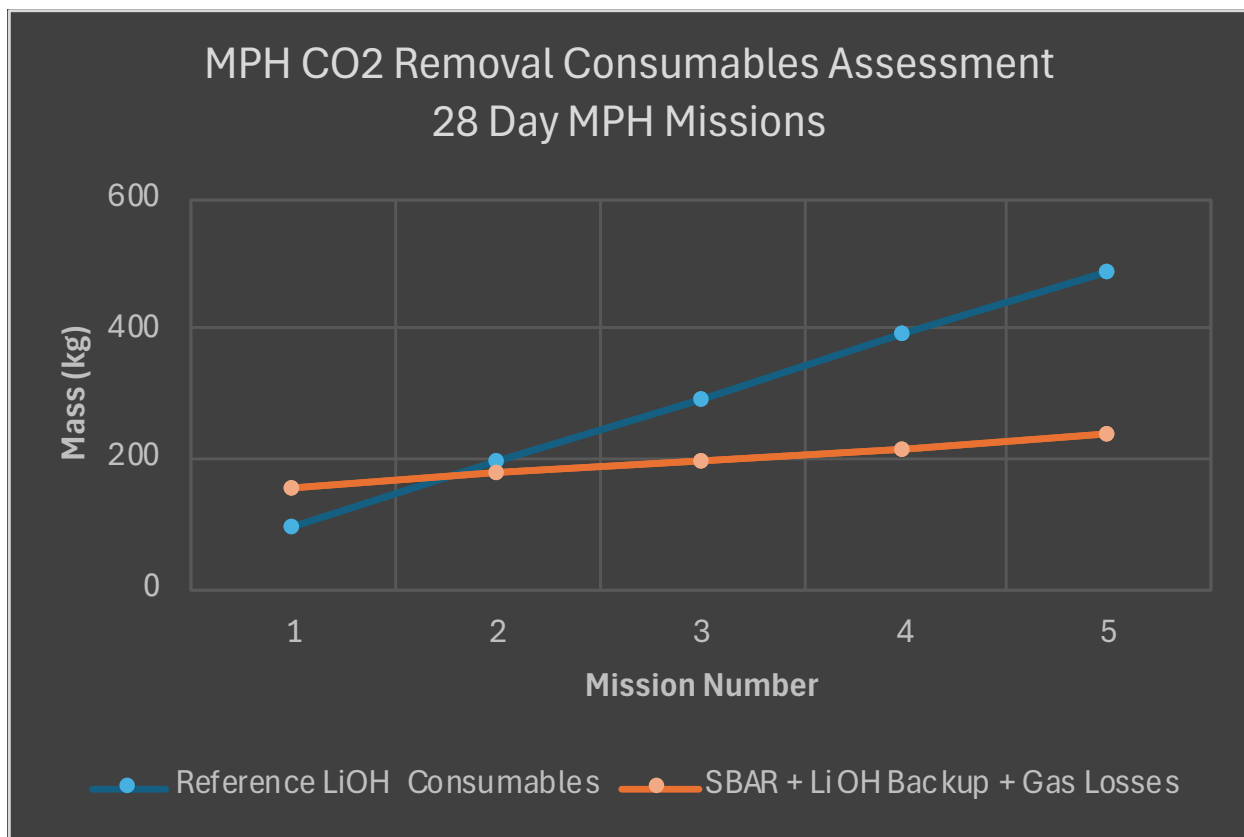


**Figure 18. CO<sub>2</sub> Removal Consumables Assessment for 28 Day Initial Surface Habitat Missions**

## V. Considerations for Lunar South Pole Missions

Based on current NASA plans, the next missions to the Moon will target the lunar South Pole due to areas of permanent darkness in this location. This area may contain volatiles in the form of ice, potentially providing valuable resources for exploration and unique scientific value.<sup>1</sup>

However, the lunar South Pole also presents challenges, including the six-month winter period when solar illumination is not consistently available. Missions would be conducted during the summer period, then equipment would be put in a dormant state for the winter. Minimal solar power for heating would lower habitat temperatures drastically, perhaps to freezing temperatures.

