44th International Conference on Environmental Systems
13-17 July 2014, Tucson, Arizona Paper Number

Amine Swingbed Payload Testing on ISS

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One of NASA Johnson Space Center's test articles of the amine-based carbon dioxide (CO_2) and water vapor sorbent system known as the CO_2 And Moisture Removal Amine Swing-bed, or CAMRAS, was incorporated into a payload on the International Space Station (ISS). The intent of the payload is to demonstrate the spacecraft-environment viability of the core atmosphere revitalization technology baselined for the new Orion vehicle. In addition to the air blower, vacuum connection, and controls needed to run the CAMRAS, the payload incorporates a suite of sensors for scientific data gathering, a water save function, and an air save function. The water save function minimizes the atmospheric water vapor reaching the CAMRAS unit, thereby reducing ISS water losses that are otherwise acceptable, and even desirable, in the Orion environment. The air save function captures about half of the ullage air that would normally be vented overboard every time the cabin air-adsorbing and space vacuum-desorbing CAMRAS beds swap functions. The JSC team conducted 1000 hours of on-orbit Amine Swingbed Payload testing in 2013 and early 2014. This paper presents the basics of the payload's design and history, as well as a summary of the test results, including comparisons with prelaunch testing.

Nomenclature

CAMRAS	=	CO_2 And Moisture Removal Amine Swing-bed
cfm	=	cubic feet per minute, unit of volumetric flow
CO_2	=	carbon dioxide
ECLSS	=	Environmental Control and Life Support Systems
ESCG	=	Engineering and Science Contract Group
EXPRESS	=	Expedite the PRocessing of Experiments to the Space Station
°F	=	degrees Fahrenheit, unit of temperature
g	=	grams, unit of mass
hr	=	hour
ICES	=	International Conference on Environmental Systems
ISIS	=	International Subrack Interface Standard
ISS	=	International Space Station
JETS	=	JSC Engineering, Science, and Technology contract
JSC	=	Johnson Space Center
lbm	=	pounds mass, unit of mass
min	=	minutes
mmHg	=	millimeters of mercury, unit of pressure
NASA	=	National Aeronautics and Space Administration
$ppCO_2$	=	partial pressure of CO_2
ppH_2O	=	partial pressure of water vapor
psia	=	pounds per square inch absolute, unit of pressure

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VES = Vacuum Exhaust System

I. Background and Payload Development History

UNITED Technologies Aerospace Systems has spent many years developing amine-based, vacuum-regenerated adsorption systems an alternative to traditional spacecraft atmospheric CO_2 sorption systems. The current iteration of the system, the CAMRAS, uses a pair of interleaved-layer beds filled with SA9T, which is a sorbent system comprised of highly porous plastic beads coated with an amine. SA9T is a good CO_2 sorbent and has a great affinity for water vapor. The beds in this system require no supplemental heating or cooling and, furthermore, interleaving the bed layers uses thermal links to minimize total cabin heat loads from the adsorption and desorption processes. One linear multiball valve rotates 270° back and forth, via a small stepper motor, to control the flows of air and vacuum to the adsorbing and desorbing beds. One compact unit, provided good process air flow and high vacuum conductance, can control the atmospheric CO_2 to a safe level for up to six crew members for extended periods at the cost of small ullage air losses when the beds switch functions and the loss of adsorbed atmospheric water (and potential water from CO_2 reduction) vented overboard during regeneration. Figure 1 shows photos of CAMRAS Unit 3 as modified for this payload application. The large red block on the top of the unit is the rotary multiball valve, and the long metal block hanging off one end is the motor and gear reducer that rotate the valve 270° from one position to the other. The sorbent canister is the block of vertical bed layers comprising the bottom two-thirds of the unit. The curved plumbing lines and triangular structures on the valve block and sides of the canister are flow manifolds.

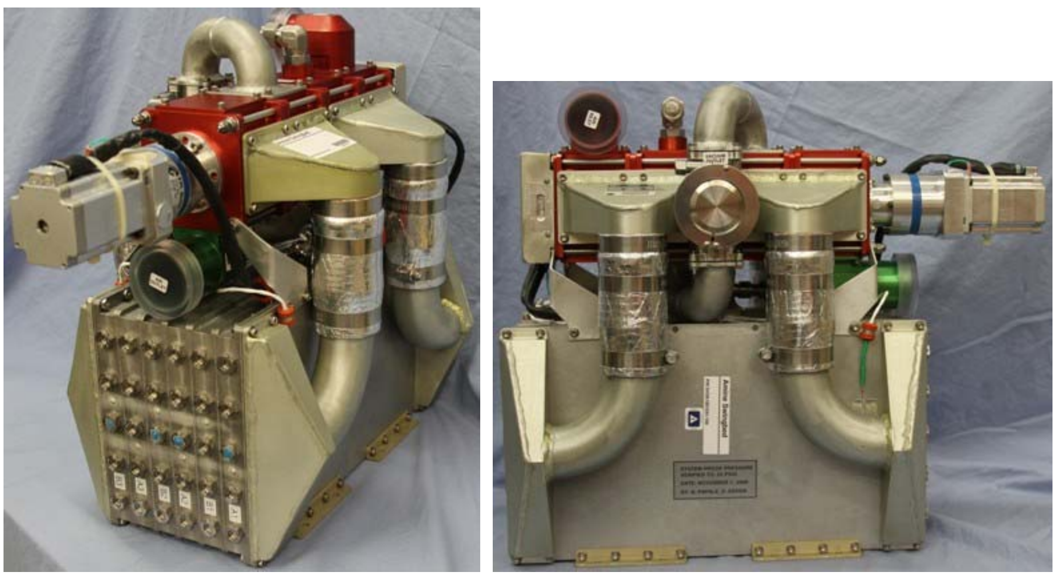

Figure 1. Amine Swingbed, also known as CAMRAS Unit 3.

The CAMRAS technology has been tested on the ground at Johnson Space Center (JSC) since 2006. Tests have included ambient- and reduced-pressure sealed cabin environments with simulated human metabolic loads, and an ambient-pressure sealed cabin environment with four or six humans. Tests have also included an extravehicular activity environment with simulated metabolic loads, and closed-loop emergency mask and space suit environments with humans. Results of each round of testing have been published in papers at the International Conference of Environmental Systems (ICES).[1-4] In early 2010, ISS Program management requested that one of the engineering demonstration units undergoing ground tests be integrated into a payload package and flown as an experiment and technology demonstration on the ISS. This effort would also help ensure that the baselined CO_2 removal technology for the Orion Multipurpose Crew Vehicle is viable in a microgravity spacecraft environment.

A. Payload Hardware Development

Upmass was available on Japanese transport vehicle HTV2, and a soft-packaging slot was reserved for CAMRAS Unit 3. However, the late-delivery deadline was July 2010, less than six months from the initiation of the project, which was insufficient time to perform necessary modifications to the laboratory test unit and design, build, and test all of the support equipment needed to run it as a payload for 1000 hours. The payload development process normally takes approximately three years. The payload team agreed to ship the CAMRAS itself on this short deadline, and was asked to provide some minimal support equipment with it so that it could be used in a contingency situation on the ISS. The team developed a few simple pieces of equipment that would allow the CAMRAS unit to be hooked up to a standard power supply, to an ISS onboard spare Avionics Air Assembly for process air flow, and to a vacuum hose connection to the Lab or Japanese Experiment Module Vacuum Exhaust System for regeneration. Two mounting plates could tie all the equipment together and attach to the back plane of any half-empty International Standard Payload Rack. The laboratory CAMRAS controller was modified to allow automated operation at any of four switch-selectable cycle periods, and was included in the shipment. This "Phase A" set of equipment, aside from the CAMRAS itself, was not officially certified for operation, but had been sufficiently tested and documented to be approvable real-time for contingency operations. The Phase A hardware launched on HTV2 in January 2011.

