Rapid Cycle Amine (RCA 2.0) System Development

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The Rapid Cycle Amine (RCA) system is a low-power assembly capable of simultaneously removing carbon dioxide (CO_2) and humidity from an influent air steam and subsequent regeneration when exposed to a vacuum source. Two solid amine sorbent beds are alternated between an uptake mode and a regeneration mode. During the uptake mode, the sorbent is exposed to an air steam (ventilation loop) to adsorb CO_2 and water (H_2O) vapor, whereas during the regeneration mode, the sorbent rejects the adsorbed CO_2 and H_2O vapor to a vacuum source. The two beds operate such that while one bed is in the uptake mode, the other is in the regeneration mode, thus continuously providing an on-service sorbent bed by which CO_2 and humidity may be removed. A novel valve assembly provides a simple means of diverting the process air flow through the uptake bed while simultaneously directing the vacuum source to the regeneration bed. Additionally, the valve assembly is designed to allow for switching between uptake and regeneration modes with only one moving part while minimizing gas volume losses to the vacuum source by means of an internal pressure equalization step during actuation. The process can be controlled by a compact, low-power controller design with several modes of operation available to the user. Together with NASA Johnson Space Center, Hamilton Sundstrand Space Systems International, Inc. has been developing RCA 2.0 based on performance and design feedback on several sorbent bed test articles and valve design concepts. A final design of RCA 2.0 was selected in November 2011 and fabricated and assembled between March and August 2012, with delivery to NASA Johnson Space Center in September 2012. This paper provides an overview of the RCA system design and results of pre-delivery testing.

Nomenclature

ACFM = actual cubic feet per minute
CAMRAS = carbon dioxide and moisture removal amine swing-bed system
CFD = computational fluid dynamics
COTS = commercial off-the-shelfCO_2 = carbon dioxide
EDO = Extended Duration Orbiter
EMU = Extravehicular Mobility Unit
EVA = extravehicular activity
FPGA = Field Programmable Gate Array
H_2O = water

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HSSSI = Hamilton Sundstrand Space Systems International, Inc.
ISS = International Space Station
JSC = Johnson Space Center
mmHg = millimeters of Mercury
N_2 = nitrogen
O_2 = oxygen
PLSS = portable life support system
$ppCO_2$ = partial pressure of carbon dioxide
ProE = Pro/ENGINEER
psid = pounds per square inch differential
psig = pounds per square inch gauge
RCA = Rapid Cycle Amine
RRCRS = Redundant Regenerable CO_2 Removal System
RCRS = Regenerable CO_2 Removal System
SCCM = standard cubic centimeter per minute
SSAS = space suit assembly simulator
TRL = technology readiness level

I. Introduction

THE continuous removal of metabolically produced carbon dioxide (CO_2) is a critical life support system function of crewed spacecraft, particularly for a spacesuit environment, to maintain safe concentrations for crew respiration. For an extravehicular activity (EVA), the CO_2 removal device is required to function for the duration of the EVA plus any time the crew member must perform any pre-breathe conditioning or post-EVA suited operations. Humidity control is also a vital air revitalization system function that improves crew comfort, prevents visor fogging, condensation on internal surfaces and commensurate issues of multi-phase fluid flow in a micro-gravity environment. A particular technology that has been undergoing advanced system development work and addresses both CO_2 removal and humidity control is the employment of a solid amine sorbent in an alternating two-bed, vacuum regenerated process, namely the Rapid Cycle Amine (RCA) system. With continuous access to a vacuum source for regeneration, the RCA concept is operable over a wide range of metabolic conditions and over long durations of time with minimal power and consumables. Previous developments have demonstrated the scalability of the technology to both vehicle size and EVA size applications, with successful laboratory demonstrations of various RCA test articles to investigate different sorbent canister geometries, flow control valve designs and process control schemes aimed at optimizing the RCA for future implementation into a Primary Life Support System (PLSS).

Based on refined system requirements[1] that have been generated by NASA through testing and evaluations of several test articles, a prototype RCA 2.0 system has been designed, fabricated, and tested to be integrated into the PLSS 2.0 test system. Challenging operational requirements levied on the RCA 2.0 prototype compared with lower technology readiness level (TRL) design iterations included pressurization, oxygen (O_2) compatibility, flow-induced pressure drop, power consumption, valve operability and leakage, and CO_2 and humidity removal performance over a range of simulated metabolic conditions. The design was also challenged to minimize mass, volume, consumable losses, and complexity. In pre-delivery testing, the resultant RCA 2.0 design met the operational requirements within stated development goals and demonstrated CO_2 and humidity removal performance over a range of simulated metabolic challenges using a CO_2 concentration feedback control scheme.

II. Background and Rapid Cycle Amine Evolution

The RCA system has long been a capability desired for EVA operations based largely on the attractiveness of a CO_2 removal system that does not impose significant expendable requirements and does not limit EVA duration. The ability to concurrently control humidity without phase change and the requisite two-phase flow management requirements further reinforces the system attractiveness for EVA applications. Additionally, the same vacuum-regenerated technology has been under development for vehicle applications,[2] thereby enabling the practical use of common CO_2 removal technology across a wide spectrum of exploration platforms from EVA spacesuit systems to long-duration vehicles.

Over the development cycle for these systems, the respective designs have been able to borrow ideas and improvements from advances made in each application while also illustrating the scalability of these systems and components. A number of design concepts have been explored and fabricated to evaluate sorbent performance and the impact of canister geometry, and also to address valve operability. Implementation of the RCA involves a number of design challenges involving valve design, process control, and optimization, and the design and fabrication of a thermally coupled but physically isolated sorbent canister. This section aims to trace the evolution of the RCA 2.0 through the design cycles and pinpoint what system capability gaps have been identified and reconciled through various advanced development activities.

