# Reduced Pressure Cabin Testing of the Orion Atmosphere Revitalization Technology

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**An amine-based carbon dioxide ($CO_2$) and water vapor sorbent in pressure-swing regenerable beds has been developed by United Technologies Corp. Aerospace Systems (UTAS, formerly Hamilton Sundstrand) and baselined for the Atmosphere Revitalization System for moderate duration missions of the Orion Multipurpose Crew Vehicle (MPCV). In previous years at this conference, reports were presented on extensive Johnson Space Center testing of this technology in a sea-level pressure environment with simulated and actual human metabolic loads in both open and closed-loop configurations. In 2011, the technology was tested in an open cabin-loop configuration at ambient and two sub-ambient pressures to compare the performance of the system to the results of previous tests at ambient pressure. The testing used a human metabolic simulator with a different type of water vapor generation than previously used, which added some unique challenges in the data analysis. This paper summarizes the results of: baseline and some matrix testing at all three cabin pressures, increased vacuum regeneration line pressure testing with a high metabolic load, a set of tests studying $CO_2$ and water vapor co-adsorption effects relative to model-predicted performance, and validation tests of flight project computer model predictions with specific operating conditions.**

## Nomenclature

| | | |
|---|---|---|
| *acfm* | = | actual cubic feet per minute |
| *ARS* | = | Atmosphere Revitalization System |
| *Btu/hr* | = | British thermal units per hour |
| *°C* | = | degrees Celsius |
| *CAMRAS* | = | $CO_2$ And Moisture Removal Amine Swing-Bed |
| $CO_2$ | = | carbon dioxide |
| *ELS* | = | Exploration Life Support |
| *°F* | = | degrees Fahrenheit |
| *g/min* | = | grams per minute |
| *GAC* | = | Gas Analyzer Console |
| $H_2O$ | = | water |
| *HMS* | = | Human Metabolic Simulator |
| *HSIR* | = | Human-Systems Integration Requirements |
| *JSC* | = | Johnson Space Center |
| *lbm/hr* | = | pounds mass per hour |
| *min* | = | minutes |
| *ml/min* | = | milliliters per minute |

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|---|---|---|
| *mmHg* | = | millimeters of mercury |
| *MPCV* | = | Multipurpose Crew Vehicle |
| *NASA* | = | National Aeronautics and Space Administration |
| *$ppCO_2$* | = | partial pressure of carbon dioxide |
| *psia* | = | pounds per square inch, absolute |
| *scfm* | = | standard cubic feet per minute |
| *slpm* | = | standard liters per minue |
| *UTAS* | = | United Technologies Corp. Aerospace Systems |

## I. Introduction

HUMAN beings produce carbon dioxide ($CO_2$) when they breathe, but too high a concentration in the atmosphere around them can quickly become toxic. For this reason, $CO_2$ control is critical in the closed environment of a spacecraft. Humans also exhale water vapor and exchange water vapor with the atmosphere through their skin. Although excessive water ($H_2O$) vapor is not dangerous to humans, it can be uncomfortable, and it can be hazardous to the electronic equipment in a spacecraft cabin, particularly if it condenses in undesired locations.

In the past, spacecraft have typically used separate systems to control $CO_2$ and humidity. $CO_2$ control methods have included sorption by lithium hydroxide or zeolite compounds, and water has typically been collected by condensing heat exchangers. However, those $CO_2$ sorption systems have tended to be large and heavy, whether regenerable or not, and condensate water collection systems require a lower temperature thermal control system with a large heat capacity.

As an alternative to traditional $CO_2$ sorption systems, United Technologies Corp. Aerospace Systems (UTAS) has spent many years developing amine-based vacuum-regenerated adsorption systems. The first major implementation of this type of system, known as the Regenerative $CO_2$ Removal System, was tested on the Space Shuttle in the early 1990s. This design and the associated sorbent amine have since gone through a number of improvement cycles. The current iteration of the system uses a pair of interleaved-layer beds filled with SA9T, which is a sorbent system comprised of plastic beads coated with an amine.

SA9T, in addition to being a good $CO_2$ sorbent, also has a great affinity for water vapor. When water vapor is removed from the cabin atmosphere with a regenerable sorbent instead of a traditional condensing heat exchanger, the spacecraft cooling system can be greatly simplified by eliminating a fairly significant heat load as well as the need for a low-temperature cooling loop. The interleaving of beds in this system minimizes total cabin heat loads from the adsorption and desorption processes by thermally linking them. UTAS studies have shown SA9T to be very stable over long periods. For these and other reasons, this technology was baselined as the primary $CO_2$ and water vapor removal device for the new Orion Multipurpose Crew Vehicle (MPCV) spacecraft.

While UTAS's technology was already relatively well developed and had undergone subscale and open-loop testing, NASA's Exploration Life Support (ELS) and Orion Project Environmental Control and Life Support System development groups wanted more details on the performance of a full-scale device in a realistic spacecraft environment. The ELS Air Revitalization Systems team at Johnson Space Center (JSC) refitted an existing test chamber to test UTAS's technology, which the Air Revitalization team calls the $CO_2$ And Moisture Removal Amine Swing-bed, or CAMRAS.

The JSC team tested a single CAMRAS unit in two test phases in late 2006. The preliminary results of those tests were presented at this conference in 2007[1]. A second CAMRAS unit of slightly-modified design was added to the system for the third phase of testing in mid-2007, and those results were presented at this conference in 2008[2]. A third, significantly redesigned, CAMRAS unit with a new, more flight-like, valve style was tested in the ambient-pressure portion of a fourth phase of tests during the spring of 2009, and those results were presented here in 2010[3]. A second portion of the fourth phase, involving reduced-pressure testing of many of the same fourth-phase cases, was conducted in summer 2011, and those results are presented in this paper. (These tests were run with the second test article because the third had been flown to the International Space Station for on-orbit testing.) This test series is colloquially known as CAMRAS Phase 4B.

## II. Test Rig Description

In the anticipated MPCV application, a pair of CAMRAS units would be used together for most metabolic load levels. However, only one unit was available for this test, so the volume of the test chamber usually needed to represent only half the MPCV capsule free space. The single CAMRAS unit was therefore placed in a controllable and well-mixed atmosphere of the appropriate volume: a test chamber once used for human testing during the Gemini and Apollo eras, now known as the Cabin portion of the 11-Foot Chamber. Certain test cases did call for examination of the effects of a single unit on the full Orion volume, so the Cabin served as the half volume, and when the full volume was needed, a pipe plug at the rear of the chamber was removed to expose a small tunnel that connects to another test chamber (which was sealed off from the tunnel for this test), and the normal in-chamber cooled air circulation was forced into the tunnel with a blower and a long hose. A pair of parallel blowers provided process loop airflow through the CAMRAS sorbent beds, and a vacuum source simulated a link to space vacuum for regeneration of the beds. The effects of humans on the cabin atmosphere were simulated with a second generation Human Metabolic Simulator (HMS), and the whole test rig, shown in Fig. 1 without the HMS, was outfitted with various sensors to monitor test conditions and experimental results.

