Humidifier Development and Applicability to the Next Generation Portable Life Support System

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A development effort at the NASA Johnson Space Center investigated technologies to determine whether a humidifier would be required in the Portable Life Support System (PLSS) envisioned for future exploration missions. The humidifier has been included in the baseline PLSS schematic since performance testing of the Rapid Cycle Amine (RCA) indicates that the RCA over-dries the ventilation gas stream. Performance tests of a developmental humidifier unit and commercial off-the-shelf (COTS) units were conducted in December 2009. Following these tests, NASA revisited the need for a humidifier via system analysis. Results of this investigation indicate that it is feasible to meet humidity requirements without the humidifier if other changes are made to the PLSS ventilation loop and the Liquid Cooling and Ventilation Garment (LCVG).

Nomenclature

ASDA	=	Advanced Suit Design Analyzer
Btu	=	British thermal unit
CM	=	crew member
CO_2	=	carbon dioxide
COTS	=	commercial off-the-shelf
DEV	=	Double Ended Vacuum
DP	=	dew point
EMU	=	Extravehicular Mobility Unit
EVA	=	extravehicular activity
ft	=	feet
GN2	=	gaseous nitrogen
H_2O	=	water
HSIR	=	Human-Systems Integration Requirements
hr	=	hour
JSC	=	Johnson Space Center
lbm	=	pounds mass

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LCVG	=	liquid cooling and ventilation garment
LiOH	=	lithium hydroxide
METMAN	=	41-Node Transient Metabolic Man Program
Metox	=	metal oxide
min	=	minute
ml	=	milliliter
PGS	=	Pressure Garment System
PLSS	=	Portable Life Support System
psi	=	pounds per square inch differential
psia	=	pounds per square inch absolute
psid	=	pounds per square inch differential
RCA	=	Rapid Cycle Amine
RH	=	relative humidity
SCFM	=	standard cubic feet per minute
SEV	=	Single Ended Vacuum
SWME	=	Spacesuit Water Membrane Evaporator
W	=	watts

I. Introduction

AS development of the next generation space suit system progresses, designing the most effective and efficient life support systems is critical. The baseline schematic analysis for the Portable Life Support System (PLSS) currently envisioned for future exploration indicates that the ventilation loop will need some method of humidification prior to entering the helmet (Barnes, et al., 2009). Humidifier developmental efforts performed at the Johnson Space Center (JSC) have been underway (Sompayrac, et al., 2009). Testing of candidate humidifier units was performed in December 2009 at JSC to evaluate the potential for membrane units to humidify the PLSS ventilation loop to desired levels. The specific purpose of these tests was to demonstrate the humidification of a dry gas stream with three humidifier devices in ambient and low pressure environments. In addition to testing activities, an evaluation has been performed to determine whether the humidifier function could be eliminated from the PLSS by making potential changes to the configuration.

The baseline PLSS currently includes a Rapid Cycling Amine (RCA) unit to remove carbon dioxide (CO_2) and humidity generated by the suited crew member. The current humidity requirement (HS3126 of the Human-Systems Integration Requirements (HSIR) (Connelly et al., 2009)) for the PLSS ventilation loop is to maintain humidity levels within the helmet between 25% and 75% relative humidity (RH). Performance testing of the RCA indicates that it delivers RH levels less than 25% to the helmet (Papale and Paul, 2007). As the RCA overdries the ventilation loop gas, a humidifier is necessary. The baseline PLSS schematic shown in Fig. 1 (Barnes, et al., 2009) includes a humidifier (HC-320) that introduces humidity back into the ventilation stream downstream of the RCA unit. This humidifier functions to bring the humidity levels back up to meet the required 25% to 75% RH levels. Thermal hydraulic modeling of the PLSS (Barnes, et. al., 2010) has predicted that the water vapor addition required by the PLSS to meet the 25% RH level is 0.183 lb/hr.

A feasibility study summarized herein evaluates whether changes to other PLSS technologies can be made to eliminate the need for the humidifier. The changes evaluated include controlling the RCA cycle time with a feedback loop from the CO_2 sensor to the RCA and adding insulation to the liquid cooling and ventilation garment (LCVG). These modifications may result in removal of the humidifier, thus reducing the complexity and failure modes associated with the humidifier hardware. This could add challenges associated with CO_2 feedback loop control of the RCA cycle time and would also introduce challenges associated with adding insulation to the LCVG. This study does not perform a detailed evaluation of the advantages and disadvantages associated with removing the humidifier, it simply evaluated the feasibility of providing the required humidity levels without the humidifier.

