Design and Development Comparison of Rapid Cycle Amine 1.0, 2.0, and 3.0

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The development of the Rapid Cycle Amine (RCA) swing-bed technology for carbon dioxide (CO_2) removal has been in progress since favorable results were published in 1996. Shortly thereafter, a prototype was designed, developed, and tested successfully and delivered to Johnson Space Center in 1999. An improved prototype (RCA 1.0) was delivered to NASA in 2006 and sized for the extravehicular activity (EVA). The RCA swing-bed technology is a regenerative system which employs two alternating solid-amine sorbent beds to remove CO_2 and water. The two-bed design employs a chemisorption process whereby the beds alternate between adsorption and desorption. This process provides for an efficient RCA operation that enables one bed to be in adsorb (uptake) mode, while the other is in the desorb (regeneration) mode. The RCA has progressed through several iterations of technology readiness levels. Test articles have now been designed, developed, and tested for the advanced space suit portable life support system (PLSS) including RCA 1.0, RCA 2.0, and RCA 3.0. The RCA 3.0 was the most recent RCA fabrication and was delivered to NASA-JSC in June 2015. The RCA 1.0 test article was designed with a pneumatically actuated linear motion spool valve. The RCA 2.0 and 3.0 test articles were designed with a valve assembly which allows for switching between uptake and regeneration modes while minimizing gas volume losses to the vacuum source. RCA 2.0 and 3.0 also include an embedded controller design to control RCA operation and provide the capability of interfacing with various sensors and other ventilation loop components. The RCA technology is low power, small, and has fulfilled all test requirements levied upon the technology during development testing thus far. This paper will provide an overview of the design and development of RCA 1.0, 2.0 and 3.0 including detail differences between the design specifications of each.

Nomenclature

acfm = actual cubic feet per minute
AEMU = Advanced Extravehicular Mobility Unit

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AES	=	Advanced Exploration Systems
CO_2	=	carbon dioxide
CxP	=	Constellation Program
DEV	=	dual end vacuum
EMU	=	Extravehicular Mobility Unit
EVA	=	extravehicular activity
FY	=	fiscal year
GN_2	=	gaseous nitrogen
HITL	=	human-in-the-loop
H_2O	=	water
ISS	=	International Space Station
JSC	=	Johnson Space Center
kg	=	kilogram
LiOH	=	lithium hydroxide
MetOx	=	metal oxide
NASA	=	National Aeronautics and Space Administration
NEOs	=	near-Earth objects
NGLS	=	Next Generation Life Support
PLSS	=	Portable Life Support System
psia	=	pounds per square inch absolute
RCA	=	Rapid Cycle Amine
RH	=	relative humidity
RVDT	=	Rotary Variable Differential Transformer
SEV	=	single end vacuum
SMTA	=	suited manikin test apparatus
STMD	=	Space Technology Mission Directorate
TRL	=	technology readiness level
UTC	=	United Technology Corporation
UVC	=	utility vacuum chamber

I. Introduction

THE development of an advanced extravehicular mobility unit (AEMU) is currently underway at the NASA Johnson Space Center (JSC).[1] A Rapid Cycle Amine (RCA) technology has been earmarked as the carbon dioxide (CO_2) and humidity removal system for the re-design of the Portable Life Support System (PLSS) being developed for the AEMU. The primary reason for the selection of the RCA technology is that it is a vacuum-regenerable technology for CO_2 and humidity.[2]

The current state-of-the-art technologies used for CO_2 removal in the International Space Station (ISS) EMU are lithium hydroxide (LiOH) and regenerative metal oxide (MetOx) sorbent technologies. Each of the components are removed from the spacesuit PLSS after each use. The LiOH canister can only be used once. The MetOx can be used again. However, the MetOx canister requires a 14-hour regeneration bake-out cycle with an extensive amount of heat needed. Historically, spacesuit have relied on LiOH due to its ability to absorb CO_2 and become lithium carbonate.[2,3] The development of the regenerable MetOx technology was initiated in 1996 to overcome the logistical challenges associated with shipping LiOH canisters to support ISS extravehicular activities (EVAs).[4]

The RCA has been a very attractive technology for the AEMU not only because it is regenerable, but because it has the potential to meet the stringent requirements including a wide range of metabolic conditions over long durations of time with minimal power and consumable loss. These characteristics give RCA the ability to support extended-duration missions. Over the last several years an extensive development effort has ensued to mature the RCA technology. A set of three progressively mature prototypes have been developed, RCA 1.0, 2.0, and 3.0. These prototypes have been through a series of design, development, test, and evaluation to prove the technology to be viable for the AEMU. Various canister geometries, flow control valve designs, and process control schemes have been assessed along with system integration into the PLSS. This paper provides an overview of the RCA development progression as well as the design and performance comparisons of all three prototypes. Lessons learned along with future work are discussed.

II. Background

The development of the RCA technology has been ongoing for approximately two decades. In 1995, under a NASA research announcement contract, extensive testing took place to evaluate several amine sorbents in a rapid cycling configuration. From this work, an adsorbing and desorbing cycling concept design was conceived for CO_2 and humidity removal. This work provided the confidence that an in-place regenerable system could have the potential to operate continuously for long periods of time and reduce logistics associated with MetOx and LiOH systems.[5]

An initial assessment on potential technologies was performed in 1996 evaluating regenerative concepts as compared to LiOH in the NASA Shuttle EMU. At the conclusion of the evaluation, it was determined that venting technologies were not technically mature enough for incorporation into an EMU. Meanwhile, NASA continued to develop the MetOx regenerative technology. The regenerative MetOx technology along with LiOH remain usable technologies in the ISS EMU. As non-venting systems, both MetOx and LiOH still pose significant vehicle support impacts. As for the MetOx, a separate regeneration device is needed onboard ISS for regeneration, which poses weight and power demands. As well, the LiOH canister can only remove CO_2 for a single EVA and cannot be regenerated.[6]

In-place regeneration still remained attractive to NASA. A number of design concepts have been reviewed. Detail of the early development and RCA evolution was previously reviewed by Papale, et al.[7] This paper begins with the development of the RCA 1.0 and discusses the design, development, and testing through RCA 3.0. The main focus of the RCA development has been the integration of CO_2 removal with humidity control. Additionally, it was important to accomplish regeneration in a way that would eliminate significant consumables as well as minimize logistics, power, and weight.[2,8,9] The following topics provide some insight into drivers that contributed to the successful development of the RCA technology.

A. Stakeholders and relationship to NASA strategic goals

Until the advent of the Constellation Program (CxP), most of the development associated with the RCA had been driven by the desire to replace the MetOx and LiOH technologies in the EMU. A series of subsystem and system evaluations ensued at the onset of the CxP including requirement analysis and system trades. Even other destinations beyond ISS were considered on a “flexible path” including Near Earth Objects (NEOs) as well as missions to the Moon, Phobos, or Mars. The drive for innovative technologies was paramount to increase component life, protection from radiation events, dust mitigation, interfaces with rovers and habitats, high data rate network-based communication, innovative life support systems that minimized consumables or take advantage of in-situ resources, smart caution and warning capabilities, and advanced information systems that enabled crew autonomy.[3]

The PLSS baseline architecture for future missions was started in 2005-2006 when a schematic study was launched for the CxP. By 2007, a baseline schematic was defined for the next-generation PLSS. The PLSS schematic study specifically identified the RCA CO_2 and H_2O removal system for further development.[10] The PLSS schematic was refined in 2008-2009 to include components and descriptions. Future technology development needs were focused on PLSS schematic analysis, innovative methods of packaging PLSS components, thermal control developments, ventilation developments including the RCA, and oxygen subsystem developments.[2]

The CxP continued to stimulate advanced technology development from 2005 to 2010. In 2007, the EVA Technology Development roadmap was conceived to serve as a planning tool by which to communicate a forecast of what the future held. Additionally, other programs such as the Exploration Technology Development Program, the Office of Chief Technology, and the Space Technology Mission Directorate (STMD) have contributed to the advancement of EVA technology with a focus to support the Advanced Exploration Systems (AES) program which is currently funding the development of the AEMU.[10]

In 2011, trade studies were underway to development the AEMU architecture with a focus on microgravity EVA missions. During 2011, the PLSS architecture continued to evolve with the integration of components into the design, the refinement of a bill of materials, minimization of the packaging mass. These development efforts culminated into a very successful PLSS 1.0 Breadboard test which was performed for nearly three months in 2011 with a focus on nominal and contingency EVA operational scenarios. This test is described in more detail in Section III.B.iii.1 of this paper.[1]