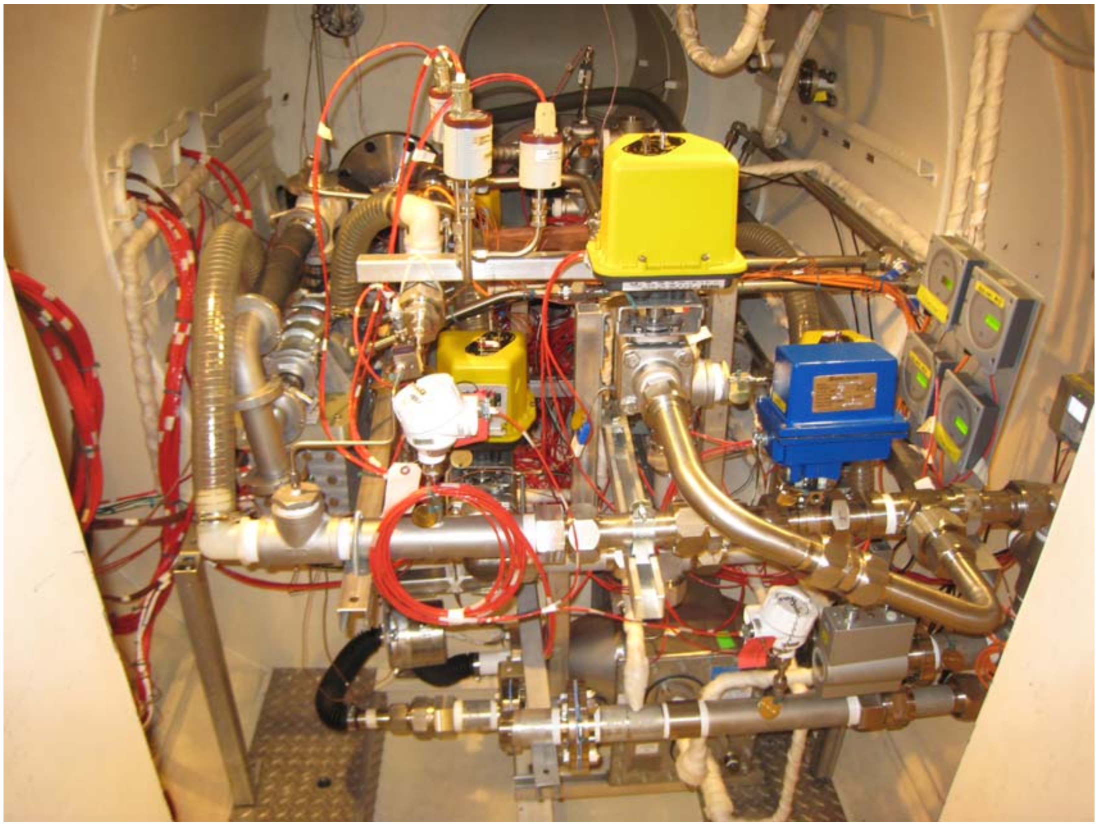

**Figure 1. CAMRAS Phase 4B test rig photo.**

Figure 2 shows a simple diagram of the test rig described in this section. Air flowed from the process loop inlet past a filter, flow meter, and several sensors before passing into the CAMRAS air inlet port on the top of the unit. Air flowed out of the CAMRAS unit through another line, where several more sensors were located. Heat added by the blowers was removed by an in-line heat exchanger, and a final suite of sensors analyzed the process air as it returned to the chamber atmosphere. In addition to normal major atmospheric constituent monitoring, the test rig allowed offline Fourier Transform Infrared Spectrometer analysis of process gas grab samples from the inlet or outlet ends of the process loop. A system of large vacuum pumps was used to depressurize the chamber when required, after which the chamber was isolated from the vacuum source to best reflect only the effects of the HMS and the CAMRAS on the chamber atmosphere. During the test cases, all pressurization of the chamber was performed using only $N_2$ and $O_2$ supplies, to simulate the Orion operations and to closely control the oxygen concentration of the chamber atmosphere, which was limited to a maximum of 34% for safety reasons. A manually controlled bleed gas system was added just before test start to slowly bleed a mix of $O_2$ and $N_2$ into the chamber to counter the CAMRAS ullage and leakage pressure loss effects. However, because it was a purely manual system, there is no automatic data log record of the settings or actual flow rates, and the system inconsistently compensated for pressure and $O_2$ concentration changes during test cases.

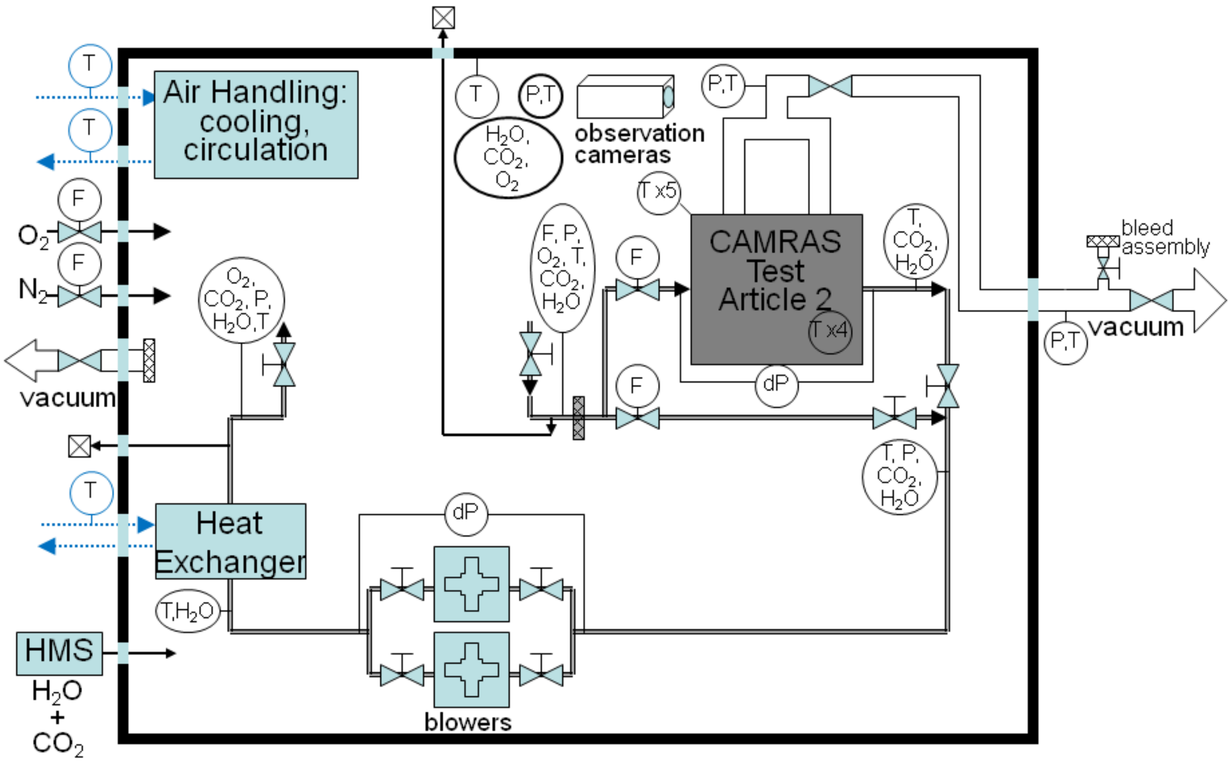


**Figure 2. CAMRAS Phase 4B simplified test rig schematic.**

## A. Test Article

The CAMRAS technology uses a pair of interleaved multilayer beds filled with sorbent beads. In the test article used for this test, CAMRAS 2, a spool-type valve directs airflow from the cabin, through the adsorbing bed, and back to the cabin while isolating the desorbing bed to a direct line to vacuum. The valve periodically switches position, swapping the bed functions and equalizing pressure between the beds as it travels, which helps minimize ullage air loss. Each adsorption or desorption period is called a half-cycle. Figure 3 shows a simple schematic of the CAMRAS operation. The left side of the figure shows the spool valve shuttle positioned for bed A adsorption and bed B desorption; the right side shows the shuttle in the opposite position and the bed functions swapped. This original design, called “dual-end desorb”, pulls a vacuum on both ends of the desorbing bed. The test article used in this test was modified to allow regeneration by a source of dry pressurized gas for launch pad applications, and because of the associated flow path modifications, it can only allow vacuum desorption from one end of each bed. That purge gas desorption functionality was not tested during CAMRAS Phase 4B.

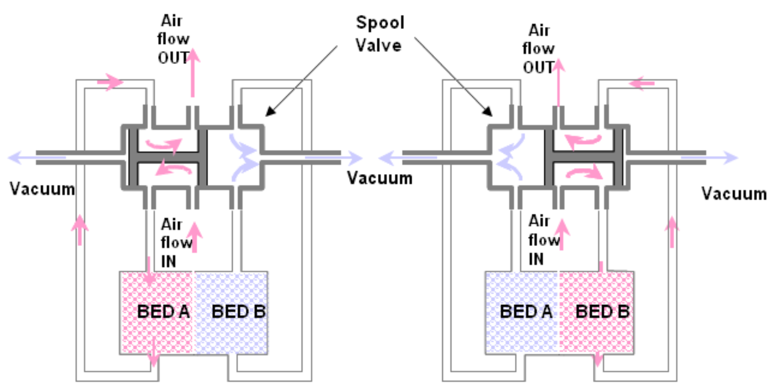


**Figure 3. CAMRAS internal flow (dual-end desorb).**

Highly porous plastic beads coated with an amine fill aluminum foam blocks in each CAMRAS and are retained in the foam with screens. The sorbent system, known as SA9T, adsorbs both carbon dioxide and water vapor. The adsorption reaction is exothermic and the vacuum-desorption reaction is endothermic; the use of aluminum foam and interleaving of bed layers for heat transfer helps conserve the overall system thermal energy so no direct heating or cooling of the device is required.