Consumable needs, as focused on in the previous section, is important for these missions as both supplies and wastes must be transported from the landing vehicle to the habitat, a distance that may be up to 5 km. Thus both the mass and volume of consumables, such as LiOH canisters, have an impact on the requirements for the transport vehicle.

Finally, the longevity of the overall mission of the Initial Surface Habitat is measured in years, although only one individual mission may be conducted per year, thus any degradation of sorbent capacity must be considered in the initial sizing of a CO<sub>2</sub> and humidity removal system.

Table 2 provides a high-level summary of design considerations for the open loop systems reviewed in this paper as applied to the lunar South Pole mission.

**Table 2. Open-Loop System Design Considerations for Lunar South Pole Mission**

| Technology                                     | Pros                                                         | Cons                                                                                | Approx. Consumable Mass (kg) |
|------------------------------------------------|--------------------------------------------------------------|-------------------------------------------------------------------------------------|------------------------------|
| <b>Lithium Hydroxide</b>                       | Low consumable mass for first mission                        | High cumulative consumable mass for subsequent missions                             | Mission 1: 98                |
|                                                | Stability of LiOH in freezing conditions unknown             | Mass and volume of consumables drive logistics vehicle sizing                       | Mission 2: 196               |
|                                                |                                                              |                                                                                     | Mission 5: 490               |
| <b>Solid Amine Swingbed (CHC)</b>              | Provides for dry-out before winter                           | Ammonia buildup during dormancy may require purge evacuation cycles during dormancy | Mission 1: TBD               |
|                                                | Stability of regenerated Amine in freezing conditions likely | Beds must be oversized to account for amine degradation over time                   | Mission 2: TBD               |
|                                                |                                                              | Vacuum regeneration required prior to dormancy                                      | Mission 5: TBD               |
| <b>Sorbent Based Atmosphere Revitalization</b> | Provides high efficiency dry-out before winter               | Thermal regeneration required prior to dormancy                                     | Mission 1: 157               |
|                                                | Stability of dry zeolite in freezing conditions likely       |                                                                                     | Mission 2: 177               |
|                                                |                                                              |                                                                                     | Mission 5: 236               |

## VI. Summary and Further Work

This paper reviewed the current high TRL open-loop technologies in general, and more specifically design considerations for application to the lunar South Pole mission. It also focused on a comparison of the consumable needs of one non-regenerable CO<sub>2</sub> removal technology, LiOH, with a regenerable technology, SBAR, for a lunar South Pole mission. One opportunity for further work is to expand the scope to include another regenerable technology, CHC. The existing comparison can also be expanded to include, for example, taking into account mass savings due to the elimination of a humidity control system, consideration of spares mass, and inclusion of the high vacuum conductance option once a tubing mass penalty has been evaluated.

## VII. Conclusions

The trade space for open loop ECLSS is amenable to multiple systems, technologies, and vehicle integration approaches. There are opportunities to reduce consumables which will likely benefit the lunar architecture as a whole by reducing the logistics footprint. Initial Surface Habitat architectures that align with operations such as dormancy and surviving lunar darkness are significant attributes and must also be considered. Other aspects of CO<sub>2</sub> and humidity control systems to minimize the generation, or even remove certain trace gas contaminants to support initial ingress promote system longevity is also a factor. Both the CHC and SBAR regenerable systems offer long term consumable benefits beyond traditional consumable based systems. Each system has unique features that offer advantages over the other. Proper evaluations that consider all relevant factors, including logistics footprint, operations, mission compatibility, and crew maintenance are all important considerations when choosing the best technology for the functions of CO<sub>2</sub> and humidity control to enable missions within the Artemis portfolio.