Once the CAMRAS and the rest of the Phase A hardware had been shipped, the team began rapid development of the "Phase B" hardware. Phase B included a double locker volume, an International Subrack Interface Standard (ISIS) drawer, and assorted cables to connect the locker and drawer to each other and to an Expedite the PRocessing of Experiments to the Space Station (EXPRESS) rack. The CAMRAS would be installed inside the double locker on orbit, joining all of the process loop, air save, water save, air temperature control, vacuum, and sensor hardware needed to run 1000 hours of payload experiments. The ISIS drawer contains most of the electronics, including power handlers, CO_2 sensor electronics, vacuum valve controls, and main controller. The Phase B hardware was shipped as late as possible, in April 2011, and launched on the final Space Shuttle mission in July 2011.

B. Payload On-orbit Activation and Troubleshooting

The Phase A operations configuration has not yet been needed, although some individual hardware pieces were used to check out the CAMRAS before it was installed into the double locker. These checkouts ensured that the complex interior pressure-containing structures of the CAMRAS, which had been built for the ground laboratory environment rather than launch loads, had survived the trip to orbit intact. During the initial CAMRAS integrity check in January 2012, in which the new ISIS drawer controller was being used with the CAMRAS for the first time, the CAMRAS valve moved a only fraction of a turn and then stopped. After extensive troubleshooting, data analysis, and research, it was determined that the valve motor had drawn too much current and blown a fuse inside the ISIS drawer. The problem was traced to the motor, which appeared to have different electrical specifications than the team had been led to believe. The laboratory controller had a different control scheme for its electronics that was not sensitive to this particular variance, so it was not detected before launch. The ISIS drawer controller had been developed based solely on the manufacturer's current specifications for that motor model, the CAMRAS itself no longer being available for ground testing. A replacement motor and gear reducer stack was launched to the ISS as a last-minute Soyuz item and installed on the CAMRAS unit, and a new fuse was soldered atop the burnt-out fuse inside the ISIS drawer controller on orbit. The payload team was immensely fortunate and thankful to have the expertise of Astronaut Dr. Don Pettit to perform most of those operations, as well as the eventual successful checkout of the CAMRAS unit's integrity and its subsequent installation into the double locker in June 2012 (Figure 2).

Figure 2. Amine Swingbed installed inside the double locker.

The ground operations team then started checkouts of the system and its individual effectors prior to initiating normal experiment operations. It soon became apparent that the CAMRAS valve was not moving as smoothly or consistently end-to-end as it should. Operations again stood down to research and troubleshoot the problem. Eventually, in January 2013, the double locker was pulled out of the rack and, without removing the CAMRAS from the locker, the set screws connecting the gear reducer to the valve drive key were tightened. A video camera was set up so that the ground team could watch the valve position indicator's movements during the post-repair checkout; unfortunately, the valve was still sticking, and then it again stopped altogether. Thankfully, this time the data and the crew member verified that the motor was turning and drawing the expected amount of current; the motor rotattion just wasn't being realized as valve rotation. The ground team went back to the fault tree for one last opportunity to fix the problems.

The team now suspected that the set screws on the connections at *both* ends of the new motor and gear box stack had been initially undertightened, and that there may have also been a manufacturing problem with that gear box, causing it to occasionally bind. The solution in February 2013 was to have the on-board crew remove the CAMRAS from the double locker and replace the new gear reducer with the original gear reducer. When the rebuilt valve drive was tested, everything moved smoothly and repeatably, to everyone's relief and delight. The CAMRAS was reinstalled in the double locker in March 2013, a minor onboard software update was performed in April, and checkouts began again in May. The Amine Swingbed Payload has run smoothly since then, and completed its 1000 hours of experimental operations in February 2014.

II. Amine Swingbed Payload Description

Figure 3 shows the Amine Swingbed Payload double locker and ISIS drawer and Figure 4 shows the entire payload as installed on the ISS. The ISS crew nominally has no interface with the payload, except for occasional cleaning of the inlet filter screen. The software is designed to run the payload autonomously after an initial startup command from the ground, and simply shut the payload down and leave it in an idle monitoring state if any of four dozen faults are detected.

Figure 3. Amine Swingbed Payload: double locker and ISIS drawer control unit before launch.

Figure 4. Amine Swingbed Payload installed in EXPRESS rack 8, in the LAB1P4 location.

Figure 5 shows the process flow inside the payload double locker. Air flows into the Amine Swingbed Payload via a debris-filtered line from the ISS Lab atmosphere. A slowly rotating, regenerable desiccant wheel dries and heats the inlet air, which is then recooled by a pair of noncondensing heat exchangers before flowing into the CAMRAS. Scrubbed air coming out of the CAMRAS flows back into the double locker, through a blower, through an electric heater block, and then through the opposite side of the desiccant wheel for cooling and rehydration. Air is returned to the cabin through another filter and a long hose that routes the return air several feet away from the supply air inlet to prevent short-circuiting of the process air. The blower is variable speed, and the heater is variable power. The process air system is also outfitted with instruments to analyze the payload performance, including those measuring temperature, moisture, and CO_2.