In the projected Orion application of this technology, three separate CAMRAS assemblies will be installed in the vehicle. Two will operate in parallel for a crew of four to six people, and the third will be reserved as a spare. The beds are sized such that, in an emergency, a single CAMRAS could maintain the cabin $CO_2$ at safe levels for a crew of six indefinitely, provided a sufficient vacuum source.

## B. Metabolic Load Simulation

The second-generation Human Metabolic Simulator simulated human production of $CO_2$ and $H_2O$ vapor. Water vapor generation is performed by a combination of evaporation and ultrasonic nebulization from a temperature-controlled bath, where the water is injected from a mass flow-controlled source and the water level in the tank is ideally balanced between vaporization and injection, as monitored by a sensitive weight scale. Gaseous $CO_2$ injection is accomplished via a traditional mass flow controller connected to a gas cylinder. The design of this HMS is presented in another paper at this conference[4].

**Table 1. HSIR metabolic $CO_2$ and $H_2O$ generation rates.**

| Crew Size & Activity | 2 Sleep | 2 Normal | 1½ Rest, ½ Exercise |
|---|---|---|---|
| **Metabolic $CO_2$ Generation Rate (g/min, slpm)** | 0.91<br>0.49 | 1.44<br>0.77 | variable:<br>peak 3.57<br>peak 1.91 |
| **Metabolic $H_2O$ Generation Rate (ml/min, lbm/hr)** | 1.26<br>0.167 | 2.35<br>0.311 | variable:<br>peak 10.69<br>peak 1.41 |

Table 1 lists the metabolic carbon dioxide and water generation rates for half of a representative four-person all-male crew (to correlate to the half-volume chamber and halved CAMRAS complement) in configurations that might be assigned to Orion. These rates are derived from the Constellation Program's Human-Systems Integration Requirements (HSIR) document. For exercise metabolic loads, the metabolic loading provided by the HMS is increased from two at nominal level to 1.5 nominal plus 0.5 person exercising for the time period that it would take for the entire simulated crew to complete their exercises. Exercise for each crew member is simulated at 75% of maximum volumetric oxygen consumption and 5% exercise efficiency with elevated $CO_2$ injection and increasing $H_2O$ injection for 30 minutes, with a 15-minute break between active exercise periods, where the $CO_2$ injection returns to normal and the water injection rate decreases. Water generation rates for each simulated exerciser remain elevated for 60 minutes post-exercise, where people would continue sweating after ceasing the actual exercise.

The water vapor injection rates required for most of the test cases in this series unfortunately fell in an HMS operational zone between pure passive evaporation and the lowest nebulizer power setting. Consequently, depending on the needed vapor generation rate, a blower above the reservoir was automatically cycled on and off for certain percentages of a 20-minute duty period. The blower moved passively evaporated water vapor away from the water surface and thus achieved the right average water evaporation rate for the full duty period. The "on" portion of the 20-minute blower duty cycle was also tweaked during test cases as test operators observed upward or downward trends on the weight scale or refined the actual flow rate. Any metabolic generation rate high enough to require the activation of the nebulizers used the blower full time. The blower cycling caused regular swings in the chamber dew point, which were frequently out of synchronization with the normal slight CAMRAS-induced chamber dew point fluctuations and large CAMRAS outlet dew point fluctuations. To mitigate this effect in determination of test point completion, partway through the test series, the required steady state evaluation period for all test cases was adjusted from a minimum of six CAMRAS half-cycles to a minimum of a whole number of both CAMRAS half-cycles (at least six) and HMS blower duty cycles. In posttest data analysis, the steady-state chamber $H_2O$ vapor levels were calculated as a mathematical moving average of the process loop inlet $ppH_2O$ reading over the previous HMS blower duty period.

During exercise periods, the weight scale under the nebulizer tank typically reported that the net tank weight was slowly trending downward during the entirety of the exercise period, suggesting that the vaporization rate was too high relative to the injection rate. However, due to the highly dynamic nature of exercise metabolic load profiles, it would have further complicated the posttest data analysis if the test operators tried to adjust the water flow rates or nebulizer settings in the middle of the exercise profile, not to mention that it was impractical with the settings changing every 7.5 minutes. As such, exercise test case results must include a caveat that extra water vapor was most likely injected into the chamber atmosphere during the dynamic exercise period, which would have biased the chamber dew point higher than might be predicted. For reference, the target amount of water injected during the active portion of an exercise profile is about 1370 ml, so according to the weight scale differential estimates listed in the various results tables below, the Phase 4B test case injections were up to about 30% high. Then again, human beings are highly variable, so most simulated exercise test case results are only an approximation of any given real crew's metabolic output.

## III. Test Results

### A. Baseline Performance Tests

A baseline set of test cases that have been run in all prior test phases was repeated in CAMRAS Phase 4B. Each standard metabolic rate was tested with the same process flow rate and CAMRAS valve cycle period, and the optimal vacuum available from facility pumps. For Phase 4B, these cases were extended to the additional two principal atmospheric pressures under consideration for Orion (Lunar transit) and Altair (Lunar lander) missions, 10.2 psia and 8.3 psia. Those pressures were selected based on those development programs, which have since been descoped, but the pressures are still likely to be representative of environments for future vehicle development programs that NASA has not yet explicitly defined. The blower flow through the CAMRAS was set to the rate recommended by UTAS (26 acfm), as was the spool valve cycle time (6.5 minutes). The exercise scenario assumes the third CAMRAS unit is completely reserved for emergency operations and that the four crew members exercise in sequence with 15-minute gaps between them. The details of the baseline test cases are described in Table 2.

**Table 2. Baseline performance test conditions.**

| | | | |
|---|---|---|---|
| Simulated Crew Size | 4 | 4 | 4 |
| Simulated Number of Operational CAMRAS Units | 2 | 2 | 2 |
| Chamber Volume | half-Orion | half-Orion | half-Orion |
| Chamber Pressure | 14.7, 10.2, 8.3 psia | 14.7, 10.2, 8.3 psia | 14.7, 10.2, 8.3 psia |
| Chamber Temperature | 70°F | 70°F | 70°F |
| Initial Chamber $CO_2$ Concentration | N/A | N/A | nominal steady |
| Initial Chamber Dew Point | N/A | N/A | nominal steady |
| HMS Crew Size | 2 HSIR | 2 HSIR | 2 HSIR |
| Crew Activity | nominal | sleep | 1½ nominal,<br>½ exercise |
| Total Metabolic $CO_2$ Injection Rate | 0.77 slpm | 0.49 slpm | nominal 0.77 slpm<br>peak 1.91 slpm |
| Total Metabolic $H_2O$ Injection Rate | 2.35 ml/min | 1.26 ml/min | nominal 2.35 ml/min<br>peak 10.69 ml/min |
| CAMRAS Valve Cycle Period | 6.5 min | 6.5 min | 6.5 min |
| CAMRAS Inlet Flow Rate | 26 acfm | 26 acfm | 26 acfm |
| Vacuum Quality | nominal | nominal | nominal |

A nominal metabolic load is a good comparison point for many test cases, and by far, this load represents the majority of the CAMRAS test data collected to date. Sleep metabolic loads present a low-end challenge for the CAMRAS system. At baseline operational settings, a pair of CAMRAS units have been found to overdry the cabin, which could cause discomfort for sleeping crew members. Baseline cases with a sleep metabolic load are a good method of comparing the performance of different CAMRAS units and different test rigs, but they do not necessarily represent the best way to operate a CAMRAS-based environmental control system while the crew is sleeping. Exercise cases are the most difficult to run correctly, and for various reasons the two reduced-pressure baseline cases ended up being cut short, which prevents their endpoint comparison to nominal baseline cases and fourth exerciser-peak points to other exercise cases; the cases could not be rerun due to schedule constraints and late discovery of the problems.

The Phase 4B results presented in Table 3 are more informative when compared to results of previous test series, but space limitation in this conference paper format precludes inclusion of those relevant earlier results. The reader is invited to review the full report on which this paper is based[5] for a more in-depth analysis of these and all other test results presented in this paper.