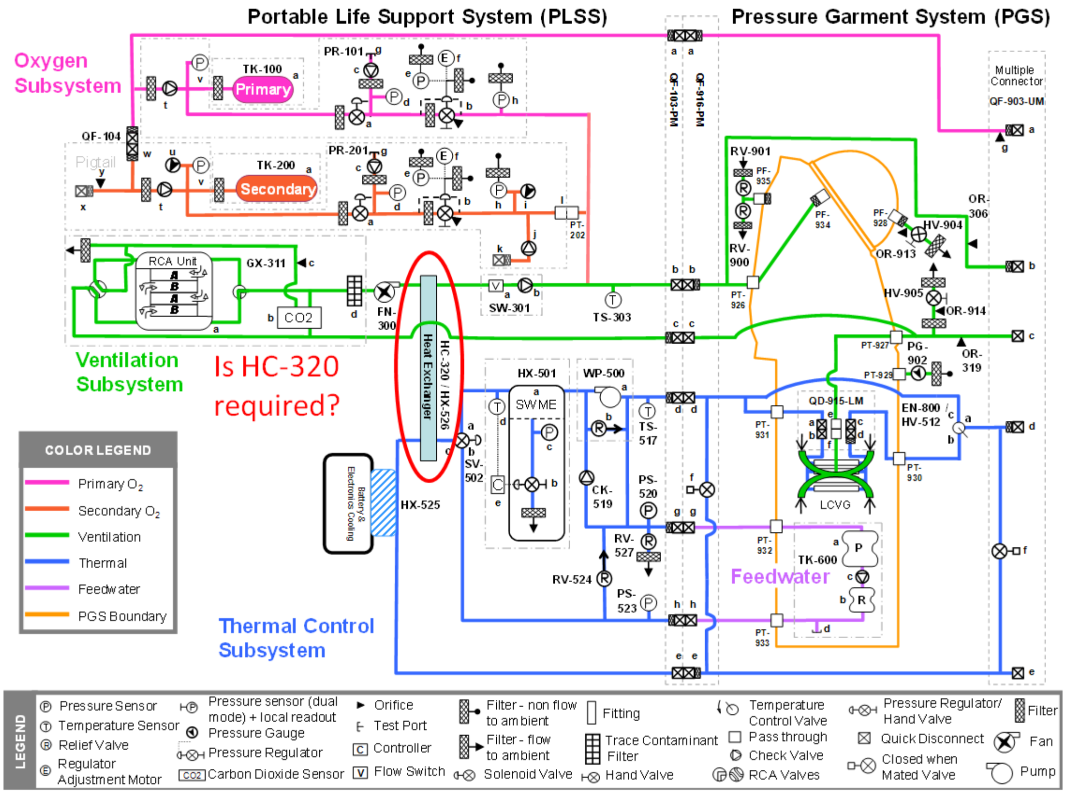

Figure 1. Baseline PLSS Schematic with Humidifier Highlighted.

II. Humidifier Development and Testing

Previously reported humidifier development at JSC (Sompayrac, et al., 2009) included a trade study to evaluate COTS humidifier technologies compared to potential custom technologies based on hydrophobic membrane and hollow fiber technologies investigated during development efforts of the JSC Spacesuit Water Membrane Evaporator (SWME) (Bue et al. 2009). COTS humidifier units were not found to be sized for direct application to satisfy the PLSS humidifier requirements. However, Membrana™ units sold as degassing units (and therefore did not have specifications or estimates for humidification capacity) were thought to be worth testing. The trade study resulted in recommendations for testing a custom hydrophobic membrane unit along with concurrent testing of 2 sizes of Membrana™ COTS hollow fiber units.

A. Test Article Descriptions

Performance testing was completed in fiscal year 2010 including evaluations of the custom unit (Fig. 2 and Fig. 3) and the Membrana™ units (Fig. 4 and Fig. 5). The custom unit consists of an annular water flow volume held between 2 Teflon membrane sheets surrounded by gas volumes. Dry ventilation gas enters these volumes and is humidified by water vapor evaporating through the membrane sheet material. The custom unit was not optimized for mass or volume.

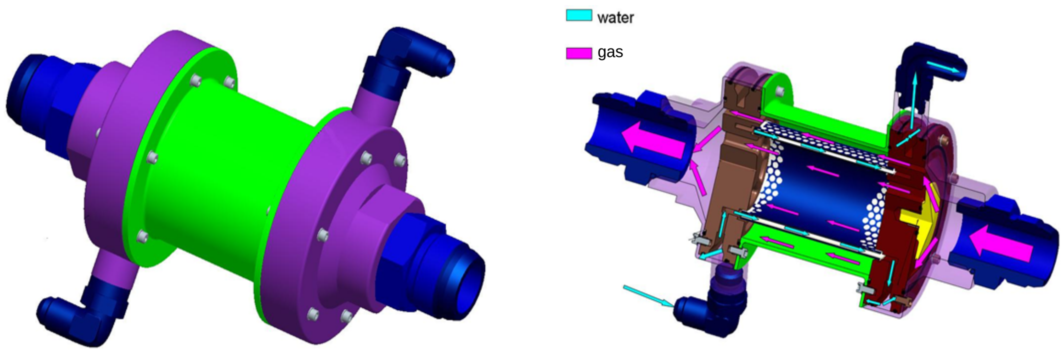

Figure 2. Custom Humidifier Conceptual Design and Cross-section.

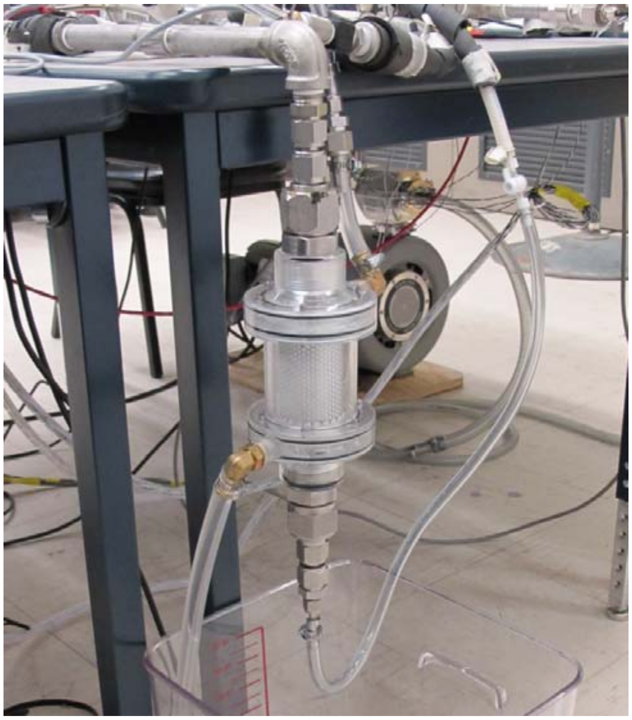

Figure 3. Custom Humidifier Test Configuration.

The second test article was a MiniModule® manufactured by Membrana™. Since the Membrana™ units were not sold as humidifiers, specifications were not available to estimate the amount of humidification these units would provide. The MiniModule® was roughly estimated to humidify at rates on the same order of magnitude as that of the custom unit. This unit contained 1.9 square feet (ft^2) of active surface area, was 0.98 inches in diameter and 7 inches in length (not including fittings or adapters). Fig. 4 includes pictures of the test article installed into the test setup.