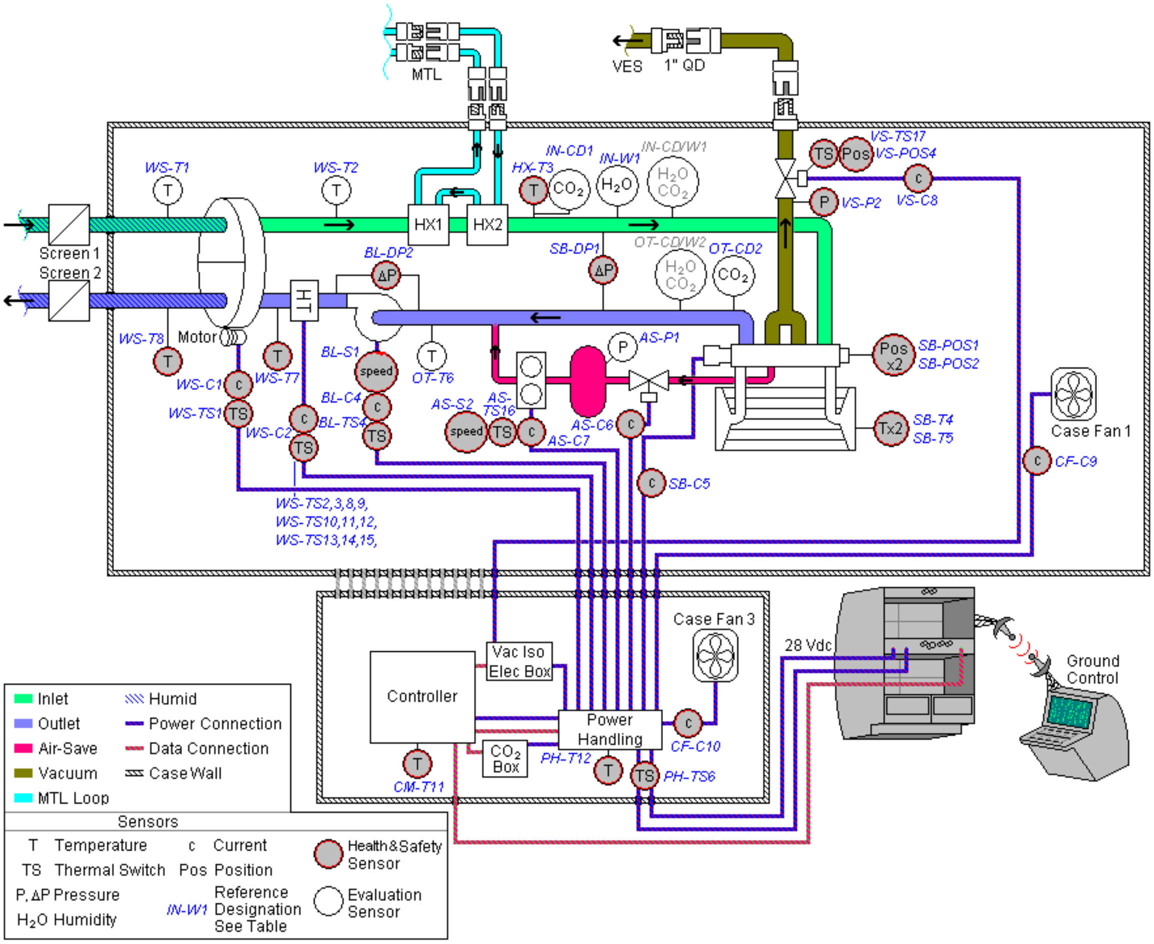

Figure 5. Amine Swingbed Payload Process Flow and Sensor Schematic.

The desiccant wheel installed upstream of the CAMRAS saves significant quantities of cabin water vapor that the CAMRAS would normally scrub and desorb to space vacuum; the dry CAMRAS outlet air is used to regenerate the desiccant. The CAMRAS is regenerated by exposure to space vacuum via direct connection to the ISS Vacuum Exhaust System (VES) at the rack interface panel, bypassing the standard in-rack vacuum plumbing due to its low vacuum conductance. To save some of the small quantity of air that the CAMRAS would normally dump to space vacuum when swapping bed functions, the built-in pressure equalization between the adsorbing and desorbing CAMRAS beds occurs, and then the bed about to be vented is equalized with a separate evacuated tank before the CAMRAS valve completes its rotation. That air is pumped back into the ISS cabin between CAMRAS valve cycles.

A. Water Save

The water save subsystem consists of a modified large commercial desiccant cylinder, referred to here as the "water wheel," plus a small motor that slowly rotates it, and an electric heater block at the inlet to the return side of its flow path. As humid air passes through the top half of the wheel, the desiccant material pulls the water vapor from it, heating the air in the process. When heated dry air is passed through the bottom half of the wheel, the desiccant material releases previously adsorbed water vapor, thereby cooling and rehumidifying the air stream and regenerating the desiccant. Temperature sensors placed at each end of the wheel provide measurements of the air temperatures entering and leaving both the supply and return sides of the wheel. Although the water wheel captures most of the water vapor entering the Amine Swingbed Payload process loop, a small fraction does continue on to the CAMRAS itself, which will capture most of the remaining water vapor.

B. Blower

The process air flow through the payload is driven by a small but powerful, aircraft-grade, variable-speed blower installed in the process line downstream of the CAMRAS and immediately upstream of the heater for the Water Save subsystem. There is no flow sensor in the process loop to directly measure the on-orbit flow rates, and the command to flow rate correlation was established using a pressure drop simulator in the absence of the actual CAMRAS, which had already been launched to the ISS. For this reason, the actual flow rate through the on-orbit payload process loop may not precisely correlate to the desired values. On-orbit CAMRAS and blower pressure drop data is used to back up the ground predictions and to monitor the system for degradations in flow.

C. Vacuum

Before launch, CAMRAS unit 3's valve was reconfigured to place both of the vacuum-access balls in the middle so they could be easily joined together with pipes and meet at a single interface flange inside the double locker. The front of the double locker is connected directly to the ISS VES with a 39-inch long, 1-inch internal diameter vacuum jumper hose that was already on orbit. Although the line size of this connection is smaller than ideal for maximizing removal efficiency, it is the largest line available to non-core ISS equipment.

The CAMRAS valve has some inherent leakage across the seals between the adsorbing and desorbing beds. In payload startup testing, that leak rate was established to be 0.103 lbm/day, and this leak rate has been incorporated into all of the air loss data presented in this paper. This passive air leakage across the CAMRAS valve seals proved higher than initially predicted, but that discrepancy can be attributed to the technique used to assess the leakage on the ground before launch. In that ground testing, vacuum was pulled down only to an order of magnitude larger pressure than the on-orbit base vacuum pressure, and then pressure equalization rates with ambient air were measured instead of measuring a feed rate for the leak across a constant pressure differential.

D. Air Save

An air save port was added to the CAMRAS unit 3 valve assembly before launch to allow one or both of the beds to be pressure-equalized with an external volume. By pausing the CAMRAS valve rotation at 180° of the full 270° rotation, the bed that is already at half an atmosphere (about 7.3 psia) and about to be exposed to vacuum can be equalized with an evacuated air save tank inside the payload, further reducing the pressure in the bed before it is vented to vacuum. The air save tank is a large, irregularly-shaped boxy volume mounted in the top of the payload double locker, and its contents are pumped into the payload's return air path with a commercial micro vacuum pump, often referred to as a compressor in this payload's vernacular. A vacuum-rated solenoid valve between the CAMRAS valve and the air save tank opens only for the period of the CAMRAS valve's pause, providing a barrier against inadvertent direct atmosphere to the vacuum flow path. The final bed pressure before venting is typically 2.7 to 3.3 psia, depending on the CAMRAS valve's cycle period, which is also the duration that the compressor has to re-evacuate the air save tank. The compressor speed can be varied, but it draws so little power and creates so little noise that there is little reason to run it at less than full power.

The second half of one early test case and most of the last dozen or so test cases (after a long break over the Christmas holidays) showed air save tank pressure signatures suggesting the seals on the compressor may not have been performing as well as they previously had at low tank pressures. The equalization pressure at the end of a long cycle was a few tenths of a psi higher than in similar earlier runs, without corresponding changes in ISS atmospheric pressure. Additionally, when the compressor was turned off at the end of a run, the tank pressure rose relatively rapidly back up to ambient, where it had previously held a relatively high pressure differential for hours at minimum. A spare compressor orbital replacement unit was launched with the Phase B components, so the compressor could be replaced if its performance is considered to be too degraded. As of the end of the main testing, however, this degraded performance was making only a small difference in the estimates of daily cumulative air losses.

III. Ground Testing

Before the payload sections were launched, four increasingly complex stages of integrated performance testing were conducted on the ground. This established the expected performance of the CAMRAS itself in both Phase A and Phase B operational configurations, and then the performance of the rest of the Phase B hardware. The results were also used to help design the on-orbit test plan details and to validate the operation and tuning of the shutdown fault software. These tests were set up much like those in the standard ground CAMRAS test series discussed in previous ICES papers.

A. Pre-modification CAMRAS 3 Test in Anticipated ISS Conditions

In March 2010, CAMRAS unit 3 was tested in a closed chamber at a select few of the conditions it might reasonably experience in its anticipated Phase A configuration. These cases were selected to complement test results obtained with Orion-like operation conditions in earlier years. The test series was not intended to dictate the actual payload operational settings, but merely to "bound the box" and provide data on different sorts of operations. The results were used to help guide the design of the Phase A and Phase B support equipment.