**Table 3. Baseline performance test results.**

| Metabolic Load Type | Nominal | | | Sleep | | | Exercise | | |
|---|---|---|---|---|---|---|---|---|---|
| Target Chamber Pressure (psia) | 8.3 | 10.2 | 14.7 | 8.3 | 10.2 | 14.7 | 8.3 | 10.2 | 14.7 |
| Average Steady State Chamber Pressure (mmHg) | 436 | 544 | 755 | 440 | 542 | 758 | 438 begin | 542 begin | 757 |
| Average Steady State Chamber Temperature (°F) | 71.5 | 72.4 | 72.1 | 72.1 | 71.7 | 71.6 | not steady | not steady | 71.3 |
| Average Steady State CAMRAS Inlet Flow Rate (acfm) | 27.7 | 27.5 | 27.5 | 27.5 | 27.5 | 27.4 | not steady | not steady | 27.4 |
| Final Steady State $CO_2$ Partial Pressure (mmHg)/ Concentration (%) | 1.37 / 0.31 | 1.34 / 0.25 | 1.28 / 0.17 | 0.83 / 0.19 | 0.81 / 0.15 | 0.77 / 0.10 | not steady | not steady | 1.33 / 0.18 |
| Final Steady State Dew Point (°F)/Relative Humidity (%) | 28.8 / 20.2 | 28.1 / 18.8 | 29.7 / 20.4 | 15.9 / 10.6 | 19.9 / 12.9 | 16.5 / 11.1 | not steady | not steady | 30.0 / 21.3 |
| Final Steady State Cycling Vacuum Pressure (mmHg) | 0.20 | 0.19 | 0.20 | 0.14 | 0.15 | 0.14 | not steady | not steady | 0.21 |
| Exercise Start $CO_2$ Partial Pressure (mmHg) | | | | | | | 1.36 | 1.27 | 1.30 |
| Exercise First Peak $CO_2$ Partial Pressure (mmHg) | | | | | | | 3.32 | 3.38 | 3.14 |
| Exercise Highest Peak $CO_2$ Partial Pressure (mmHg) | | | | | | | 4.27 | 4.13 (high of 3) | 3.87 |
| Exercise Start Dew Point (°F) | | | | | | | 28.5 | 30.9 | 29.4 |
| Exercise First Peak Dew Point (°F)/Relative Humidity (%) | | | | | | | 61.0 / 71.6 | 61.9 / 70.9 | 59.7 / 66.8 |
| Exercise Highest Peak Dew Point (°F)/Relative Humidity (%) | | | | | | | 67.9 / 86.3 | 68.2 / 84.1 (high of 3) | 64.8 / 79.5 |
| Estimated Exercise Period $H_2O$ Discrepancy (scale drop) (ml) | | | | | | | 240 | 220 (3 peaks) | 130 |

These results suggest that $CO_2$ concentration increases as chamber pressure decreases, given essentially the same temperature and process flow rate. The moisture readings seem unrelated to chamber pressure, and exhibit minimal differences that might be attributable to sensor accuracy or minor variations in the water injection rate (the flow controller is discussed in section IV, subsection A, of this paper). As previously noted, the two reduced-pressure exercise cases were not run to a final nominal metabolic load steady state condition. This prevents the comparison of these test cases to nominal baseline cases in this and previous test series. The 10.2 psia case only ran through three of the four exercise peaks, so that case cannot be fully compared to any of the other exercise cases, as the highest peaks often occur during the fourth exercise period.

### B. Degraded Vacuum Performance Tests

Ideally, the vacuum line pressure at the CAMRAS should be as low as possible to maximize $CO_2$ and $H_2O$ desorption off of each bed within the short cycle period. However, the CAMRAS units may not be granted an optimum installation within the vehicle, where the optimum would include a large, short, straight line to space. The importance of the vacuum pressure on the CAMRAS operating performance must be quantified in order to lobby for

CAMRAS vacuum-access proximity as the vehicle is designed, and to understand the performance impacts of higher vacuum line pressure. Past testing has shown that the performance of the CAMRAS unit is highly dependent on vacuum line pressure and conductance. In Phase 4A it was demonstrated that the base pressure (no load) of the vacuum line at the CAMRAS exhaust should not be much above 1 mmHg to enable the CAMRAS to remove $CO_2$ and water vapor fast enough to keep the crew safe in contingency situations such as a single operational CAMRAS for a crew of six, or to marginally keep up with an exercise metabolic load with a crew of four.

It has been hypothesized that there is a point at which flow effects internal to the CAMRAS overwhelm the effects of excellent vacuum during desorption. Further experimental insight was desired, but lower vacuum pressure and/or improved vacuum pumping speed were not practical improvements, as the existing vacuum pump system is already very large. Instead, tests were run with the high metabolic load of exercise periods. Four-person loads in both nominal and exercise levels were tested at the same conditions as the baseline cases, except with a 1 mmHg initial base vacuum pressure (most previous vacuum sensitivity tests were run with a six-person load). Two additional exercise cases were run at 8.3 psia and different base vacuum pressures between the test rig's minimum and 1 mmHg. A 14.7 psia exercise case was also run at an intermediate vacuum pressure for direct comparison with Phase 4A data, but it did not have time to run to steady state. Table 4 describes the specific test case conditions; some of the variants were not achieved within the available facility time.

**Table 4. Degraded vacuum performance test conditions.**

| | | |
|---|---|---|
| Simulated Crew Size | 4 | 4 |
| Simulated Number of Operational CAMRAS Units | 2 | 2 |
| Chamber Volume | half-Orion | half-Orion |
| Chamber Pressure | 14.7, 10.2, 8.3 psia | 14.7, 10.2, 8.3 psia |
| Chamber Temperature | 70°F | 70°F |
| Initial Chamber $CO_2$ Concentration | N/A | baseline nominal steady |
| Initial Chamber Dew Point | N/A | baseline nominal steady |
| HMS Crew Size | 2 HSIR | 2 HSIR |
| Crew Activity | nominal | 1½ nominal, ½ exercise |
| Total Metabolic $CO_2$ Injection Rate | 0.77 slpm | nominal 0.77 slpm<br>peak 1.91 slpm |
| Total Metabolic $H_2O$ Injection Rate | 2.35 ml/min | nominal 2.35 ml/min<br>peak 10.69 ml/min |
| CAMRAS Valve Cycle Period | 6.5 min | 6.5 min |
| Air Flow Rate | 26 acfm | 26 acfm |
| Base Vacuum Pressure (Absolute) | 1.00 mmHg | 1.00, 0.75, 0.5 mmHg |

Table 5 summarizes the results of all of the Phase 4B degraded vacuum test cases. Once again, in the nominal load cases, increasing $CO_2$ levels correlated well to decreasing chamber pressure, and $H_2O$ levels seem to be consistent across the range of pressures. Both constituents ran at slightly higher levels in all cases due to the degraded vacuum pressure used for regeneration of the sorbent. The 14.7 psia, 1.00 mmHg base vacuum exercise case was the first to use the extended steady state period, albeit not completely successfully. While comparisons between the non-1.00 mmHg base vacuum exercise cases cases are limited, the $CO_2$ levels are higher in the 8.3 psia case with higher vacuum pressure than the one with lower pressure, and the steady state $CO_2$ level in the 1.00 mmHg base vacuum pressure exercise case is higher yet, though its peak exercise-period $ppCO_2$ is lower, for unclear reasons. The baseline exercise case in the previous section, with the best vacuum pressure, cannot be compared for steady state conditions, but its $CO_2$ peaks are lower. Likewise, the steady state dew point seems to get slightly higher with increasing vacuum pressure, but the peaks during the exercise period are not as clear a trend. Comparison of the 14.7 psia exercise cases at 0.5 mmHg base vacuum, 1.00 mmHg base vacuum, and baseline exhibits similar patterns that might be a slight trend, but are not entirely clear.

