

Development and Testing of a Sorbent-Based Atmosphere Revitalization System 2008/2009

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ABSTRACT

The design and evaluation of a Vacuum-Swing Adsorption (VSA) system to remove metabolic water and metabolic carbon dioxide from a spacecraft atmosphere is presented. The approach for Orion and Altair is a VSA system that removes not only 100 percent of the metabolic CO₂ from the atmosphere, but also 100% of the metabolic water as well, a technology approach that has not been used in previous spacecraft life support systems. The design and development of an Orion Crew Exploration Vehicle Sorbent Based Atmosphere Revitalization system, including test articles, a facility test stand, and full-scale testing in late 2008 and early 2009 is discussed.

INTRODUCTION

In this paper a development, test, and evaluation program that is being conducted at NASA's Marshall Space Flight Center (MSFC) is discussed. The program is aimed at implementing and validating a design solution for an adsorbent based swing bed Atmosphere Revitalization System (ARS) to provide both humidity and carbon dioxide control for the Orion Crew Exploration Vehicle (CEV) and the Altair Lunar Lander. Initially, Orion will be used for missions to the International Space Station, and later provide transport to lunar orbit. The Orion spacecraft Environmental Control and Life Support System (ECLSS) is extremely limited with respect to weight, power, and volume thus driving systems to new levels of efficiency while maintaining high dependability and robustness. The

primary focus of this program was to evaluate a Sorbent Based Atmosphere Revitalization (SBAR) system as a risk mitigation alternative to the amine core technology under development for Orion and currently the baseline approach.

Unlike on previous vehicles, the VSA ARS is slated to not only remove CO₂, but is also the sole system designated for removing and controlling humidity. Metabolic water from respiration and evaporated sweat has traditionally been removed by a condensing heat exchanger. Adsorption-based water removal systems eliminate the need for gas/liquid separators and the low temperature coolant loop; however, it places additional challenges on the VSA system [1].

The specific evaluation objectives for this effort were to obtain information on SBAR system performance sufficient to characterize function to >90% for application to CEV operational phases (pre-launch, in-flight, and landing) and to acquire sufficient data to estimate fit and form to ~50% while addressing the full range of operational conditions.

The conditions over which the SBAR system was evaluated for this project were:

- CEV Cabin pressure ranges (high & low)
- CEV Cabin temperature ranges (high & low)
- CEV Cabin humidity ranges (high & low)
- Sensitivity to metabolic transients (high & low)

The SBAR Test Article was tested in a wide range of mission scenarios and operational conditions to meet the performance objectives over the length of a mission. The scenarios included off-nominal conditions to include operation of a single SBAR unit for a sufficient duration to return a crew from lunar orbit as well as operation at the low suit loop pressure required during evacuated cabin operations.

The Altair Lunar Lander will utilize a VSA ARS and the performance requirements are quite similar to that of the CEV. The SBAR technology is also undergoing test and evaluation for application in the Altair vehicle.

SBAR SYSTEM OVERVIEW

An air revitalization system is an integral part of any spacecraft ECLSS and must reliably perform over a wide range of cabin conditions. Figure 1 shows a simplified CEV loop which illustrates the two primary modes of operation; 1) the normal mode in which cabin air is pulled through the SBAR System and then returned to the cabin volume, and 2) the suit loop mode in which the conditioned air flows directly to the crewmember's suits. In the suit loop mode the SBAR has to operate at pressures as low as 4.3 psia (225 Torr) and the entire volume in the loop is quite small. For both modes, all water and CO₂ generated by crew activity must be removed by the SBAR and condensation must be prevented.