A. Rapid Cycle Amine Concept Development[3,4]

The concept of an RCA system was explored in an early configuration that employed a pneumatically actuated spool valve (based on integration with a cryogenic portable life support system (PLSS) concept) to direct the ventilation flow and vacuum porting to the appropriate bed. The original canister design that mated to this valve assembly had relatively poor thermal conductivity between the beds, resulting in lower-than-expected sorbent performance.[4] Later efforts undertaken by Hamilton Sundstrand Space Systems International, Inc. (HSSSI) and NASA provided for an improved canister design (2006), which was mated to the original pneumatic spool valve for breadboard system evaluations. Results from these development activities demonstrated the system need for a canister with proper thermal considerations to achieve the desired chemical sorbent performance as well as a means of optimizing and controlling the adsorption and regeneration cycles.[4] Figure 1 shows several pieces of hardware from the 1998 initial RCA breadboard concept.

Figure 1. Initial RCA breadboard concept (1998).

B. Redundant Regenerable Carbon Dioxide Removal System Development[5,6]

The Redundant Regenerable CO_2 Removal System (RRCRS) concept as shown in Fig. 2 was a full-scale breadboard test based on the Extended Duration Orbiter (EDO) Regenerable CO_2 Removal System (RCRS) canister design coupled to a linear spool valve test article. The canister was half-filled with SA9T sorbent to demonstrate the increased capacity and effectiveness over previous solid amine sorbent formulations and to illustrate packaging of a redundant RRCRS system within the original EDO volume. The labtoratory testing demonstrated significantly improved sorbent performance; however, as the International Space Station (ISS) began operations, the need for an EDO limited the applicability to the shuttle. The breadboard system testing proved valuable in understanding the SA9T performance in a relatively high TRL canister configuration. Also, the tests proved that a prototype spool valve assembly simplified the air and vacuum porting over the EDO RCRS[5] as the bed functions were switched between adsoprtion and regeneration modes. Results further illustrated the ability to reduce system size based on the improved SA9T sorbent performance over the RCRS flight sorbent (HSC+).

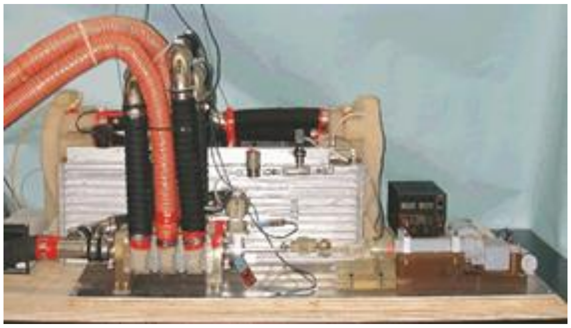


Figure 2. RRCRS breadboard test (2001).

C. Carbon Dioxide and Moisture Removal Amine Swing-Bed System Development[7,8,2]

Under a cooperative agreement with NASA, HSSSI developed three prototype amine swing-bed systems for extensive ground testing and evaluations of combined CO_2 and water (H_2O) vapor removal in a cabin environment. These prototypes are known as the CO_2 and Moisture Removal Amine Swing-Bed System (CAMRAS) prototypes. The first two prototypes (CAMRAS 1 & 2) incorporated a linear spool valve design for process flow control through the sorbent beds. The third prototype system, CAMRAS 3, as shown in Fig. 3, employed a multi-ball valve assembly that improved system fluid interfaces and regeneration capabilities. The prototype of the multi-ball valve assembly is shown in Fig. 4.

Figure 3. CAMERAS 3 configured for swing-bed payload (2010).

The multi-ball valve designed and implemented for CAMRAS 3 (2008) was based on an internally developed valve concept that was driven by a desire to improve operability over the original RCA pneumatically actuated spool valve assembly. Along with improved pressure drop characteristics, the multi-ball valve assembly provides a means of isolating each half of the system and each of the fluid connections to and from the system. The operational performance of these prototypes has been validated in a number of test environments,[7,2] through both simulated human metabolic loads in a closed chamber and through human subject testing in a closed chamber at NASA Johnson Space Center (JSC). In 2010, CAMRAS 3 was configured for a payload experiment (Amine Swingbed Payload) on the ISS[9] and integrated with water-save and air-save systems to limit overboard expendable losses during experiments on the ISS.

Figure 4. Prototype multi-ball valve (2007).

D. Rapid Cycle Amine 1.0[4,10,11,12,13]

The RCA 1.0 test article (Fig. 5), described in previous work, was developed to demonstrate feasibility in a representative scale system and to generate system-level performance data, particularly with respect to CO_2 removal and humidity removal capabilities. As previously described, the spool valve from the original RCA concept (1998) was coupled to an improved canister design (2006). Testing of this prototype canister and valve assembly, along with other test articles such as the radial flow canister design in Fig. 6, demonstrated the dynamics of RCA operation, and supported modeling efforts[11,12] and the conclusion that the RCA would benefit by having an active feedback control architecture to aid in optimizing the system performance over the anticipated range of metabolic loads.[10,13] These crucial development activities also provided the insight for assessing the system performance gaps, such as improving the valve operability and interfaces between system components, to be addressed in subsequent design work.

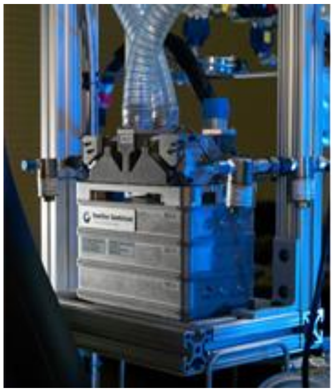


Figure 5. RCA 1.0 (2006).