**Table 5. Degraded vacuum performance test results.**

| Metabolic Load Type | Nominal | | | Exercise | | | Exercise | | |
|---|---|---|---|---|---|---|---|---|---|
| Target Vacuum Base Pressure (mmHg) | 1.00 | | | 1.00 | | | 0.75 | 0.50 | 0.50 |
| Target Chamber Pressure (psia) | 8.3 | 10.2 | 14.7 | 8.3 | 10.2 | 14.7 | 8.3 | 8.3 | 14.7 |
| Average Steady State Chamber Pressure (mmHg) | 438 | 528 | 754 | 442 | 557 | 761 | 430 | 434 | 767 dur. exer. |
| Average Steady State Chamber Temperature (°F) | 72.2 | 72.2 | 72.7 | 72.5 | 73.7 | 72.4 | 72.0 | 72.1 | not steady |
| Average Steady State CAMRAS Inlet Flow Rate (acfm) | 27.7 | 27.5 | 27.5 | 27.6 | 27.5 | 27.5 | 27.4 | 27.5 | not steady |
| Final Steady State $CO_2$ Partial Pressure (mmHg)/ Concentration (%) | 1.59 / 0.36 | 1.58 / 0.30 | 1.50 / 0.20 | 1.60 / 0.36 | 1.57 / 0.28 | 1.49 / 0.20 | 1.53 / 0.36 | 1.46 / 0.34 | not steady |
| Final Steady State Dew Point (°F)/Relative Humidity (%) | 30.8 / 21.2 | 30.8 / 21.4 | 31.8 / 21.9 | 31.6 / 21.9 | 31.2 / 20.8 | 29.9 / 20.5 rising slow | 30.8 / 20.0 | 29.3 / 21.7 | not steady |
| Final Steady State Cycling Vacuum Pressure (mmHg) | 1.04 | 1.04 | 1.04 | 1.04 | 1.03 | 1.03 | 0.78 | 0.55 | 0.55 begin |
| Exercise Start $CO_2$ Partial Pressure (mmHg) | | | | 1.62 | 1.58 | 1.45 | 1.47 | 1.49 | 1.39 |
| Exercise First Peak $CO_2$ Partial Pressure (mmHg) | | | | 3.77 | 3.82 | 3.56 | 3.69 | 3.52 | 3.25 |
| Exercise Highest Peak $CO_2$ Partial Pressure (mmHg) | | | | 4.43 | 4.48 | 4.23 | 4.54 | 4.40 | 4.35 |
| Exercise Start Dew Point (°F) | | | | 31.4 | 36.3 | 32.2 | 33.5 | 30.8 | 30.2 |
| Exercise First Peak Dew Point (°F)/Relative Humidity (%) | | | | 61.8 / 71.2 | 63.3 / 72.9 | 61.7 / 57.0 | 62.0 / 64.2 | 61.9 / 65.7 | 61.8 / 61.8 |
| Exercise Highest Peak Dew Point (°F)/Relative Humidity (%) | | | | 68.8 / 85.2 | 68.9 / 83.0 | 67.5 / 69.0 | 69.9 / 79.4 | 69.9 / 82.8 | 68.2 / 70.3 |
| Estimated Exercise Period $H_2O$ Discrepancy (scale drop) (ml) | | | | 250 | 320 | 160 | 315 | 285 | 210 |

### C. Cycle Time and Flow Rate Matrix Performance Tests

The spacecraft cabin $CO_2$ level should ideally be maintained at an average concentration of 1% or less over the long term. The chamber dew point should be maintained above 33°F based on an MPCV requirement to maintain at least 25% relative humidity in the cabin (on daily average) at the typical 70°F target cabin temperature used in these tests. The higher the cabin temperature, the higher the minimum dew point value required to maintain the minimum 25% relative humidity. The higher the relative humidity (up to the maximum dew point), the more comfortable the crew for long durations. The maximum chamber dew point target of 45°F is intended to prevent condensation on the uninsulated MPCV coolant loops, which will run at 47°F. The Orion Project has conceded that condensation may be allowed for transient time periods of high water load, such as during exercise periods, with the assumptions that the water will preferentially condense inside the cabin air heat exchanger (anticipated to be the coldest spot in the cabin) and that the condensed water will evaporate shortly after the high water load period, when the CAMRAS has had the opportunity to return the chamber dew point below the condensation temperature. In general, controlling the dew point within this relatively narrow band has turned out to be the most significant driver when optimizing process flow rate and cycle time in past testing. High $CO_2$ levels were never an issue in nominal scenario tests, so long as the water vapor was sufficiently controlled.

In previous JSC test series, cases were run with a variety of process flow rates and cycle times at each of the metabolic rates in order to characterize the performance of the technology over a wide range of conditions. Data gathered from those tests was used to develop recommendations of system operational settings to maintain the cabin moisture and $CO_2$ levels in the desired ranges while conserving blower power and ullage resource losses. Note that these matrix operational settings are intended to characterize the technology's performance with metabolic rates simulated by the HMS; however, current Orion MPCV system designs are more limited in terms of available flow rates and cycle times. All recommendations were based on using two of the three nominally-available CAMRAS units in a full-size MPCV cabin free volume; the actual tests were run with a single unit in a half-size volume.

Phase 4A tested the recommended settings with CAMRAS unit 3. In Phase 4B those same settings, plus a selection of other combinations, were tested at the additional two principal atmospheric pressures under consideration. A few cases were also run at 14.7 psia to provide direct comparisons for CAMRAS unit 2 and a simulated crew size of four people, where earlier general matrix condition test data was mostly gathered with other units and/or with a simulated crew size of six people. The basic test case conditions of all three types of metabolic loads are the same as those described in Table 2, except the specific chamber pressures, process flow rates, and cycle periods of individual test cases are presented in Table 6; additional variants were intended to be run, but were not achieved within the available facility time. In most of the Phase 4B test cases, the process flow rate at different chamber pressures was maintained constant as an actual flow rate; in other words, the test at each pressure might use 26 acfm, but the standard flow rates natively measured by the flow meters differed, principally because of the pressure difference. Three cases in this section examine the relative performance of the system at different pressures when using the same standard flow rate. The test results of all of the completed matrix settings cases are presented in Table 7 (nominal and sleep loads) and Table 8 (exercise loads).

**Table 6. Phase 4B cycle time and flow rate matrix test case operational conditions.**

| Metabolic Load | Chamber Pressure (psia) | CAMRAS Inlet Flow Rate (acfm) | CAMRAS Valve Cycle Period (min) | Note |
|---|---|---|---|---|
| nominal | 14.7 | 15 | 10 | repeat of CAMRAS Phase 4A recommended conditions with CAMRAS unit 2 |
| nominal | 10.2 | 15 | 10 | 14.7 psia recommended conditions |
| nominal | 8.3 | 15 | 10 | 14.7 psia recommended conditions |
| sleep | 14.7 | 7.5 | 15 | repeat of CAMRAS Phase 4A recommended conditions with CAMRAS unit 2 |
| sleep | 10.2 | 7.5 | 15 | 14.7 psia recommended conditions |
| sleep | 8.3 | 7.5 | 15 | 14.7 psia recommended conditions |
| exercise | 14.7 | 39 | 3 | repeat of CAMRAS Phase 4A recommended conditions with CAMRAS unit 2 |
| exercise | 8.3 | 39 | 3 | 14.7 psia recommended/maximum conditions |
| exercise | 10.2 | 39 | 3 | 14.7 psia recommended/maximum conditions |
| exercise | 10.2 | 39 | 6.5 | |
| exercise | 8.3 | 39 | 6.5 | |
| exercise | 14.7 | 26 scfm | 3 | |
| exercise | 10.2 | 26 scfm | 3 | approximately 37.5 acfm |
| exercise | 8.3 | 26 scfm | 3 | approximately 46 acfm |

**Table 7. Nominal and sleep load recommended settings test results.**

| Metabolic Load Type | Nominal | | | Sleep | | |
|---|---|---|---|---|---|---|
| Target Operational Settings | 15 acfm flow, 10 min cycle | | | 7.5 acfm flow, 15 min cycle | | |
| Target Chamber Pressure (psia) | 8.3 | 10.2 | 14.7 | 8.3 | 10.2 | 14.7 |
| Average Steady State Chamber Pressure (mmHg) | 437 | 527 | 763 | 438 | 527 | 761 |
| Average Steady State Chamber Temperature (°F) | 71.9 | 71.5 | 71.5 | 71.2 | 71.4 | 71.5 |
| Average Steady State CAMRAS Inlet Flow Rate (acfm) | 16.0 | 16.0 | 15.9 | 8.1 | 8.0 | 7.9 |
| Final Steady State $CO_2$ Partial Pressure (mmHg)/Concentration (%) | 2.00 / 0.46 | 1.92 / 0.36 | 1.83 / 0.24 | 2.21 / 0.50 | 2.15 / 0.41 | 2.03 / 0.27 |
| Final Steady State Dew Point (°F)/ Relative Humidity (%) | 40.0 / 31.3 | 39.0 / 30.6 | 37.5 / 28.8 | 42.3 / 35.2 not steady | 42.5 / 35.2 | 40.8 / 32.7 not steady |
| Final Steady State Cycling Vacuum Pressure (mmHg) | 0.18 | 0.18 | 0.18 | 0.11 | 0.11 | 0.10 |

The JSC team's recommended operating conditions for both nominal and sleep metabolic loads meet the specified 25% relative humidity to 45°F dew point range at all three pressures, and keep the $CO_2$ concentration at or below 0.5% at all three pressures. The previously noted trend of higher $ppCO_2$ at lower cabin pressures holds here too, and the dew point seems to exhibit a similar trend, but the differences are small enough that they are within the sensor's nominal error.

