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# Continued Development of the Rapid Cycle Amine (RCA) System for Advanced Extravehicular Activity Systems

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**Development activities related to the Rapid Cycle Amine (RCA) Carbon Dioxide ($CO_2$) and Humidity control system have progressed to the point of integrating the RCA into an advanced Primary Life Support System (PLSS 2.0) to evaluate the interaction of the RCA among other PLSS components in a ground test environment. The RCA 2.0 assembly (integrated into PLSS 2.0) consists of a valve assembly with commercial actuator motor, a sorbent canister, and a field-programmable gate array (FPGA)-based process node controller. Continued design and development activities for RCA 3.0 have been aimed at optimizing the canister size and incorporating greater fidelity in the valve actuator motor and valve position feedback design. Further, the RCA process node controller is envisioned to incorporate a higher degree of functionality to support a distributed PLSS control architecture. This paper will describe the progression of technology readiness levels of RCA 1.0, 2.0 and 3.0 along with a review of the design and manufacturing successes and challenges for 2.0 and 3.0 units. The anticipated interfaces and interactions with the PLSS 2.0/2.5/3.0 assemblies will also be discussed.**

## Nomenclature

*ACFM* = Actual Cubic Feet per Minute
*AEMU* = Advanced Extravehicular Mobolity Unit
*ACM* = Aspen Custom Modeler
*CFD* = Computational Fluid Dynamics
*COTS* = Commercial Off-The-Shelf

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$CO_2$ = Carbon Dioxide
*DEV* = dual end vacuum
*EMU* = Extravehicular Mobility Unit
*EVA* = Extravehicular Activity
*FPGA* = Field Programmable Gate Array
$GN_2$ = Gaseous Nitrogen
$H_2O$ = Water
*HSSSI* = Hamilton Sundstrand Space Systems International, A UTC Aerospace Company
*ISS* = International Space Station
*JSC* = Johnson Space Center
*LiOH* = lithium hydroxide
*MetOx* = metal oxide
*mmHg* = Millimeters of Mercury
*NASA* = National Aeronautical and Space Administration
*NEOs* = near-earth Objects
$N_2$ = Nitrogen
$O_2$ = Oxygen
*PLSS* = Portable Life Support System
*POR* = primary oxygen regulator
$ppCO_2$ = Partial Pressure of Carbon Dioxide
*psig* = Pounds per Square Inch Gauge
*RCA* = Rapid Cycle Amine
*SEV-I* = single end vacuum–inlet
*SEV-O* = single end vacuum–outlet
*SOR* = secondary oxygen regulator
*SSAS* = Space Suit Assembly Simulator
*SWME* = suit water membrane evaporator
*TRL* = Technology Readiness Level
*UTC* = United Technology Corporation

## I. Introduction

Because Extravehicular Activities (EVAs) (otherwise known as spacewalks) are performed in the vacuum of space, the technological challenges associated with the maintaining life support functions for an extended period of time become unique. The spacesuits have to be pressurized and therefore critical environmental control functions have to be sustained over the course of a spacewalk. Of the critical functions that a spacesuit provides to accomplish the EVAs, delivering breathing gas to and removing the carbon dioxide ($CO_2$) from an astronaut are two of the most challenging. In particular, the current technology used for $CO_2$ removal in the International Space Station (ISS) Extravehicular Mobility Unit (EMU) is primarily the limiting factor in the amount of time that a spacewalk can occur.

From the early days of the U.S. space program, lithium hydroxide (LiOH) was the favored chemical sorbent technology for $CO_2$ removal due to its ability to absorb $CO_2$ and become lithium carbonate. Early spacesuits in the Apollo program relied on non-regenerative LiOH technology to remove $CO_2$. The technologies that currently perform $CO_2$ removal in the ISS spacesuits are LiOH and regenerative metal oxide (MetOx) sorbent technologies. Canisters (either LiOH or MetOx) are installed into the spacesuit as individual components and are removed after use. The LiOH canister can only be used one-time. A 14- hour regeneration cycle with extensive energy is necessary for the MetOx technology.[1,2]

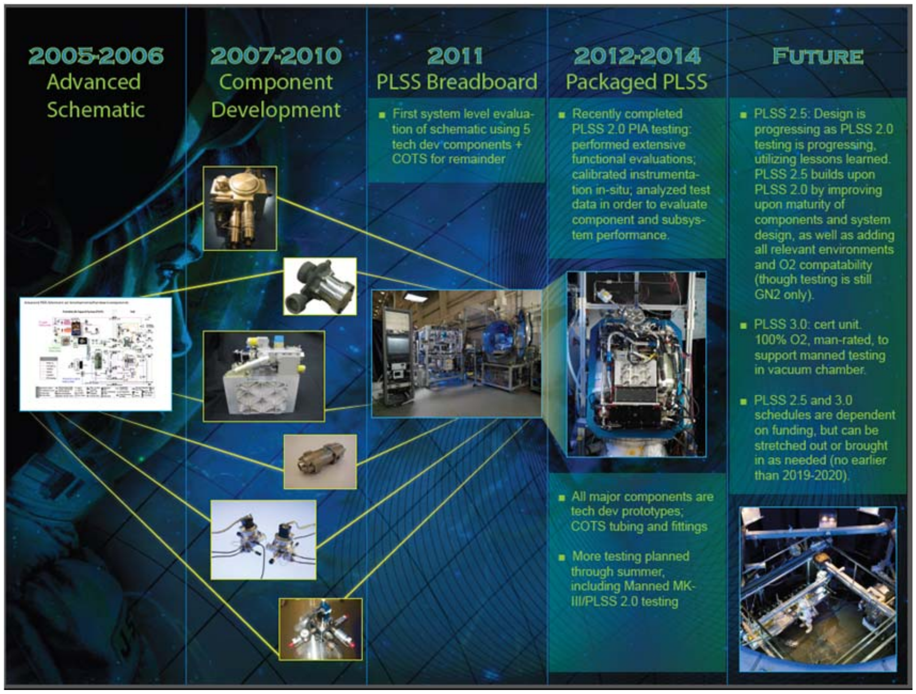
Over the last several years, NASA has invested in a new technology for $CO_2$ removal and humidity control in an advanced spacesuit. The pursuit of this new technology has been driven by mission applications beyond ISS. Those missions will necessitate EVAs that adapt to destinations such as near-earth Objects (NEOs) and surface missions to the moon, Phobos, or Mars.[3] Therefore, these destinations necessitate that the technology be operable over a wide range of metabolic conditions, over long durations of time with minimal power and consumable loss, and be regenerative.

The particular advanced technology for $CO_2$ removal system that has the potential to meet the stringent requirements for the next generation spacesuit is the Rapid Cycle Amine (RCA) technology. This technology addresses both $CO_2$ removal and humidity control in the Advanced EMU (AEMU). This technology employs a solid amine sorbent that has the ability to remove substantially all the $CO_2$ in either a dry or humid environment.[4] Additionally, once the $CO_2$ is absorbed, it can be desorbed at vacuum. The RCA technology is being employed in the AEMU in an alternating bed configuration whereby the solid amine sorbent can absorb $CO_2$ in one bed and desorb the $CO_2$ in the alternate bed. The desorption process occurs with the exposure to vacuum creating a regenerative process. Therefore, this swing-bed regenerative process for the AEMU is known as the RCA system. With continuous access to space vacuum, the RCA system can be continuously regenerating.[5] Additionally, the RCA system can operate over a wide range of metabolic conditions, over a long duration of time, with minimal power, and with minimal consumable losses.

Over the last several years, the RCA swing-bed technology has gone through a series of design, development, test, and evaluation to prove the technology viable for the AEMU and EVA applications. These previous efforts and further laboratory demonstrations have investigated the scalability of the technology, different sorbent canister geometries, flow control valve designs, and process control schemes aimed at optimizing the RCA for system integration into an advanced Primary Life Support System (PLSS). This paper provides an overview of the RCA 1.0, 2.0 and 3.0 system designs, system integration of the RCA, functional and performance testing, and analysis performed.