In April 2012, NASA authorized the Technology Area 06 Road Map for Human Health, Life Support and Habitation Systems which identifies EVA systems as critical to every foreseeable human exploration mission for in-space microgravity EVA and for planetary surface exploration. In particular, the roadmap addresses introducing regenerable technologies for removing CO_2 and H_2O from a space suit via the PLSS. It specifically indicates that an amine swing bed technology currently under development at that time could be proven via a demonstration test on

ISS.[11] Additionally, the AES development of the AEMU addresses key technical challenges within one or more of the Space Technology Roadmaps[12] and is relevant to one or more Space Technology Grand Challenges.[13]

B. Infusion from STMD to AES programs

Beginning in Fiscal Year (FY) 2012, the RCA technology development was funded by the Next Generation Life Support (NGLS) Project. The NGLS is one of 20 development projects under NASA's Game Changing Development Program within STMD. The RCA was one of NGLS's key technologies. The NGLS project was aimed at increasing affordability, reliability, and vehicle self-sufficiency while decreasing mass and mission cost along with supporting a capability-driven architecture for extending human presence beyond low-Earth orbit. STMD targeted technologies found in NASA's Technology Roadmaps.[14,15] A primary project goal was to advance the Technology Readiness Level (TRL) of the technologies and infuse these technologies into the AES system demonstrations. The RCA technology addresses the challenge "In-situ regenerable technologies that will allow on-back regeneration and enable sustained EVA."[11]

III. Rapid Cycle Amine Development Progression

Based on the favorable results achieved in 1996 in evaluating regenerative technologies, NASA contracted with Hamilton Standard (now Hamilton Sundstrand Space Systems International [HSSSI], a United Technologies Corporation [UTC] Aerospace Company) to develop and build a prototype CO_2 and H_2O removal and regenerative system that was designed and fabricated under a NASA contract in 1999. As the technology was further developed, a successfully designed, fabricated, and laboratory-tested RCA 1.0 was delivered to NASA in 2006. The unit was specifically sized for EVA operation. The RCA 1.0 was one of the five advanced development components included in the PLSS 1.0 breadboard level test.[10] The design and the testing of RCA 1.0 is covered in Section III.B.

Based on the results of the PLSS 1.0 breadboard test results and attention given to more detailed operation requirements set forth for the next level of integration into PLSS 2.0, the RCA 2.0 was designed, developed, tested, and delivered to NASA in 2012. The development focused on valve operability considerations, sorbent canister sizing, and a controller for valve actuation.[7] The RCA 2.0 was successfully tested in the PLSS 2.0 integrated testing. The design and testing aspects of RCA 2.0 is covered in Section III.C.

Based on the result of the PLSS 1.0 and 2.0 integrated test results, NASA decided it was warranted to proceed with the development of a RCA 3.0. The development span over 2-year time frame which initiated in April 2013 and concluded in June 2015. Besides being right-sized, the RCA 3.0 was targeted to be integrated into the PLSS 2.5 design which is in the final stages of being designed. It was also important for the RCA 3.0 to be adaptable to space-like environments including vacuum, thermal, and launch and vibration requirements. Also, it was important that the ball valve be successfully life tested which it surpassed tremendously.[16]

Overall, the RCA 1.0 was a proof-of-concept unit. The RCA 2.0 was built as a full-size assembly. The RCA 3.0 unit was built to be flight-like and oxygen compatible. All three units are shown in Figure 1.

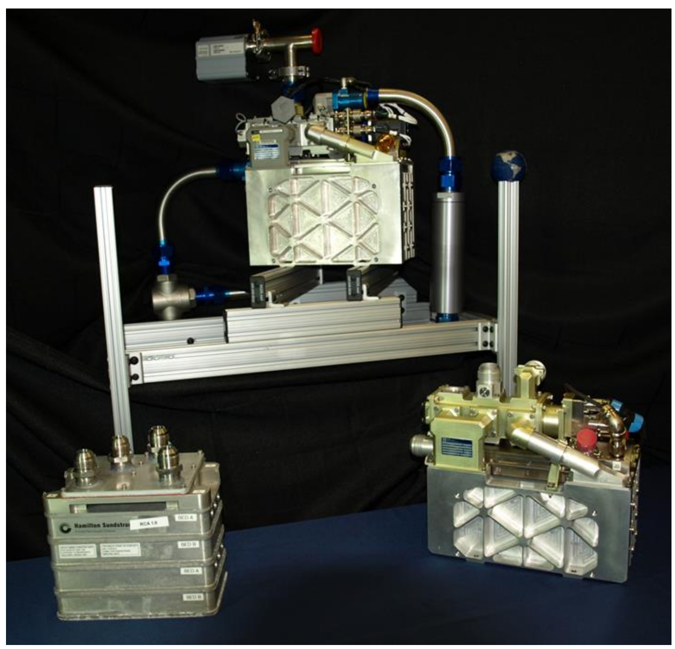

Figure 1. RCA 1.0 (left without spool valve), RCA 2.0 (top on rack), and RCA 3.0 (right)

A. Rapid Cycle Amine Components

The RCA 1.0, 2.0, and 3.0 is designed with three main components. They are as follows: 1) chemical sorbent (SA9T), 2) the two-bed sorbent canister, and 3) the valve assembly. RCA 2.0 and 3.0 both have an additional component known as the controller. Also, the RCA 1.0 was originally designed and fabricated with a spool valve. The RCA 2.0 and 3.0 was designed and manufactured with a ball valve assembly. The SA9T sorbent in all three units is a proprietary formulation that reversibly chemisorbs both CO_2 and moisture at favorable rates over a range of operating conditions. The canister is a two-bed system that 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 in the adsorption bed is thereby moderated and cooled by the regenerating bed undergoing the reverse endothermic desorption process. The canister is fabricated in a brazing process which prevents leakages. The valve assembly provides the physical interfaces between the sorbent canister and the PLSS 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/regeneration). In the RCA 2.0, the 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 field programmable gate array-based controller for external software monitoring and commanding.[10] The RCA 3.0 has an improved integrated controller that has the ability to control other components in the ventilation loop such as the fan and CO_2 sensor.[16]

B. Rapid Cycle Amine 1.0

i. RCA 1.0 Design

The main design feature of the RCA 1.0 is that it contains a spool valve for cycling the amine beds. RCA 1.0 was design and fabricated as the initial prototype. An original amine canister was designed and fabricated. However, RCA 1.0 canister was redesigned. The same spool valve was used on both canisters. The canister volume was reduced by 30 % to achieve a system weight goal of 4 kg. Also, the RCA 1.0 canister design increased the heat transfer surface area between the sorbent beds with a layered heat exchanger approach. The RCA 1.0 is shown in Figure 2.

Figure 2. RCA 1.0 System Assembly

ii. UTAS Testing

Pre-delivery testing of the RCA 1.0 assembly was conducted by UTAS between October and December 2006. The assembly was tested over a range of ppCO2 and humidity conditions and in several regeneration configurations, including dual end vacuum (DEV), single end vacuum (SEV) and nitrogen sweep gas regeneration. Further, the testing validated a feedback control approach whereby the helmet return ppCO2 (RCA outlet ppCO2) could provide a trigger the RCA valve to actuate and switch the bed functions when a pre-determined setpoint is reached. The ppCO2 feedback control, along with a time-based default mode have become the basis for subsequent RCA iterations. The full scale testing at 6 actual cubic feet per minute (acfm) also validated performance testing utilizing subscale test techniques and equipment. These subscale tests served to allow the design team to study various bed size assumptions and predict performance, which eventually compared well with the full scale RCA 1.0 deliverable. RCA 1.0 accumulated approximately 80 hours of test at UTAS prior to delivery to NASA-JSC in January 2007.

iii. JSC System Integration and Testing

1. PLSS 1.0 Integration, Testing, & Results

PLSS 1.0 testing was performed between June 17 and September 30, 2011 and included 168 test points. RCA 1.0 was integrated into the PLSS 1.0 test stand as shown in Figure 3. The body of steady state test points, of which there were 147, attempted to characterize the PLSS 1.0 performance and/or individual component performance with respect to one or more variables. The most common variable regarding steady state system performance was the crew metabolic rate followed by the RCA bed switch mode and criteria. General RCA 1.0 performance characteristics will be shown later along side of RCA 2.0 performance for easy comparison.