Figure 6. Subscale Cylindrical RCA Test Article (2009)

The most significant test for the RCA 1.0 was in the PLSS 1.0 Breadboard test setup (Fig. 7) in 2011 at NASA. The objective of this breadboard testing was to demonstrate basic life support functions. These functions included habitable pressurization, thermal control, and moisture and CO_2 removal across a range of metabolic and thermal profiles. This was the first time that the RCA technology had ever been integrated with other components into a system-level configuration to undergo an experimental evaluation of the full functionality of an advanced PLSS design. Additionally, it was the first time in over 3 decades that a newly developed PLSS concept had been integrated. The test was conducted with nitrogen versus 100% O_2 for safety precautions. The test ran for 233 hours over 45 days, accomplishing 119 test points. The RCA 1.0 performed as expected throughout the PLSS 1.0 testing.[14]

Figure 7. PLSS 1.0 test setup.

III. Rapid Cycle Amine 2.0 Design Overview

The RCA system requirements definitions are derived from the PLSS 2.0 operational requirements.[1] Considerations for pressurization conditions, ventilation flow and diverter valve operation, pressure drop, power allocation, system operating life, allowable CO_2 concentrations and desired humidity levels at various metabolic conditions, as well as overall system mass, volume, safety, and relative technical maturity all had to be reconciled to some degree during the design phase. With minimal constraints imposed on the physical design, development goals focused on designing a system that met the operational performance requirements and also addressed issues identified in previous development activities.

A. Valve Operability Considerations

The spool valve assembly (originally fabricated in 1997) implemented in the RCA 1.0 prototype is a reasonably operable component and has endured a relatively long life among development articles. Testing demonstrated difficulty in the original means of pneumatic actuation and there existed design challenges in achieving the further refined valve operability requirements.[11,12] Among the various system and component concepts explored to date, HSSSI had been exploring the implementation of a multi-ball valve concept, which was later scaled up and incorporated into CAMRAS 3. This multi-valve design concept was adapted for use in the RCA 2.0.

For RCA 2.0, the desired valve operation between the two end states is depicted in Fig. 8. In the initial state, the valve assembly is aligned such that Bed A is exposed to ventilation loop flow while Bed B is exposed to vacuum for regeneration. As the capacity of Bed A is consumed, the outlet CO_2 concentration increases. For a given outlet CO_2 concentration set point, a logic device can be programmed to change the valve state by actuating a stepper motor until the other end state is reached, namely where Bed B is exposed to ventilation loop flow and Bed A is exposed to vacuum for regeneration. The intermediate state during this transition requires the valve assembly to isolate all of the fluid interfaces (inlet, outlet, vacuum) while the sorbent beds equalize pressure between the bed at vent loop pressure and the bed at vacuum. Furthermore, a bypass valve was desired to open to allow flow around the assembly during the valve transition. The bypass valve was not implemented into the design of RCA 2.0 due to funding limitations. The multi-ball valve assembly accomplished the majority of these operability requirements except for the bypass functionality.

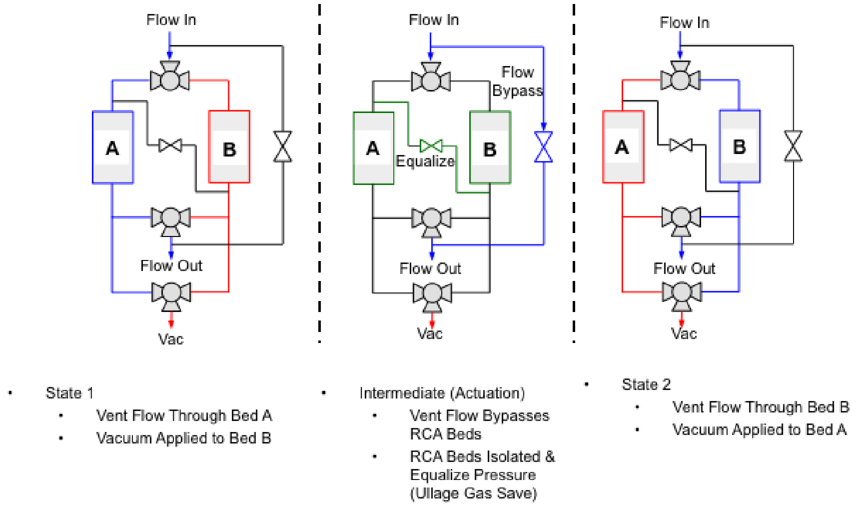


Figure 8. RCA valve state diagram.

As shown in Fig. 9, the initial detailed design for RCA 2.0 incorporated a bypass valve into the multi-ball valve assembly. However, it was omitted in favor of incorporating this functionality separately into the PLSS system to decrease the cost of RCA 2.0 and to improve weight, volume, and device complexity.

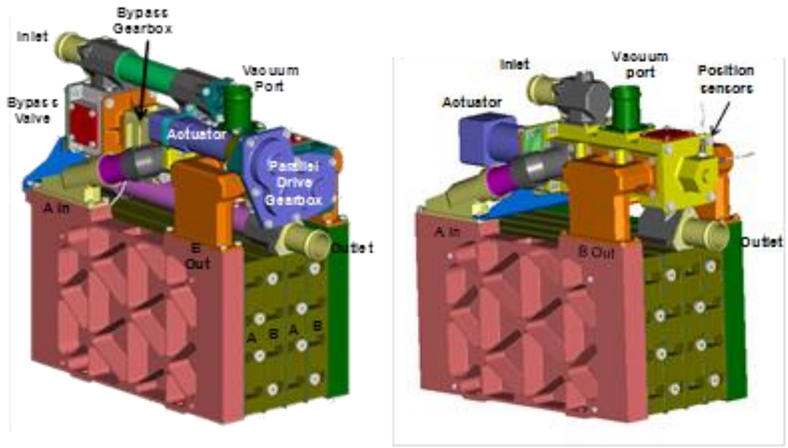


Figure 9. RCA 2.0 with bypass (left) and without bypass (right).