## II. Background

Over the last nine years, a remarkable amount of work has gone into formulating the advanced PLSS. A depiction of the development progression of the advanced PLSS is shown in Fig. 1. It all started during 2005 and 2006 when a schematic study was launched to baseline a PLSS schematic for the Constellation program. A kickoff meeting held at NASA JSC in April 2005 formulated the approach to a new schematic study and provided an overall plan. The study had two purposes: 1) To generate a recommended technology roadmap to aid the Constellation program in considering the development of the next-generation PLSS, and 2) To identify primary and alternate technologies for the advanced PLSS. This study was carried out over 18 to 19 months and resulted in the selection of a baseline schematic for the next-generation PLSS and associated alternate technologies. A technology development roadmap was created for the baseline and alternate technologies recommended under the schematic study. The results of the study were documented in a formal NASA report published in January 2007.[6]



- First system level evaluation of schematic using 5 tech dev components + COTS for remainder

- Recently completed PLSS 2.0 PIA testing: performed extensive functional evaluations; calibrated instrumentation in-situ; analyzed test data in order to evaluate component and subsystem performance.
- All major components are tech dev prototypes; COTS tubing and fittings
- More testing planned through summer, including Manned MK-III/PLSS 2.0 testing

- PLSS 2.5: Design is progressing as PLSS 2.0 testing is progressing, utilizing lessons learned. PLSS 2.5 builds upon PLSS 2.0 by improving upon maturity of components and system design, as well as adding all relevant environments and O2 compatability (though testing is still GN2 only).
- PLSS 3.0: cert unit. 100% O2, man-rated, to support manned testing in vacuum chamber.
- PLSS 2.5 and 3.0 schedules are dependent on funding, but can be stretched out or brought in as needed (no earlier than 2019-2020).

**Figure 1. Development progression of the advanced PLSS**

The EVA focus was given clearer direction after the schematic study culminated with a technology development roadmap for alternate technologies. In addition, NASA has realized a tremendous increase in EVA technology development over the past several years. Initially, the Constellation Program stimulated advanced technology development from 2005 to 2010. Over the last several years, other programs such as Exploration Technology

Development Program, .Office of Chief Technology, and the Space Technology Mission Directorate have continued to facilitate the advancement of EVA technology with a focus to infuse into the Advanced Exploration Systems (AES) AEMU PLSS. The demand for efficient and reliable EVA technologies, particularly regenerable technologies, is apparent and will continue to be needed as future mission opportunities arise. The technology advancements have accumulated through decades of EVA experience and present significant advances over the current systems.

The PLSS schematic study specifically identified the RCA $CO_2$ and moisture removal system for further development. The RCA was one of several technologies targeted for advanced PLSS application. Considerable development work had already begun on the RCA $CO_2$ and moisture removal technology before the PLSS schematics study ensued; consequently, it already had a Technology Readiness Level (TRL) of 4 at the time of the study.[6] A detailed progression of the RCA development is conveyed in Section III below.

In all tests conducted at the JSC, the RCA technology has performed well. Prior to 2011, all testing for the AEMU PLSS had been performed at the component level. The first system level evaluation of the advanced PLSS 1.0 schematic using five technology development components plus several commercial off the shelf (COTS) components occurred at JSC from June 17 to September 30, 2011. The PLSS 1.0 breadboard testing completed 168 test points over 44 days of testing.[7] The RCA 1.0 was one of the five advanced development components included in the PLSS 1.0 breadboard level test as shown in Fig.1. Overall, the entire test was successful, including the RCA 1.0. The test demonstrated performance for parameters such as pressure and metabolic rates which demonstrated that the test stand was functioning properly and could meet performance objectives. Overall, the PLSS.1.0 test accomplished it requirements. And, much of that success was due to the RCA 1.0 vacuum swing bed within the ventilation subsystem.[8]

Over the last several years (2012-2014), the PLSS team at NASA JSC has been performing the buildup and packaging of a PLSS 2.0.[5] The team has recently completed PLSS 2.0 pre-installation acceptance testing of the entire PLSS 2.0 assembly. This assembly included the RCA 2.0. The testing included extensive functional evaluations including RCA 2.0. All the instrumentation was calibrated in-situ. The test data is being analyzed in order to evaluate the components such as RCA 2.0 and subsystem performance. All major components including RCA 2.0 are technology development prototypes. Also, COTS hardware along with tubing and fittings were used throughout the PLSS 2.0. More testing is being planned through the summer 2014, including a manned test using the Mark III spacesuit. The RCA 2.0 unit used for the packaged PLSS 2.0 is described in more detail under Section III below.

The next technology iteration from the RCA 2.0 is RCA 3.0. Currently the RCA 3.0 is targeted for the PLSS 2.5 assembly. The PLSS 2.5 is in the design phase and it is progressing as PLSS 2.0 testing is progressing, utilizing lessons learned. PLSS 2.5 builds upon PLSS 2.0 by improving upon maturity of components and system design, as well as adding all relevant environments and $O_2$ compatibility (though testing is still $GN_2$ only). The plan is to design and assemble PLSS 3.0 as the certification unit whereby it will be 100% $O_2$ compatible and man-rated. This unit is currently targeted toward supporting manned testing in a vacuum chamber. PLSS 2.5 and 3.0 schedules are dependent on funding, but can be stretched out or brought in as needed (no earlier than 2019-2020).

## III. RCA Development Progression

Research associated with the RCA technology orginated as early as 1996 when Hamilton Standard (now Hamilton Sundstrand Space Systems International, A United Technology Corporation (UTC) Aerospace Company (HSSSI)) demonstrated that $CO_2$ and water ($H_20$) vapor removal was achievable in a venting-type system. Earlier research did include solid amines, however they were not of the venting nature. A venting system uses the vacuum of space to regenerate a sorbent during an EVA. A dual-bed solid amine approach was used to demonstrate the $CO_2$ and water removal system. Fig. 2 shows the original schematic used for testing. Additionally, there were over 20 amine sorbents that were studied and tested as well. Although the technology was not mature enough to incorporate

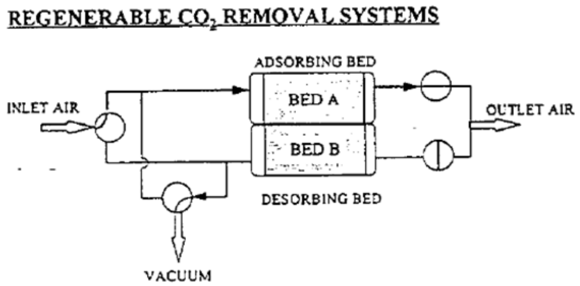


Figure 2. Dual Bed Solid Amine System Schematic

into an EMU at that time, it was evident that the venting solid amine swing-bed sytsem had potential. This venting approach proved to be very successful and could support an indefinite EVA.  This benefit would eliminate the $CO_2$ removal system from being the limiting factor on the length of EVAs. Other factors such as battery power, $O_2$ supply, crew member endurance would be the influencing factors.[9]

Shortly thereafter the favorable results materialized and was published in 1996, NASA contracted with HSSSI to develop and build a prototype $CO_2$/$H_2O$ removal and regeneration system and deliver it to NASA Johnson Space Center (JSC) by 1999. The prototype was successfully designed, fabricated, and laboratory-tested, and delivered to NASA. The prototype was named the RCA 1.0 system. The prototype unit was specifically sized for EVA operation. The prototype unit employed two alternating solid-amine sorbent beds to remove $CO_2$ and $H_2O$ vapor continuously. Fig. 3 shows the schematic used for this prototype.[10]

The RCA design consists of alternating adsorbing and desorbing beds. While one sorbent bed is exposed to the spacesuit ventilation loop to continusously remove $CO_2$ and $H_2O$ vapor (Bed A adsorb), the other sorbent bed regenerates (Bed B desorb). The beds switch by using a pneumatically actuated linear motion spool valve. Inside the beds contain reticulate aluminum foam. The foam serves to provide support, a means of heat transfer media between the beds, space for growth and skrinkage to occur within the individual sorbent particles.[10,11]

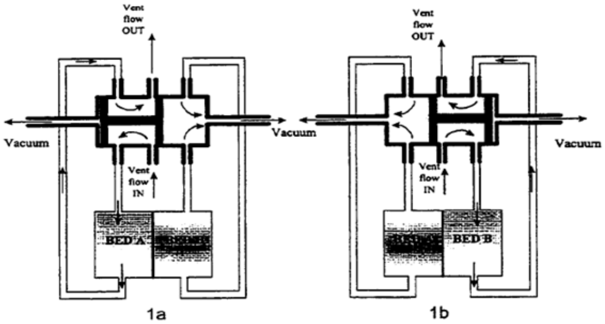


**Figure 3. RCA Flow Schematic**

The RCA 1.0 is rectangular in design, however cylindrical canister designs were also developed by a different vendor so as to have alternate early proof of concept development of the RCA.[12] Also, other valving types were investigated including a spool valve, ganged valve, and drum valve. A trade study based on test data and a correlated math model suggested the rectangular canister be pursued for future work.