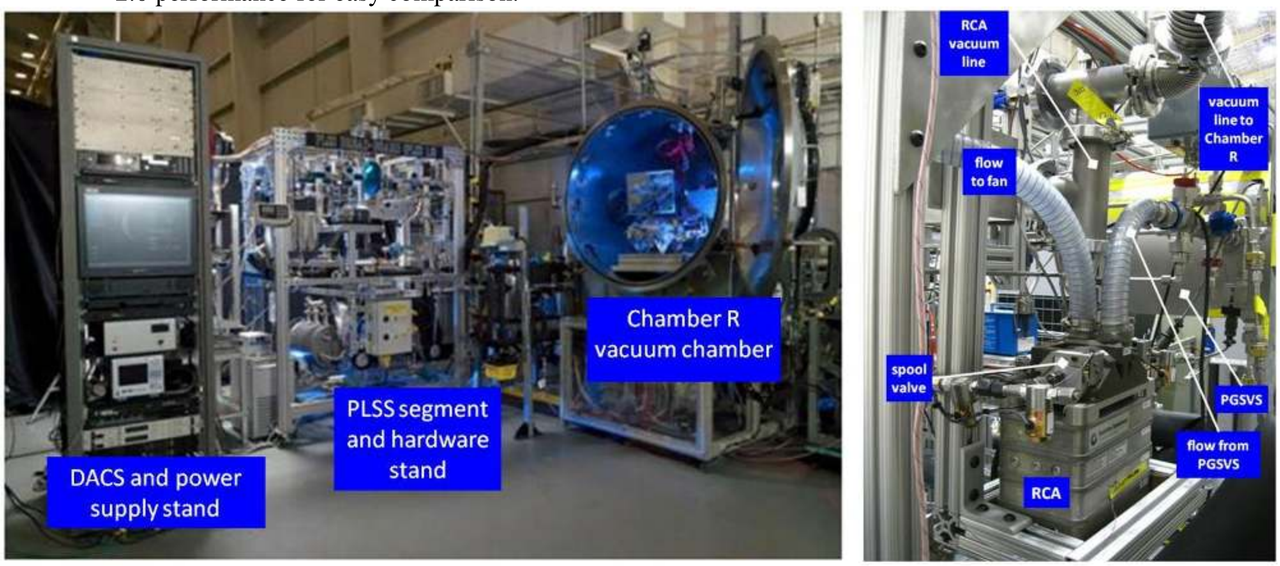

Figure 3. View of Complete PLSS 1.0 Test Bed (left) and RCA location in the Test Bed (right)

As an example of PLSS 1.0 test results, one test series evaluated how a compromised vacuum source would affect the RCA performance. Degraded vacuum conditions could occur if an RCA vacuum port or a vacuum line became partially blocked, thus increasing the vacuum pressure that the desorbing bed experiences. Also, results of this test gives some guidance on the vacuum quality requirements related to vacuum line design requirements for potential airlock applications. Test points were operated by metering ambient air into the vacuum line between the RCA and Chamber R by adjusting a hand valve until the RCA vacuum line pressure reached its setpoint as measured by the RCA vacuum port pressure sensor. Figure 4 summarizes RCA degraded vacuum pressure test results by plotting mean inlet partial pressure of CO_2 and average RCA bed B half cycle times as a function of mean RCA vacuum pressures for 3 different metabolic rates.

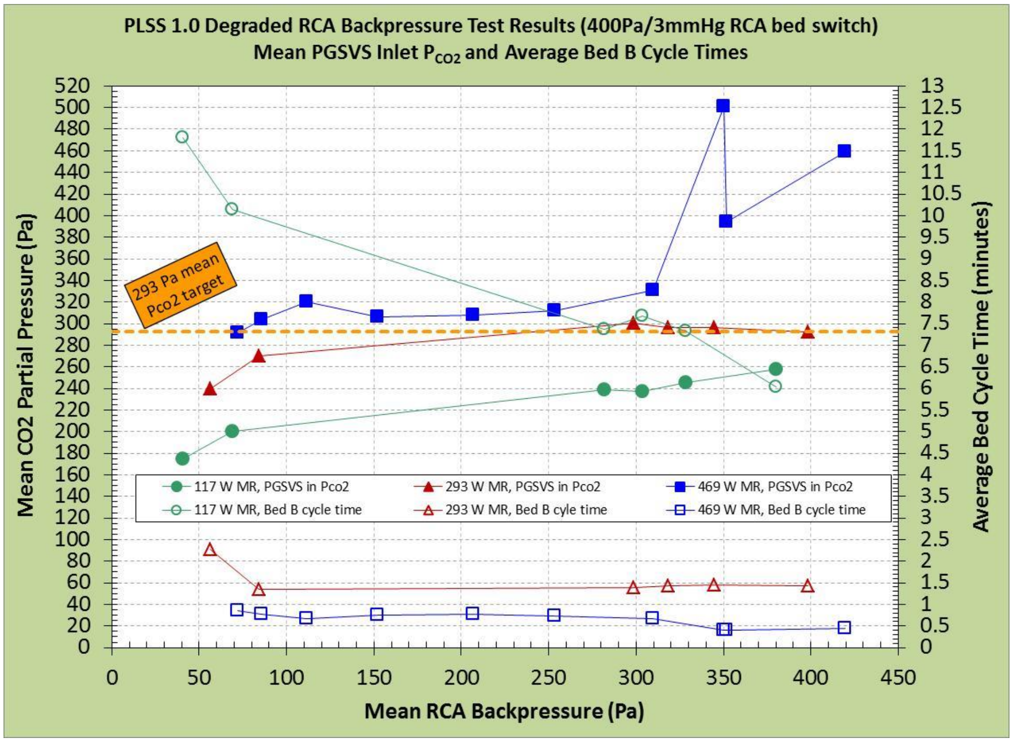

Figure 4. RCA Degraded Vacuum Pressure Test Results from PLSS 1.0 Testing

2. RCA 1.0 Integrated Ventilation Subsystem Test Loop, Testing, & Results

After receipt of the RCA 1.0 at JSC, it was tested within the integrated ventilation subsystem test loop in the PLSS Ventilation Laboratory, located in room 2006 of JSC building 7. Figure 5 shows a picture and a schematic of the Integrated Ventilation Subsystem Test Loop. Construction of the Integrated Ventilation Subsystem Test Loop was based on a rounded design for a re-circulating closed loop to minimize pressure drops and unnecessary bends within the test stand. The system was designed to integrate all required sensors to analyze the performance of the HS RCA test article while providing the proper volumetric flow rate and CO_2 and H_2O injection rates. The system provided the collection of CO_2 concentration and relative humidity (RH) data immediately before and after the test article, allowing for analysis of each constituent to be calculated based on the effect of the test article. A 56.6 L (2.0 ft^3) mixing volume was integrated into the test loop to simulate the empty volume of the spacesuit. The RCA vacuum port was interfaced with the utility vacuum chamber (UVC) for the vacuum desorption process.

There were two operational modes of the Integrated Ventilation Subsystem Test Loop: test and bypass mode in which the RCA 1.0 unit was part of the flow loop or was bypassed. The bypass mode allowed for sensor evaluation while maintaining the integrity of the test article.

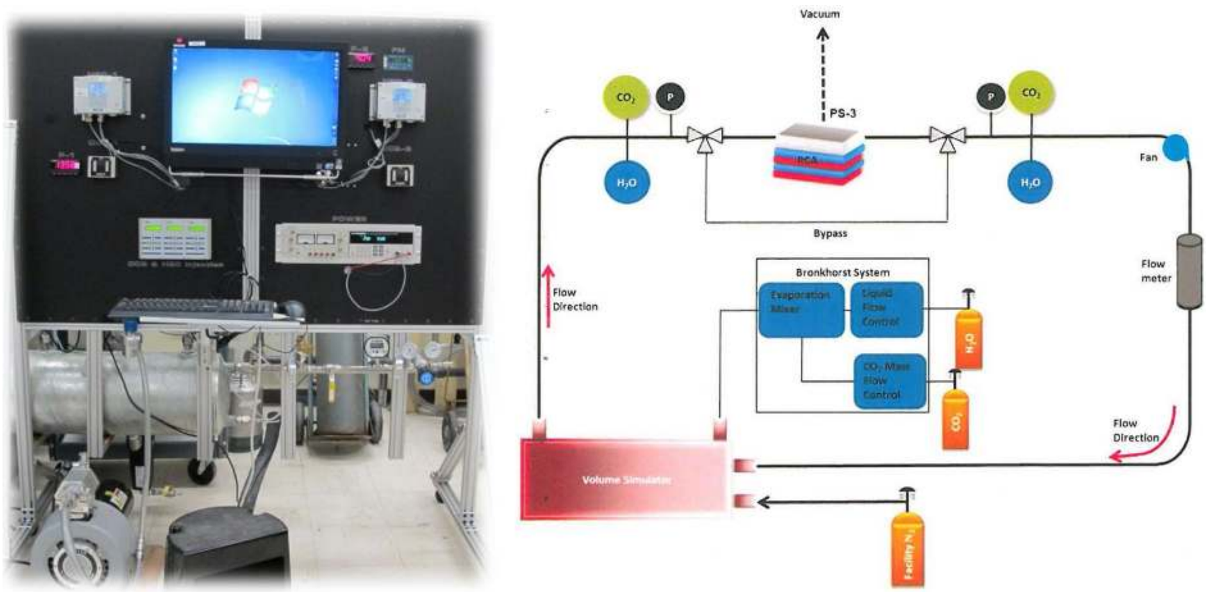

Figure 5. Integrated Ventilation Subsystem Test Loop Picture (left) and Schematic (right)