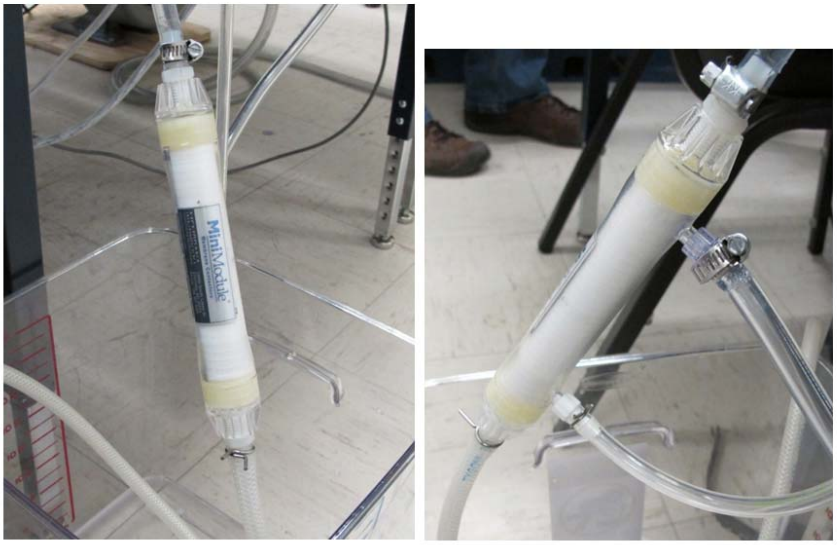

Figure 4. MiniModule® in Test Setup, Front and Side View.

The third test article was a MicroModule® also manufactured by Membrana™. It contained 0.11 ft^2 of active surface area and was approximately 1.2 inches by 1.2 inches by 0.5 inches excluding fittings and ports. This unit was selected for testing because it was believed that the hollow fibers within this unit had better exposure to the circulating gas than the MiniModule® and it was estimated that performance per unit active surface area would be better in the MicroModule® as compared to that of the MiniModule®. This unit was tested in a four-in-parallel configuration because a single unit was not believed to be able to handle a high enough flow rate to be testable. The design of the connections between the four modules was a custom design and the test setup is shown in Fig. 5.

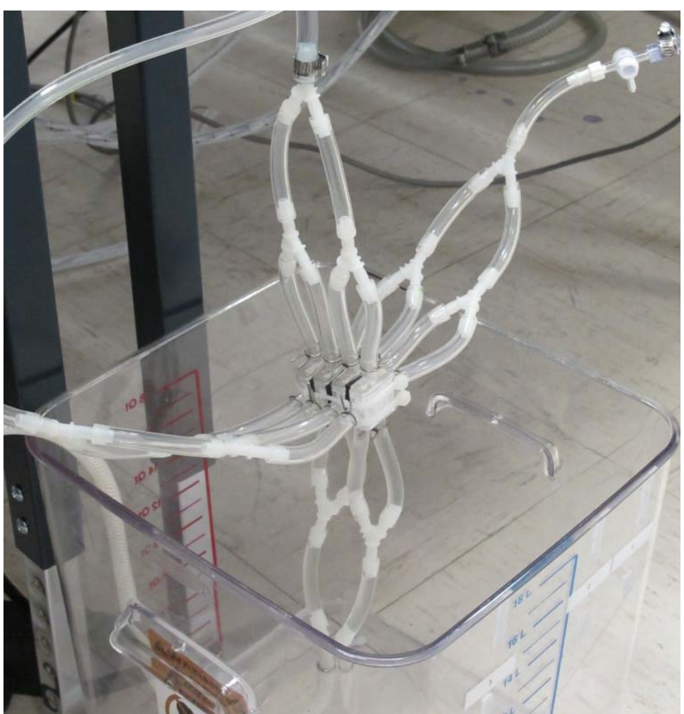

Figure 5. MicroModule® in Test Setup.

B. Humidifier Test Setup

The purpose of the test setup was to be able to flow water and dry gas to the test articles. Inlet flow rates, temperature, and pressure were varied, per the test points in Table 1. Additionally, on the gas side it was desired to control the inlet water content (i.e., RH and dew point). On the downstream side, the test setup measured the changes in the control parameters as a result of the humidifier in the system. The main objective was to determine the amount of water added to the gas stream and determine the heat exchange effect, if any.

The test setup is shown in Fig. 6. Dry gaseous nitrogen (GN2) was introduced into the gas lines with pressure sensors (PA-1 and PW-1), humidity sensors (HA-1 and HA-2) and flow meters (FA-1 and FA-2) positioned in order to quantify humidity and flow conditions upstream and downstream of the test article. Valve VA-4 allowed for partially humid room air to be introduced into the flow stream in order to adjust test article inlet humidity conditions. Valves VA-1, VA-2 and valve VA-3 were adjusted to produce desired pressure and flow conditions at the test article inlet. The water loop included a Water Test Cart to control water temperature based on the reading at temperature sensor TW-1. Valve VA-1 was adjusted to produce the desired water flow rate based on the reading at flow meter FW-2.

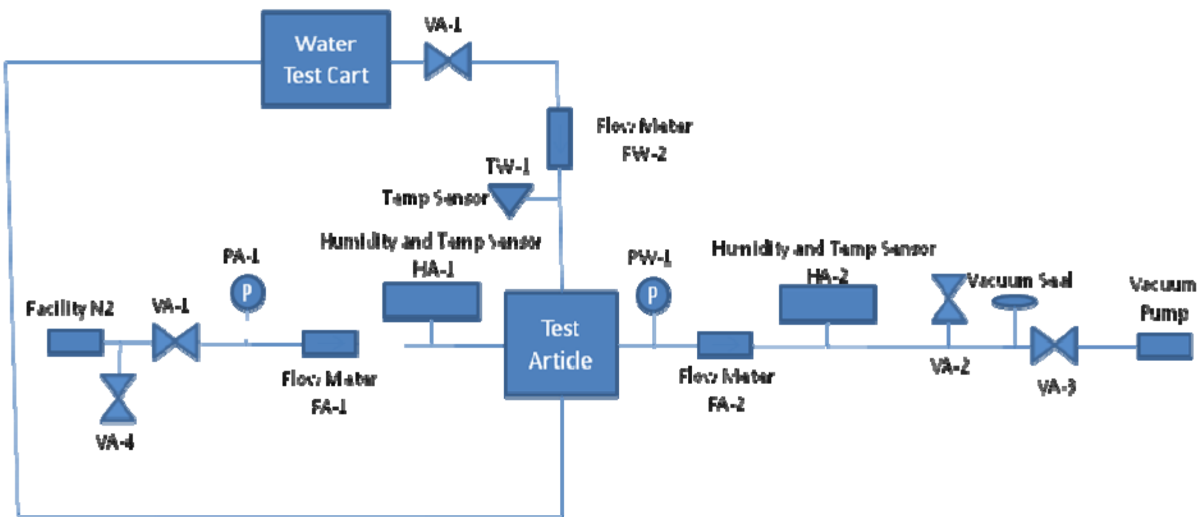

Figure 6. Test Schematic.