The RCA swing bed technology was matured from proof-of-concept by building a full-sized assembly, RCA 2.0. The RCA 2.0 consists of an integrated rectangular canister and a ganged ball valve. The ball valve proved to be reliable in other related projects and therefore was selected for PLSS 2.0. RCA 2.0 was fabricated, tested, and evaluated by HSSSI and then delivered to NASA for the integration into the AES Advanced PLSS 2.0. The AES Advanced PLSS 2.0 has completed a series of pre-installation acceptance testing and will begin integrated test in 2014 as well. The testing will involve vacuum chamber testing of the integrated PLSS 2.0 using a metabolic simulator. HSSI has just recently been authorized to fabricate a high-fidelity oxygen-compatible RCA 3.0. for evaluation in the advanced PLSS 2.5. The packaging design is currently underway at Johnson Space Center (JSC) for the PLSS 2.5.

The RCA system has long been a capability desired for the advanced PLSS based largely on the attractiveness of a $CO_2$ removal system that does not impose significant expendable requirements and does not limit EVA duration. With the RCA swing-bed amine sorbent optimized, it further reinforces the system attractiveness for EVA applications. Over the development cycles of the RCA systems, the respective designs have been able to borrow ideas and improvements from advances made in each evolution and application.

Additional knowledge has been gained because the same vacuum-regenerated technology has been under development for vehicle applications.[2] This investment of research on the RCA technology enable the practical use of common $CO_2$ removal technology across a wide spectrum of exploration platforms from EVA spacesuit systems to long-duration vehicles. In the following sections, an overview will be provided of the RCA components and each of the three RCA development units: RCA 1.0, RCA 2.0, and RCA 3.0.

### A. RCA Components

The RCA is constructed of four principal components; namely the chemical sorbent, the two-bed sorbent canister, the valve assembly and controller. The chemical sorbent is a proprietary formulation that reversibly chemisorbs both $CO_2$ and water vapor at favorable rates over a range of predicted operating conditions. The canister is constructed such that the bed exposed to vent loop conditions is in thermal contact with the bed exposed to the vacuum regeneration path. Exothermic heat rise in the on service bed is thereby moderated by the regenerating bed undergoing the reverse endothermic desorption process. Induced loads from cyclic pressurization over a range of operating conditions as well as anticipated environmental conditions are also canister design factors. The valve assembly provides the physical interfaces between the sorbent canister and the ventilation loop as well as to the vacuum regeneration pathway. It controls the physical process of properly diverting vent loop air flow and vacuum between the two sorbent beds and also executing a simultaneous physical change in bed operating states (adsorb/desorb, on/vent, and uptake/regen). In the current development stage, the RCA controller continually monitors the valve position state and periodically controls the drive motor to actuate the valve assembly. An RS-485 serial interface provides the communication interface to the FPGA-based controller for external software monitoring and commanding.

## B. RCA 1.0

### 1. *Concept Design*

Among other development efforts, this design was undertaken to demonstrate the feasibility of the RCA concept to control both $CO_2$ and humidity over a range of simulated EVA ventilation loop conditions. A previously developed pneumatically actuated spool valve assembly was paired with a redesigned canister assembly intended to accommodate improved heat transfer characteristics.[11] Further, a feedback control concept based on the helmet return $ppCO_2$ was also developed and demonstrated.

### 2. *System Integration and Testing*

a. Vendor testing

Prior to accepting the RCA 1.0 unit, functional and performance testing was conducted at the vendor facility, UTAS.[11]Testing evaluated the general $CO_2$ and $H_2O$ removal efficiencies of the unit for simulated metabolic loads ranging from 350 Btu/hr to 1968 Btu/hr at approximately 6 acfm and 1 atmosphere. The RCA 1.0 testing evaluated three-vacuum desorption configurations, or regeneration pathways: single end vacuum–inlet (SEV-I), single end vacuum–outlet (SEV-O), and dual end vacuum (DEV) configuration. The SEV-I and SEV-O configurations are regenerated with vacuum applied to either the inlet side or outlet side of the regenerating sorbent bed, respectively. DEV configuration is regenerated with vacuum at both the bed inlet and bed outlet. Each configuration controlled the regeneration flow path of the test article and allowed for comparison of desorption rates of $CO_2$ and $H_2O$ in the each configurations. The DEV configuration was tested over the metabolic range of 349 Btu/hr to 1968 Btu/hr and the SEV configurations were tested over the range of 349 Btu/hr to 919 Btu/hr. The test setup schematic is shown in Fig. 4 and the test matrix is shown in Table 1.[11] The test results indicated good performance of the unit and that outlet RCA humidity levels are not as dry with the SEV-O desorb configuration.

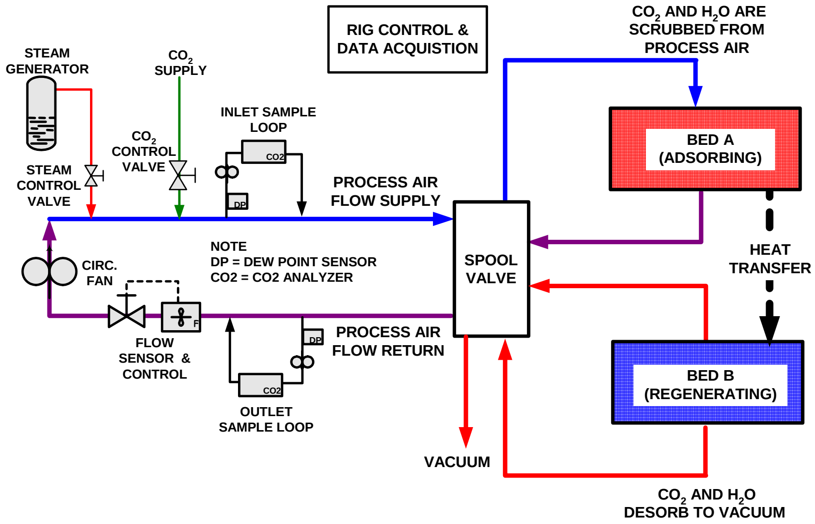


**Figure 4. UTC Aerospace Systems Test Bed**

**Table 1. UTC Aerospace System's Simulated Metabolic Test Matrix**

| Vacuum Regeneration Configuration | $CO_2$ Input Challenge | Simulated Metabolic Rate (Estimated) | | $H_2O$ Input Challenge | Estimated Latent Challenge | |
|---|---|---|---|---|---|---|
| | gram / min $CO_2$ | Watts | BTU/hr | gram / min $H_2O$ | Watts | BTU/hr |
| DEV, SEV | 0.5 | 102 | 349 | 0.78 | 31 | 108 |
| DEV, SEV | 0.8 | 152 | 518 | 0.91 | 37 | 126 |
| DEV, SEV | 1.4 | 269 | 919 | 1.17 | 47 | 161 |
| DEV | 1.6 | 307 | 1050 | 1.29 | 52 | 177 |
| DEV | 2.1 | 403 | 1378 | 1.48 | 60 | 204 |
| DEV | 3.0 | 576 | 1968 | 1.45 | 58 | 200 |
| DEV | 7 hour variable profile. | | | 1.2 - 1.4 | 48 - 57 | 165 - 195 |

b. Johnson Space Center (JSC) Testing

The method of testing the RCA 1.0 unit at JSC was to independently test the unit in an isolated ventilation test loop and then evaluate the RCA 1.0 in an integrated PLSS 1.0 test bed. Fig. 5 shows the RCA 1.0 in test in PLSS 1.0 breadboard.