One of the series of testing with the Integrated Ventilation Subsystem Test Loop was conducted to gather CO_2 and H_2O performance data at several metabolic loads over a range of system temperatures. Metabolic loads of 400, 100 and 1600 Btu/hr were evaluated at system temperatures ranging from 50°F to 87°F. These tests were performed at a system pressure of 4.3 psia and a flow rate of 6 acfm. The beds were switched when the outlet CO_2 partial pressure reached 6 mmHg. For temperatures below ambient, an ice bath was used and adjusted until the desired RCA gas outlet temperature was reached. For temperatures above ambient, heaters were used on the suit volume simulator tank which was upstream of the RCA.

Test results demonstrated a detrimental impact to RCA performance as RCA amine temperatures drop below 75°F as shown in Figure 6. RCA cycle times decreased as the amine temperatures are lowered. Optimal performance of the RCA occurs near 75°F to 80°F. A small decrease in half cycle times appears to occur as the amine temperatures increase above 85°F. This trend is to some extent expected since desorption performs better at higher temperatures and adsorption performs better at lower temperatures. The optimal performance occurs when a good balance is achieved between the two processes.

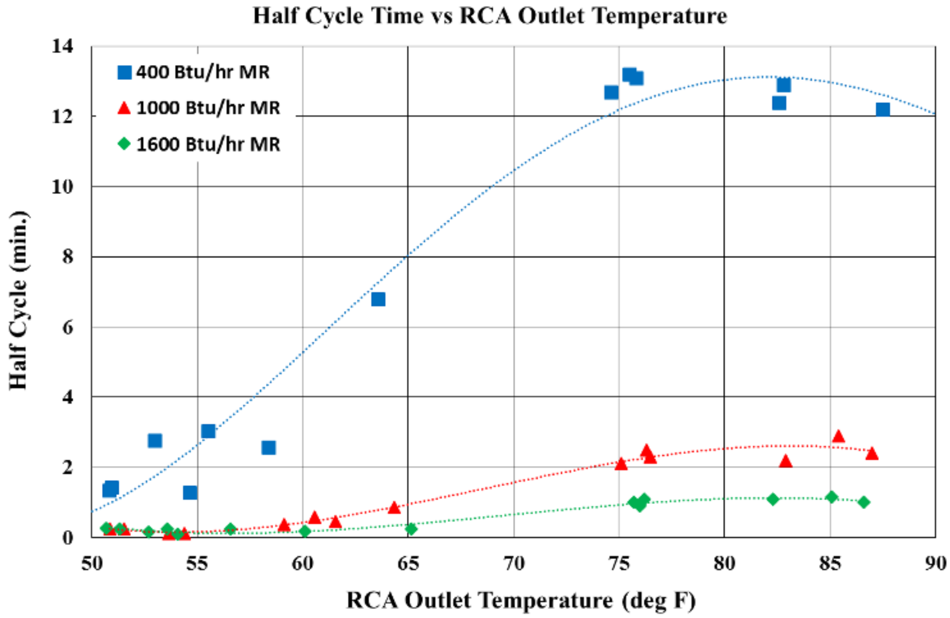

Figure 6. RCA #1 Integrated Ventilation Subsystem Test Loop Temperature Test Results

3. Ventilation Test Loop #1 and SMTA Test plans

After completion of RCA 1.0 testing in the Integrated Ventilation Subsystem Test Loop, a suited manikin test apparatus (SMTA) integrated with a space suit ventilation test loop was designed, developed, and assembled within the PLSS Ventilation Laboratory in order to experimentally validate adequate CO_2 removal throughout the PLSS ventilation subsystem and to quantify CO_2 washout performance under various conditions. The test results from this integrated system will be used to validate analytical models and augment human testing. Due to space limitations within the PLSS Ventilation Laboratory, the previously developed Integrated Ventilation Subsystem Test Loop was dismantled and the Ventilation Test Loop #1 was developed with a much smaller footprint as shown in Figure 7 sitting next to the SMTA. RCA 1.0 is the CO_2 removal unit being used in the Ventilation Test Loop #1 since RCA 2.0 and RCA 3.0 are being tested elsewhere as described later in this paper.

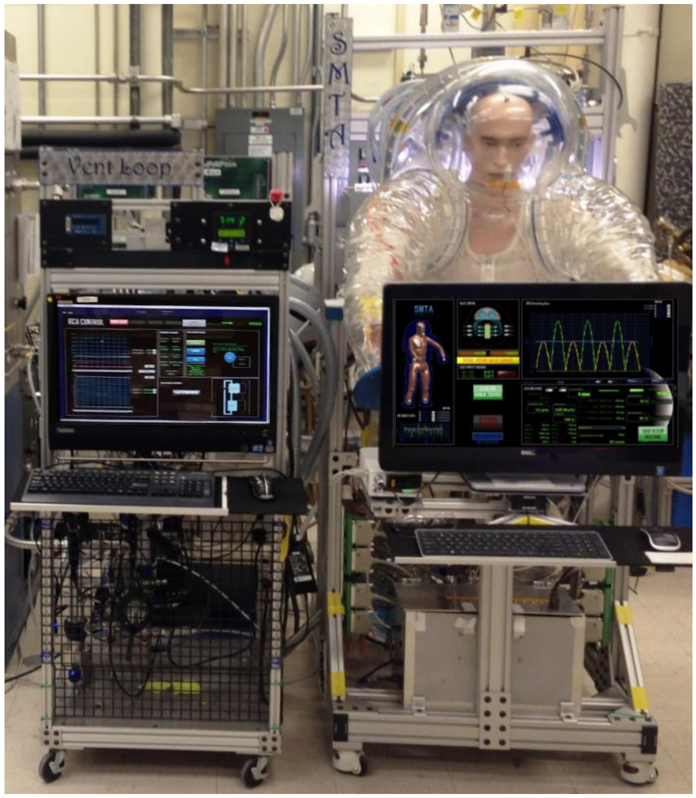

Figure 7. Ventilation Test Loop #1 (left) and the SMTA (right)

A CO_2 washout test series has been recently initiated with the SMTA and Ventilation Test Loop #1 to help evaluate the CO_2 concentration levels within a simulated space suit with breathing effects while interfaced to the ventilation loop representing the configuration of the Advanced PLSS. The objectives of CO_2 washout test series are as follows: 1) Use the SMTA breathing manikin to simulate breathing profiles with CO_2 and water vapor (H_2O), metabolic gas consumption, and variation with metabolic rate; 2) Assess the uniformity of mixing within the helmet of the SMTA; 3) Validate CFD model predictions and compare results to human CO_2 washout test results; and 4) Evaluate various helmet ventilation configurations. Recently, the RCA 1.0 spool valve failed and the RCA 1.0 canister is being reconfigured with 8 solenoid valves that will perform the function of the spool valve. Currently, open loop SMTA CO_2 washout test points are being performed that do not require the Ventilation Test Loop #1. Once RCA 1.0 is reconfigured and re-integrated into Ventilation Test Loop #1, the closed loop test points will be reinitiated.