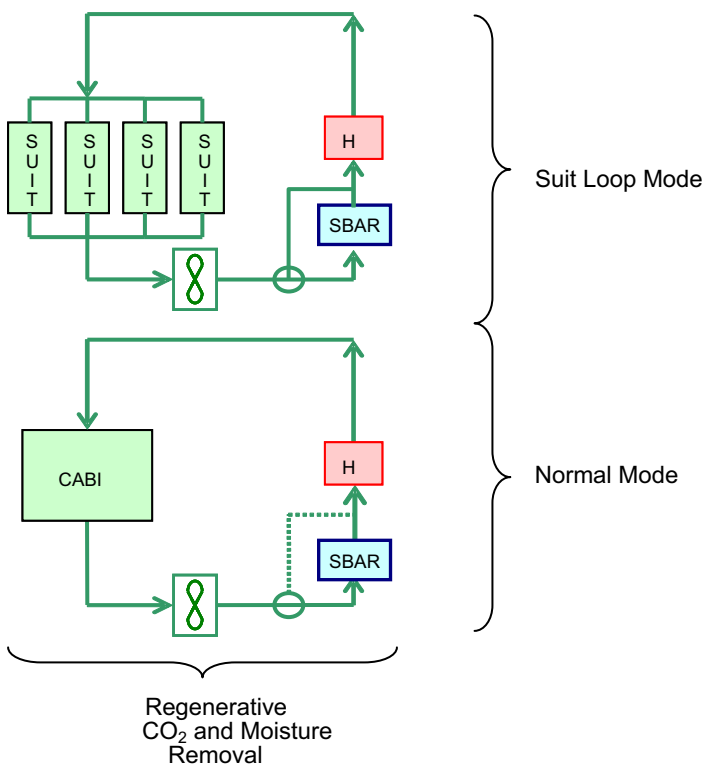


Figure 1 - CEV ARS Loops

The SBAR design evaluated for this program incorporates the experience gained from previously tested configurations. Two specific results provided important feedback; (1) for certain operational conditions, water tends to slowly propagate down the bed in the flow direction thereby decreasing CO₂ removal performance over time and (2) providing additional vacuum access to the sorbent bed during desorption can have a dramatic positive effect on the removal performance. Subsequent development testing demonstrated that a large increase in CO₂ removal rate is obtained by locating a desorption port at the center as well as at both ends of the bed [2].

The SBAR system is configured with two identical beds with the zeolite layers as shown in Figure 2. The SBAR bed provides three locations for vacuum access, at the inlet, center, and outlet ports of the bed. The center port provides an additional access to space vacuum for water desorption, increasing water removal performance, retarding propagation of water through the bed, and reducing the size and weight of the inlet vacuum line and valves. The center plenum is located at the center of the bed and within the 13X material to minimize the pressure gradient.

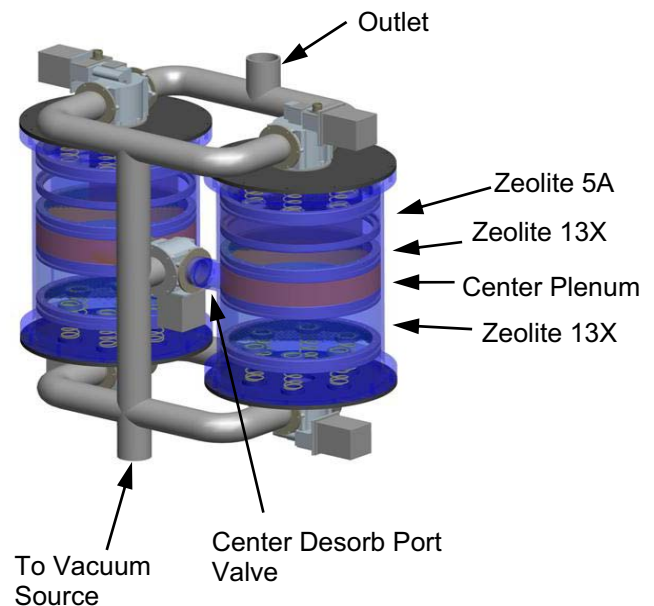


Figure 2 - SBAR Assembly

Figure 3 depicts the sequence of SBAR system cyclic operation in which the vacuum of space is used to desorb the CO₂ and H₂O from the zeolite material. For the adsorb half-cycle, the CO₂ and water vapor laden gas is drawn from the cabin/suit loop through the adsorbing bed. The dry and CO₂ reduced air is then returned to the cabin/suit loop. Simultaneously, the second bed of the system is placed under vacuum to remove the previously adsorbed CO₂ and H₂O regenerating the bed for the next half-cycle.