Along with being the interface to the PLSS ventilation loop, the RCA valve assembly was designed with considerations for pressurization requirements, allowable seat leakage, pressure drop considerations, materials of construction, operating life, power, actuation speed, and positional accuracy. The approach taken was to address the key operational requirements and addressing power and actuation speed as the assembly was built up and torque requirements established.

B. Sorbent Canister Considerations

Figure 10 is a schematic representation of the RCA 2.0 design with both the valve assembly and canister assembly shown as discrete subassemblies. The sorbent canister needed to address several key considerations. It needed to contain two individual sorbent beds with the capability to be pressurized to vent loop conditions and subsequently evacuated to vacuum in a cyclic fashion to perform the CO_2 and humidity removal function. It also needed to transfer heat generated in the on-service bed to the regenerating sorbent bed. Flow-induced pressure drop through the packed bed and various flow distribution headers and manifolds must be considered and effectively modelled to achieve the allocated value while minimizing overall mass and volume. Interfacing the canister to the valve assembly is also important in minimizing the internal system gas volume, minimizing flow disturbances (pressure drop), and providing structural rigidity between the components. Considerations for fatigue life over the pressurization envelope are also important in the mechanical design of the canister.

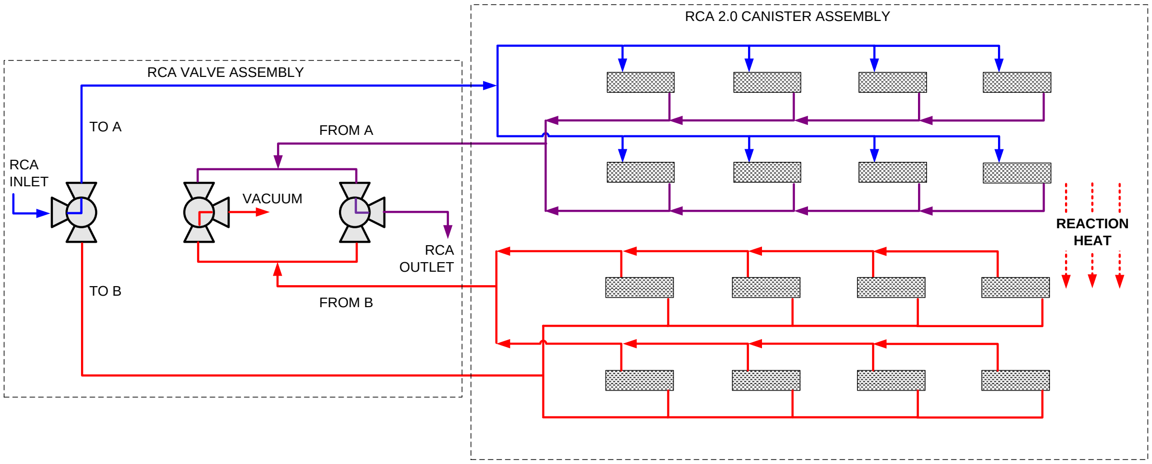


Figure 10. Schematic illustration of RCA 2.0.

The approach taken in the canister design was to achieve the overall system pressure drop goal of 2.5 inches of H_2O at 6 ACFM flow and atmospheric pressure. The packed bed section of the system is typically the more significant contributor to the overall system pressure drop; therefore, having multiple, parallel paths improves the pressure drop. Both the valve and canister assemblies were studied and iterated upon, using computational fluid dynamics (CFD) modelling tools, to minimize the overall volume while meeting the pressure drop target. Figure 11 illustrates some of the results using Pro/ENGINEER (ProE) models imported into the CFD design analysis package. Furthermore, the canister was designed as a complete brazement, with the valve interfacing to machined header plates that allowed for mounting positions of the RCA 2.0 into the PLSS 2.0 assembly.

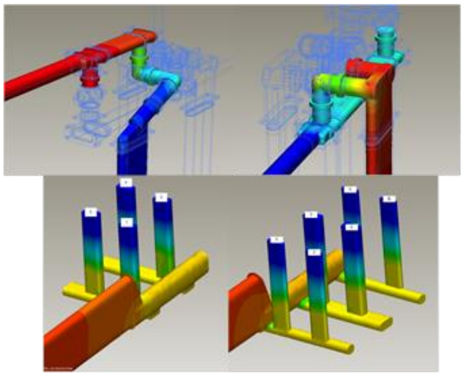


Figure 11. CFD analysis of valve and canister.