C. Rapid Cycle Amine 2.0

i. RCA 2.0 Design

The RCA 2.0 was the first unit funded by STMD that was considered full scale in its design (see Figure 8). The focus of the design was to support the PLSS 2.0 Integrated testing. The main design feature that was different from the RCA 1.0 was the replacement of the spool valve with a multi-ball valve design. The ball valve provides for an intermediate state during the transitions between switching from one bed to another as the RCA cycles from adsorption to desorption. This allows the fluid interfaces (inlet, outlet, and vacuum) to be isolated while the sorbent beds equalize pressure between the bed open to the vent loop pressure and the bed open to vacuum.[7] A bypass value was considered for this design to allow for the flow to go around the RCA assembly while the valve was transitioning. Funding prohibited the implementation on the RCA design. By not including the bypass, it help to improve weight, volume, and reduce the RCA 2.0 complexity. The bypass valve was implemented on the PLSS 2.0 test bed and after testing was completed and test results were reviewed, it was found to be not needed because test subjects reported that the ventilation flow interruption was negligible.[17]

In the RCA 2.0, the canister size was driven by the pressure drop requirements anticipated for the PLSS 2.0 Integrated Test. The overall pressure drop goal was 2.5 inches of water at 6 ACFM flow and atmospheric pressure. Multiple parallel paths created in the design improved the overall pressure drop which is driven heavily by the packed beds. Computational fluid dynamics (CFD) modeling tools were used to minimize the overall volume and meet the pressure drop target. Like RCA 1.0, the RCA 2.0 canister was a completely brazed canister. The RCA frame and aluminum foam (support for amine beads) is brazed to the parting sheets allowing for effective and efficient heat transfer between the beds.

The last item that was unique and new with the RCA 2.0 was addition of an integrated controller. The controller included a combination of custom circuitry and commercial-off-the-shelf (COTS) hardware. The primary focus of the controller was to provide a means of controlling the ball valve position. The integrated controller occupies the space between the valve assembly and the canister to yield a compact design.[7]

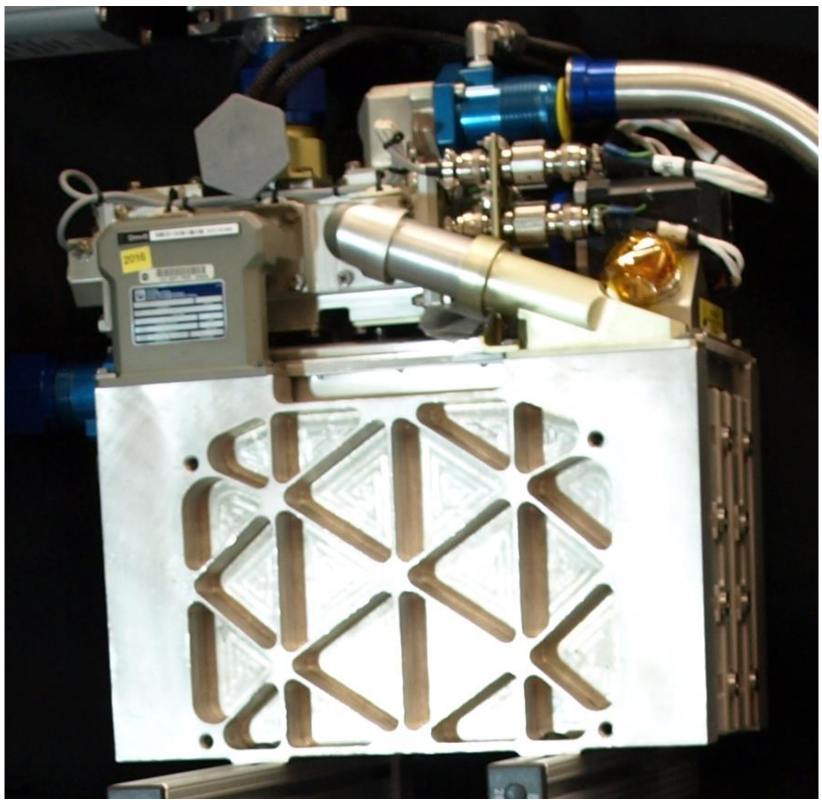

Figure 8. RCA 2.0 with Controller.

ii. RCA 2.0 UTAS Testing

Pre-delivery testing of RCA 2.0 was conducted by UTAS between August and September 2012, with delivery in to NASA-JSC in September 2012. The unit was verified through a number of tests including flow-pressure drop evaluations, proof pressure verification, bed pressure equalization during actuation, valve seat leakage measurements and overall CO_2 and humidity removal performance evaluations. The selected test points for CO_2 and humidity removal were based on previous RCA 1.0 testing to provide a basis of comparison and included an 8-hour simulated CO_2 input profile. A commercially available stepper gearmotor that was initially selected for valve actuation had insufficient torque at the desired actuation speed, however, this did not impact the overall unit performance. A direct replacement stepper gearmotor with the correct torque and speed output characteristics was subsequently identified and evaluated by UTAS and verified with a brassboard valve assembly along with an embedded stepper motor controller that fit within the RCA 2.0 package. The embedded controller was installed in April 2013 at JSC, however package constraints on the PLSS 2.0 assembly prevented gearmotor changeout at that time. The final commercial gearmotor was integrated with the RCA 2.0 in April 2014 during a PLSS 2.0 maintenance availability. This final configuration supported the PLSS 2.0 testing conducted by NASA-JSC in FY15.

iii. RCA 2.0 JSC System Integration and Testing

1. PLSS 2.0 Integration and Testing

RCA 2.0 was installed into PLSS 2.0 shortly after delivery of PLSS 2.0 and this configuration is shown in Figure 9. PLSS 2.0 was the first attempt to package the Advanced PLSS into a more flight-like condition. PLSS 1.0 was roughly the size of a large cubical and was built as a breadboard to obtain PLSS performance information. With PLSS 2.0, the packaging was a goal to determine potential performance characteristics and challenges associated with packaging the Advanced PLSS components into a realistic PLSS volume. PLSS 2.0 testing included unmanned testing as well as Human in the Loop (HITL) testing. RCA 2.0 performed well during PLSS 2.0 testing and an example of test results are shown in the next section.

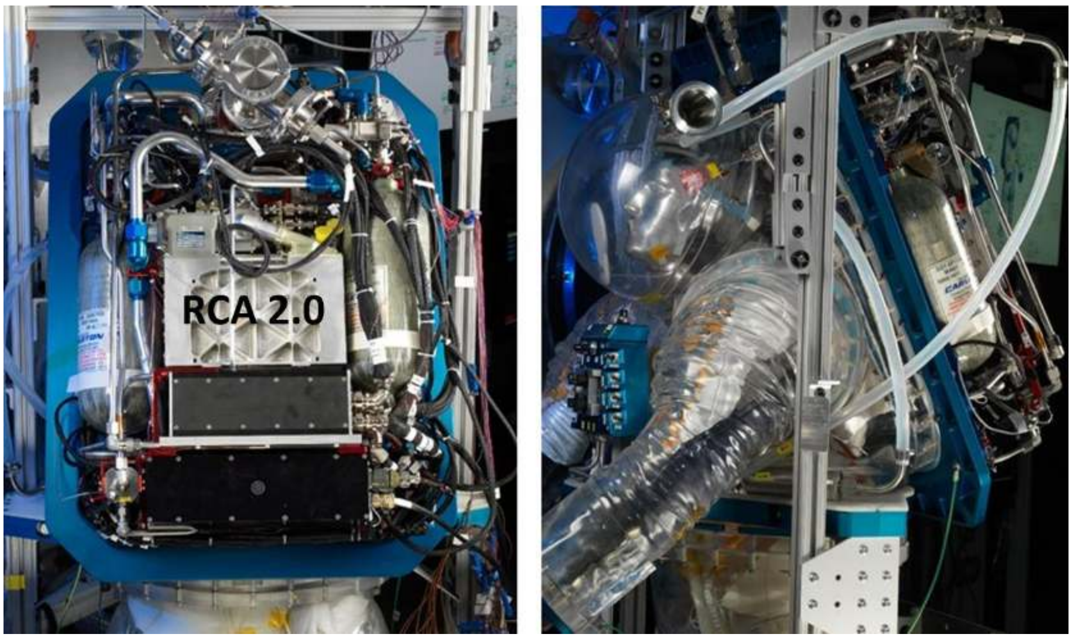

Figure 9. RCA 2.0 Packaged within PLSS 2.0 – Shown Installed on Space Suit Assembly Simulator to Provide a Better View

2. PLSS 2.0 Performance Results

One example of PLSS 2.0 results during PLSS 2.0 testing is shown in Figure 10. PLSS 2.0 was built with a bypass around the RCA 2.0 unit in order evaluate the need for this bypass. When the RCA performs a bed switch operation, the flow to the helmet is temporarily interrupted. The HITL testing was performed with PLSS 2.0 in order to obtain human response data to performance characteristics of PLSS 2.0. Figure 10 shows the ventilation flow rate, CO_2 concentrations at the suit inlet and outlet locations as well as the RCA and bypass valve activity.