Most of the test cases tried to match the CO_2 injection rate to the CAMRAS's CO_2 scrubbing rate and thereby maintain a constant CO_2 level in the chamber. To simulate the anticipated effect of the desiccant, no water vapor was injected and the chamber was run at approximately 90°F. The facility vacuum system was run at either full effectiveness to simulate the nominal base pressure available at ISS rack interfaces, or at 1 mmHg base pressure to simulate a worst-case condition under which the CAMRAS could be expected to keep up with the CO_2 load of six crewmembers (based on previous CAMRAS-series test results). An air save analogue was not available. Two air flow rates and three cycle periods were examined, and the cases were designed to complement, rather than duplicate, the results of prior test series' cases. CAMRAS 3 was then sent back to the manufacturer for modifications to the valve, its housing, and its manifolding; plus autonomous control modifications to its controller that would be used in the Phase A configuration.

B. Pre-launch CAMRAS 3 Test in Phase A and Phase B Conditions

The modified CAMRAS unit 3 was tested in much the same closed chamber configuration. A single baseline case (3-crew metabolic load, 6.5-minute cycles, 26 cfm) was run again in May 2010 to verify that the scrubbing performance of the unit remained fundamentally unchanged.

In July 2010, a final set of test cases was run with parameters selected to represent likely ISS atmospheric conditions for Phase A-configuration operations: 3- and 6-crew metabolic loads, including both moisture and CO_2. The CAMRAS vacuum connection, shown in Figure 6, was modified to simulate the Phase A configuration's ISS vacuum line conductance with the facility vacuum pumps running at full effectiveness. Three cases were run with one of two process air flow rates and one of two valve cycle times. Another set of five test cases run with four combinations of process flow rate and cycle period represented anticipated worst-case nominal ISS in-locker conditions for Phase B-configuration operations: constant CO_2 inlet concentration, no added moisture, and slightly elevated temperature. This testing immediately preceded final Phase A hardware fit checks and shipment of CAMRAS unit 3 and all of the Phase A hardware.

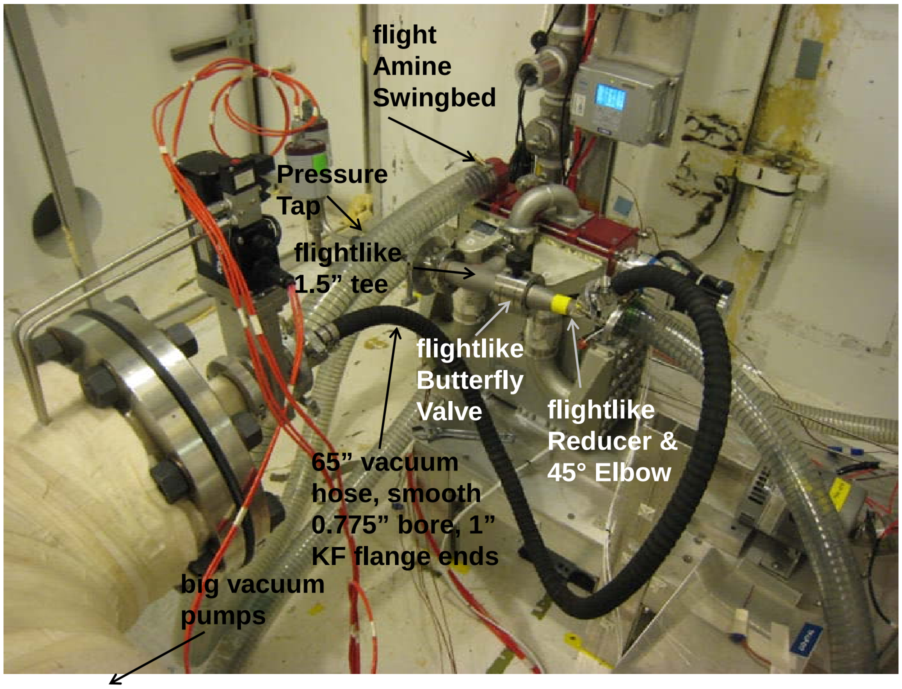

Figure 6. Final Amine Swingbed test configuration.

The test results were used to design the initial on-orbit test plan and refine the requirements for Phase B hardware design. Based on these results, it was proven that the original goal of the payload – being able to remove the metabolic CO_2 load of 6 crew members (4.32 g/min) to maintain an ISS cabin CO_2 partial pressure ($ppCO_2$) of 4 mmHg – appeared to have been inadequately researched, as that performance was on the high end of normal even with significantly more favorable vacuum configurations. Based on these test results, the Phase B-configuration payload should be able to keep up with a contingency metabolic load, but the $ppCO_2$ would be significantly higher than the target level; performance at the expected normal Phase B operational conditions would yield a typical CO_2 removal rate equivalent to the load of approximately two crew members.

C. Phase B Integrated Hardware Test with CAMRAS 1

By February 2011 the Phase B hardware had been designed and built, so development performance testing was conducted in a modified configuration (Figure 7) that accommodated supplemental performance sensors and CAMRAS unit 1 to simulate the function of CAMRAS unit 3 (already on board the ISS). The two units perform similarly but are packaged differently, so CAMRAS 1 had to sit beside the double locker volume instead of inside, it was connected by longer hoses, its sliding spool valve was controlled by the Phase B hardware via an intermediary electronics box, and the air save subsystem equalized with the chamber atmosphere instead of the CAMRAS. The fault detection portion of the control software had not yet been completed, so this was only a test of performance at various atmospheric conditions and of basic functionality of the various Phase B components. The payload contains no dedicated flow rate sensor and CAMRAS 1's pressure drop is higher than CAMRAS 3's, so a blower setting vs. pressure drop and flow rate correlation test was also performed. That correlation used a handheld flow sensor held at the payload outlet and a length of pipe inserted in the doulbe locker that had been designed to match the pressure drop through CAMRAS 3. Similar, but less complex, correlation tests were done for the heater and air save compressor setpoints; all three setpoints are implemented in the software as dimensionless numbers.

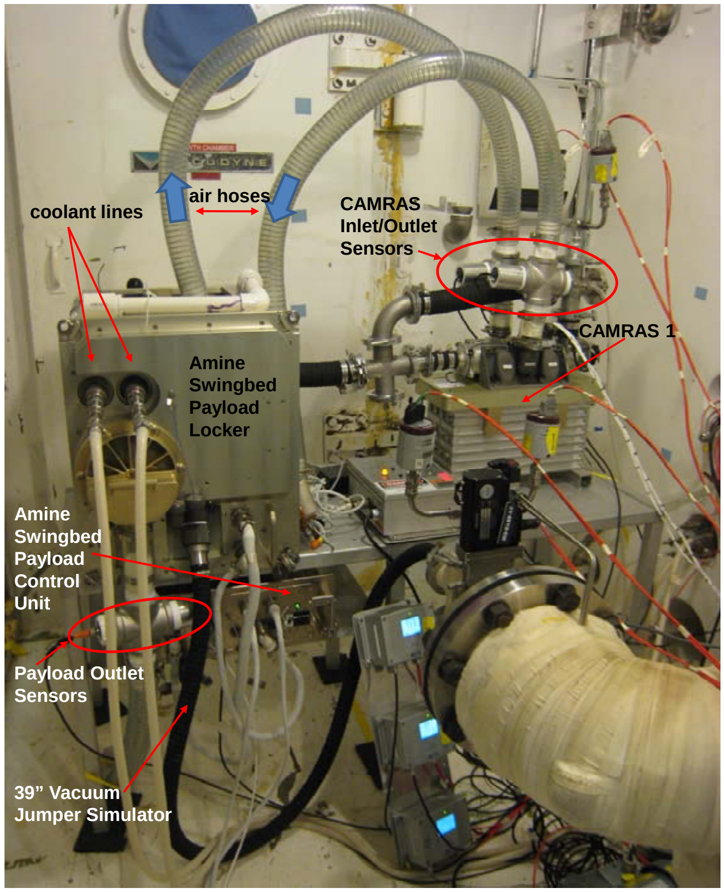

Figure 7. Amine Swingbed Phase B hardware test configuration with CAMRAS 1.