C. Test Point Matrix

Table 1 shows the test point matrix for this testing. The gas side in each unit was run at ambient and sub-ambient conditions with 6.0 psi being chosen as the inlet gas pressure to the humidifier for the sub-ambient condition. This pressure was higher than the projected PLSS ventilation loop of 4.3 psia to approximately account for test setup pressure drop effects. The fittings used in this test setup caused significant pressure drop to occur across the test article (pressure difference between pressure sensors PA-1 and PW-1). Gas flow rates were moderated to control the delta pressure across the test article to less than 2 pounds per square inch delta (psid). Three water temperatures were evaluated (50 °F, 68 °F, and 85 °F) to determine water temperature effects on humidifier performance. Also, 50 °F to 85 °F is the potential range of water temperatures that could be experienced in the PLSS water loop that would be used to drive the humidifier. With the exception of tests 7, 14, and 21, very dry GN2 was used. Tests 7, 14, and 21 mixed humid lab air with the dry GN2 to obtain an inlet dew point of about 23°F to simulate the RCA outlet conditions. Water flow rates were set based on flow capacity and pressure drop characteristics of each test article.

Table 1. Heat Exchanger Test Point Matrix.

	Test Point Number	Inlet Gas Pressure (psia)	Goal Pressure Loss (<2 psid)*	Goal Outlet Gas Pressure (psia)	Water Flow Setting (ml/min)	Water Temperature °F (°C)
Custom Unit	1	14.7	<2	>12.7	Full Open (≈ 1200)	50(10)
	2					68(20)
	3					85(30)
	4	6.0	<2	>4	Full Open (≈ 1200)	50(10)
	5					68(20)
	6					85(30)
	7**					85(30)

	Test Number	Inlet Gas Pressure (psia)	Goal Pressure Loss (<2 psid)	Goal Outlet Gas Pressure (psia)	Water Flow Setting (ml/min)	Water Temperature °F (°C)
Mini Module®	8	14.7	<2	>12.7	500	50(10)
	9					68(20)
	10					85(30)
	11	6.0	<2	>4	500	50(10)
	12					68(20)
	13					85(30)
	14**					85(30)

	Test Number	Inlet Gas Pressure (psia)	Goal Pressure Loss (<2 psid)	Goal Outlet Gas Pressure (psia)	Water Flow Setting (ml/min)	Water Temperature °F (°C)
Micro Module®	15	14.7	<2	>12.7	120	50(10)
	16					68(20)
	17					85(30)
	18	6.0	<2	>4	120	50(10)
	19					68(20)
	20					85(30)
	21**					85(30)

Note: ml/min = milliliters per minute
* Pressure drop goal drives gas flow rate.
** Mix Lab GN_2 with lab air to fix dew point (DP) to 23°

D. Test Results

Table 2 is a summary table of the water vapor production capability resulting from the 21 test points. The minimum required water vapor addition capability for the PLSS humidifier is 0.183 lb/hr as stated in the introduction of this paper. This requirement, based on results of the Thermal Hydraulic PLSS model (Barnes, et al., 2010), is compared in Table 2 to the water vapor production capacity of each test article in order to estimate of the number of units of each test article that would meet the PLSS humidification requirement.

For the custom unit, 2 units would be required to meet the PLSS water vapor production requirement. However, if the humidification requirement could be waived for 14.7 psi operations of the PLSS, only one custom unit would be needed to meet the requirement at the EVA conditions of 4.3 psi. For the MiniModule®, 2 units would be required to meet the requirement. However, using only one MiniModule® unit comes extremely close to meeting the PLSS requirement by delivering 0.018 lb/hr of water vapor in test point 8 which is just under the 0.0183 lb/hr requirement. Also, the MiniModule® meets the requirement with only one unit for test points 9 through 14. For the

MicroModule®, the test evaluated 4 COTS units in parallel. Table 2 shows that 4 COTS units could meet the water vapor production requirement for all test points completed. Again, if the humidification requirements could be waived for 14.7 psi PLSS operations, then only 2 MicroModule® units would be needed to satisfy humidification requirements at 4.3 psi EVA conditions.

Table 2. Water Vapor Transferred and Number of Test Units Required.

Unit	Test Point	Temp H2O F	Psia Gas in	Psia Gas out	Avg H_2O added (test) lbm/hr	Minimum H_2O Required lbm/hr	Min Req # Units
Custom	1	50			0.012	0.0183	2
	2	68			0.0114	0.0183	2
	3	85	14.7	13	0.018	0.0183	2
	4	50			0.06	0.0183	1
	5	68			0.069	0.0183	1
	6	85			0.087	0.0183	1
	7	85	6	4.3	0.102	0.0183	1
Mini	8	50			0.018	0.0183	2
	9	68			0.03	0.0183	1
	10	85	14.7	13	0.048	0.0183	1
	11	50			0.048	0.0183	1
	12	68			0.054	0.0183	1
	13	85			0.075	0.0183	1
	14	85	6	4.3	0.072	0.0183	1
Micro	15	50			0.0225	0.0183	4
	16	68			0.033	0.0183	3
	17	85	14.7	13	0.0465	0.0183	2
	18	50			0.0465	0.0183	2
	19	68			0.072	0.0183	2
	20	85			0.072	0.0183	2
	21	85	6	4.3	0.072	0.0183	2

It is interesting to note that the custom unit water vapor production capability is less than that of the MiniModule® during ambient tests, but that trend reverses when the pressure is sub-ambient (Fig. 7). Also, it has been previously stated that the custom unit was not optimized for mass or volume during this developmental effort. There is reason to believe that significant volume reduction could be achieved for the custom unit based on experience gained during the development of the hollow fiber SWME. During SWME development efforts, a custom technique was developed to enhance SWME performance beyond that of COTS hollow fiber units (Bue et al. 2009). This technique incorporates the use of chevrons that increase hollow fiber surface area exposure to the water vapor (gas) side of the unit. This would indicate that a similar approach for the humidifier might result in a custom unit that would outperform the Membrana™ COTS units. Since the MiniModule® unit performed either better or on par with the custom sheet membrane unit, it is likely that enhanced performance of a chevron-type hollow fiber custom design would also outperform the custom sheet membrane unit tested.