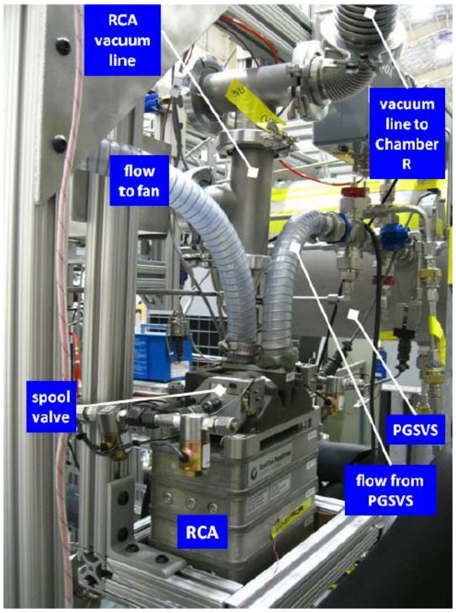


**Figure 5. RCA 1.0 in PLSS 1.0 test**

The PLSS ventilation subsystem test loop was based on a recirculating closed-loop setup as shown in Fig. 6. This system was designed to integrate all required instrumentation to characterize the performance of the RCA 1.0 unit while providing proper system volumetric flow rate and metabolic $CO_2$ and $H_2O$ injection rates. The system setup allowed for the collection of $CO_2$ concentration and relative humidity data immediately before and after the test article while collecting the system volumetric flow rate immediately prior to the test article.[15]

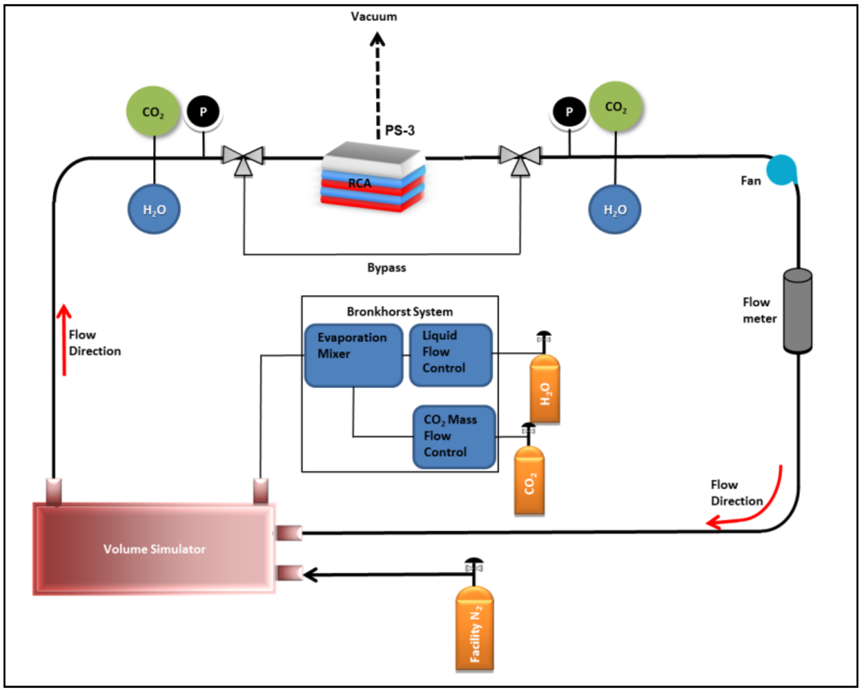


**Figure 6. PLSS Ventilation Test Loop**

The RCA 1.0 test series included a sequence of representative EVA operational scenarios. Each EVA operational scenario correlated to a specific systematic test condition of $CO_2$ and $H_2O$ injection rates (see Table 2) to simulate human metabolic loads, system flow rates, temperature and pressure. The system outlet partial pressure of CO2 (ppCO2) was maintained at or below the allowable helmet inlet (inhaled) limits, of 6 millimeters of Mercury (mmHg), established by requirements at the time of testing. Developing a parametric understanding of the interrelationships between pressure, flow rate, temperature, and concentrations provided insight that defined requirements for the regeneration system.[15]

**Table 2. JSC Simulated Metabolic Test Matrix**

| Test Case | Simulated Metabolic Rate | $CO_2$ Injection Rate | $H_2O$ Injection Rate |
|---|---|---|---|
| | BTU/hr | slm | g/min |
| 1 | 350 | 0.271 | 0.60 |
| 2 | 520 | 0.402 | 1.02 |
| 3 | 850 | 0.658 | 1.13 |
| 4 | 1000 | 0.774 | 1.44 |
| 5 | 1250 | 0.967 | 1.59 |
| 6 | 1600 | 1.238 | 1.36 |
| 7 | 2000 | 1.548 | 1.29 |

The effects of varying operational flow rates were a major segment of the RCA testing. This phase of testing included the evaluation of various flow rates that could be experienced in the suit. At the time of testing, the flight design flow rate for the Advanced PLSS was yet to be determined; this testing provided data on the performance of the RCA at numerous flow rates, which varies the residence time of the gas stream to the media within the RCA unit, thereby allowing for differing adsorption and desorption rates. Residence time is the average time a molecule of gas spends in the system. The RCA 1.0 was tested at flow rates of 4.0, 4.5, 5.0, and 6.0 acfm.[15]

The RCA 1.0 testing characterized the effects of the reconfiguration of desorption, or regenerative, flow paths. The RCA 1.0 testing evaluated three-vacuum desorption configurations, or regeneration pathways: single end vacuum–inlet (SEV-I), single end vacuum–outlet (SEV-O), and dual end vacuum (DEV) configuration. The SEV-I and SEV-O configurations are regenerated with vacuum applied to either the inlet side or outlet side of the regenerating sorbent bed, respectively. DEV configuration is regenerated with vacuum at both the bed inlet and bed outlet. Each configuration controlled the regeneration flow path of the test article and allowed for comparison of desorption rates of $CO_2$ and $H_2O$ in the each configurations. The full RCA 1.0 test series including each simulated metabolic rate at each flow rate and valve configuration was conducted at 1 atmosphere and at 33.1 kPa (4.8 psia) to investigate the effects of reduced pressure on the RCA 1.0 unit. The reduced pressure test conditions more accurately predict the operational suit conditions during an EVA.[15]

Further testing of the RCA 1.0 investigated several challenging test scenarios: a) moving average control algorithm; b) pre-breathe protocol simulation; c) suitport interface; d) fixed cycle time; and e) off-nominal temperature performance. All single metabolic rate test cases were performed until cyclic steady state conditions were achieved or until accurate $CO_2$ and $H_2O$ removal profiles were achieved. It should be noted that the following testing was completed after PLSS 1.0 testing, when the RCA 1.0 unit was reinstalled into the ventilation loop for further testing.