The chamber environment was typically maintained at a defined high-normal dew point and normal temperature for the performance tests so that the payload hardware would do its anticipated on-orbit conditioning. One test case stopped moisture injection partway through to characterize the payload's water vapor scrubbing rate and to observe any overall payload performance differences with low-normal inlet dew point. CO_2 was injected either at a crew metabolic load equivalent or to maintain a consistent level in the chamber and the injection rate measured to determine the payload's steady-state removal rate. Three test cases were run in the first batch of testing, and there was extensive troubleshooting and incremental testing related to what turned out to be a problem with the controller chassis grounding.

Over the course of the spring, the fault detection software was completed, problems uncovered in the first section of these tests were resolved, and all of the other acceptance and certification tests were completed. In late March and early April 2011, just before shipment of the Phase B hardware, the integrated Phase B hardware package was further functionally tested. One case was rerun, one was modified, another was run for the first time, and as many as possible of the fault and interlock conditions were created and the appropriate software responses validated. As suggested in the results of the previous round of testing, it was determined that the payload would typically remove CO_2 at a 1- to 2-person equivalent rate under nominal operations, up to about 3.5-persons' worth at the "high-speed" settings (high process flow rate and short cycle period). In a contingency, the Amine Swingbed Payload alone could maintain cabin CO_2 concentration at around 1% by volume.

IV. On-board Test Plan

The 1000 hours of on-board payload testing was initially divided into six groups. The groups generally had similar objectives, as described below. Group 5's objectives were modified midway through the series, as anticipated, and an additional operation period requested mid-series by the ISS Environmental Control and Life Support System (ECLSS) team can be considered an extra group. Other planned test points were modified as the series progressed, typically to keep the water save heater and air save compressor at full power for all runs, there being little cost-benefit to running either at lower power. However, after a few test points, it was decided that the heater should be run at less than full power during any cases at 5 cfm process air flow. This was done to stabilize its temperature output and power draw; at full power the heater was tripping internal thermal cutoffs due to such a low air flow rate.

Group 1: Functional Checkouts
Group 2: Baseline Performance Tests
Group 3: Optimize CO_2 Scrub vs. Air Loss by Varying Cycle Time
Group 4: Optimize CO_2 Scrub vs. Water Loss by Varying Flow Rate, Cycle Time, and Heater Temperature
Extra Group: Long Duration at High Flow
Group 5: Fill Out the Flow Rate and Cycle Time Matrix
Group 6: Rerun Cases and Last High Flow Test

Initially, operations had been restricted to allow process air flow at more than 10 cfm for only three 8-hour periods, each in its own 24-hour period, due to noise constraints. Consequently, three identical 26 cfm cases had been planned: one each at the beginning, middle, and end of the 1000 hours, with the intent of providing insight into if (and how) the performance of the CAMRAS degrades over time and extended operational periods. The extra test period was then granted a special waiver to allow continuous operation at 26 cfm for 72 hours straight. That long test took the place of the planned mid-run 26 cfm case, allowing an additional 26 cfm case to be run with a different cycle time in the revised Group 5. A separate waiver allowed an additional 144 hours of operation at flow rates above 10 cfm and below 26 cfm, albeit still in individual 8-hour runs, so several 15 and 20 cfm test points were added to Group 5. Group 5 was underway when continuous Amine Swingbed Payload operations were specifically requested to supplement ISS core CO_2 removal systems during a few days in November 2013 while there were nine astronauts aboard; those extra high-flow cases fit nicely into the payload's operational support plan.

Table 1 shows the matrix of flow rates and cycle times that were tested during the 1000 hours, although it does not include any details on heater and compressor setpoint or test duration. The numbers represent the quantity of 8 to 10-hour periods run at that combination of flow rate and cycle time. The inlet CO_2 levels, pulled directly from the ISS Lab aisle, varied and were out of the test team's control, as were the inlet temperature (small variance), humidity (minimal variance), and atmospheric pressure (occasional small variance). Past testing has shown that at flow rates under about 7 cfm, a CAMRAS bed more or less saturates with CO_2 after about 30 minutes; over about 7 cfm, saturation takes only about 20 minutes, which is why the higher flow rate cases were not run with long cycle periods.

Table 1. Amine Swingbed Payload test case matrix.

Swingbed Cycle Period	Process Air Flow Rate				
	5 cfm	10 cfm	15 cfm	20 cfm	26 cfm
6.5 min	8	9	2	2	12
10 min	8	6	2	2	
15 min	6	12	2		1
20 min	6	7	6	2	
25 min	6	9			
30 min	7	6			

V. Payload Operation Data

The on-orbit CO_2-scrubbing performance of the payload closely matched predictions based on ground testing, both of the payload hardware and of CAMRAS units in earlier test series. The prelaunch tests described in an earlier section were generally conservative. The prelaunch CAMRAS 3 ground tests used higher temperatures, but the payload's heat exchangers cool the CAMRAS inlet air to a fairly consistent 68°F, which has been shown in past testing to be approximately an optimal temperature for CAMRAS efficiency.

A. CO_2 Scrubbing Performance

Several of the ground tests were run with chamber $ppCO_2$ levels at the high end of the normal ISS operational range, around 4 mmHg, but the typically observed on-orbit levels during payload operations were in the 2.0 to 3.5 mmHg range. Most on-orbit cases were run while the ISS crew complement was six people. A few cases were run during a period between crews, when only three people were on board, and several cases were run during a 9-crew operations period, while normal ISS CO_2-control systems were running at elevated rates. The CAMRAS is effective, although less efficient, at scrubbing CO_2 when there is less CO_2 in the process stream to be scrubbed, and lower cabin CO_2 by any means is good for the crew. Figure 8 shows the average CO_2 scrubbing rates calculated during the on-orbit operations of the Amine Swingbed Payload based on process flow rate and CAMRAS valve cycle period, and using data from the payload's built-in CO_2 sensors at the inlet and outlet of the CAMRAS, as averaged over the course of each test case; CO_2 levels typically stayed flat (when they normally would have risen due to crew or other payload activity) or dropped over the course of a case. Microsoft Excel-generated power trendlines were added to the plot to illustrate general trends; these trends can be used to roughly extrapolate scrubbing rates at slightly higher and lower ambient CO_2 loads, as was done during the planning of the 9-crew operations period test case sequence. The accuracy of the trendlines are, of course, limited by the quantity and span of the data incorporated into them.