C. Rapid Cycle Amine Controller

The breadboard electrical system architecture for the RCA 2.0 valve actuation motor drive consists of a mix of both commercial off-the-shelf (COTS) parts and custom circuitry. The function provided by the circuitry provides a means to control the valve position through stepper motor drive and read position sensors to control the amount of travel. Position feedback through inductive magnetic proximity sensors at the end states prevents the stepper motor from stalling at the end points and provides two calibration points for a step-counting subroutine to move to pre-programmed intermediate positions. A serial USB interface was used to facilitate communications with a Windows-based PC for specific status information and to provide additional modes of control to the user. Figure 12 is a top-level diagram of the electrical system. The baseline power consumption, when idle, was observed at 3 Watts (28 VDC, 0.106 A), which powers the motor controller, Field Programmable Gate Array (FPGA), indicator lights, and position sensors. When set for a 7.4-second actuation time, the observed power consumption increased to 12 Watts (28 VDC, 0.43 A) while actuating. Therefore, the net power for valve actuation using the stepper motor actuator is approximately 9 Watts at that actuation speed. Increasing actuation speed with the selected COTS gearmotor was not possible without increasing probability of stalling. Without a bypass valve, the total time of a no-flow condition is approximately 1/3 of the total actuation time, or approximately 2.5 seconds at this actuation speed. It is desired to improve this actuation time, which will drive slightly increased power consumption during actuation.

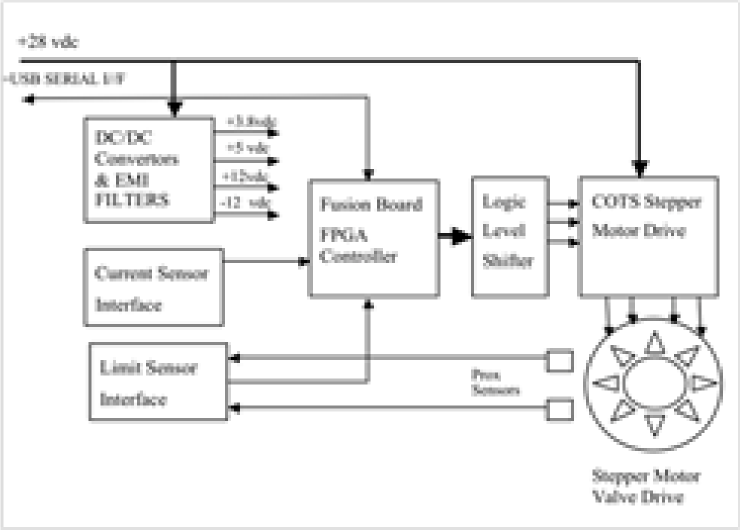


Figure 12. RCA breadboard controller diagram.

The controller portion of the hardware design is based on an Actel Fusion FPGA Embedded development board. The use of the Fusion board helped facilitate rapid development of the detailed Very High Speed Integrated Circuits Hardware Description Language (VHDL), which is ported into the FPGA device. The FPGA controls the stepper motor drive, reads the position sensors, and controls the serial data interface to the USB Serial PC interface data port. It also provides system oversight during automatic operation, which, in the current configuration, will indicate a fault and exit automatic operation if the program driven valve position is not detected properly. An improved integrated circuit with FPGA controller and stepper driver circuit is currently being developed to provide a distributed control architecture to the RCA. The integrated controller, illustrated in Fig. 13, occupies the open space between the valve assembly and canister to yield a compact design. The controller has a 28 VDC power interface and RS485 communication to replace the current USB serial communication port.

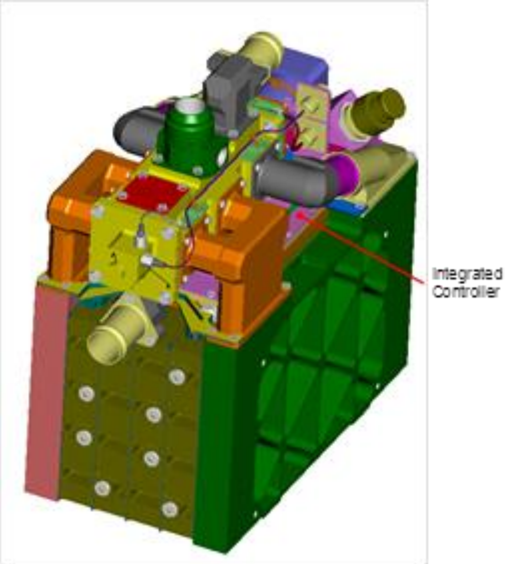


Figure 13. Illustration of integrated RCA controller.

IV. Rapid Cycle Amine 2.0 Assembly and Testing

The finalized design for the RCA 2.0 deliverable was completed in February 2012. Following procurement and fabrication, RCA 2.0 was assembly complete in August 2012. Photographs of the actual RCA 2.0 assembly is shown in Fig. 14. The overall assembly was then evaluated for proof pressure up to 13.7 psig. Each bed was then individually tested to 13.7 psig with the alternating bed evacuated to vacuum. Total seat leakage to vacuum at atmospheric pressure (14.7 psid) was less than 1 SCCM with leakage at proof pressure (~28.4 (psid)) calculated at 3 SCCM, meeting the development goal of less than 6 SCCM. Ullage volume measurements demonstrated a free volume of 1.95 liters for each bed and associated header volumes. Valve and benchtop controller operability had been previously evaluated in June and July 2012 while the RCA canister was undergoing assembly. The valve assembly had undergone more than 5000 back-and-forth cycles on the bench with no detected issues in the controller performance or in the valve hardware.