a) In an effort to develop an algorithm to accommodate the maximum and minimum RCA outlet ppCO2 concentration, a moving average control algorithm investigation was performed at four different outlet ppCO2 concentrations: 2, 4, 6, and 8 mmHg. The determining pass/fail criterion for the moving average investigation was the average maximum outlet ppCO2 experienced during the testing. Each moving average ppCO2 setting was examined at four simulated metabolic rates of 400, 1000, 1600, and 2000 BTU/hr. These two variables allowed an average maximum outlet ppCO2 to be calculated to determine the effects of each condition on the system.[16]

b) The pre-breathe protocol simulation evaluated the RCA's performance under dynamic depressurization or re-pressurization. Depressurization removes the air pressure from a specified volume, whereas re-pressurization is the process of pressurizing a specified volume. The pre-breathe protocol simulated a spacesuit depress or repress to determine the RCA's response capabilities during the course of a dynamic drop in pressure from atmospheric to EVA pressures. The pre-breathe protocol simulation evaluated the RCA at an ambient pressure of 14.7 psia to a suit pressure of 4.3 psia.[16]

c) The suitport interface investigation evaluated the RCA's performance when the vacuum conductance was varied under various suitport interface connections. The suitport interface is identified as the vacuum port, or desorption path, connection to the RCA. Conductance is the ratio of material, under steady-state conditions, to the pressure differential between two specified sections. The suitport interface assessed stainless steel tubing at three port interface sizes: 1, 0.75, and 0.5 inch to determine the vacuum conductance influence on the RCA. [16]

d) The established process of the RCA is governed by the outlet ppCO2 concentration in the spacesuit. The fixed cycle time tests evaluated the performance of the RCA in the event that the CO2 sensors in the spacesuit failed. The primary purpose of assessing the fixed cycle time was to determine a conservative cycle time that will keep the astronaut safe and to enhance the understanding of the RCA's capabilities under a fixed cyclic criterion. The RCA was evaluated at several fixed cycle times with several corresponding simulated metabolic loads.[16]

e) The RCA is designed with a series of adjacent sorbent sections that alternate between adsorption and desorption. Each section is fabricated with a thermally conductive metallic foam element to enhance the heat transfer between adjacent sections, since adsorption is an exothermic reaction. The sorbent must be cooled to remove the heat of adsorption to maximize $CO_2$ loading. Conversely, the desorbing bed must be heated efficiently to remove the $CO_2$. The objective of the off-nominal temperature tests was to assess the performance of the RCA in a high or low temperature environment. The temperature of the system ranged from 10-37.7°C (50-100°F). The off-nominal temperature performance investigation showed the performance effects of the RCA to remove $CO_2$ from the system while temperature was increased or decreased.[16]

Once the RCA 1.0 unit demonstrated the ability to sufficiently remove $CO_2$ and $H_2O$ from a closed loop ambient or sub-ambient atmosphere, it was then evaluated in an integrated test stand, known as the PLSS 1.0 test bed (Fig. 7). The PLSS 1.0 test bed consisted of integrating the major technology development components of the PLSS, to evaluate how readily each component would perform together along with any ancillary equipment required to simulate PLSS operations. The PLSS 1.0 test bed consisted of three major subsystems: oxygen, ventilation, and thermal subsystems which provide the life support functions of the PLSS. The major technology development components in the PLSS 1.0 test bed consisted of the oxygen subsystem primary oxygen regulator (POR) and secondary oxygen regulator (SOR), ventilation subsystem RCA 1.0, Fan, and the thermal subsystem suit water membrane evaporator (SWME).[7,8] Results from the JSC testing indicated similar performance to the Vendor testing and validated the capabilities of RCA 1.0. The additional testing including off-nominal test points were also successful. A photo of the test configuration is shown in Fig. 8.

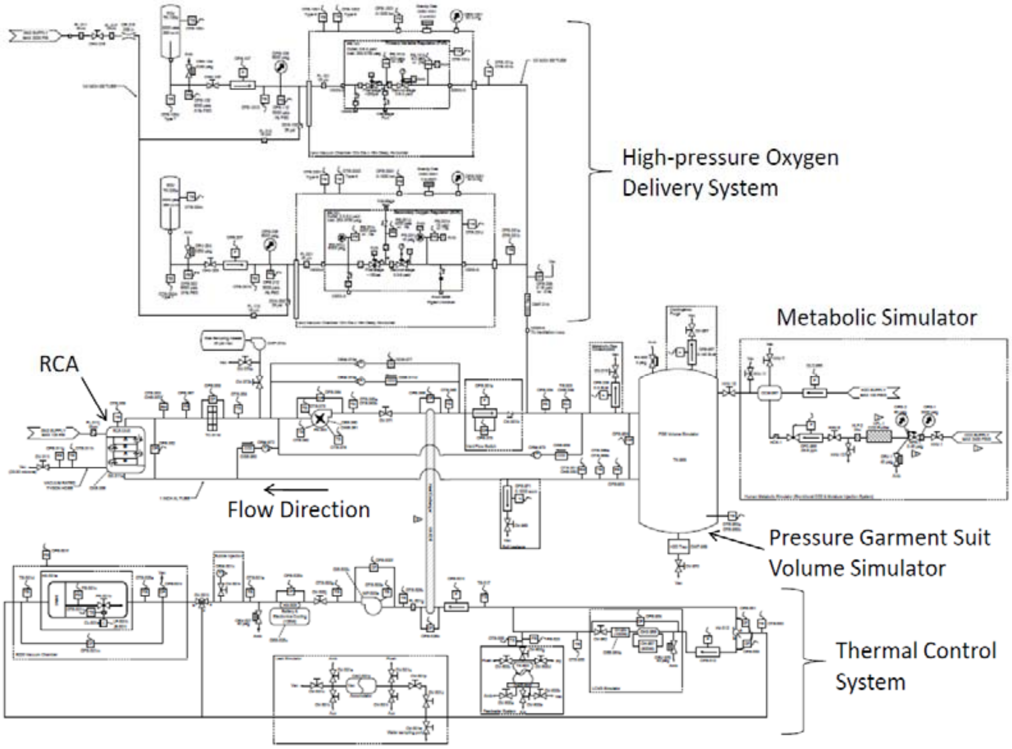


**Figure 7. PLSS 1.0 Test Configuration**

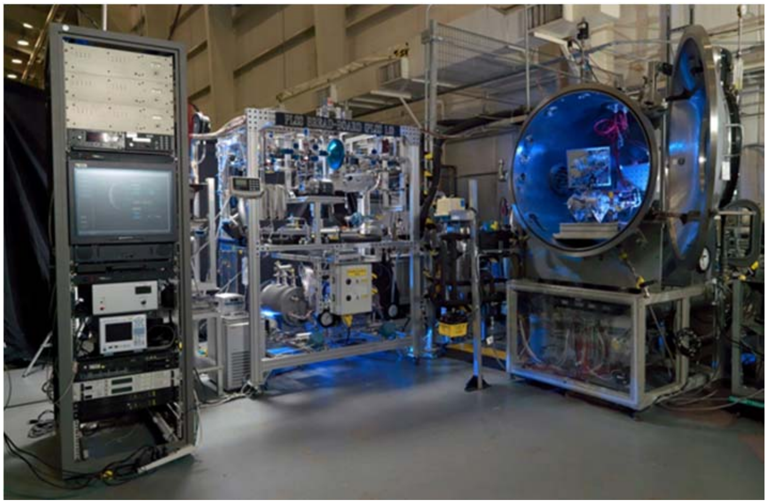


**Figure 8. PLSS 1.0 Breadboard test Configuration**

### 3. *Analysis*

The RCA model was built using Aspen Custom Modeler (ACM) tool and model predictions have been compared to the functional and performance based testing performed at the vendor facility. The ACM RCA model was cross checked with test data that originated in-house at JSC.

Aspen Custom Modeler (ACM) was used to simulate the performance of Portable Life Support System (PLSS) 1.0. Fig. 9[18] shows schematic of PLSS in ACM. Gaseous Nitrogen ($GN_2$) module (i.e. block) in ACM introduces make-up $N_2$ gas which represents metabolic oxygen consumption in the PLSS. A portion of the $GN_2$ is lost during the RCA bed switching while desorption occurs. A fan keeps constant recirculation gas flow in the PLSS. The $CO_2$ block introduces $CO_2$ levels based on test metabolic rate and the $H_2O$ block supplies metabolic moisture to the loop. The $CO_2$ and moisture is merged in CEM block at the desired test temperature and pressure. The PGS simulates the spacesuit system volume as a continuously-stirred tank in the model. A 2.0 cubic foot volume was assumed for the free volume within the PGS. The SPOOLVALVE block distributes exhaled gas mixture alternatively between adsorption and desorption sorbent beds of RCA. Block VOUT simulates two outlet gas flows from RCA: 1) Recirculates regenerated cleaned gas ($N_2$) back to $GN_2$ block of PLSS, 2) Accumulated $CO_2$ and moisture is vented to space vacuum in order to desorb a RCA bed. The Vacuum Chamber block simulates the facility vacuum source. The regenerated gas flows to $GN_2$ block and completes the loop.

