

Space Suit Portable Life Support System (PLSS) 2.0 Human-in-the-Loop (HITL) Testing

Carly Watts¹

NASA Johnson Space Center, Houston, TX, 77058

and

Matthew Vogel²

HX5, LLC., Houston, TX, 77058

The space suit Portable Life Support System (PLSS) 2.0 represents the second integrated prototype developed and tested to mature a design that uses advanced technologies to reduce consumables, improve robustness, and provide additional capabilities over the current state of the art. PLSS 2.0 was developed in 2012, with extensive functional evaluations and system performance testing through mid-2014. In late 2014, PLSS 2.0 was integrated with the Mark III space suit in an ambient laboratory environment to facilitate manned testing, designated PLSS 2.0 Human-in-the-Loop (HITL) testing, in which the PLSS prototype performed the primary life support functions, including suit pressure regulation, ventilation, carbon dioxide control, and cooling of the test subject and PLSS avionics. The intent of this testing was to obtain subjective test subject feedback regarding qualitative aspects of PLSS 2.0 performance such as thermal comfort, sounds, smells, and suit pressure fluctuations due to the cycling carbon dioxide removal system, as well as to collect PLSS performance data over a range of human metabolic rates from 500-3000 Btu/hr. Between October 27 and December 18, 2014, nineteen two-hour simulated EVA test points were conducted in which suited test subjects walked on a treadmill to achieve a target metabolic rate. Six test subjects simulated nominal and emergency EVA conditions with varied test parameters including metabolic rate profile, carbon dioxide removal control mode, cooling water temperature, and Liquid Cooling and Ventilation Garment (state of the art or prototype). The nineteen test points achieved more than 60 hours of test time, with 36 hours accounting for simulated EVA time. The PLSS 2.0 test article performed nominally throughout the test series, confirming design intentions for the advanced PLSS. Test subjects' subjective feedback provided valuable insight into thermal comfort and perceptions of suit pressure fluctuations that will influence future advanced PLSS design and testing strategies.

Nomenclature

acfm	=	Actual Cubic Feet Per Minute
AEMU	=	Advanced Extravehicular Mobility Unit
ATCL	=	Auxiliary Thermal Control Loop
BPV	=	Back Pressure Valve
CO ₂	=	carbon dioxide
DACS	=	Data Acquisition and Control System
DCM	=	Display and Control Module
EMU	=	Extravehicular Mobility Unit
HITL	=	Human-in-the-Loop
ISS	=	International Space Station
JSC	=	Johnson Space Center
LCVG	=	Liquid Cooling and Ventilation Garment
MAG	=	Maximum Absorbency Garment
MSPV	=	Multiposition Suit Purge Valve
NPRV	=	Negative Pressure Relief Valve
OSS	=	Oceanering Space Systems
OVL	=	Oxygen Ventilation Loop

¹ Engineer, Space Suit and Crew Survival Systems Branch, 2101 NASA Parkway, Houston, TX 77058.

² Thermal Analyst, Thermal Analysis and Electronics Design, 2224 Bay Area Boulevard, Houston, TX 77058.

P _{CO2}	=	partial pressure of carbon dioxide
PIA	=	Pre-Installation Acceptance
PLSS	=	Portable Life Support System
PPRV	=	Positive Pressure Relief Valve
RCA	=	Rapid Cycle Amine
RL-LCVG	=	Redundant Loop Liquid Cooling and Ventilation Garment
SI	=	suit inlet
SO	=	suit outlet
SSA	=	Space Suit Assembly
TCU	=	Thermal Comfort Undergarment
TP	=	test point
UA	=	Overall heat transfer coefficient

I. Introduction

The Advanced Extravehicular Mobility Unit (AEMU) Portable Life Support System (PLSS) technology development effort led by NASA's Johnson Space Center (JSC) continues to progress with increasing sophistication as exemplified by recent integrated PLSS test beds. The first integrated AEMU PLSS test bed, denoted PLSS 1.0 and tested for several months in 2011, comprised five key PLSS technology development components and extensive commercial-off-the-shelf hardware to provide PLSS functionality. Successful PLSS 1.0 testing facilitated the study of PLSS subsystem interactions and furthered performance characterization, experimental and analytical, of the individual PLSS 1.0 technology developments components.