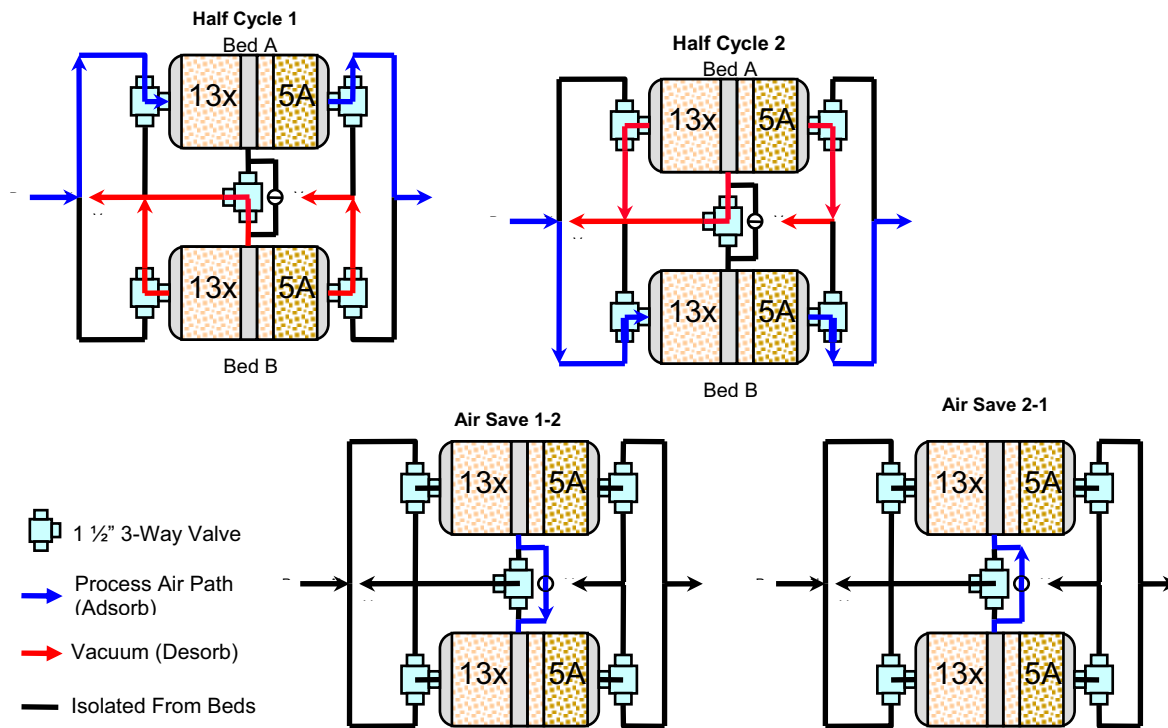


Figure 3 – SBAR VSA Cyclic Operation

At the start of the desorption half-cycle, the valves are sequenced so that the vacuum source is opened to the flow inlet end of the bed (13X side) first. The center port is then opened to the vacuum source and then, after a delay, the 5A end of the bed is opened to the vacuum. This sequence insures that the material with the greatest water loading is evacuated first and that the flow direction minimizes water propagation into the 5A material. At the end of each half-cycle, both beds are temporarily isolated from the external interfaces and allowed to equalize with each other. This decreases the amount of ullage gas lost during half-cycle changes.

SBAR TEST ARTICLE

Due to time constraints, the test article evaluated for this program was a single bed system as illustrated in Figure 4. A photo of the SBAR Test Article integrated with the test facility is shown in Figure 5. The test article is a single bed with a center plenum and containing 6.6 liters of zeolite material. A bypass valve and plumbing is used in place of the second bed which allows constant flow during the desorption half-cycle of the SBAR Test Article. The CO₂ and water removal performance required for full-scale SBAR testing is based on a CEV ECLSS system that utilizes two SBAR units to meet the removal requirements for the full CEV crew complement.

The SBAR Test Article utilizes commercial ball valves and actuators that have not been optimized for size,

speed, or conductance. The valves are a 3-way flow configuration with port to port isolation during transition. The flow conductance through the valves is equivalent to a 90° miter bend in a 35 mm (1.38") diameter pipe. The actuators have been modified to incorporate digital motor controllers to improve reliability and to provide real-time position feedback.