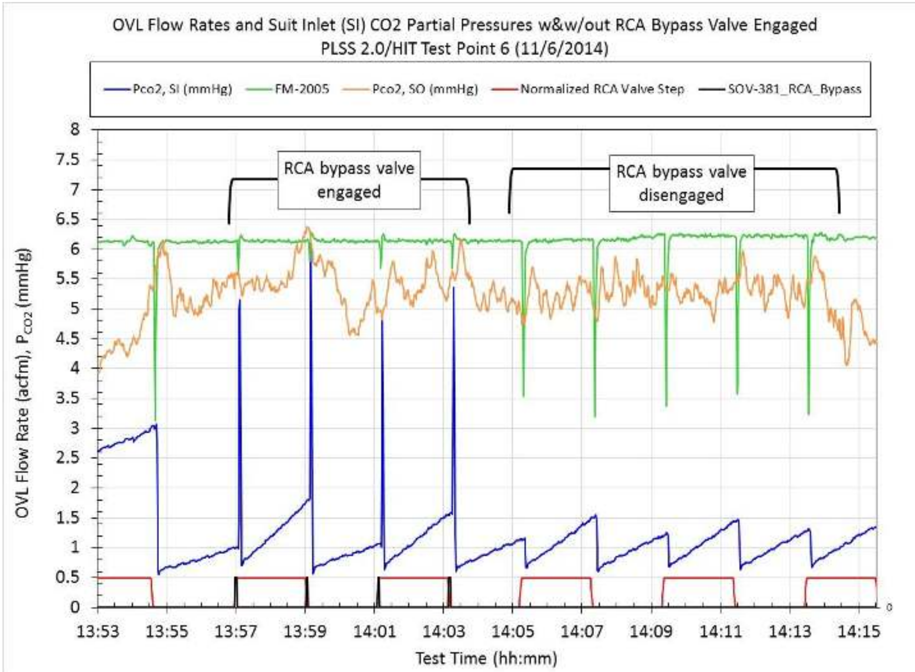

Figure 10. OVL Flow Rates and Suit Inlet CO_2 Partial Pressures with & without the RCA Bypass Valve Enabled

General performance of RCA 2.0 is shown in Figure 11. This chart shows half-cycle timing for RCA 1.0 and RCA 2.0 as determined from various testing series as a comparison of the relative performance of each. The RCA 2.0 is a large unit and shows longer half-cycle timing for similar conditions as compared to RCA 1.0 half-cycle timing. RCA 3.0 is in between the sizing of RCA 1.0 and RCA 2.0 and is predicted to perform at half-cycle times that are near the average value of the RCA 1.0 and 2.0 results.

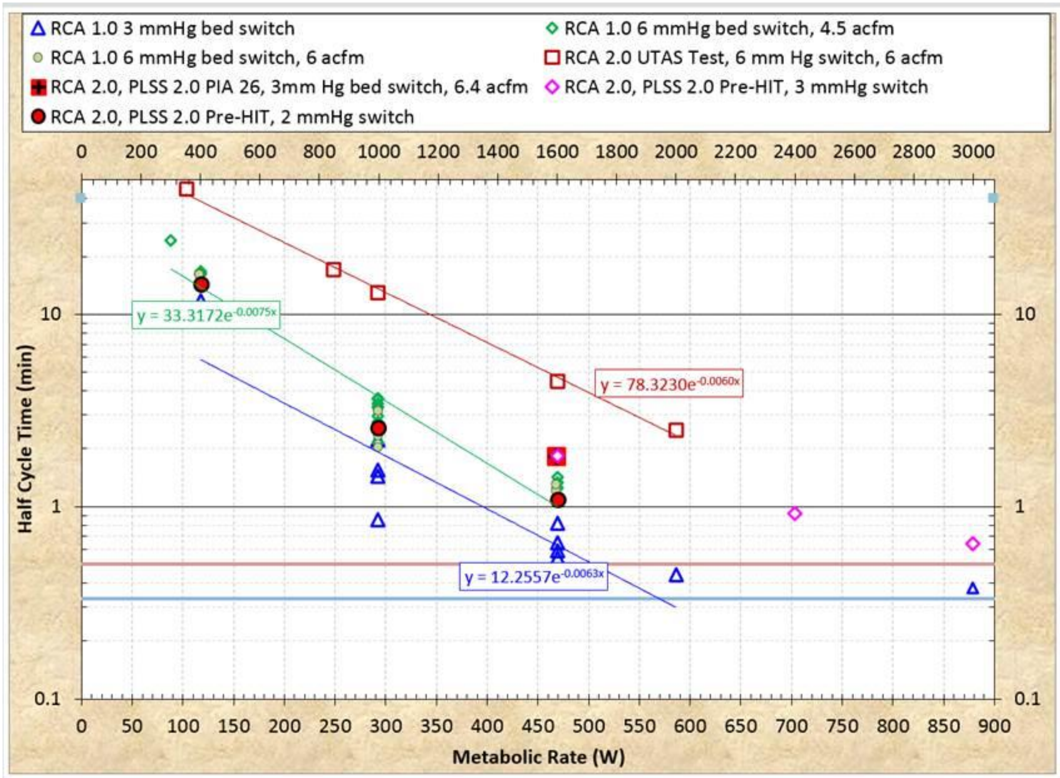

Figure 11. Half-Cycle Timing for RCA 1.0 and RCA 2.0 at Various Metabolic Rates and at Bed Switching Triggers of 3 and 6 mmHg.

3. Ventilation Test Loop #2 Integration and Testing - Plans

Ventilation Test Loop #2 has been designed to accommodate either the RCA 2.0 or RCA 3.0 testing with the required instrumentation. The ventilation loop will maintain the desired simulated metabolic rate, flow rate, and pressure to interface with the RCA units. The ventilation test loop will interface to facility gaseous nitrogen (GN2), facility CO_2, and a Triscroll® vacuum pump. The facility GN2 will supply the test loop with dry GN2 and provide any ullage lost from the RCA actuation. The facility CO_2 will supply the test loop with the required simulated metabolic CO_2. The Triscroll® vacuum pump connected to the test loop will draw the system pressure down to the desired operating pressure for all test cases. A back pressure regulator will control the system pressure at all times. The UVC will be connected to the RCA vacuum port to represent the space vacuum that is required to desorb the amine. The system flow rate will be evaluated between 4 to 6 acfm at various system pressures: 4.3 and 14.7 psia. Figure 12 shows the schematic for Ventilation Test Loop #2.