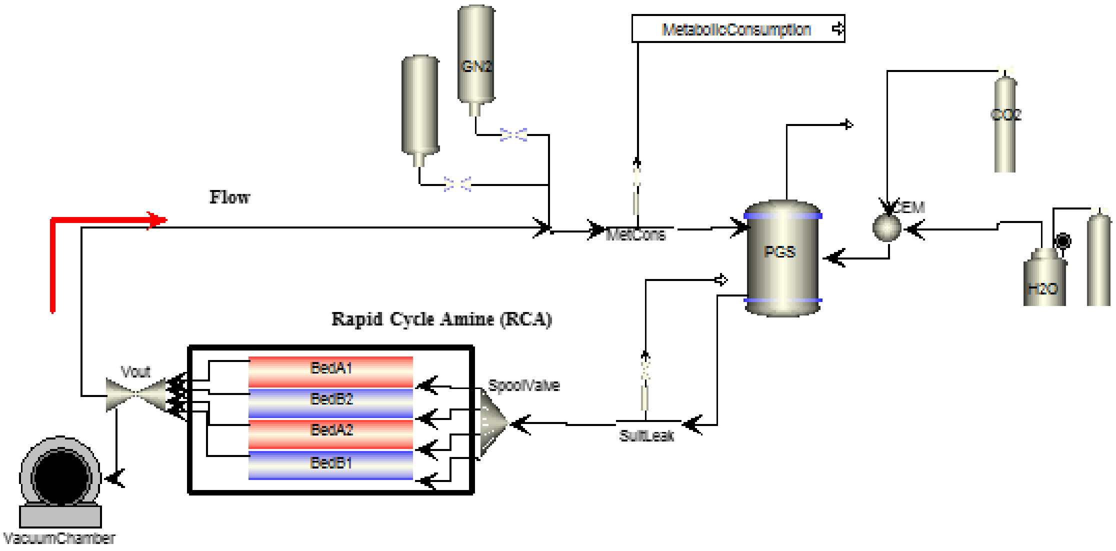


**Figure 9. Portable Life Support System 1.0 Integrated Test Model**

$CO_2$ and moisture adsorption/desorption in RCA are modeled using ACM. Within each of the layers of adsorption and desorption beds, the model depicts are three columns of SA9T sorbents. The aluminum foam that holds the SA9T in the physical system is represented in the model as a heat conducting material. The actual SA9T is a porous polymeric material that is coated with a polyamine and is a patented proprietary sorbent of UTC Aerospace Systems.

The flow of exhaled gas from the PGS to the SA9T/foam block is simulated as one-dimensional flow to the SA9T block. The aluminum foam, due to its high thermal conductivity, helps dissipate heat generated in adsorption of $CO_2$ and moisture in the adsorption layers to the desorption layers. In the desorption layers, the supply of adsorption heat and vacuum promote desorption of $CO_2$ and moisture. Because of the unique arrangement of adsorption/desorption layers, the RCA operation is close to an isothermal process.

The adsorption of $CO_2$ and $H_2O$ vapor on SA9T is essentially at a constant pressure. Additionally, the pressure drop across the RCA beds is modeled. Desorption flow of $CO_2$ and moisture from the SA9T bed was modeled as both choked and non-choked flow cases, depending upon pressure upstream and downstream of the bed exit.

Isotherms of $CO_2$ and moisture over SA9T was reported earlier.[19] The $CO_2$ and moisture isotherms over SA9T were correlated by Swickrath.[20] These isotherms were used in development of the RCA model.

Mass conservation of $CO_2$ and $H_2O$ vapor along gas flow through the SA9T blocks in adsorption and desorption is modeled using Eq. (1). Mass transfer between $CO_2$ and $H_2O$ vapor in gas phase and the SA9T sorbent surface is modeled by Eq. (2). Energy conservation during adsorption and desorption cycles is modeled using Eq. (3).

Adsorption / desorption

$$\epsilon \frac{\partial C_i}{\partial t} + \rho_s \frac{\partial q_i}{\partial t} + \frac{\partial (v C_i)}{\partial x} = D_{L,i} \frac{\partial^2 C_i}{\partial x^2} \tag{1}$$

Mass Transfer

$$\frac{\partial q_i}{\partial t} = k'(C_i - C_{eq,i}) \tag{2}$$

Energy Conservation Equations

$$\left[\rho_s C_{p,s} + \epsilon C_{p,gas}\right] \frac{\partial T}{\partial t} + v \epsilon C_{p,gas} \frac{\partial T}{\partial x} - K_f \frac{\partial^2 T}{\partial x^2} = \rho_s \left(\sum_i H_i \frac{\partial q_i}{\partial t}\right) - \frac{4 h_{w,g}}{D_s}(T - T_{w,Top}) - \frac{4 h_{w,g}}{D_s}(T - T_{w,Bot.}) \tag{3}$$

Swickrath developed the original ACM RCA model and conducted simulations for tests.

The above model has been used to simulate the UTC Aerospace Systems 2006 RCA 1.0 test with single-ended vacuum desorption. Figure 10 shows the predicted $ppCO_2$ at RCA outlet and $ppCO_2$ of the PGS with a metabolic rate at 852 BTU/hr, simulating a RCA 1.0 test at UTC Aerospace Systems on December 06, 2006. The RCA adsorption/desorption cycling was activated when ppCO2 at the RCA outlet reached 6.0 mmHg. The cycle time predicted by the model was 6.3 minutes, is close to test measurements.

The RCA model will be used for pre-test prediction. With slight change in the amount of SA9T sorbent, RCA 1.0 model could be used to simulate the performance of RCA 2.0 and RCA 3.0.

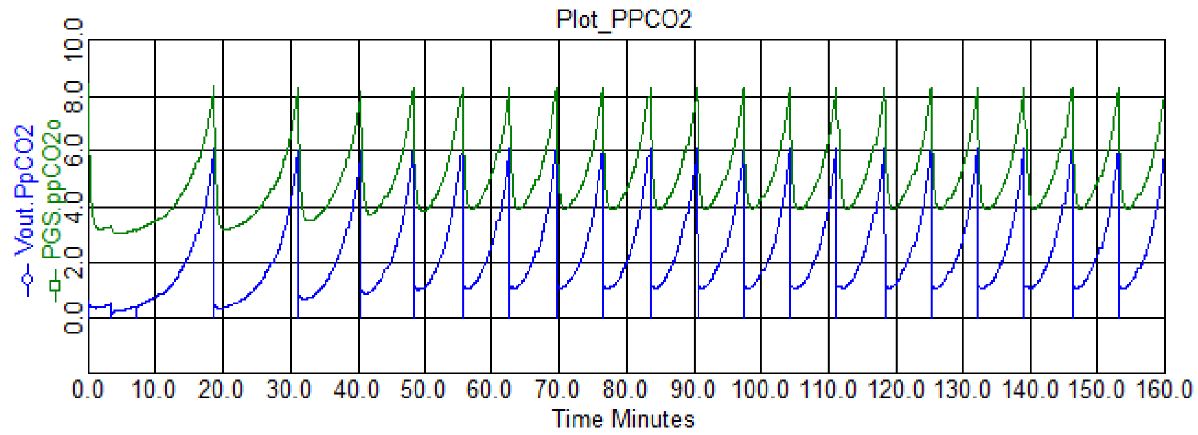
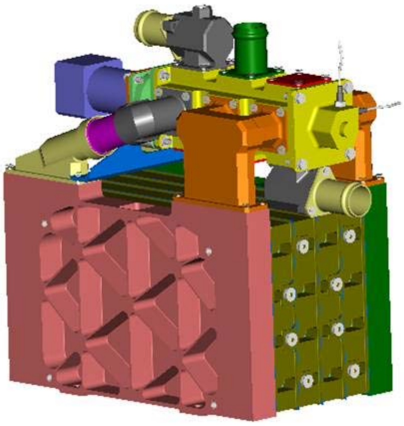


**Figure 10. ppCO2 at RCA outlet and in the Pressure Gas Suit simulating RCA 1.0 test at UTC Aerospace Systems December 12, 2006.**

## C. RCA 2.0

### *1. Concept Design*

The RCA 2.0 iteration was challenged to bring the design from feasibility of meeting $CO_2$ and humidity removal requirements to meeting advanced PLSS functional and operational requirements. The design was implemented with a multi-ball valve assembly driven by a single actuator to improve valve operability and system interfaces over the pneumatically actuated spool valve. The RCA 2.0 prototype with an integrated controller was assembled into PLSS 2.0 to undergo integrated system testing at NASA-JSC. Component testing of an identical valve assembly has accumulated over 105,000 cycles to date against a preliminary design requirement of 5,000 cycles.[5] The RCA 2.0 assembly is shown in Fig.11 as designed and Fig. 12 as fabricated.