Given PLSS 1.0 was a breadboard test bed occupying approximately 128 ft³, it was a natural objective of the follow on integrated AEMU PLSS test bed, PLSS 2.0, to package the hardware within a volume and geometric form factor representative of a flight-like PLSS design concept occupying approximately 4 ft³. PLSS 2.0 objectives also included furthering experimental characterization of key technologies, with PLSS 2.0 hardware representing first generation or later prototypes for all components less instrumentation, tubing, and fittings. Another PLSS 2.0 objective was to investigate a new contingency cooling method intended to extend the operational capacity of the emergency systems and add robustness via backup thermal control. The concept is predicated on relieving the Oxygen System of crew cooling requirements during purge flow operations and involves a new subsystem, the Auxiliary Thermal Control Loop (ATCL). In theory, the ATCL will cool the crew and purge flows can be lowered while still providing adequate helmet carbon dioxide washout.

PLSS 2.0 was designed and developed from late 2011 through early 2013. Following assembly of the prototype, testing commenced in March 2013 with Pre-Installation Acceptance (PIA) testing¹. Pre-Installation Acceptance is carryover terminology from the functional acceptance testing that was performed on the EMU PLSS prior to its installation into the Space Shuttle. With respect to PLSS 2.0, PIA was a test series comprising 27 individual test sequences designed to functionally evaluate component performance as installed in the integrated system. PLSS 2.0 PIA testing was completed in March 2014, at which point the PLSS prototype was disassembled in order to repair, modify, or upgrade several items. After PLSS 2.0 was reassembled, a select set of PIA test sequences was repeated in order to verify functionality of the items that had been changed or for which previous interface verifications had been invalidated. Several component performance characterization tests were also completed in preparation for follow-on test series.

Plans for unmanned PLSS 2.0 testing, including PIA testing, involved the use of specialized hardware to simulate the crew. While this approach enables a rigorous, quantitative characterization of the PLSS performance, it fails to capture critical qualitative aspects of a PLSS that a human test subject would experience and sense. PLSS engineers always considered human evaluation of the AEMU PLSS necessary and, fortunately, an opportunity to conduct the first such evaluation arose earlier than expected. The idea was to extend the long history of Mark III space suit human testing to evaluation of PLSS 2.0. This test configuration became known as the Integrated PLSS 2.0/Human-in-the-Loop (HITL) test configuration and commonly referred to as PLSS 2.0/HITL or HITL for short.

AEMU PLSS testing serves the high level objectives of demonstrating life support capabilities and advancing AEMU PLSS technology development hardware towards flight technology readiness levels; in addition, each test has a set of lower level, test specific objectives. Eight primary test objectives were identified for this test series:

1) Evaluate airlock operations while using the Manual Display and Control Module (DCM).

This objective emphasized simulating PLSS 2.0 start up and shutdown with flight-like International Space Station (ISS) airlock operations.

2) **Evaluate PLSS 2.0 Rapid Cycle Amine (RCA) swing bed operations with the RCA bypass valve enabled or disabled.**

RCA operations with and without the bypass valve enabled resulted in unique ventilation loop pressure and flow perturbations in each configuration.

3) **Evaluate airflow based noise.**

Ventilation loop flow rates were varied and test subject evaluations were recorded.

4) **Evaluate perceptible smells in the ventilation loop during all operational phases.**

During testing the test subject was periodically questioned regarding this objective.

5) **Evaluate three thermal control schemes denoted Flow Control, Flow/Temperature Control, and Auto-Cooling.**

The first control mode maintains a fixed Liquid Cooling and Ventilation Garment (LCVG) inlet water temperature with flow varied as needed. The second simultaneously varies the LCVG water inlet temperature and flow rate, while the third control scheme automatically varies LCVG water inlet temperature and flow rates per calculated test subject metabolic rate.

6) **Extend measured EMU Liquid Cooling and Ventilation Garment (LCVG) performance to metabolic rates up to 3000 Btu/hr.**

Historical data existed previously for metabolic rates up to 1600 Btu/hr.

7) **Evaluate the Oceanering Space Systems (OSS) Redundant Loop LCVG (RL-LCVG) to metabolic rates up to 3000 Btu/hr.**

PLSS 2.0/HITL testing provided an opportunity to increase the OSS RL-LCVG experimental performance database and directly compare to EMU LCVG performance by virtue of using the same test configuration, operation, and test subject.

8) **Evaluate the PLSS 2.0 Auxiliary Thermal Control Loop.**

The ATCL represents a new concept to extend contingency operations by offloading crew cooling requirements that have historically caused gas purge flow rates to be higher than needed for CO₂ washout. The PLSS 2.0/HITL test series was the first time this technology development system was tested.