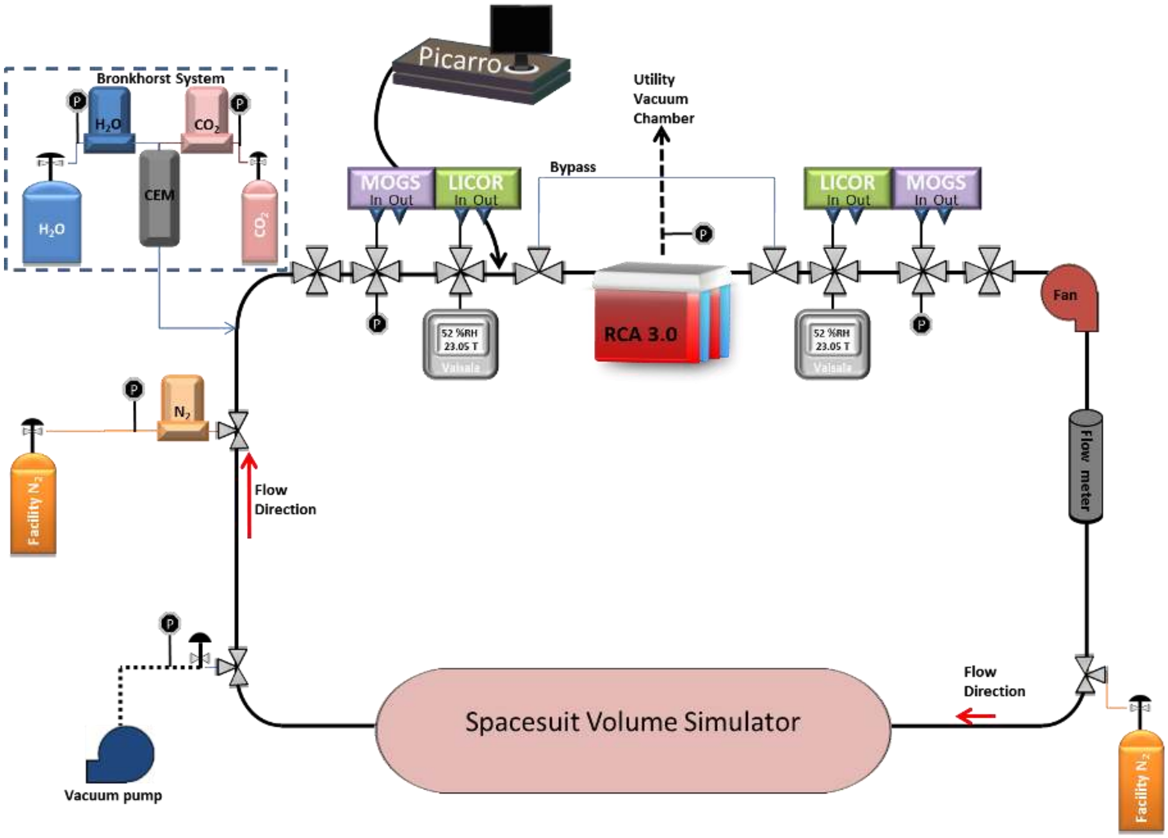

Figure 12. Ventilation Test Loop #2 Schematic – Note: RCA 2.0 and RCA 3.0 will tested with this loop.

D. Rapid Cycle Amine 3.0

i. RCA 3.0 Design

The development of the RCA 3.0 was warranted based on the successful testing accomplished during the PLSS 1.0 breadboard testing and the PLSS 2.0 integrated testing. RCA 3.0 design is targeted to be integrated into the PLSS 2.5 integrated system as well as the PLSS 3.0 integrated system. The final RCA 3.0 unit was designed, fabricated, assembled, performance tested in 2014 and then delivered to NASA in June 2015. The RCA 3.0 as delivered to NASA is shown in Figure 13.

The RCA 3.0 was designed to comply with the document CTSD-ADV-955, Technology Development Specification for the RCA CO_2 and Humidity Removal System. The RCA 3.0 was designed to be similar in functionality to the RCA 2.0 with several improvements. Both RCA 2.0 and 3.0 test articles were designed with a novel valve assembly that allows for switching between uptake and regeneration modes with an internal pressure equalization step during actuation. The ball valve design did not change between the two designs. Specified goals were set to accomplish the improvements. The highest priority improvement for RCA 3.0 was for it to be operable in an environment where oxygen is the working fluid. Oxygen compatibility is essential for space suit application in order to control ignition sources. It was also important for RCA 3.0 to be compatible in vacuum and thermal environments along with the ability to tolerate certain launch and vibration loads based on the targeted launch vehicle. Other notable goals were focused on mass, system life, and CO_2 and H_2O removal rates. The RCA 3.0 design was able achieve all of the targeted improvements.[16]

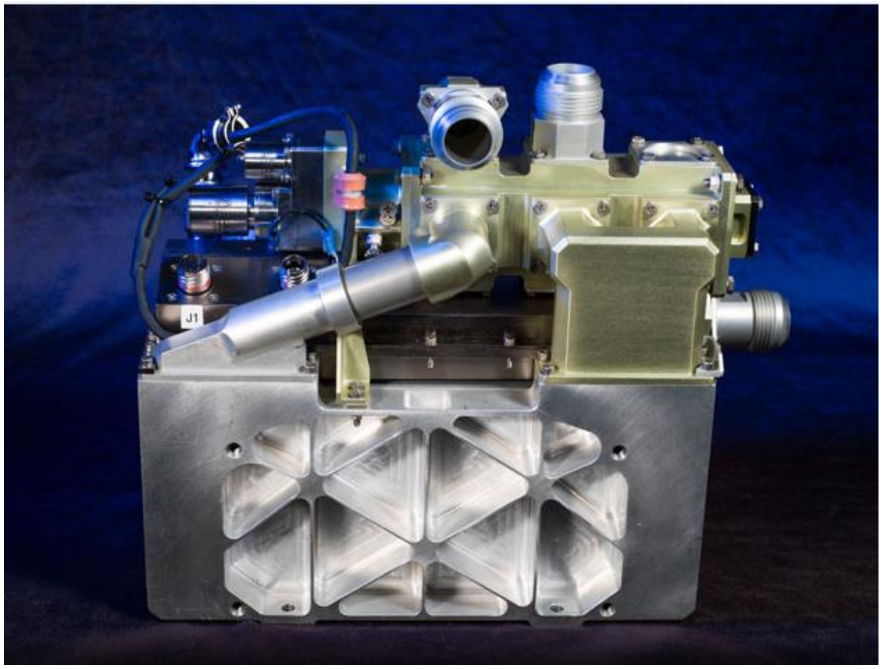

Figure 13. RCA 3.0 with Controller.

ii. RCA 3.0 UTAS Testing

Pre-delivery performance testing of RCA 3.0 was conducted by UTAS in November 2014, including flow-pressure drop evaluations, proof pressure verification, bed pressure equalization, valve seat leakage measurements and overall CO_2 and humidity removal performance evaluations. The test setup for RCA 3.0 testing is shown in Figure 14. The selected test points for CO_2 and humidity removal were based on previous RCA 1.0 and 2.0 testing and also included an 8-hour simulated CO_2 input profile. RCA 3.0 incorporated a spaceflight-pedigree stepper gearmotor with Rotary Variable Differential Transformer (RVDT) for valve position feedback. Performance testing utilized commercially available electronics to allow for testing while the embedded RCA 3.0 controller was completed through assembly and test. Data collected during testing with the commercial electronics supported the eventual integration testing of the embedded controller by providing insight into RVDT output and motor operation characteristics. The embedded controller was also verified to support a brushless DC motor for eventual fan integration as well as various analog and digital inputs that the controller supports. The final integrated RCA 3.0 assembly with embedded controller was delivered to NASA-JSC in June 2015.

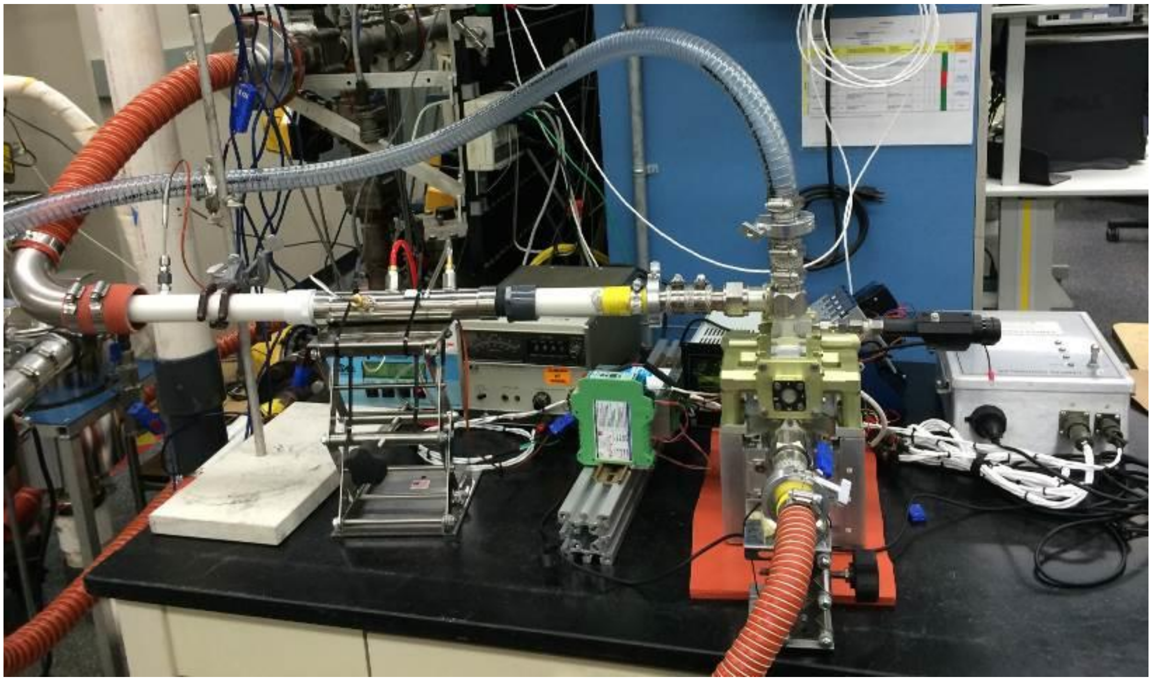

Figure 14. RCA 3.0 Performance Testing – November 2014

iii. RCA 3.0 JSC System Integration and Testing – Plans

The Ventilation Test Loop #2 has been built assuming that the RCA 2.0 unit will be replaced with the RCA 3.0 unit when RCA 3.0 is not required for any of the PLSS 2.5 testing series. The PLSS 2.5 is the next version of the Advanced PLSS. A suite of test series will be performed with RCA 3.0 within Ventilation Test Loop #2 that will characterize RCA 3.0 performance at various metabolic rates, flow rates, and system pressures. The performance results will be compared with results from prior RCA 1.0 and RCA 2.0 testing. Alternate CO_2 sensors will also be testing in the Ventilation Test Loop #2.