Fig. 7 shows water vapor production capability for the three test articles at equivalent test conditions. Test sequence #1 compares performance of the three test articles and refers to test points 1, 8, and 15 in which the water temperature was 50 °F, the inlet gas pressure was 14.7 psia, and the outlet gas pressure was 13 psia. Similarly, test sequence numbers 2 through 8 compare test article performance at equivalent test conditions.

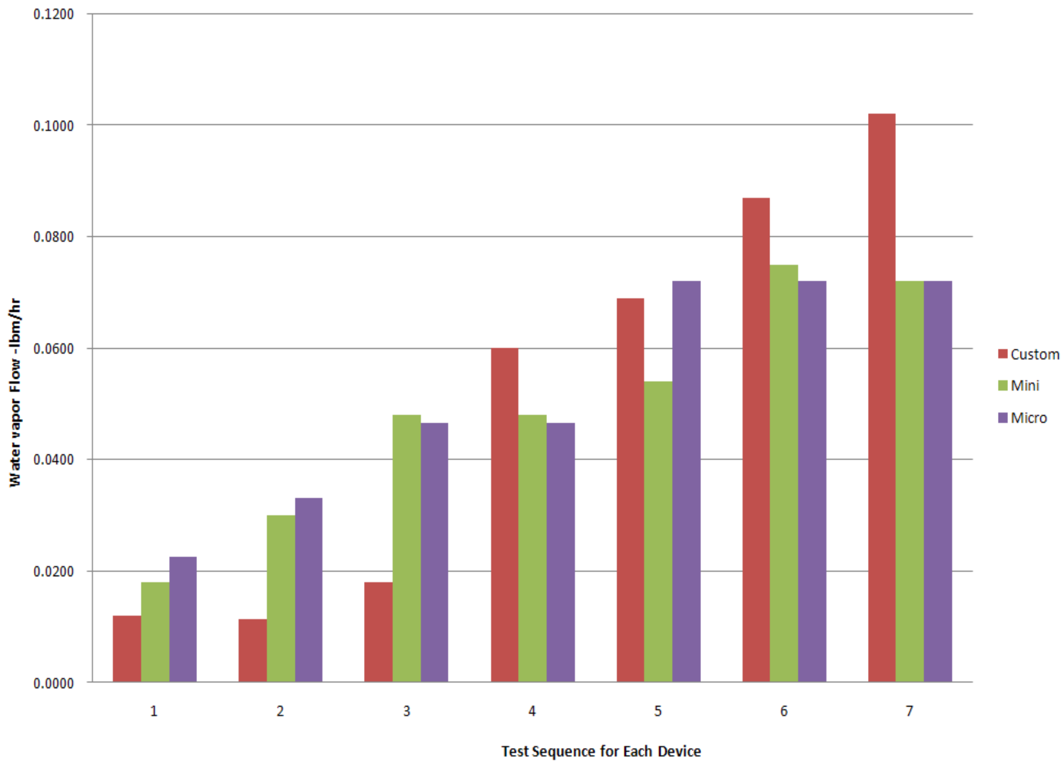

Figure 7. Comparison of Water Vapor Production Capacity at Equivalent Test Conditions

E. Humidifier Test Summary

The test matrix shown in Table 1 was successfully completed to evaluate the performance of a custom humidifier and two COTS humidifier units. The test results show that it is possible to use these technologies to perform the humidifier function required by the baseline PLSS envisioned for future exploration missions. Results from the testing performed in this test series lead to the following trends and observations:

- Reduced pressure in the gas side of the humidifier increases water vapor transfer to the gas stream.
- Water vapor transfer to the gas stream is increased as the water-side temperature increases.
- The humidifier devices all raise the RH and dew point of the gas stream: the custom and MiniModule® showed greater capabilities than the MicroModule®. However, the MicroModule is significantly smaller than either the MiniModule® or the custom unit. Also, it is possible that enhanced performance of a chevron-type hollow fiber custom design, such as that used in the hollow fiber SWME development unit (Bue et al. 2009), would outperform the custom sheet membrane unit and the COTS units tested.
- All devices show a small amount of gas stream cooling. However, additional cooling will be required to reduce the ventilation gas temperature to the 60 to 80 °F range.
- It is not clear why the vapor production performance of the custom unit is lower than the MiniModule® when the devices are tested at ambient conditions, while the custom unit performs slightly better than the MiniModule® at reduced pressure conditions.

III. Feasibility of Eliminating the PLSS Humidifier

Since the RCA unit removes humidity generated by the suited crew member, the need for re-humidification of the ventilation gas post-RCA is inefficient. If changes to the ventilation loop and to the LCVG can eliminate the need for the humidifier, it should result in a more efficient ventilation system. Good engineering practice suggests that it is better to control the humidity with one unit instead of having to remove the humidity with one unit and then add humidity back to the loop with a second unit to meet requirements. A study was therefore implemented to address these considerations.

For this evaluation, the RCA beds were resized to provide proper helmet inlet CO_2 levels to meet CO_2 washout requirements. Then, the following configurations were evaluated to determine humidity levels associated with implementing various modifications to the PLSS schematic. These configurations assume that the humidifier is removed, no LCVG insulation is added unless otherwise noted, and that the RCA unit is resized as presented in the following section.

a) Double Ended Vacuum (DEV) desorption of the RCA with fixed cycle time
b) Single Ended Vacuum (SEV) outlet desorption of the RCA with fixed cycle time
c) SEV-outlet with fixed cycle time and LCVG insulation
d) SEV-outlet with variable cycle time without LCVG insulation
e) SEV-outlet with variable cycle time with LCVG insulation

It should be noted that the currently assumed baseline configuration of the RCA is SEV-outlet. However, in this study, DEV is evaluated to verify and quantify the need for the SEV-outlet configuration. The SEV-outlet configuration is less efficient at removing water in the ventilation loop than the DEV configuration (Papale and Paul 2007). The SEV-outlet configuration is therefore desirable since it results in less over-drying of the ventilation loop than does the DEV configuration.