## References

- <sup>1</sup>Exploration Systems Development Mission Directorate, "NASA's Moon to Mars Architecture," NASA/TP- 20240015571, 2025
- <sup>2</sup>Parsonson, Andrew., "NASA Greenlights Next Phase of Italian Lunar Habitat Project," *European Spaceflight* [online newsletter], URL: <https://europeanspaceflight.com/nasa-greenlights-next-phase-of-italian-lunar-habitat-project/#:~:text=A%20NASA%20review%20board%20has,its%20MPH%20lunar%20surface%20habitat>. [cited 03 May 2025]
- <sup>3</sup>Marandola, Elizabeth A., and Sam A. Moffatt, "ECLSS Architecture and Breakeven Analysis for Mission-Flexible LIFE Habitat," *51st International Conference on Environmental Systems*. St. Paul, Minnesota, 2024.
- <sup>4</sup>Lange, K. E., "Carbon Dioxide and Moisture Removal Trade Study for CEV and Lunar Lander," ESCG-4470-07-TEAN-DOC-0167, Engineering and Science Contract Group, Houston, Texas, 2007.
- <sup>5</sup>Isobe, Jun, Phoebe Henson, Allen MacKnight, Stephen Yates, Daryl Schuck, and Dale Winton., "Carbon Dioxide Removal Technologies for U.S. Space Vehicles: Past, Present, and Future," *International Conference on Environmental Systems*. Vienna, 2016.
- <sup>6</sup>James, John T, and Ariel Macatangay, "Carbon Dioxide-Our Common" Enemy," *SAMAP Submarine Air Monitoring Air Purification Conference*. San Diego, CA, 2009.
- <sup>7</sup>Silverman, J., Irby, A. and Agerton, T., "Development of the Crew Dragon ECLSS," *51st International Conference on Environmental Systems*, St. Paul, Minnesota; 2022.
- <sup>8</sup>Stromgren, Chel, Victor Alvarez, Michael Ewert, Michael Galluzzi, Kandyce Goodliff, and Douglas Craig, "Exploration Logistics Planning Guide," NASA ESDMD SAO-TM20230615-1A, Exploration Systems Development Mission Directorate, 2023
- <sup>9</sup>Ahmadi, M., A. Ghaemi, and M. Qasemnazhand, "Lithium hydroxide as a high capacity adsorbent for CO(2) capture: experimental, modeling and DFT simulation," *Sci Rep*, 13: 7150, 2023
- <sup>10</sup>Ray, Charles D., "Skylab Atmospheric Contamination Control," NASA TM X-64900, 1974.
- <sup>11</sup>Hopson, G. D., "Skylab Life Support and Habitability System Requirements and Implementation," *XXIInd International Astronautical Congress*, Brussels, 1971.
- <sup>12</sup>Knox, J., Miller, L., "Development and Testing of a Sorbent-Based Atmosphere Revitalization System 2010/2011," *41st International Conference on Environmental Systems*, Portland, OR, 2011
- <sup>13</sup>Knox, James C., and Lee A. Miller. 2017. "Sorbent-Based Atmosphere Revitalization System." U.S. Patent No. 9,802,149 B1, 2017
- <sup>14</sup>Knox, James C., Lyndsey Winslette, and Warren Peters, "Advances in Zeolite CO<sub>2</sub> Removal System Design for Dust Mitigation," *54th International Conference on Environmental Systems*, Prague, Czech Republic, 2025.
- <sup>15</sup>Button, Amy B., and Jeffery Sweterlitsch, "Amine Swingbed Payload Testing on ISS," *International Conference on Environmental Systems*, Tucson, AZ, 2014
- <sup>16</sup>Knox, James C., and Lee Miller, "Development and Testing of a Sorbent-Based Atmosphere Revitalization System for the Crew Exploration Vehicle," Huntsville, Alabama: Marshall Space Flight Center. Unpublished.
- <sup>17</sup>MSFC Skylab Airlock Module Final Report, NASA TMX-64810, MSFC, 1974
- <sup>18</sup>Skylab Project Airlock ECS and RCRS Component Descriptions, 73-9337, AiResearch, 1973
- <sup>19</sup>ACD Medical Operations Requirements Document (MORD) ACD-52105, Revision A, NASA, December 15, 2022
- <sup>20</sup>"Gateway Subsystem Specification for the Environmental Control and Life Support Subsystem (ECLSS)." GP 10004 Revision C, NASA, 2022.