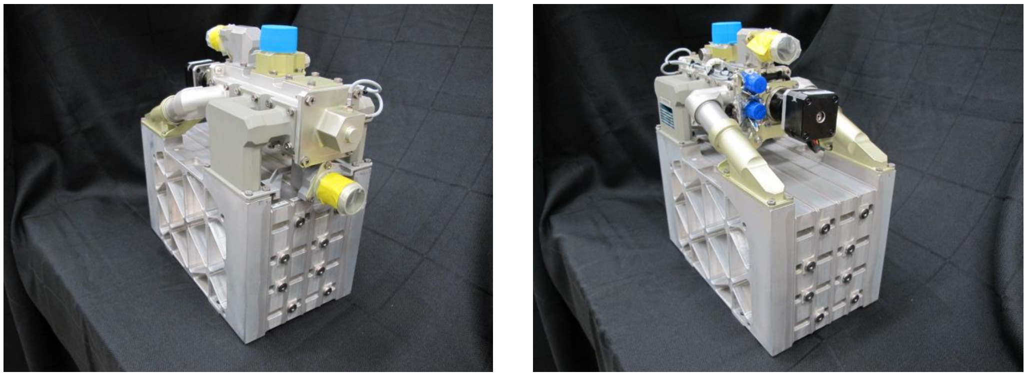


Figure 14. Views of RCA 2.0 assembly complete.

The CO_2 removal performance of the system for a representative metabolic profile challenge was modeled based on the new canister design and a switching setpoint of 6 mmHg $ppCO_2$ on the outlet of the RCA. The model assumed a ventilation loop air flow of 6 ACFM and atmospheric pressure. Model results are presented in Fig. 15.

Performance testing at 6 ACFM at atmospherc pressure and similar CO_2 injection rates using the same $ppCO_2$ set point yielded the anticipated behavior, as shown in Fig. 16. The RCA H_2O vapor removal performance was also investigated and matched predicted performance. Results demonstrate the RCA is capable of concurrently reducing the ventilation loop relative humidity to levels on the order of 10% to 20%. Further testing under relevant conditions will be completed in PLSS 2.0 testing at JSC.

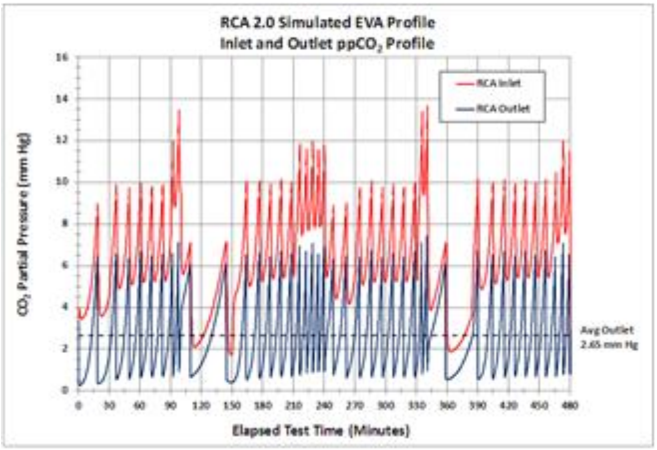


Figure 15. Predicted CO_2 performance for RCA 2.0 and simulated metabolic profile.

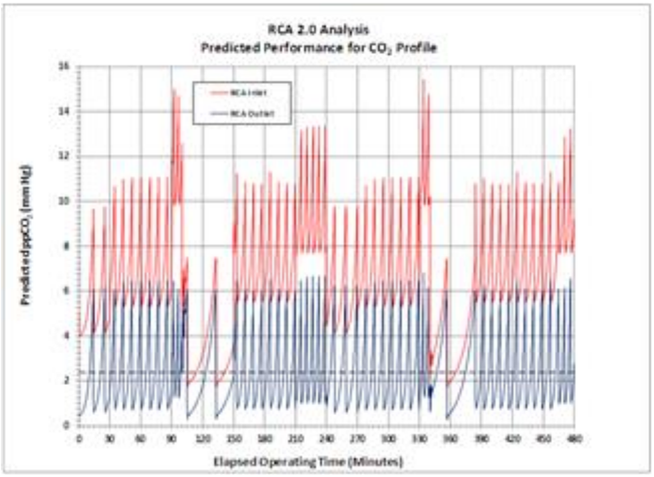


Figure 16. Observed CO_2 performance for RCA 2.0 and simulated metabolic profile.

V. Portable Life Support System 2.0 Integration

After the PLSS 1.0 testing was complete, the initiation of the developmental iteration of test article PLSS 2.0 began with the objective to integrate more mature PLSS components and integrate them into a flight-like packaged configuration. In 2011, the majority of the PLSS components underwent a significant design revision to increase the fidelity of the hardware and refine the designs based on lessons learned from the previous iteration.

The majority of the PLSS 2.0 design and build up occurred in fiscal year 2012 with the test article fully assembled in early fiscal year 2013. Two programs were instrumental in advancing the PLSS project overall. The Advanced Exploration Systems Program funded the progression of the PLSS development and testing whereas the component development progression of the RCA 2.0 was funded by the Next Generation Life Support technology development project sponsored the NASA Office of Chief Technologist's Game Changing Development Program. Fig. 17 depicts the PLSS and RCA progression and infusion of the RCA into the PLSS overall test schedule.