These eight test objectives capture essential questions that this first in several decades, integrated human in the loop test opportunity made possible. PLSS 2.0/HITL testing, carried out from October 29 through December 18, 2014, produced an extensive, valuable dataset and enabled a first look at human perceptions and comfort related to the Advanced PLSS design.

II. An Overview of the Advanced Portable Life Support System 2.0

The advanced PLSS schematic has evolved over the past several years based on lessons learned from PLSS 1.0 development and testing, analytical models, insights gained through considerations of failure modes, and other assessments of the design^{2,3}. When the PLSS 2.0 schematic was developed, it was reflective of the status of the medium fidelity advanced PLSS design conceived for flight operations in 2012-2013. The pneumo-hydraulic schematic is illustrated in Figure 1 and the as-build assembly is shown in Figure 2.

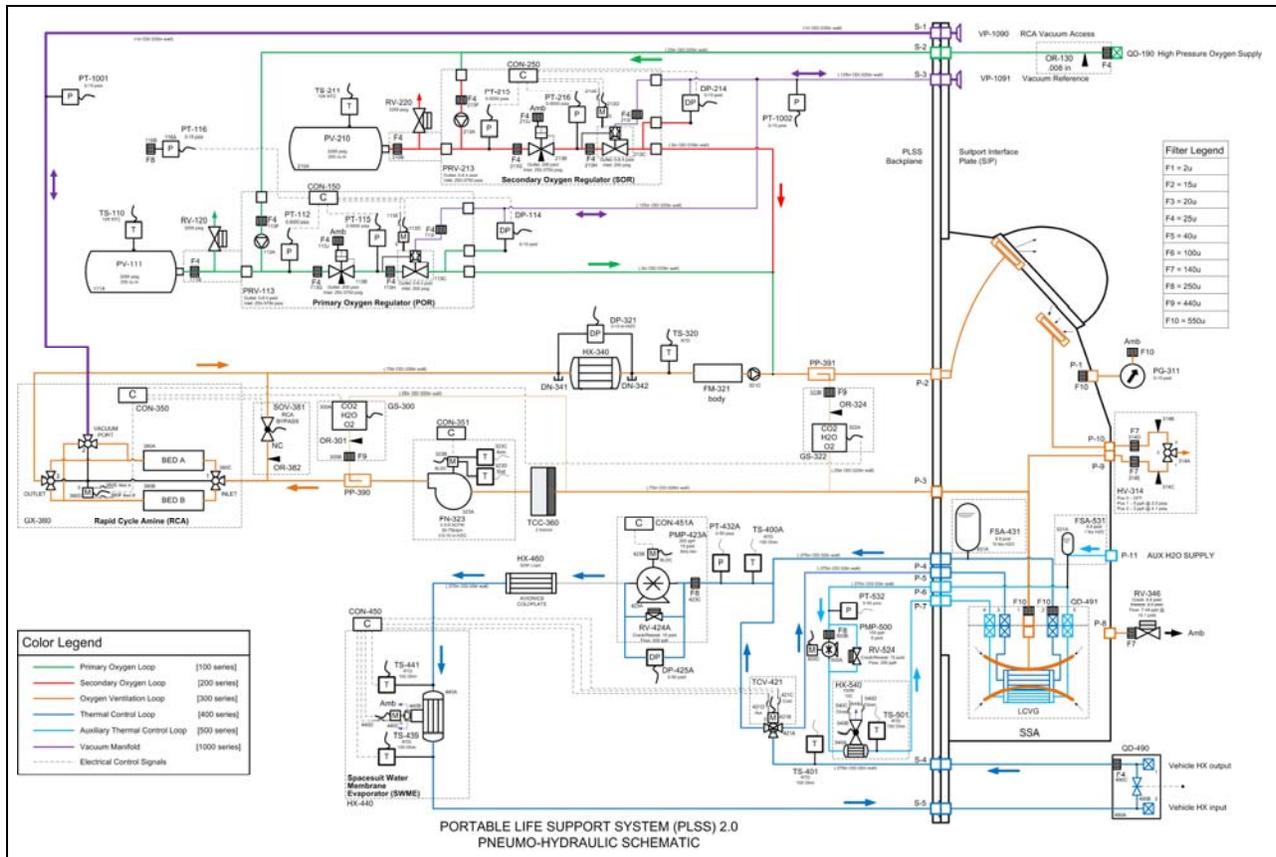


Figure 1. PLSS 2.0 PNEUMO-HYDRAULIC SCHEMATIC

The PLSS 2.0 pneumo-hydraulic design comprises the Primary Oxygen Loop (POL), Secondary Oxygen Loop (SOL), Oxygen Ventilation Loop (OVL), Thermal Control Loop (TCL), and Auxiliary Thermal Control Loop (ATCL). The POL and SOL are identical in design and serve the critical life support functions of replacing consumed oxygen and maintaining the space suit at habitable pressures. They differ in purpose with the POL providing nominal oxygen flow over a large range of suit-to-environment delta pressures of 0.4 to 8.2 psid, while the SOL provides contingency oxygen flow should the space suit pressure drop to 3.7 psid for any reason. The OVL serves the critical function of controlling CO₂ inspired by the crew and does so by providing to the helmet gas flow of sufficiently high flow rates and low CO₂ partial pressures (P_{CO2}). Expired CO₂ is carried away by the OVL gas flow and removed from the gas stream before flowing back to the helmet. In addition, the OVL removes trace contaminants from the gas stream, provides convective cooling of the crew, and contributes to crew comfort and cooling by carrying water vapor, expired by breathing and evaporated from the skin, away from the crew and removing it from