**Table 8. Exercise load matrix settings test results.**

| Metabolic Load Type | Exercise | | | Exercise | | | Exercise | |
|---|---|---|---|---|---|---|---|---|
| Target Operational Settings | Recommended: 39 acfm flow, 3 min cycle | | | 26 **scfm** flow, 3 min cycle | | | 39 acfm flow, 6.5 min cycle | |
| Target Chamber Pressure (psia) | 8.3 | 10.2 | 14.7 | 8.3 | 10.2 | 14.7 | 8.3 | 10.2 |
| Average Steady State Chamber Pressure (mmHg) | 418 | 524 | 748 | 429 | 533 | 761 | 428 | 533 |
| Average Steady State Chamber Temperature (°F) | 74.4 | 74.1 | 74.0 | 76.0 | 73.6 | 72.2 | 74.3 | 73.3 |
| Average Steady State CAMRAS Inlet Flow Rate (acfm/scfm) | 41.3 | 41.1 | 40.9 | 50.3 / 25.5 | 40.7 / 26.0 | 28.2 / 26.0 | 41.5 | 41.2 |
| Final Steady State $CO_2$ Partial Pressure (mmHg)/ Concentration (%) | 1.07 / 0.26 | 1.02 / 0.19 | 0.96 / 0.13 | 0.99 / 0.23 | 1.04 / 0.20 | 1.18 / 0.16 | 1.17 / 0.27 | 1.13 / 0.21 |
| Final Steady State Dew Point (°F)/ Relative Humidity (%) | 24.4 / 14.7 | 21.8 / 13.2 | 23.6 / 14.4 | 21.7 / 12.3 | 23.1 / 14.3 | 28.8 / 19.5 | 24.3 / 14.8 | 24.3 / 15.3 |
| Final Steady State Cycling Vacuum Pressure (mmHg) | 0.24 | 0.22 | 0.24 | 0.23 | 0.23 | 0.24 | 0.19 | 0.19 |
| Exercise Start $CO_2$ Partial Pressure (mmHg) | ~1.3 not steady | ~1.2 not steady | 1.02 | 1.05 | 1.18 | 1.22 | 1.19 | 1.17 |
| Exercise First Peak $CO_2$ Partial Pressure (mmHg) | 2.88 | 2.92 | 2.60 | 2.85 | 2.86 | 3.01 | 3.19 | 3.20 |
| Exercise Highest Peak $CO_2$ Partial Pressure (mmHg) | 3.30 | 3.32 | 3.05 | 3.12 | 3.38 | 3.58 | 3.95 | 3.80 |
| Exercise Start Dew Point (°F) | ~23 not steady | ~23 not steady | 24.4 | 26.8 | 28.4 | 31.1 | 26.5 | 25.7 |
| Exercise First Peak Dew Point (°F)/ Relative Humidity (%) | 57.3 / 62.5 | 57.6 / 61.7 | 55.1 / 50.7 | 56.0 / 50.2 | 58.3 / 59.1 | 59.8 / 63.4 | 60.0 / 56.6 | 60.2 / 61.1 |
| Exercise Highest Peak Dew Point (°F)/ Relative Humidity (%) | 63.0 / 72.9 | 63.1 / 73.2 | 60.6 / 57.8 | 61.7 / 61.2 | 63.7 / 69.8 | 65.8 / 71.9 | 67.4 / 77.1 | 66.2 / 72.8 |
| Estimated Exercise Period $H_2O$ Discrepancy (scale drop) (ml) | 315 | 395 | 200 | 360 | 410 | 180 | 365 | 410 |

The exercise matrix case results show that the recommended settings case dew points exceeded the nominal Orion coolant loop temperature, as expected, but the shorter cycle time induced lower peak dew points than in the model projection cases or the baseline cases. As discussed in other test reports, spreading the exercise periods further apart than the tested 15 minutes would further reduce the peaks after the first exerciser. The excess water vapor generation in these cases also artificially inflates the peak exercise-period moisture values. Likewise, the $CO_2$ concentration peaked well above the ideal maximum of 0.5%, but still comfortably below 1%, but spreading the exercise periods out would reduce the maximum value. The steady state moisture levels are below the target range, but these recommended operational settings are tuned only for the exercise period; the intent would be to switch back to the nominal load recommended settings shortly after the last exerciser completed his or her cooldown period and after the cabin dew point was back down within the target range.

For most of these test cases, the mass of gas flowing through the CAMRAS at the lower chamber pressures was reduced because the volumetric flow rate was held constant while the air density decreased. In these cases, the single-pass efficiency was roughly the same at all three pressures, but less mass flowing through the bed meant less mass was available to be adsorbed. Meanwhile, the mass injection rate of the metabolic constituents was unchanged. Therefore, at lower chamber pressures, the injection rate was effectively higher relative to the total chamber gas mass. In the middle three cases above, the lower the pressure, the higher the actual volumetric flow rate; the mass flow rate through the CAMRAS stayed constant. Higher volumetric flow rates mean higher linear velocities, meaning that as the pressure decreased, the gas had less time in the bed to be adsorbed, and the lower the single-pass eficiency. However, it also means that the fixed volume of air in the chamber was moved through the sorbent beds more often. The test results show that more passes through the bed overwhelmed both the effects of less time on each pass and the proportionally higher metabolic mass injection rates. These three cases show net lower quantities of both $CO_2$ and $H_2O$ vapor as the pressure was decreased, although the $CO_2$ was not scrubbed quite fast enough to reduce its relative proportion (concentration) as well as its simple quantity ($ppCO_2$). The Orion blower is currently expected to operate at a set rotation rate rather than a particular standard flow rate, and that control system should allow consistent actual flow rates, like the majority of the test scenarios presented in this paper.

The right two columns of results in Table 8 show higher constituent levels than in the left three columns, but lower than the baseline cases in Table 3. In the past it has been observed for the smaller metabolic rates of nominal and sleep loads that increasing the flow rate through the CAMRAS greatly reduces the ultimate levels of $CO_2$ and moisture in the air, while decreasing the cycle time also reduces them, but not as drastically. However, exercise loads are so high and so water-heavy that the difference between the constituent peaks in the Phase 4B case sets with half again as much flow rate and the same cycle period is on the order of only half as much as the difference between the case sets with just under half the cycle period and the same flow rate. Stated another way, for exercise cases, a shorter cycle period buys you more margin on the peaks than does an increased flow rate, but a combination of both shorter cycles and higher flows is still best. Then again, the shorter cycle period also comes with higher ullage losses of the cabin air, and higher flow rates require more power and generate more noise and heat, so a balance must be sought.

### D. Orion Project Model Projection Validation Tests

UTAS developed a set of anticipated MPCV cabin and atmosphere revitalization system operation conditions for the prime contractor, Lockheed Martin, using a computer model. Two different information releases on these cases were received by the JSC team, but the latter release did not contain several nominal operation scenarios, so the earlier results were used as the basis of these tests. To provide context for relating the results of the battery of JSC tests to UTAS's models, JSC ran several test cases specifically emulating the UTAS model conditions. All of these test cases were previously run in Phase 4A at ambient pressure. However, the model conditions specify reduced pressure for the four-person crew cases, which only the Phase 4B test rig could replicate.

A full set of representative metabolic cases was tested, in addition to a case simulating a large crew struggling into or out of their space suits. The exercise and don/doff cases were run at a constant average metabolic rate, unlike the standard JSC exercise cases, which use a profile of increasing and decreasing water and $CO_2$ injection rates for exercise scenarios. The vacuum system provided a space simulation pressure on par with that assumed by the Orion models, about 0.6 to 0.7 mmHg base pressure. Hamilton's models assume that the third CAMRAS unit is used in heavy moisture loading conditions and that 78 acfm of available air flow is divided between the three parallel units. However, the Phase 4B JSC test rig was limited to a single test article and a physical configuration that could only halve the Orion-equivalent chamber volume. The JSC tests therefore modified the Hamilton conditions for two test cases (suit don/doff and exercise) by assuming that the third vehicle CAMRAS unit would be completely reserved for emergency capability. The Hamilton models also assume that only one CAMRAS unit will operate during sleep cases; the JSC test reflected that assumption by using the single test article in the full chamber volume with the full metabolic rates. The conditions and results for the model projection validation tests are described in Table 9.