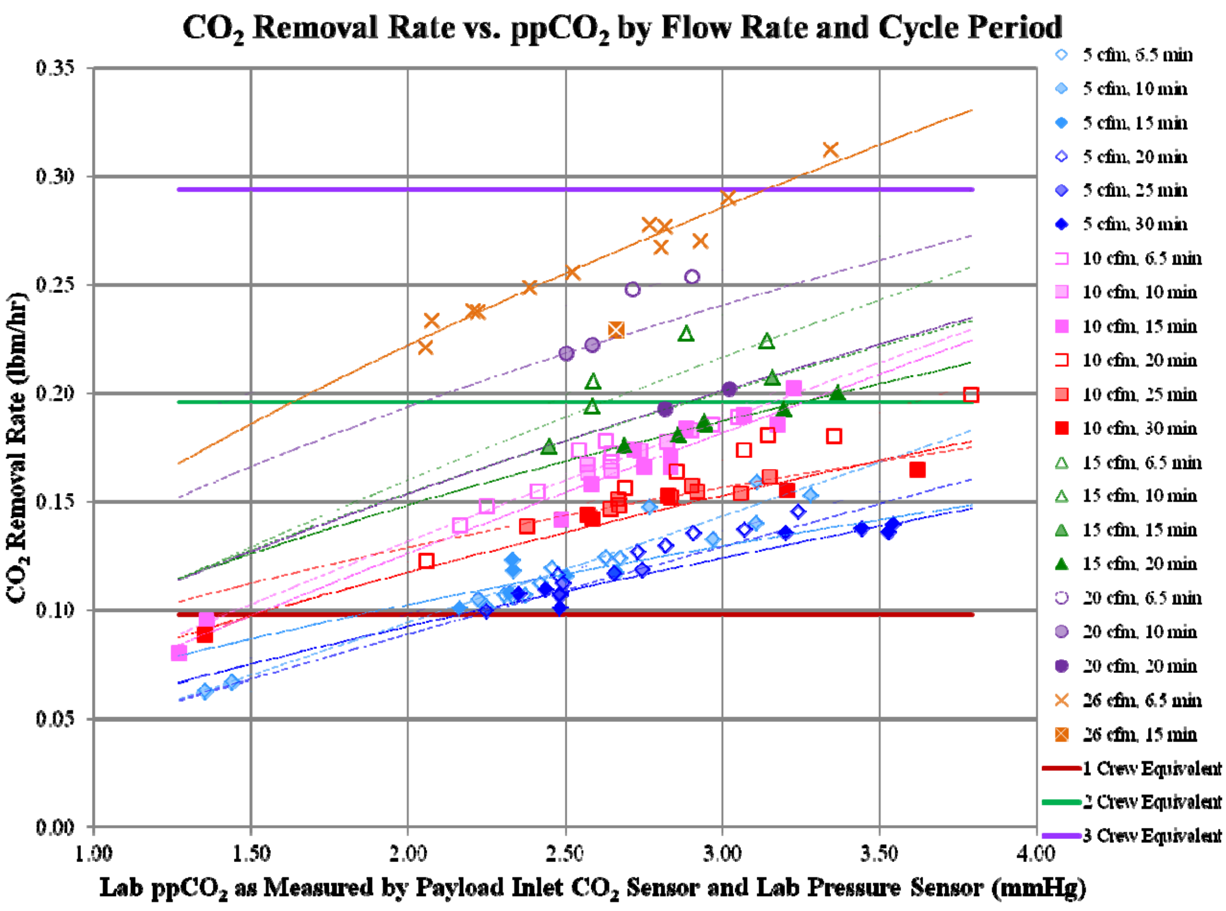

Figure 8. Amine Swingbed Payload on-orbit average CO_2 scrubbing rates in all test points.

Over the course of the 1000 hours of testing, test data suggests that the CO_2 scrubbing performance of the payload package may have degraded very slightly. However, in addition to being of small magnitude, based on the short-duration missions planned for the CAMRAS technology in the Orion vehicle, such long-term degradation is of little concern relative to the technology's benefits. Figure 9 shows the CO_2 scrubbing performance of the Amine Swingbed Payload at the 26 cfm test cases spread over its lifetime, where several of the complicating factors such as ISS atmospheric pressure and $ppCO_2$ have been factored out.

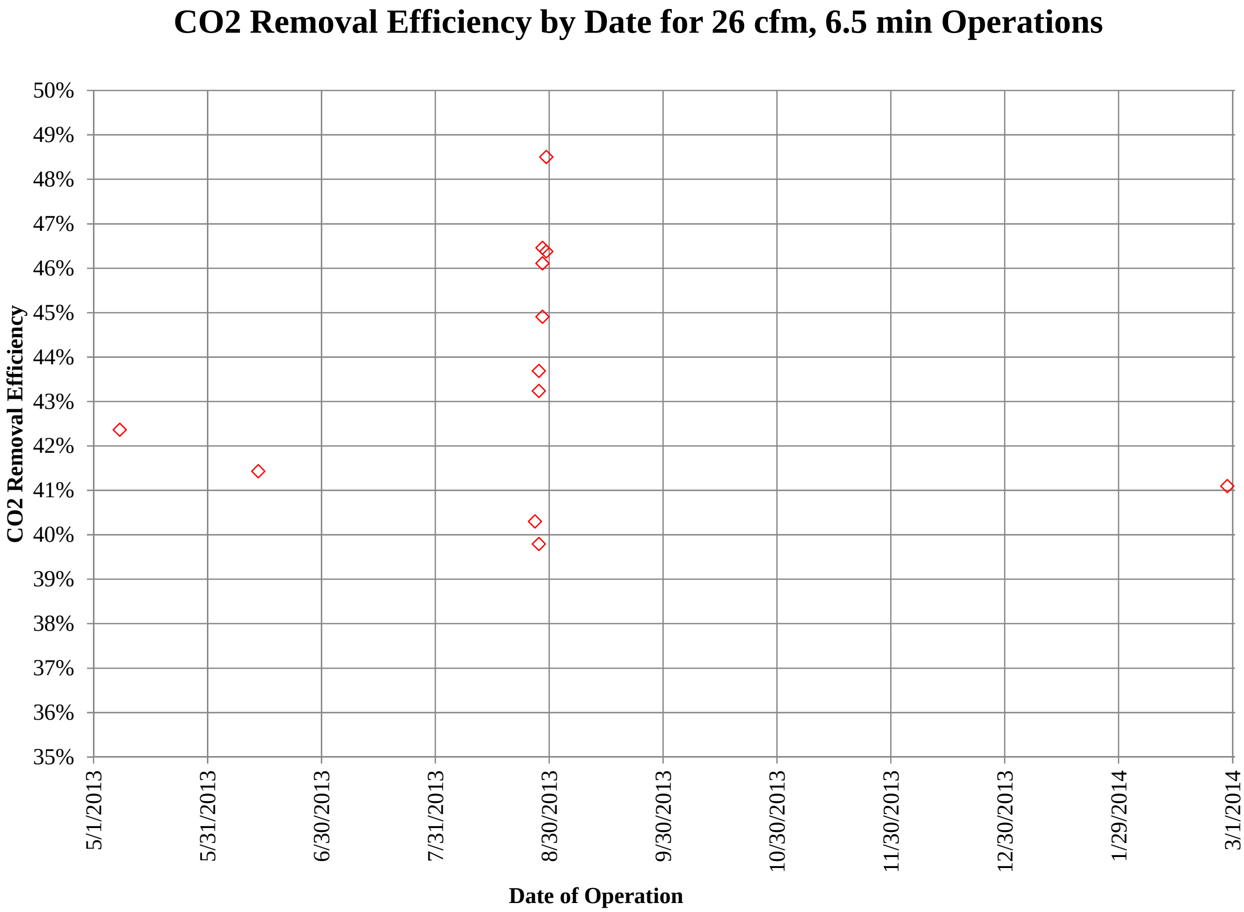

Figure 9. Amine Swingbed Payload 26 cfm, 6.5 min CO_2 scrubbing degradation over 1000 hours of operation.