The FloCAD Advanced Suit Design Analyzer/41-Node Transient Metabolic Man Program (ASDA/METMAN) PLSS model (Barnes, et al., 2010) was used to evaluate humidity levels in the PLSS ventilation loop for the various configurations listed above. The following section describes the assumptions and conditions modeled in this study.

IV. Assumptions and Conditions Evaluated

The CO_2 washout study performed in 2009 (Augustine 2009) indicates that meeting CO_2 washout requirements when helmet inlet CO_2 levels are at 2.5 mmHg is challenging but doable. At higher helmet inlet CO_2 levels, helmets may not be able to meet CO_2 washout requirements. Therefore, it is recommended that the RCA be sized to ensure that helmet inlet CO_2 levels do not exceed 2.5 mmHg. Testing of the RCA unit (Papale and Paul, 2007), resulted in CO_2 levels well above 2.5 mmHg at the RCA exit. Therefore, in this study, the RCA is resized to provide exit CO_2 levels at or below 2.5 mmHg for metabolic rates up to 469 W (1600 Btu/hr). The following additional assumptions are made in this evaluation.

A. Disable Humidifier

The humidifier is disabled in the PLSS model by setting the mass flow rate of water vapor entering the ventilation stream at the humidifier to zero.

B. RCA Half Cycle Time

The Half Cycle time of the RCA is evaluated at fixed and variable durations. For fixed durations, the half cycle time is set to 1 minute to maintain appropriate CO_2 washout performance as recommended in the 2009 RCA Drive System Trade Study (Dillon, et al. 2009). The variable cycle time is accomplished by allowing the CO_2 sensor at the outlet of the RCA to determine when the RCA beds are cycled. The assumption used in this evaluation is to allow the RCA outlet CO_2 level to increase to a level of 3 mmHg and at that point, cycle the beds.

C. Volumetric Flow Rate

Since all RCA testing to date (Papale and Paul, 2007) was performed at a volumetric flow rate of 6 ACFM, uncertainty exists for RCA performance at other flow rates. Therefore, all evaluations in this study assumed that the ventilation flow rate is 6 ACFM at the inlet to the helmet.

D. Metabolic and Environmental Conditions

Each configuration evaluated is simulated at 3 metabolic rates and 3 external thermal environments. The 3 metabolic rates are low (117 W (400 Btu/hr)), moderate (293 W (1000 Btu/hr)) and high (469 W (1600 Btu/hr)). The

3 external thermal environments simulated include cold (-198 °C (-325 °F)), neutral (21 °C (70 °F)), and hot (121 °C (250 °F)) thermal sink temperatures to span the full range of lunar surface thermal environments.

E. RCA Amine Volume Resizing

With the size of the current Hamilton Sundstrand RCA prototype unit, the partial pressure of CO_2 entering the helmet exceeds the value of 2.5 mm Hg (Papale and Paul, 2007) at a metabolic rate of 469 W (1600 Btu/hr). Therefore, the volume of the RCA amine beds is adjusted to be able to provide CO_2 levels at the helmet inlet at or below 2.5 mmHg. Fig. 8 shows the effect of increasing RCA bed volume on the partial pressure of CO_2 and the dew point entering the helmet based on performance predictions resulting from correlations to RCA prototype test results (see Dillon et al., 2009 for CO_2 efficiency equations).

There are 6 bed segments per bed in the Hamilton Sundstrand RCA prototype. Each bed in the prototype has a volume of 715 cm^3 (43.6 in^3) and each bed segment has a volume of 119 cm^3 (7.26 in^3). A bed segment volume of 162 cm^3 (9.9 in^3) is selected for this study. This volume selection results in the partial pressure at the helmet being 2.5 mmHg at the 469 W (1600 Btu/hr) metabolic rate. As shown in Fig. 8, the dew point also drops as the RCA bed size increases. Additional testing of the RCA is scheduled to be performed in 2010 and the results may impact the RCA bed size assumptions in this study.

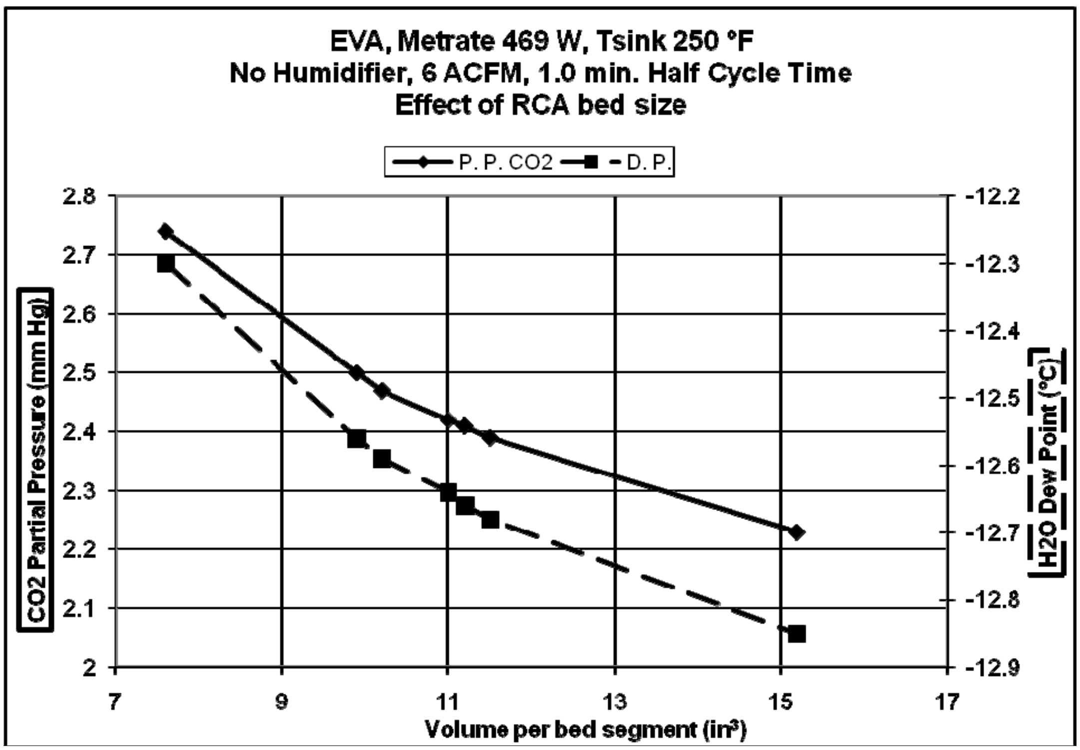

Figure 8. Effect of Increasing Amine Volume.