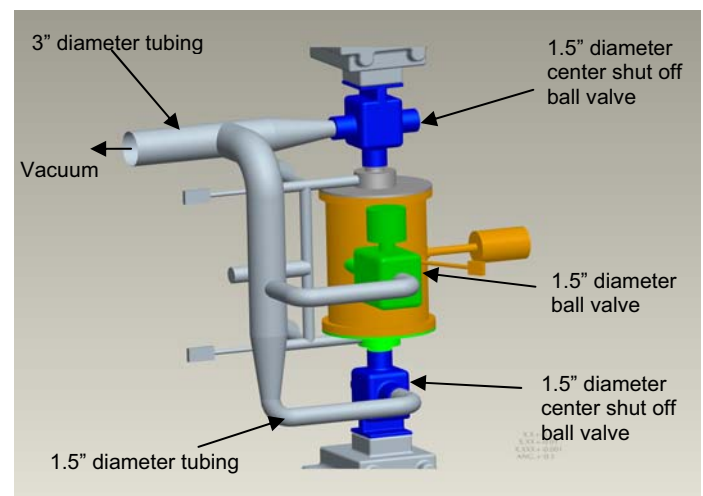


Figure 4 – SBAR Test Configuration

Sensors integrated with the test article include vacuum/pressure transducers at the top (inlet side), the center plenum, and the bottom (outlet side) while

thermocouples measure the temperature at the top, center, and bottom as well. A delta pressure sensor is used to measure the pressure drop across the bed during the adsorb half-cycle.



Figure 5 – SBAR Test Article in Test Facility

TEST APPROACH

The molecular sieve material utilized in the SBAR VSA system tends to not desorb water fully without added heat. Over time this water will gradually decrease CO₂ removal performance and the material must then be regenerated with heat to regain full removal performance. Due to this slow degradation in performance, a test approach that fully accounted for this characteristic was implemented.

To meet the stated project test objectives over the extreme cabin environment conditions as specified in the “Exploration Life Support Requirements Document” [3] while complying with the specific requirements of the “Constellation Program Human-Systems Integration Requirements” (HSIR) [4], a test plan was implemented to:

- Evaluate the requirements and objectives to establish the conditions and performance parameters necessary for complying with test objectives.
- Develop a test facility with capability to evaluate the SBAR test article over the full range of nominal and off-nominal operational ranges.
- Implement a control system that simulates CEV cabin environment and controls inlet conditions according to metabolic profile and mission timelines.
- Define and perform a series of mission scenario test cases that encompass the extremes of CEV operational parameters.

- Evaluate SBAR performance in response to the applied conditions over the duration of the mission scenario.

SYSTEM AND TEST REQUIREMENTS - The two primary mission types addressed are; 1) the ISS Ferry Mission: 3-6 crew, ≤5 Days (total) without exercise, and 2) the Lunar Transit Mission: 4 crew, ≤21 Days (total) with exercise.

For all missions the SBAR system must provide 100% removal of Metabolic CO₂ and H₂O. The HSIR limits for CO₂ exposure allow time limited excursions above a partial pressure of 5 Torr but the goal is for the partial pressure to remain <5 Torr for all nominal operations. The HSIR specified tolerance ranges for relative humidity is between 25% and 75% except during temporary transient excursions. However, condensation in the CEV cabin must be prevented which places an upper limit on the cabin dew point. The Orion CEV baseline ECLSS incorporates a temporarily condensing heat exchanger to capture and hold excess moisture. To represent operation in the same architecture, the majority of test cases were required to maintain a nominal cabin dew point below 10°C (50°F) while limiting transient excursions to below 14.4°C (58°F).

The SBAR system removes nearly 100% of the water vapor that flows through it. Because of this removal performance, an SBAR system can potentially be operated with flow rates that eliminate the need for a condensing heat exchanger. To test this configuration, selected test cases were operated at flow rates sufficient to maintain the nominal dew point below 7°C (45°F). This dew point is below the temperature of the coolant loop and condensation would be prevented.

The metabolic loads applied for the test cases at nominal temperatures were obtained from the HSIR. For off-nominal temperature operation, the applied metabolic loads were as per the Shuttle Operational Data Book.

TEST FACILITY OVERVIEW

The Orion CEV ECLSS Simulator (OCES) is the integrated hardware and software system designed to simulate the full range of cabin conditions anticipated throughout a defined mission scenario while capturing all required performance parameters. The primary enhancements implemented in the OCES over previous SBAR test facilities were the capability to operate at sub-ambient absolute pressures and the capability to simulate and control to dynamically changing real-time CEV cabin conditions.

The OCES utilizes LabView® programming software, as shown in Figure 6, for control system functions. While the MSFC developed PACRATS (Payload And Components Real-time Automated Test System)