B. Air Loss Performance

Figure 10 shows the progressive direct air resource loss – from both valve seal leakage and valve cycle ullage – calculated over the course of the payload's on-orbit operations. The higher air save equalization pressure in the last several cases (see discussion in section II.d) cost a little extra loss.

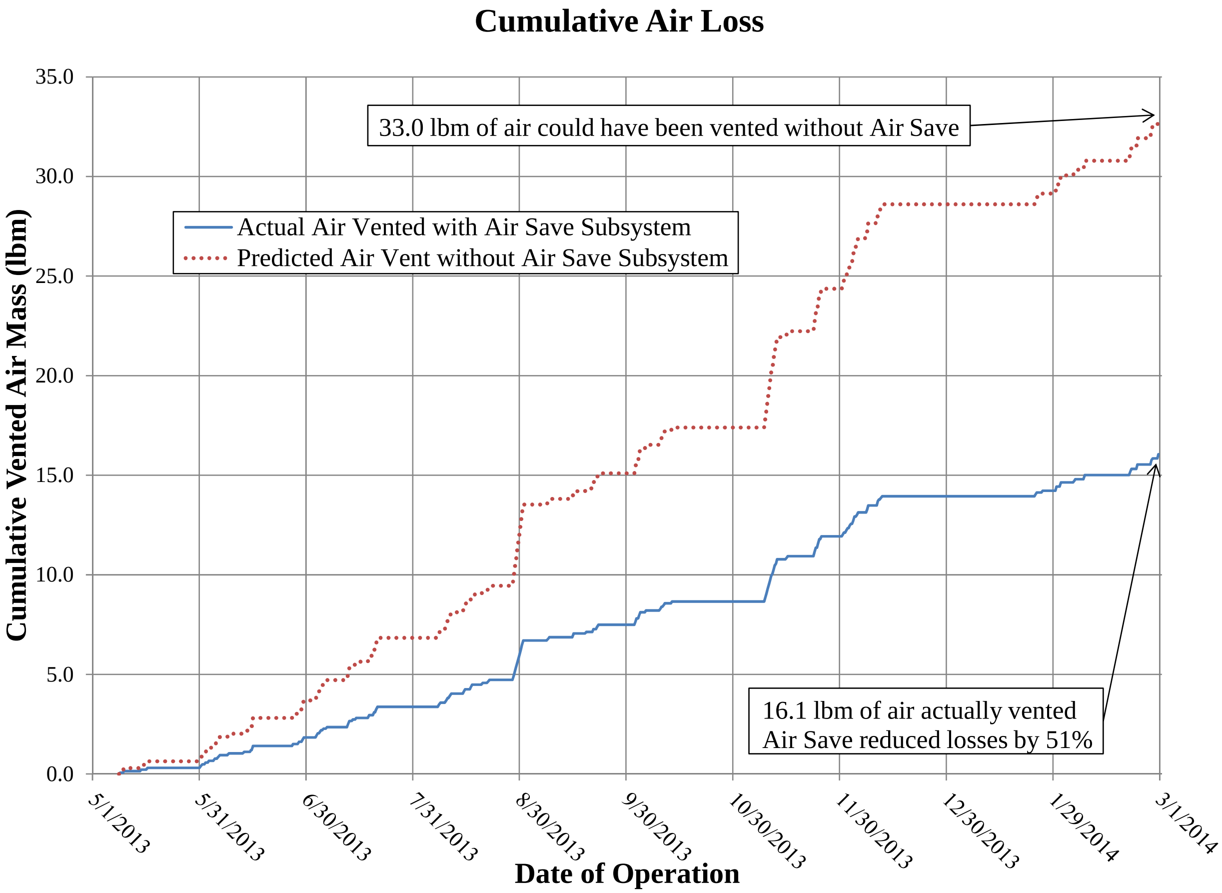

Figure 10. Amine Swingbed Payload calculated cumulative air loss over 1000 hours of operation.

C. Water Loss Performance

Most of the Phase B hardware ground tests were run with a dew point near 60°F, the high end of the theoretical normal ISS range, but the typical dew point in the on-orbit environment was in the 45 to 48°F range. This should result in slightly lower on-orbit water loss, as the water save subsystem should be able to capture a larger fraction of a smaller amount of incoming water vapor. Figure 11 shows the progressive direct water vapor resource loss calculated over the course of the payload's on-orbit operations.

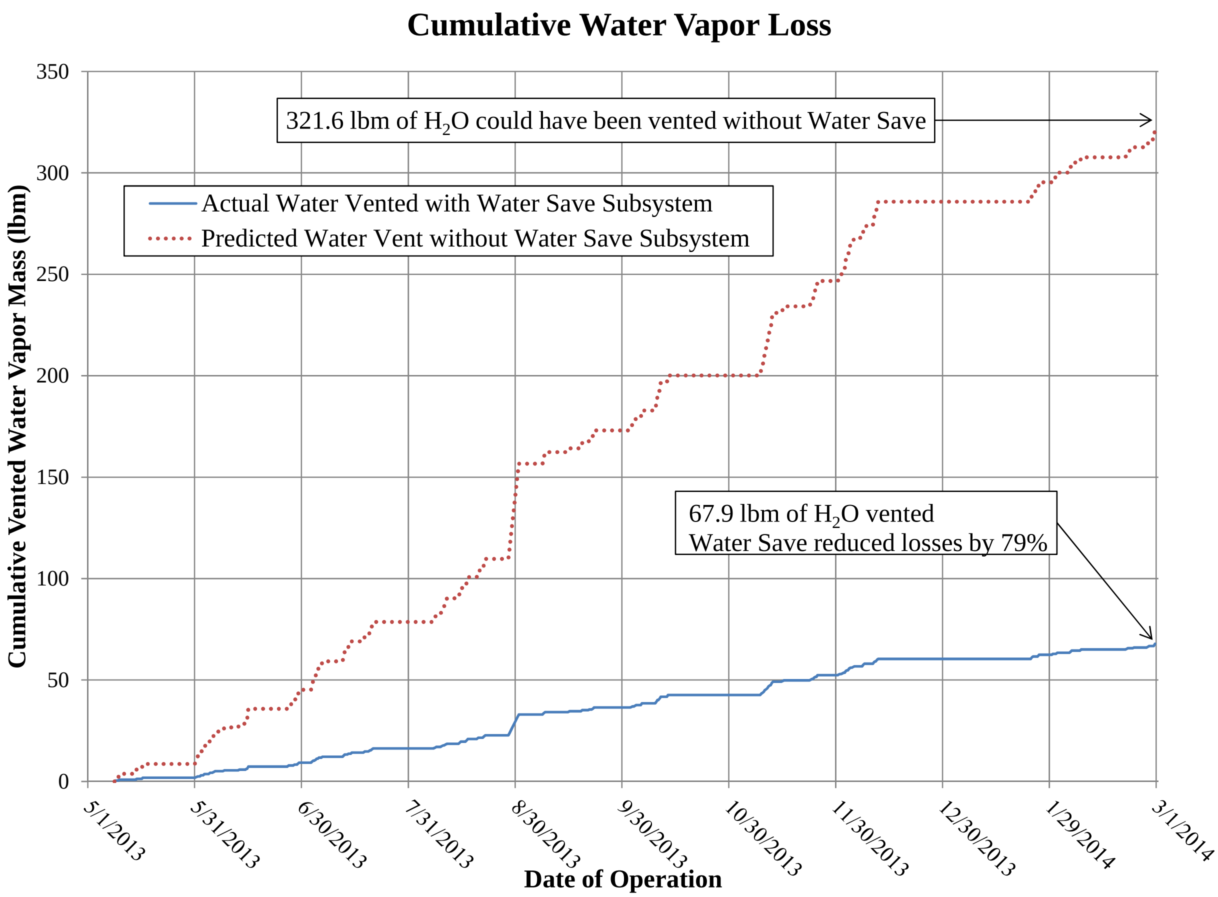

Figure 11. Amine Swingbed Payload calculated cumulative water vapor loss over 1000 hours of operation.