F. LCVG Tube Insulation

Three configurations are assessed without LCVG insulation which is the currently assumed LCVG configuration for the baseline PLSS. Two configurations include insulation on the LCVG. In many situations, the humidity added by the crewmember to the ventilation stream would result in a dew point within the Pressure Garment System (PGS) higher than temperature of the water tubes within the LCVG. Of course, in this situation, condensation occurs on the water tubes and the PGS outlet dew point is lowered down to the temperature of the water tubes. This effect was demonstrated in Shuttle Extravehicular Mobility Unit (EMU) testing performed in 1994 (Thomas et al., 1995). The condensation onto the LCVG water tubes may be significantly reduced by adding a layer of insulation on the side of the tubes away from the body (Fig. 9).

To demonstrate this, a simple thermal model was created to determine the thickness of insulation that would be required to raise the temperature of the surface in contact with the air above the dew point. The insulation used had an assumed conductivity of 0.0008 BTU/(hr in °F). Convection at the surface in contact with the air was assumed to be 0.2 BTU/(hr ft^2 °F). The resulting temperature of the exterior surface was 55°F using an insulation thickness of 0.25 inches. These results are labeled in Figures 9 and 10. This insulation should prevent a majority of the condensation on the LCVG.

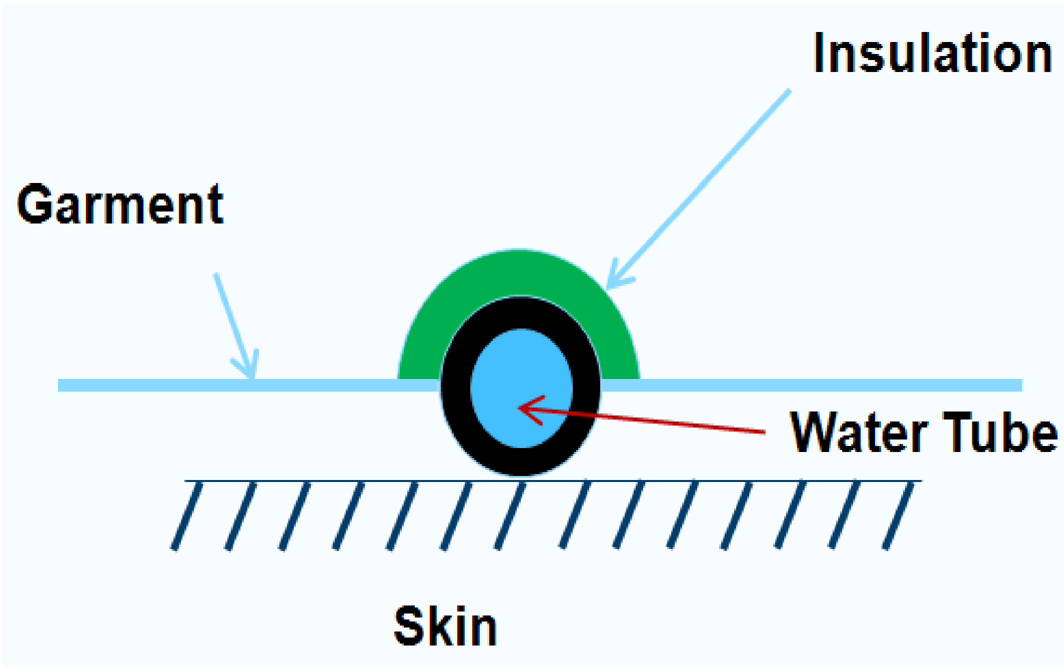

Figure 9. LCVG Water Tube Insulation Configuration.

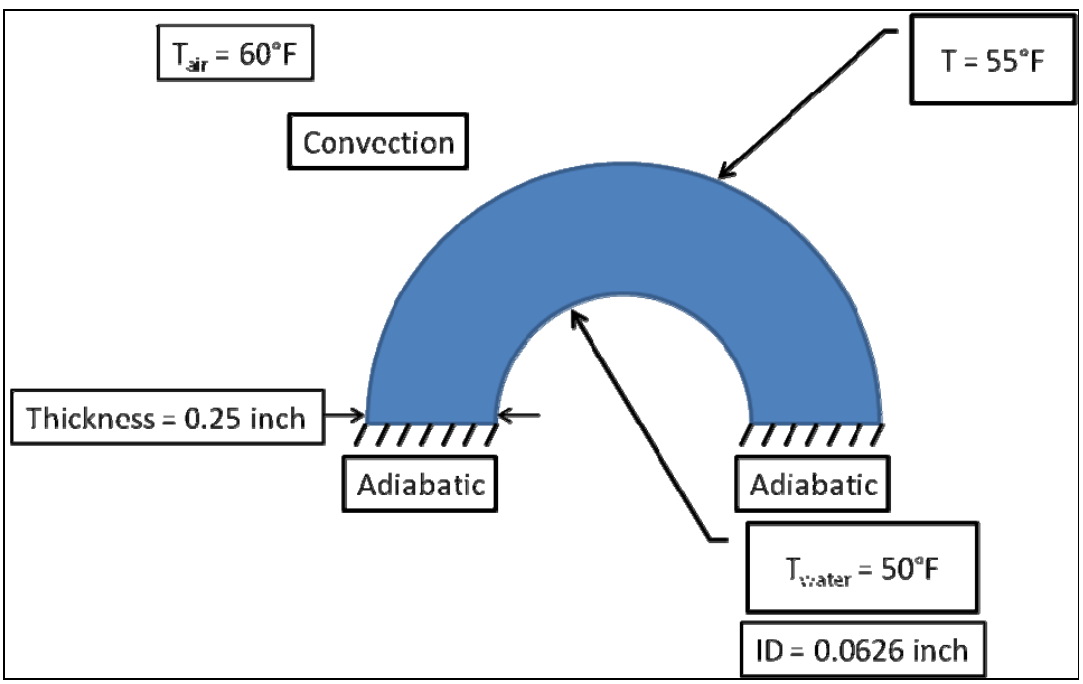

Figure 10. LCVG Insulation Model.