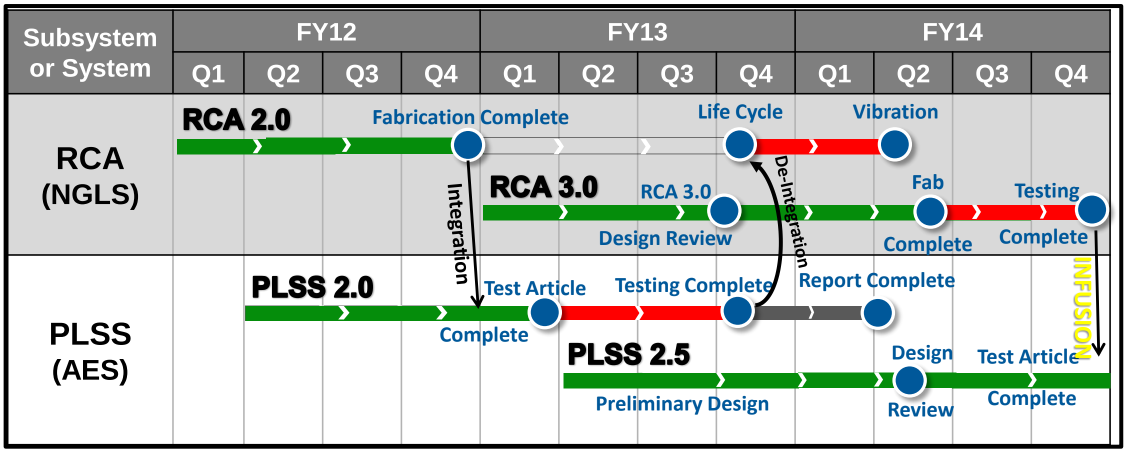


Figure 17. RCA and PLSS schedule through fiscal year 2014 with Next Generation Life Support and Advanced Exploration Systems partnership PLSS integrated testing.

The purpose of PLSS 2.0 testing is to experimentally characterize the performance of the PLSS 2.0 integrated system as a packaged PLSS with the RCA 2.0, along with other components. The desire is to build confidence in the advanced PLSS design by operating the test configuration in ambient and vacuum environments using simulated human and vehicle interfaces. All system-level testing will be done in-house at JSC. The system-level design is applicable for any of the destinations currently under consideration for advanced EVA, including low Earth orbit, lunar surface, near-Earth objects, or Lagrange points. PLSS 2.0 testing will use nitrogen as the primary gas constituent. This will eliminate the flammability concerns with pure O_2. The test will also be unmanned.[15]

Some of the objectives of the ventilation loop for the RCA 2.0 while in test with the PLSS 2.0 include the following:

1) Demonstrate CO_2 and H_2O removal at various metabolic rates
2) Determine helmet flow rate and pressure response with the RCA configured in various modes
    a. Swing without bypass valve
    b. Swing with bypass valve
3) Determine the RCA bypass valve timing to minimize helmet flow interruption across suit pressures
4) Demonstrate CO_2, O_2, and relative humidity monitoring at the helmet inlet and RCA inlet across suit pressures

As the PLSS 2.0 progresses to the next iteration, PLSS 2.5, the lessons learned from the progression of design, fabrication, assembly, and testing will be implemented. It is currently planned that RCA 3.0 iteration will be the RCA iteration that infuses into the PLSS 2.5. An image of the PLSS 2.0 design is shown in Fig. 18 next to the actual assembled PLSS 2.0 in Fig. 19.

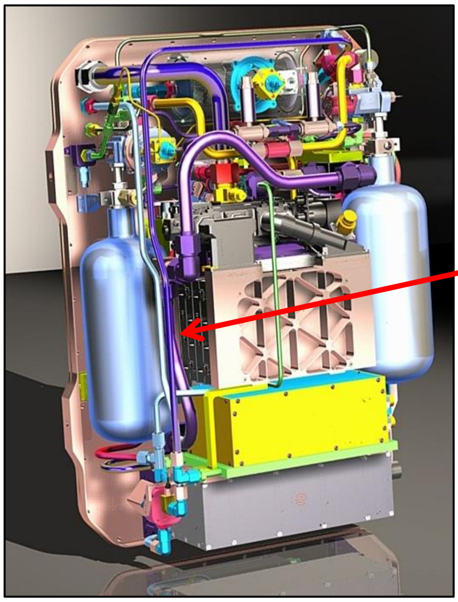
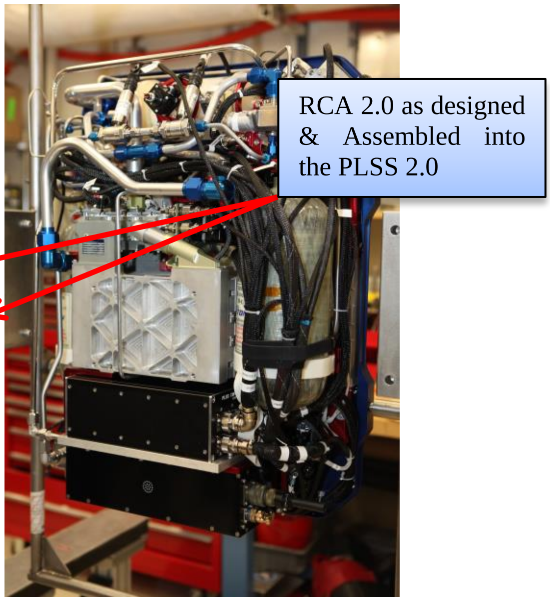


Figure 18. Integrated PLSS 2.0 design (Pro/E).



RCA 2.0 as designed & Assembled into the PLSS 2.0

Figure 19. Assembled PLSS 2.0.