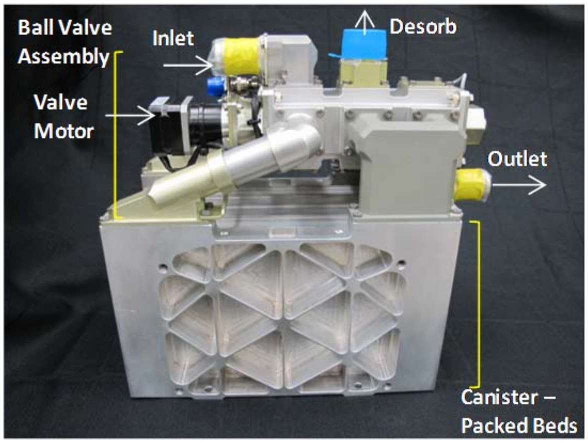


**Figure 11 RCA 2.0 as designed** **Figure 12. RCA 2.0 as fabricated**

*2. System Integration and Testing*

a. Vendor testing

Pre-delivery testing of the RCA 2.0 assembly was conducted at UTC Aerospace Systems in Windsor Locks, CT. Following system proof pressure and leakage testing, performance evaluations were conducted at atmospheric conditions and over a range of $CO_2$ input conditions as well as an 8 hour variable $CO_2$ profile. The RCA 2.0 demonstrated the ability to maintain $ppCO_2$ below specified limits over a range of 100 to 586 Watts of equivalent metabolic $CO_2$ input to the RCA. Concurrent water vapor removal was also demonstrated for water vapor input rates between 0.69 to 1.44 gram $H_2O$/min, maintaining relative humidity between 20 and 50%.

Flow-$\Delta P$ testing was conducted over a range of absolute pressure (4, 8, 10, 14.7 psia) and range of volumetric air flow (2, 4, 6, 8 ALPM) at each pressure condition, which yielded a wide range of data over relevant mass flow conditions for the RCA, and the observed results compared well with Computational Fluid Dynamics (CFD) analysis results. RCA 2.0 is shown in test at UTC Aerospace Systems in Fig. 13.

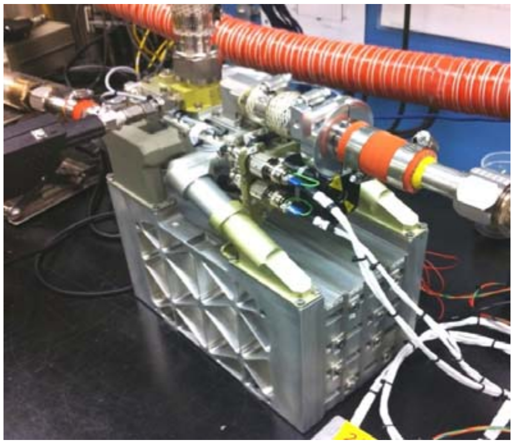


**Figure 13. RCA 2.0 in test**

b. JSC testing

Due to time constraints, RCA 2.0 was integrated into the PLSS 2.0 test rig. The PLSS 2.0 testing will obtain engineering data characterizing the performance of a packaged PLSS and PAS/CWCS integrated system in ambient and vacuum environments using simulated human and vehicle interfaces. Testing will demonstrate operation of the PLSS in nominal configurations (IVA, pre-EVA, EVA, and post-EVA). The testing will experimentally characterize the performance of the PLSS 2.0 system, identify unexpected system interactions, and build confidence in the PLSS design.[17] RCA 2.0 is shown installed in the PLSS 2.0 integrated system in Fig. 14.

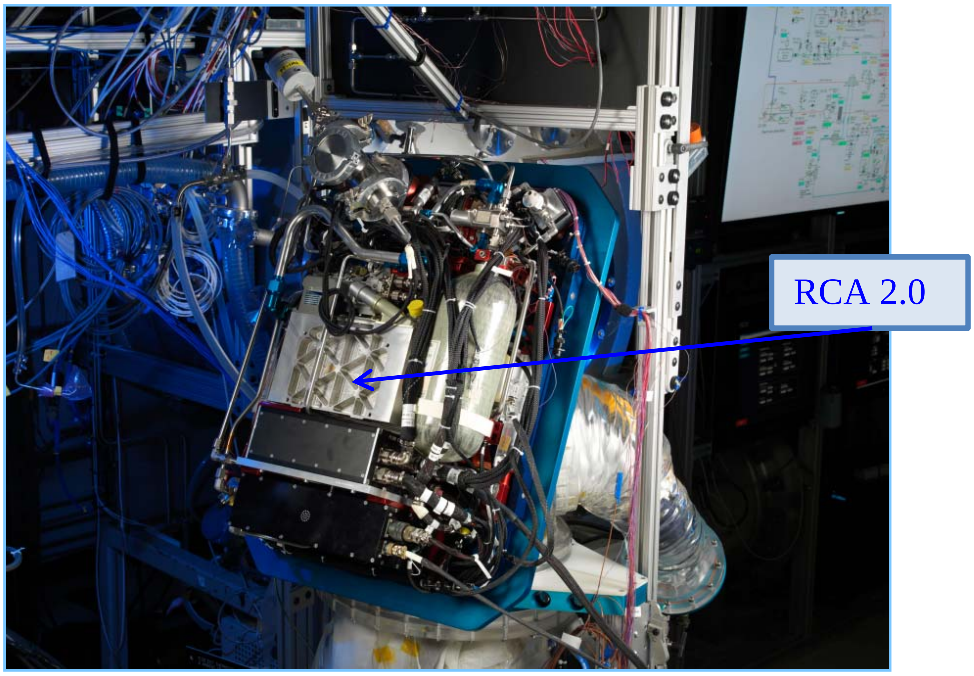


**Figure 14. RCA 2.0 installed in PLSS 2.0**

## D. RCA 3.0

### 1. *Concept Design*

The RCA 3.0 design utilizes the same valve as the RCA 2.0 design with a slightly modified canister assembly. Refined pressure drop requirements along with test data on the RCA 2.0 prototype demonstrated that increased pressure drop could be accommodated by reducing the chemical sorbent volume by 25%. The integrated controller design also offers the ability to include greater functionality with respect to monitoring of the RCA and other ventilation loop parameters such as $ppCO_2$, air flow, pressures and temperatures. The design of RCA 3.0 is shown in Fig. 15.

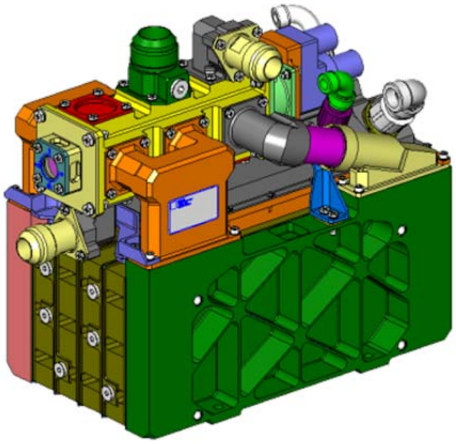


**Figure 15. RCA 3.0 design**

### 2. *System Integration and Testing*

It is expected, or planned, to test the RCA 3.0 unit independently in an isolated PLSS ventilation test loop and then evaluate the RCA 3.0 in PLSS 3.0 test rig.

The PLSS ventilation subsystem test loop will be based on a recirculating closed-loop setup. This system will be designed to integrate all required instrumentation to analyze the performance of the RCA 3.0 test article while providing proper system volumetric flow rate and metabolic $CO_2$ and $H_2O$ injection rates. The system setup allowed for the collection of $CO_2$ concentration and relative humidity data immediately before and after the test article while collecting the system volumetric flow rate immediately prior to the test article.