**Table 9. Orion model projection validation test conditions and results.**

| | | | | | | |
|---|---|---|---|---|---|---|
| Simulated Crew Size | 4 | 6 | 4 | 6 | 4 | 6 |
| Crew Activity Type | nominal | nominal | sleep | sleep | exercise (average) | don/doff (average) |
| Chamber Volume | half-Orion | half-Orion | full-Orion | full-Orion | half-Orion | half-Orion |
| Simulated Number of Operational CAMRAS Units | 2 | 2 | 1 | 1 | 2 | 2 |
| Target Chamber Pressure (psia) | 10.2 | 14.7 | 10.2 | 14.7 | 10.2 | 14.7 |
| Target Chamber Temperature (°F) | 75 | 75 | 70 | 70 | 80 | 80 |
| Target HMS Crew Size and Heat Load (Btu/hr) | 2 @ 500 | 3 @ 500 | 4 @ 300 | 6 @ 300 | 2 @ 781 | 3 @ 612.5 |
| Total Metabolic $CO_2$ Injection Rate (slpm / lbm/hr) | 0.82 / 0.202 | 1.22 / 0.302 | 0.98 / 0.242 | 1.46 / 0.362 | 1.27 / 0.315 | 1.50 / 0.370 |
| Total Metabolic $H_2O$ Injection Rate (ml/min / lbm/hr) | 3.51 / 0.464 | 5.26 / 0.696 | 2.03 / 0.269 | 3.05 / 0.404 | 8.32 / 1.101 | 8.78 / 1.162 |
| CAMRAS Valve Cycle Period (min) | 10 | 5 | 26 | 16 | 5 | 5 |
| Target CAMRAS Inlet Flow Rate (acfm) | 26 | 26 | 26 | 26 | 39 | 39 |
| Target Vacuum Base Pressure (mmHg) | 0.6 – 0.7 | 0.6 – 0.7 | 0.6 – 0.7 | 0.6 – 0.7 | 0.6 – 0.7 | 0.6 – 0.7 |
| Average Steady State Chamber Pressure (mmHg) | 534 | 762 | 531 | 762 | 534 | 760 |
| Average Steady State Chamber Temperature (°F) | 72.7 | 74.9 | 72.1 | 71.8 | 80.7 | 79.1 |
| Average Steady State CAMRAS Inlet Flow Rate (acfm) | 27.9 | 27.7 | 27.5 | 27.6 | 41.7 | 41.6 |
| Model Projected $ppCO_2$ (mmHg) | 1.54 | 2.21 | 2.47 | 4.06 | 1.52 | 1.80 |
| Final Steady State $CO_2$ Partial Pressure (mmHg)/ Concentration (%) | 1.64 / 0.31 | 2.34 / 0.31 | 4.17 / 0.79 | 5.04 / 0.66 | 2.29 / 0.43 | 2.77 / 0.36 |
| Model Projected Dew Point (°F) | 43.9 | 51.7 | 34.8 | 40.8 | 53.8 | 55.2 |
| Final Steady State Dew Point (°F)/Relative Humidity (%) | 42.1 / 33.2 | 50.0 / 41.7 | 35.0 / 25.7 | 39.1 / 30.4 | not steady | 58.6 / 49.5 |
| Final Steady State Cycling Vacuum Pressure (mmHg) | 0.67 | 0.74 | 0.61 | 0.66 | 0.77 | 0.83 |

Both of the nominal cases yielded slightly higher $CO_2$ levels and slightly lower dew points than the model predicted, but they are relatively close. The 4-person nominal case is best compared to the JSC team's recommended condition results at 10.2 psia in Table 7. The JSC team assumed better vacuum and the same cycle period, but would use less power for the blower in exchange for the better vacuum pressure. The resultant $CO_2$ levels are similar, around one-third of one percent concentration, and the steady state dew point is higher in this model validation case, which is most likely a result of a significantly higher assumed water injection rate.

Both of the sleep cases yielded significantly higher $CO_2$ levels and comparable dew points relative to the model predictions. The 4-person sleep case is best compared to the JSC team's recommended condition results at 10.2 psia in Table 7. The JSC team assumed better vacuum and higher moisture injection rates; the resultant $CO_2$ levels are significantly lower in the JSC-recommended case, and the steady state dew point is quite a bit lower in this model validation case. The JSC team's recommendation would use more ullage by cycling more frequently, but much less power for the blower; the JSC team's plan also has the advantage of keeping both beds of the main two units evenly loaded and ready to respond most effectively to contingency situations, while the model's plan would saturate one of the two beds of the idle unit, which would then take roughly an hour to rebalance when its cycling was started again.

Unfortunately, the moisture readings for the exercise case were unusable as test results, as they were highly unsteady and the error went undiscovered until after the test series was ended. The high-load cases are not directly comparable to any of the JSC-recommended cases due to the very different injection rate strategies, but they can still be compared to the model's projected results. The $CO_2$ levels in the test cases ended up significantly higher than the model predicted, but these tests simulated the use of 2 CAMRAS units, while the model simulated the use of 3 units, so some differences are expected. The moisture levels were a little higher than predicted, and probably would have been somewhat lower than predicted if the third CAMRAS unit could have been simulated in testing.

### E. Co-adsorption Tests

JSC modeling staff have developed computer models of the CAMRAS technology performance based on data gathered in past JSC test series. In order to validate the models, occasional test cases are requested to replicate the inputs to a model case and see how closely the results of an actual test match the model's predictions. The modeling team requested three test cases as part of CAMRAS Phase 4B testing, and the cases can also be used to compare the removal rates of $CO_2$ and water vapor separately versus together. Past testing has showed a slight co-adsorption effect, although it may be partially or wholly attributable to bed temperature differences; bed temperature swings are driven much more strongly by water vapor adsorption and desorption than by that of $CO_2$.

Instead of injecting water vapor and $CO_2$ into the chamber at metabolic rates and waiting to find out the steady state conditions, like all of the cases described in previous sections, these cases specified chamber conditions and sought out the correct HMS constituent injection rates to maintain those steady state conditions while the CAMRAS operated. These particular test cases were run with relatively long cycle times. The JSC model predictions of the injection rates required to maintain steady chamber conditions are included along with the test case details and results in Table 10.

**Table 10. Co-adsorption test conditions and results.**

| | | | |
|---|---|---|---|
| Chamber Volume | full-Orion | full-Orion | full-Orion |
| Target Chamber Pressure | 10.2 psia | 10.2 psia | 10.2 psia |
| Target Chamber Temperature | 75°F | 75°F | 75°F |
| Target $CO_2$ Concentration ($ppCO_2$) | 0.57% (3 mmHg) | 0.00% | 0.57% (3 mmHg) |
| Target Dew Point | very dry (<-20°F) | 50°F | 50°F |
| CAMRAS Valve Cycle Period | 20 min | 20 min | 20 min |
| Target CAMRAS Inlet Flow Rate | 10 acfm | 10 acfm | 10 acfm |
| Vacuum Quality | nominal | nominal | nominal |
| Average Steady State Chamber Pressure | 531 mmHg | 529 mmHg | 530 mmHg |
| Average Steady State Chamber Temperature | 73.6°F | 74.4°F | 74.6°F |
| Average Steady State CAMRAS Inlet Flow Rate | 10.6 acfm | 10.7 acfm | 10.7 acfm |
| Model Predicted $CO_2$ Injection Rate | 0.89 slpm | 0 slpm | 0.94 slpm |
| Test Final $CO_2$ Injection Rate | 0.84 slpm | N/A | 0.83 slpm |
| Final Steady State $CO_2$ Partial Pressure / Concentration | 2.99 mmHg 0.56% | 0.01 mmHg 0.00% | 3.04 mmHg 0.57% |
| Model Predicted $H_2O$ Injection Rate | 0 ml/min | 2.30 ml/min | 2.30 ml/min |
| Test Final $H_2O$ Injection Rate | N/A | 2.37 ml/min | 2.42 ml/min |
| Final Steady State Dew Point/Relative Humidity | offscale low and dropping | 50.0°F 42.4% | 50.1°F 42.1% |
| Final Steady State Cycling Vacuum Pressure | 0.08 mmHg | 0.05 mmHg | 0.12 mmHg |

As was observed in a similar test group with single constituents and then both constituents at targeted levels in earlier testing, there does appear to be a small effect on the adsorption of the individual constituents when combined in a normal environment as compared to when they are evaluated individually. In Phase 4B, the $CO_2$ adsorption rate was very slightly lower in combination with water vapor than without, while the water vapor seemed to be better adsorbed when combined with $CO_2$ than it was alone. In the earlier testing, the differences were more pronounced for $CO_2$, and water vapor was better alone. However, there were a few major differences in the two tests, any of which could have an effect. The 4B tests were run at 10.2 psia chamber pressure, while the earlier tests were run at ambient; the results in all of the above sections have suggested that $CO_2$ adsorption is reduced at reduced chamber pressure, while water vapor adsorption remains generally unaffected. The earlier co-adsorption tests had somewhat higher cycling vacuum pressures, about 0.3 mmHg for the individual constituents and 0.6 mmHg for the combination, and the efficiency of water removal has previously been shown to fall off more quickly with vacuum pressure than does the $CO_2$ removal efficiency. The earlier single constituent cases were also run at a much higher chamber temperature, which, like degraded vacuum pressure, has been shown to reduce the efficiency of water removal faster than it does $CO_2$ removal. Therefore, with lower chamber temperature and lower cycling vacuum pressure, one would expect the water vapor removal to be better in these Phase 4B cases than in the earlier series cases.