The majority of the PLSS 2.0 test points will be taken in Configuration S. In Configuration S, the PLSS will be mounted directly on the back of the space suit assembly simulator (SSAS) in the upright orientation. In this configuration, the RCA will have vacuum access lines that can be reconfigured to interface with various locations in the vacuum system to most accurately simulate different operations concepts. The detail for Configuration S is shown in Table 1. The design of Configuration S is shown in Fig. 20.[15]

Table 1. PLSS 2.0 Configuration S

Configuration S	
PLSS Location	Mounted directly on back of the SSAS
Orientation	Upright (battery towards bottom)
Pressure Environment	Ambient Lab
Thermal Micrometeoroid Garment Installed	No

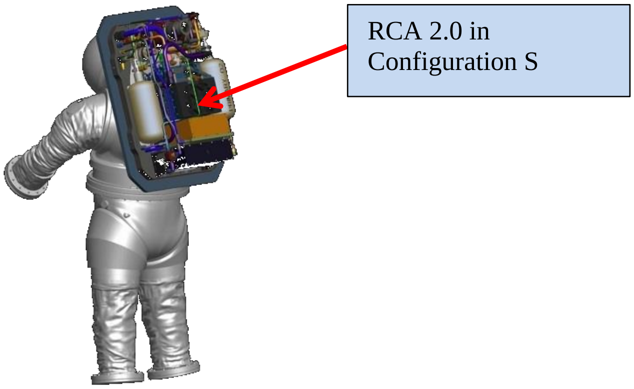


Figure 20. PLSS 2.0 test Configuration S.

VI. Conclusions

The RCA 2.0 assembly completed the planned functional tests satisfactorily and with results that demonstrated good correlation to predicted and past performance measurements. Table 2 is the tabulated RCA 2.0 development goals and the observed test results. Where the result is highlighted in green, the test results are considered met against the development goals. Where highlighted in orange, the result is below or marginal to the stated development goal. The two development goals not met in this iteration were the RCA outlet (helmet return) relative humidity and the valve actuation time.

Table 2. RCA Development Goals & Observed Test Results

Requirement	Development Goal	Test Results
Pressurization		
BTA	8.3 PSI above ambient pressure (23 PSIA over vacuum)	System proof pressure demonstrated to 13.7 PSIG, 28.4 PSIA over vacuum.
IVA	1 to 4.3 PSI above ambient pressure (15.7 to 19 PSIA over vacuum)	
EVA	4.3 PSI above ambient pressure (4.3 PSIA over vacuum)	
Power Input	5 Watts or less	Lab Controller: 3 Watts Idle, 12 Watts Peak (3.1 Watts 8-Hour Time Weighted Average)
		Valve drive power at test point is 0.5 to 0.8 Watt
Performance	Primary Goal	
	Maintain helmet return $ppCO_2 < 2.2$ mm Hg (TWA) for given	Demonstrated average return $ppCO_2$ of 2.65 mm Hg with a set point
	metabolic profile	of 6 mm Hg. Lower set point of 3 to 4 mm Hg will achieve goal.
	Secondary Goal	
	Maintain helmet return RH 25 to 75%	Measurements not conclusive, however trend data is between 10 to 15% RH.
Environment	Loop: 100% Oxygen (23.9 psia Maximum)	Materials of construction compatible with oxygen.
	Vacuum: <0.01 Torr	System tested and rated for vacuum and pressure condition.
	Ambient: 0 to 14.7 psia	System verified leak tight to proof pressure (13.7 PSIG)
	Temperature: 15 to 30°C (Laboratory/Chamber Environment)	System demonstrated expected performance at room temperature (23°C)
Operation	Bed equalization during actuation	Measured and verified bed equalization during actuation.
	Minimize FOD generation/susceptability	Valve seat design is low wear material (Rulon J)
	Less than 6 sccm leakage (to vacuum or ambient)	No external leakage observed. Measured < 1 sccm leakage at 14.5 psid over vacuum.
		Calculated 3 sccm leakage at system proof condition (28.4 psid bed to bed)
	Valve actuation time < 5 seconds	Full actuation time ~7.4 seconds (~2.5 seconds of no-flow condition during actuation)
Pressure Drop	2.5 in H2O @ 6 ACFM, 14.7 psia (System)	Measured system pressure drop over range of conditions. Goal met.
	Note: 1 to 1.5 in H2O budgeted for Valve Assembly	
	Maximize vacuum conductance	System demonstrated expected performance.
Overall Volume	Minimize Volume	Final System Volume: ~0.47 ft^3 (~13.3 Liters)
Overall Mass	Minimize Mass	Final System Mass: 16 lbm (7.26 kg)
Ullage Volume	Minimize plumbing volume to reduce lost air volume overboard	Measured 1.95 Liters of empty gas volume per bed (Bed volume and header volume)
Manufacturing	Lower complexity	Valve and canister assemblies are modular and based on heritage processes.
Relative Maturity	Higher maturity	Valve and canister assemblies are based on flight heritage and prior assemblies.

The relative humidity at the RCA outlet is dictated by the chemical properties of the sorbent and the dynamics of the process.[12] Since the process is driven by CO_2 capacity, the H_2O vapor removal capacity and kinetics are a resultant of the dynamic equilibrium that is eventually established for the system operating conditions. Decoupling the H_2O vapor capacity and CO_2 capacity are not likely possible without adversely impacting the CO_2 capacity.

With respect to the actuation time, the commercial gearmotor assembly selected did not have sufficient torque at the desired actuation speed to prevent potential for stalling. Sufficient margin to the stall torque was observed at a valve rotation speed of approximately 0.10 rotations per second, which for a 270-degree range of rotation results in the total time of just under 7.5 seconds. However, the time of the no-flow condition is only 1/3 of this time as the valve assembly rotates through the equilibrium position. A slightly larger stepper motor on the same gearbox may yield a higher actuation speed with sufficient torque output, with a small increase in actuation power. Additionally, since this was the first valve assembly to be built, no torque data existed to match the optimal gearmotor to the assembly, and time constraints prevented further iteration on selection of the gearmotor. The design is, however, capable of being changed in the field with some minor assembly work and retesting, if changes are required.

Plans are under way to design, build, and test an RCA 3.0 over fiscal years 2013 and 2014. The RCA 3.0 unit will infuse into the PLSS 2.5 iteration for testing, as protrayed in Fig. 16.

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