## IV. Design Comparison of RCA 1.0, 2.0, and 3.0

Based on testing and evaluations of several test articles, a prototype of RCA 1.0, a designed and fabricated RCA 2.0, a design formulated for RCA 3.0, a comparison of the three designs can be formulated. The technological development of the RCA has been pursued in order to raise the technology readiness level (TRL). The TRL level plan for each RCA unit can be seen in Fig. 16.

Mass and volume of the SA9T have been design drivers from the beginning. The volume has been a significant driver due to the strick size requirements for placement in the confines of the PLSS. However, through the designs, it has been a challenge to minimize consumable losses and reduce the complexity. All of the RCA units have met NASAs requirements, especially for performance in $CO_2$ removal and humidity control. Additional parameters measured include flow-$\Delta$P, actuation, and actuation time, power, controller design, and maximum pressure.

Overall, tremendous effort has gone into the production of RCA 1.0 and RCA 2.0 design, fabrication, and testing and currently RCA 3.0 is undergoing fabrication. The detail design feature comparison associated with each RCA designed iteration is depicted in Table 3.

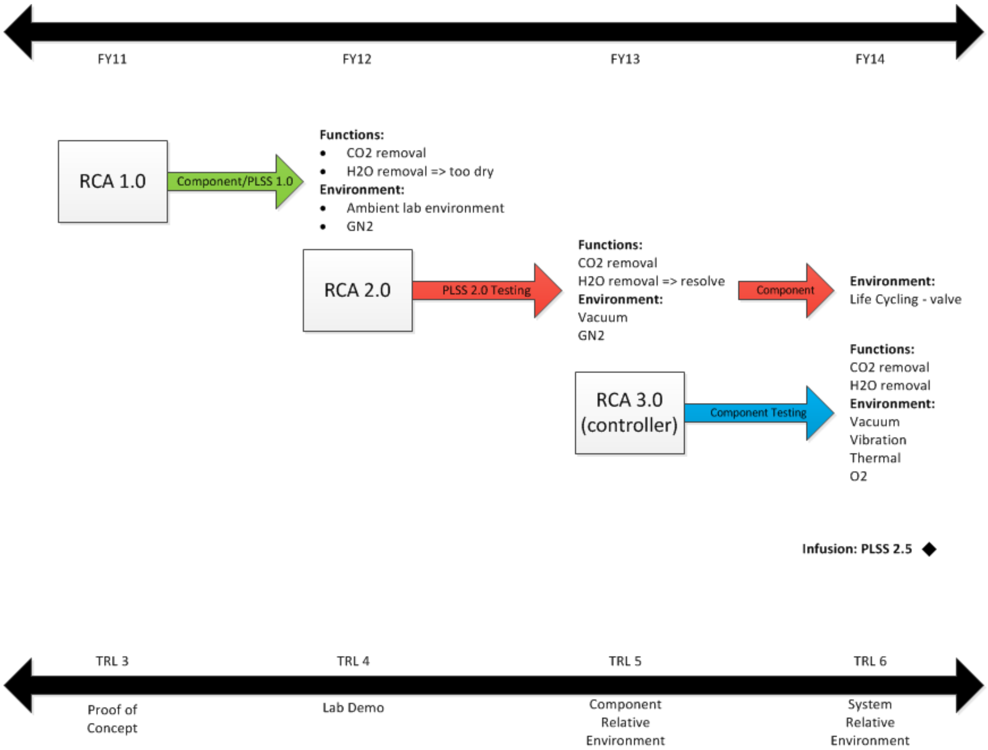
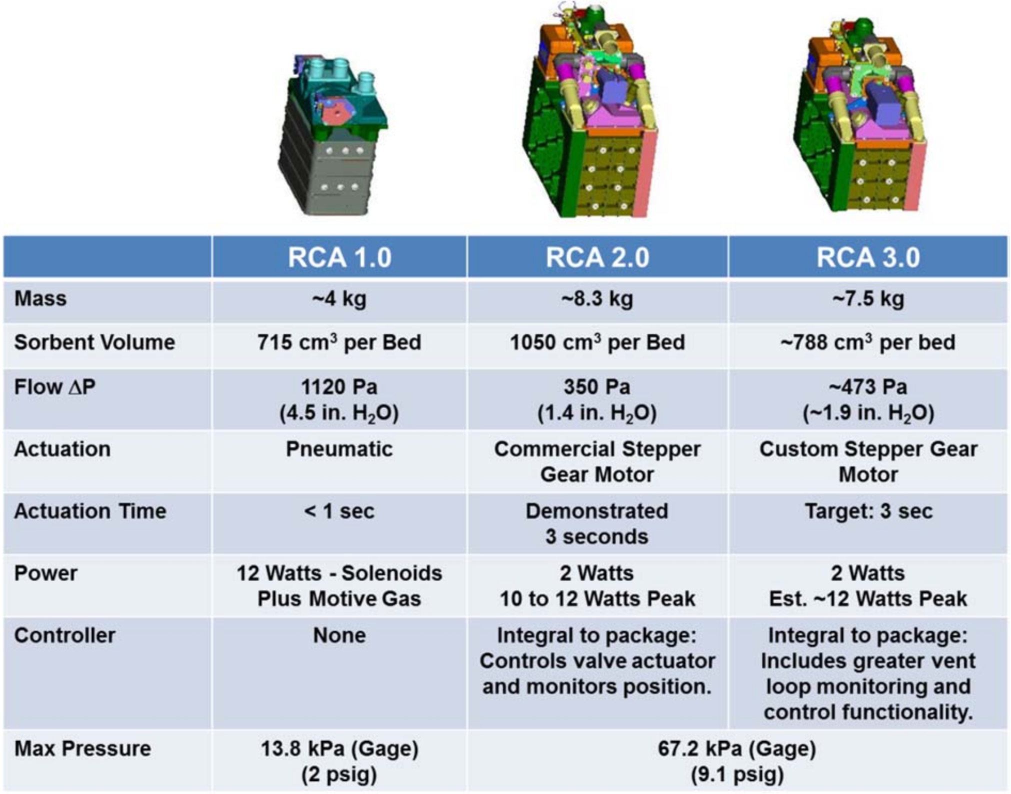


**Figure 16. RCA Technology Readiness Levels**

**Table 3. RCA 1.0, 2.0, and 3.0 Design feature comparison**



| | RCA 1.0 | RCA 2.0 | RCA 3.0 |
|---|---|---|---|
| Mass | ~4 kg | ~8.3 kg | ~7.5 kg |
| Sorbent Volume | 715 $cm^3$ per Bed | 1050 $cm^3$ per Bed | ~788 $cm^3$ per bed |
| Flow $\Delta P$ | 1120 Pa<br>(4.5 in. $H_2O$) | 350 Pa<br>(1.4 in. $H_2O$) | ~473 Pa<br>(~1.9 in. $H_2O$) |
| Actuation | Pneumatic | Commercial Stepper Gear Motor | Custom Stepper Gear Motor |
| Actuation Time | < 1 sec | Demonstrated 3 seconds | Target: 3 sec |
| Power | 12 Watts - Solenoids Plus Motive Gas | 2 Watts<br>10 to 12 Watts Peak | 2 Watts<br>Est. ~12 Watts Peak |
| Controller | None | Integral to package: Controls valve actuator and monitors position. | Integral to package: Includes greater vent loop monitoring and control functionality. |
| Max Pressure | 13.8 kPa (Gage)<br>(2 psig) | 67.2 kPa (Gage)<br>(9.1 psig) | |

## V. Conclusion

This paper has provided a development summary of the RCA technology development. It has included the early research into the TEPAN amine sorbent. The background of the PLSS development and testing has been provided. The progression of the RCA technology has been discussed including the design, system integration, testing, and analysis. Overall, the RCA technology has progress successfully in the development phases and has thus far provide evidence of being a viable alternate technology to the existing technologies of MetOx and LIOH that are currently used the in ISS spacesuits.

## Acknowledgments

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