Unfortunately, there is a moderate amount of uncertainty in this data. The payload does contain a dew point sensor at the CAMRAS inlet, but in ground testing it was determined to be of dubious reliability and accuracy; however, the design and schedule were too far along at that time to switch to a different product. Furthermore, the actual water vapor removal by the CAMRAS could not be measured even with the one data point. Instead, this plot's underlying data relies on mathematical models of CAMRAS unit 3's water scrubbing efficiency based on historical ground performance test data, and on data from the ISS dew point sensor in the Columbus module, a moderate distance from the Lab module installation location of the Amine Swingbed Payload. The temperatures at the supply- and return-side air inlets to the water wheel are included in the water loss calculation as an estimate of the water wheel's efficiency, which directly affects how much of the ISS ambient water vapor reaches the CAMRAS to be scrubbed. The calculation also uses the pressure drop across the CAMRAS as an analogue for flow rate, and as previously discussed, pressure drop was correlated to blower setting and flow rate on the ground at various blower setpoints with a pressure drop simulator. Historical flow versus pressure drop data from earlier ground testing with more accurate flow sensors is also factored into the mathematical model. The calculations do not include atmospheric water vapor remaining in the ullage air vented overboard every time the CAMRAS valve cycled. The amount of water removed from the inlet air stream by the desiccant wheel can be calculated as a fraction of the amount entering the wheel:

$$\textbf{\% Removal of Water} = \boldsymbol{A * (B^{C} * D^{E} * F^{G})} \qquad (1)$$

Where:
- A = constant
- B = flow equivalence calculation based on the CAMRAS differential pressure (SB-DP1 in Figure 5)
- C = constant
- D = cabin partial pressure of water vapor (ppH_2O)
- E = constant
- F = outlet-side water wheel inlet temperature minus inlet-side water wheel inlet temperature (WS-T7 - WS-T1 in Figure 5)
- G = constant

This result can then be used to calculate the Amine Swingbed inlet dew point:

$$\textbf{Dew Point (°F)} = \boldsymbol{(-B + (B^{2} - 4 * A * C)^{0.5}) / (2 * A)} \qquad (2)$$

Where:
- A = constant
- B = calculation based on P_v
- C = calculation based on P_v
- P_v = cabin ppH_2O from ISS systems data * (1 - % Removal of Water as calculated in Equation 1)

Partway through the on-orbit test series it became apparent that the maximum cumulative water vapor resource loss estimated at the beginning of the project would be exceeded, although Figure 11 shows the significant savings that were still achieved. Another iteration of the water wheel sizing may have resulted in more water savings, as several assumptions about the CAMRAS water scrubbing efficiency were made, and were generally overestimates relative to final actual operation conditions. A more robust and reliable sensor package would also have improved the quality of these water loss calculations. However, given this suite of limitations, the Amine Swingbed Payload team remains confident that the losses calculated here are accurate enough for the purposes of on-board resource tracking; the water loss shown in Figure 10 equates to less than 10 gallons of water over the 1000 hours of the payload's operation.

D. Sensor Data Limitations

It is important to note that all of the data collected from the payload is subject to the caveat that the built-in sensors were already out of their typical calibration windows (usually 1 year) at the start of the payload operations due to the long periods between build and launch and the even longer delay while the problems with the CAMRAS valve motor were sorted out. The air save tank absolute pressure and CAMRAS and blower differential pressure sensors were of a type frequently used in ground tests, which are known to drift off their zero points while largely maintaining the slope of the calibration curve; the on-board data collected from these sensors has been biased to account for the negative offsets in the zero values observed since the payload's on-orbit startup. Data from the vacuum pressure sensor is not directly used in any calculations; its primary use is to ensure safe operation of the system, and it secondarily provides supplemental rough data on the vacuum quality. The limitations of the dew point sensor were discussed above, and its data was generally not used for these analyses. Midway through the test series, a CAMRAS bed was allowed to saturate for a long period without regeneration, and the payload's inlet and outlet CO_2 sensor readings were then compared to the readings of Lab module samples from the ISS Major Constituent Analyzer (the sample port is very near the payload's installation location); the readings were found to be close to one another. Current sensors were used only to monitor the health of the payload subsystems. In the JSC team's experience, temperature sensors are typically reliable, particularly in the relatively limited range of temperatures seen in this payload.

VI. Future of the Amine Swingbed Payload

The future ownership and operations of the Amine Swingbed payload is still being debated, but it will most likely remain on board the ISS for at least a couple more years. Since the completion of the 1000 hours of planned science testing at the end of February, the payload has already been called upon to support regular ISS operations both to help reduce the overall atmospheric CO_2 level on the ISS, and to supplement the removal of CO_2 by core systems that were operating in degraded modes. Further such operations, while not explicitly planned, are nonetheless expected to arise in the coming months, and the Amine Swingbed Payload team remains prepared to support short-turnaround requests of this nature.

Acknowledgments

The Amine Swingbed Payload project was instigated by a request from the ISS Project. An enormous number of people contributed to its conception, design, build, test, flight, repair, and operation. Figure 12 shows many of the JSC people along with the Phase A and Phase B hardware sets. Several key people include:

- Liz Hayley (initial NASA project manager)
- Tony Williams (lead systems engineer)
- Randy Lovell and Daniel Molina (Engineering and Science Contract Group (ESCG) project managers)
- Ed Hodgson and Bill Papale (Hamilton Sundstrand/United Technologies Aerospace CAMRAS designers and experts)
- Matt Cates (TDA Research water wheel developer)
- The JSC Air Revitalization Technology Development team:
    - Jeffrey Sweterlitsch (principal scientist and third NASA project manager)
    - Mary Walsh (team lead and second NASA project manager)
    - Su Curley (first operations lead and operator)
    - Melissa Campbell (second operations lead and operator)
    - Amy Button (lead operator, crew trainer, and technical expert)
    - Courtney McManus (operator)
    - Katie Collier (operator)
    - Javier Jimenez (all-around project assistant)
- Stuart Fields, Charles Sager, Devin Cole, and Adrian Ramos (ESCG project engineers)
- Eric Harvey (project safety engineer)
- Ron Blakemore (documentation systems engineer)
- Manuel Mauricio and Eric Kanon (lead electrical engineers)
- Rich McMahon (lead mechanical designer)
- Lori Motes (software project manager)
- Glen Steele and Adam Rawlin (lead software engineers)
- Walt Vonau, Jr. (mathematical model developer and analyst)
- Larry Hoff (build manager)
- Gene Teets (lead assembler)
- Karen Somers (Payload Operations and Integration Center liaison)
- Jay Leggett and Dan Sweeney (ISS Chief Engineers)
- The ISS Astronauts who helped assemble and configure the payload on orbit:
    - Dan Burbank
    - Don Pettit
    - Joe Acaba
    - Kevin Ford
    - Chris Hadfield
    - Luca Parmitano

Figure 12. Amine Swingbed Payload Phase A (top) and Phase B (bottom) JSC development teams.

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