V. Results

Results for each of the configurations modeled are discussed below and Fig. 11 shows a summary of humidity levels attained with each configuration.

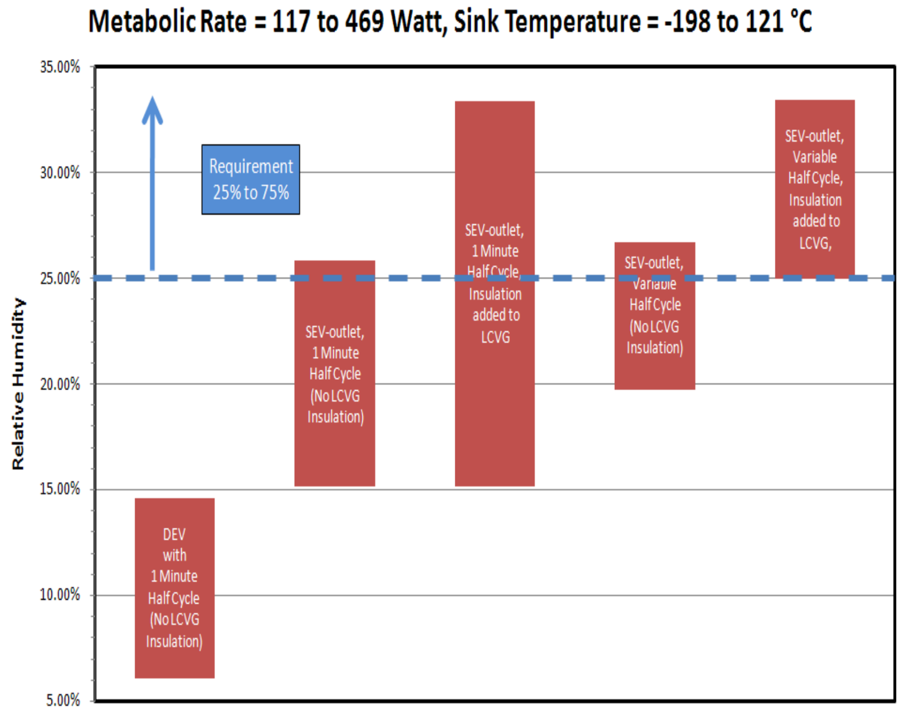

Figure 11. Humidity Ranges for Configurations Analyzed.

A. Double Ended Vacuum (DEV) Desorption of the RCA with Fixed Cycle Time

Fig. 11 shows predicted range of RH for the metabolic rates and thermal environments simulated for the DEV, fixed cycle time configuration. It shows that the RH at the helmet inlet is well below the minimum requirement of 25% RH with this configuration. RH values range from 6% to just under 15% at the helmet inlet for this configuration. This demonstrates that the DEV RCA configuration is too efficient at removing humidity from the ventilation loop and delivers very dry breathing gas to the helmet. No LCVG insulation is assumed for this configuration.

B. SEV-Outlet Desorption of the RCA with Fixed Cycle Time

Fig. 11 shows that the humidity levels are increased significantly with SEV-outlet configuration as compared with the DEV desorb configuration. However, the increase is not sufficient to keep the RH level above 25%. This result shows the advantage of using the SEV-outlet RCA configuration but it does not solve the over-drying problem. This SEV-outlet configuration modeled is the current assumption in the baseline PLSS schematic with the exception that the RCA beds have been increased in size as previously discussed.

C. SEV-Outlet with Fixed Cycle Time and LCVG Insulation

Fig. 11 shows that the upper range of humidity levels are extended to a level of approximately 33% RH with the addition of LCVG insulation. However, the minimum humidity levels are the same as those of the SEV-outlet configuration (~15% RH) without LCVG insulation. This is due to the fact that at low metabolic rates, the crewmember is not generating much moisture and condensation does not occur on the LCVG regardless of whether there is insulation.

D. SEV-Outlet with Variable Cycle Time without LCVG Insulation

Fig. 11 shows that the lower bound of humidity range is raised from 15% RH to approximately 20% RH with the introduction of a variable cycle time as compared to the results of the previous 2 configurations. The upper bound is limited to 26.7% since condensation is occurring on the LCVG tubes.

E. SEV-outlet with Variable Cycle Time with LCVG Insulation

Fig. 11 shows that the SEV-outlet with variable cycle time with LCVG insulation configuration results in a humidity range of 25.0% to 33.4% RH. This configuration just meets the requirement by limiting condensation on the LCVG and adjusting the cycle time based on CO_2 levels at the RCA outlet.

It should be noted that the HSIR requirement allows for excursions below 25% RH for short durations (1 to 4 hours). This allows for some margin in the results for this configuration.

VI. Conclusions and Recommendations

Performance testing was successfully completed to evaluate the performance of a custom humidifier and two COTS humidifier units. The test results show that it is possible to use these technologies to perform the humidifier function required by the baseline PLSS envisioned for future exploration missions.

Further analysis shows that it is feasible to eliminate the humidifier from the baseline PLSS and still meet humidity requirements if changes are made to the current schematic. The first assumption is to insure that the RCA is configured so vacuum is only applied to the outlet end of the beds (the baseline plans already assumes this configuration). The first actual change to the current baseline PLSS would be to use a variable RCA half cycle duration by implementing a feed-back control loop with the CO_2 sensor. The second change is to add insulation to the LCVG tubes to minimize condensation within the LCVG.

Removal of the humidifier would reduce the part count in the PLSS therefore removing the possibility of the unit's failure. However, in order to meet the Relative Humidity requirement at the helmet inlet, the CO_2 sensor must be used for feedback to the RCA controller and the LCVG should be modified to include insulation that will minimize condensation within the PGS. The PLSS development team has reviewed this evaluation and has agreed that the humidifier should be removed at this time. If the proposed changes to eliminate the humidifier encounter developmental issues, the humidifier could be added back into the schematic.

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