IV. Design and Performance Comparison of Rapid Cycle Amine 1.0, 2.0, and 3.0

The design goals and actual characteristics of RCA 1.0, RCA 2.0 and RCA 3.0 are shown in Table 1. In general, the lessons learned and tests results from the predecessor RCA unit were utilized to improve the successor RCA unit. However, the goals for RCA 3.0 needed to be defined before full testing results from RCA 2.0 were available. Some changes were made to the RCA 3.0 design once the RCA 2.0 test results were available. One example of this is the mass of RCA 3.0 which was able to be brought in well below the goal since the RCA 2.0 showed sufficient margin in being able to meet requirements.

Table 1. Development goals and observed performance for RCA 1.0, 2.0, and 3.0

	RCA 1.0		RCA 2.0		RCA 3.0	
	Goal	**Actual**	**Goal**	**Actual**	**Goal**	**Actual**
Sizing	Subscale	☑	Full scale	☑	Full scale, optimized size	☑
Controller	External	☑	Locally mounted	☑	Improved and integrated	☑
Operating Pressure Environment	Ambient Lab	☑	Lab or vacuum	☑	Flight environments	☑
TRL	4	☑	5	☑	6	☑
Mass - kg (lbm)*	< 4 (8.8)	3.84 (8.5)	Minimize	7.26 (16.0)	< 10 (22)	6.38 (14.1)
Volume - m^3 (ft^3)	Minimize	☑	Minimize	13.3 (0.47)	Minimize	11.3 (0.40)
Sorbent Volume per Bed - cm^3 (in^3)	N/A	715 (43.6)	N/A	1050 (64.1)	N/A	788 (48.1)
Performance - max CO_2 (mmHg)	< 6 mmHg	☑	< 2.2 mmHg	< 2.65 mmHg***	< 2.2 mmHg	< 3 mmHg***
Valve Design		Pneumatic spool valve		Motorized ball valve		Motorized ball valve with high efficiency actuator
Humidity (% RH)**	25 - 75%	10 - 15%	25 - 75%	10 - 15%	25 - 75%	10 - 15%
Operating fluid	Nitrogen	☑	Material compatibility with oxygen	☑	Material compatibility with oxygen	☑
Pressure Drop	N/A	N/A	2.5 in H_2O @ 6 ACFM, 14.7 psia	☑	2.5 in H_2O @ 6 ACFM, 4.3 psia	☑
Maximum Pressure - kPa (psig)	13.8 (2)	☑	67.2 (9.1)	☑	67.2 (9.1)	☑
Bed equalization during actuation	N/A	N/A	Required	☑	Required	☑
Minimize FOD generation/susceptability	N/A	N/A	Required	Valve seat design is low wear material.	Required	Valve seat design is low wear material, demonstrated 105,089
leakage (to vacuum or ambient)	N/A	N/A	< 6 sccm	☑	< 1 sccm	☑
Valve actuation time	N/A	< 1 second	< 5 seconds	~5 seconds	< 3 seconds	~3.5 seconds
Ullage Volume - liter (in^3)	N/A	0.82 (50)	Minimize	1.95 (119)	Minimize	1.3 (79)

* Without controller
** Actual values are trend data
*** Demonstrated values shown here but actual max CO_2 not determined to date

V. Lessons Learned

A. Design Lessons Learned

An important lesson learned during the RCA development is the RCA state indicator, i.e. the valve position, and how it has evolved. The spool valve on RCA 1.0 only had 2 states (position A or B) and had mechanical switches for indication, which had reliability issues due to complex mechanism internal to the spool valve.

The next development iteration (2.0) saw the need (or advantage) of having an additional state of being able to isolate the two beds when the RCA is not in use (storage, maintenance, fault, etc…). The position sensors were changed to inductive magnetic proximity sensors, but still only provided two positive state indications. Coupled with a controller that could precisely index the actuation motor was the means of reaching the isolation state. These switches have proven simple and reliable but perhaps not suitable for the ultimate environment requiring radiation hardening.

The RCA 3.0 iteration included an RVDT position feedback mechanism that provides continuous position indication at the expense of some additional complexity in the control and monitoring circuit. Because there is normally no contact between the RVDT's core and coil structure, parts are less likely to wear or become damaged, an important consideration in high reliability applications such as space vehicles and life support systems. The continuous position feedback also allows for rapid fault detection and isolation.

B. Integration and Testing Lessons Learned

The strategy of testing PLSS 1.0, PLSS 2.0, PLSS 2.5, etc., has allowed the Advanced PLSS team to learn from the prior testing activities to use this knowledge to improve the designs and operations for the follow-on iterations of the design. The team has gained knowledge of the system via ground based testing as well as by performing system level analysis and evaluations including failure mode assessments. The RCA has benefitted from this knowledge growth in a few areas that will be discussed below.

One of the areas of improvement are the RCA valve improvements that were discussed in the previous section. The RCA 1.0 spool valve is a pneumatic valve that uses a little less power than the valves used in RCA 2.0 and RCA 3.0, but it would have necessitated the use of pressurized oxygen in a flight PLSS to drive the pneumatic spool valve. Nitrogen gas was used to pressurize the RCA 1.0 spool valve during the testing of that unit since it was not built to be compatible with oxygen. PLSS 1.0 testing showed pressure fluctuations caused by the pneumatic gas that was design to be dumped into the ventilation loop in order to minimize consumable gas loss that would occur if it were dumped overboard. Also, complexities and failure modes associated with the spool valve connection to the high pressure oxygen system in a flight PLSS outweighed the minor power savings of the pneumatic spool valve approach. Therefore, RCA 2.0 and RCA 3.0 include motor driven valves instead of pneumatic valves.

Another aspect of the RCA design that evolved was the CO_2 removal capacity. The RCA 1.0 was required to maintain the RCA outlet concentration to < 6 mmHg which was similar to the ISS EMU requirement. This resulted in a fairly small unit that achieved the stated CO_2 requirement. As CO_2 levels continue to be investigated by NASA medical personnel, the requirements are expected to be lowered.[18] In anticipation of this, RCA 2.0 and RCA 3.0 were scaled up in size to meet the stricter CO_2 requirement. RCA 2.0 test results showed some margin in meeting the anticipated CO_2 requirement. This allowed the RCA 3.0 amine content to be reduced to a volume that was in between the volumes of RCA 1.0 and RCA 2.0. These examples among others show the value of having the ability to iterate on the prototype design before the flight design is finalized.

VI. Conclusions and Recommendations

The RCA has been identified as a major component in all the progressions of the Advanced PLSS and has evolved with the development of the RCA 1.0, 2.0 and 3.0 units. The amine technology used within the RCA provides CO_2 and humidity removal functions for the AEMU and the amine beds regenerate in real time during the EVA using a vacuum swing approach. This approach eliminates CO_2 removal as an EVA duration limitation, reduces consumables (one-time use LiOH) and eliminates the costly regeneration time and power associated with the MetOx technology currently in use with ISS EVAs. The RCA units are low mass compared to the MetOx mass and since the RCA removes humidity, the need for a condensing heat exchanger, slurper, and rotary separator in the PLSS is eliminated. Since the RCA allows for full separation of the PLSS water loop from the ventilation loop, it eliminates most of the failure modes that introduce water in to the helmet and space suit.

The design and performance characteristics of the three RCA units have been presented and testing continues with these units. The success of these testing programs have allowed the RCA design to be improved with each iteration. Continuation of the testing and evaluation activities should provide a nearly optimal flight design of this unit.

Acknowledgments

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