The components of the model used to generate the predicted results in this case are not known to the JSC test team. The earlier test results suggest that the combined $CO_2$ removal rate should be lower than the individual removal rate, and that was again reflected in these results, but the model predicted the reverse relationship and overall higher removal rates. The water injection rates were predicted to be the same, but both sets of test results showed differences, albeit in opposite directions.

## IV. Data Analysis Challenges

### A. Additional HMS Operational Challenges

A major source of uncertainty in this test series is related to the performance of the new HMS. The system used in most prior tests, while far from perfect, was at least reasonably well understood and integrated with the rest of the test rig. However, it was not suited to operate with a reduced-pressure test chamber. Ideally for the new HMS operation, the combined evaporation and nebulization rates should precisely match the liquid water injection rate, and the weight on the internal reservoir's scale should remain unchanged. Unfortunately, the real world is rarely ideal, plus this device was newly developed, then tested under time duress in a different chamber; it became apparent soon after test start that the settings weren't quite right, so there were several challenges. Refinement efforts were attempted as testing started, but there were still inconsistent discrepancies over time.

One of these discrepancies discovered in testing was that the water flow controller was behaving inconsistently, and afterward it was found to be oversized for these tests and a more appropriate model had become available since the original was purchased. There may also have been air bubbles trapped in the lines. To compensate for these flow controller issues, users set the desired flow rate, then manually spot-checked the rate with a stopwatch and graduated cylinder dripping water from the bypassed line. Adjustments to an extra software setting could then subtly adjust the computer control of the flow controller to generate the targeted flow rate. Unfortunately, the flow check was purely manual and temporarily diverted the water flow from the chamber; there are only non-comprehensive manual log records of when and for how long the flow was checked, the test operators did not check the flow on any particular pattern of times, and sometimes (early in the series) the flow was checked during critical phases, such as during an exercise profile. After the test it was discovered that the value of this extra setting was not recorded in the HMS automatic data file, so it, too, is subject to the uncertainty of manual log entries.

### B. Chamber Pressure and $O_2$ Partial Pressure Inconsistency

In post-test data processing it was found that the steadiness of the chamber pressure and $ppO_2$ during any given test case was generally poor. By design, the gross chamber pressure was not to be deliberately manipulated with the vacuum or repressurization systems during a test case. However, the CAMRAS was always subjecting the atmosphere to gas losses from leakage and ullage; the HMS was usually injecting water vapor and gaseous $CO_2$ into the chamber; the chamber was subject to some small seal leakage to and from the ambient building air; changing temperature of the atmosphere inside the chamber, particularly during exercise cases, induced some natural pressure rise and fall; and the manual make-up gas injection state was not exhaustively monitored. All of these factors conspired to create chamber pressure and $ppO_2$ conditions that were decidedly not steady state in most of the cases. All steady-state chamber pressure and temperature values presented in this report are simply averages of the instantaneous values during the steady state periods.

### C. Dew Point Pressure Sensitivity

Post-test consultation with the vendor of the probe-type dew point sensors revealed that the sensors are slightly susceptible to pressure-based error, but the error should induce a reading bias of less than 1.5°C low at the lowest test pressure.

### D. $CO_2$ and $H_2O$ Sensor Array Reading Spread

Several $CO_2$ probe sensors in series in the process loop frequently exhibited different readings (near or outside manufacturer accuracy limits) despite there being no components between them that should affect $CO_2$ level. These sensors are known to be influenced by the surrounding pressure, so an in-house static comparison method was used to create calibration curves for the reduced pressures in use during this test series, which could add another layer of uncertainty. The moisture sensors downstream of the CAMRAS exhibited a similar range of values relative to one another when they should be reading the same value. When checked in static conditions at the beginning of testing, both types of sensors were within the manufacturer's accuracy limits, but the array of sensors covered much or all of the full extent of a centered ± error range. Comparison of periodic grab sample spectra to $CO_2$ and $H_2O$ instrument readings from the equivalent locations in the process loop showed generally good correlation.

### E. Outlet Dew Point Reading Shift

For an as-yet unknown reason, most of the in-line moisture sensors downstream of the CAMRAS shifted their relative reading bias to one another early in the no-water co-adsorption case, and that shift appeared to be persistent in all subsequent test cases. Luckily, two runs of the Orion Project Model Validation 6-person sleep case had been done, one right before the co-adsorption cases and one right after them, so the differences can be clearly seen in two case runs that ought to have been more or less identical. Comparing the moisture steady state periods of the two cases can relate the effects of this dew point shift to the majority of cases that were run before the shift and the few cases that were run afterward. Test results after the dew point shift were adjusted slightly to counter the sensor shift, but the adjustments are only apparent in calculated operational efficiency results, which have not been included in this paper.

### F. Effects of the Grab Sample System

The CAMRAS Phase 4B test rig was equipped with sample lines at the inlet and outlet that could be flushed and connected to a sample container outside the chamber for offline analysis. Partway through the test series it was discovered that turning on the line heaters and/or the sample pumps for the sample lines in preparation for taking a sample frequently caused a downward step change in the HMS tank's weight scale reading, and there was not a corresponding upward step change in the reading when the heaters were turned off. There may have been correlating minor upward ticks in the chamber dew point, but they were not consistently observed. Complicating this assessment is the fact that the sample line heaters and sample pumps were manually controlled and the data from the sampling system was not automatically recorded, so the manual event logs must be relied upon to try to determine correlations. Shortly into the test series the team shifted to try to take final grab samples after the end of the steady state period to avoid the associated data complications. Where possible, any effect of the sample system was avoided in the selection of steady state periods for the presentation of the data in the reports.

## V. Conclusion

In conclusion, CAMRAS-controlled steady state $ppCO_2$ levels seem to correlate very well to chamber pressure: operation at lower chamber pressures yields higher stable $CO_2$ partial pressures and concentrations, assuming equivalent actual flow rates. The same-scfm cases further prove this relationship by yielding relatively lower $CO_2$ partial pressures at lower chamber pressures. It should be noted, however, that although it is unlikely, it is possible that the $CO_2$ removal change could also or instead be related to changing $O_2$ concentration in the process stream. The Phase 4B test series was not designed to decouple the effects of changing atmospheric pressure and changing oxygen concentrations.

CAMRAS water vapor removal seems to be largely unrelated to chamber pressure. Although there are slight differences between test cases at different pressures, they are not consistent, nor can they be said to be significant, as the manufacturer specifies the accuracy of the inlet sensor as approximately ±1.5°C or better for most of the range of the test results, not accounting for any pressure sensitivity.

In previous test series, it was observed that at ambient pressure and flow rates above approximately 10 scfm, $CO_2$ saturation (when outlet concentration rises to match inlet concentration) occurs at about 20 minutes of continuous bed exposure. At lower flow rates, however, the saturation takes longer. This suggests that the $CO_2$ adsorption rate and quantity are limited, and at ambient pressure and moderate to high flow rates through the bed, the mass of $CO_2$ flowing through the bed exceeds the mass that the bed can adsorb in the time available, such that the reaction continues at its maximum rate until it hits its maximum mass, which takes about 20 minutes. At lower pressure, a given volume of air flowing through the bed contains less mass, and for most Phase 4B cases, the flow rates were controlled volumetrically (lower scfm, equivalent acfm), so the overall $CO_2$ level ended up being higher than the equivalent operational conditions at higher atmospheric pressure. The sorbent has a strong affinity for water vapor, and has previously been observed to take on the order of an hour to saturate a CAMRAS bed. Water vapor adsorption may even be slightly preferential, as demonstrated in the Phase 4B co-adsorption cases. The result of this is that the sorbent still appears to capture essentially as much water vapor at lower pressures as at higher pressures. However, it is unknown if there is a lower pressure limit where this relationship may change.

The computer models developed by the Orion Project seem to relate moderately well to real-world test results, but the JSC test team believes that its own recommended operational conditions should be seriously considered as viable alternates to the Project model's propositions, as a potentially better balance of system functionality, power use, heat and noise generation, ullage losses, and maintenance of the cabin conditions within the target ranges.

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