the gas stream. Whereas POL, SOL, and OVL requirements specify oxygen as the working gas and many aspects of the hardware were designed accordingly, it was never intended to operate PLSS 2.0 with 100% oxygen. For PLSS 2.0/HITL testing, certified breathing air (CGA-G-7.1-1997, Grade D, 19.5-23.5% O₂) was used exclusively as the working gas.

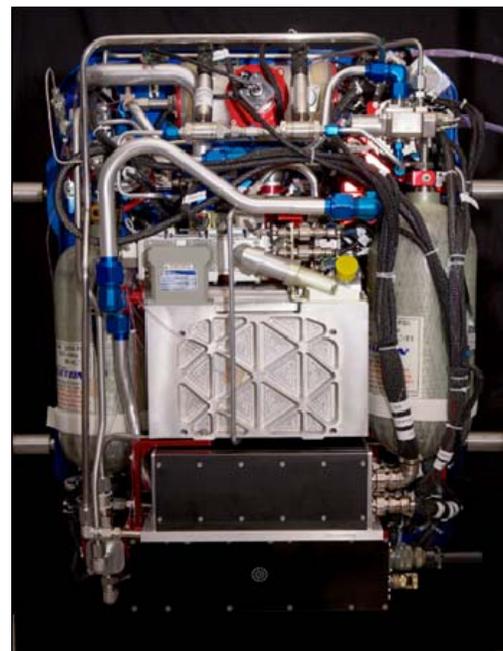


Figure 2. PLSS 2.0 Assembly

The critical life support function provided by the TCL is to acquire crew heat and reject that heat while maintaining the crew at a safe and comfortable temperature. The TCL also acquires heat from the avionics. The ATCL represents a new approach to contingency purge flow operations, high flow operations triggered by OVL failures or significant space suit leakage. Traditionally, as in the Apollo and Shuttle/ISS EMU PLSS designs, contingency oxygen purge flows provide crew cooling and makeup oxygen with the former requiring much higher flow rates than the latter in many situations. The advanced PLSS design offloads this contingency cooling to the ATCL, which will allow the oxygen stored in the SOL to last significantly longer in many contingencies.

Interfacing with all of the PLSS 2.0 loops is the onboard Caution, Warning, and Control System (CWCS), part of the Power, Avionics, and Software (PAS) subsystem of the Advanced EMU. For PLSS 2.0, the CWCS was responsible for power distribution, control of most PLSS 2.0 components, and facilitating two-way communication between PLSS 2.0 components (instrumentation, motor controllers, etc.) and the PLSS 2.0 Test System Data Acquisition and Control System (DACS, often denoted as DAQ). Namely, the CWCS provided control of the Primary and Secondary Oxygen Regulators (POR/SOR), fan, RCA, pump, TCV, and SWME, but not the Mini-ME or ATCL pump; these items were powered and controlled via the test system DACS.

Technology development components are the critical, enabling building blocks of the AEMU PLSS and merit emphasis. PLSS 2.0 contained numerous technology development components with a large range of technology readiness levels including the Primary and Secondary Oxygen Regulators (POR, SOR) in the POL and SOL. Key OVL technology development components included the RCA swingbed CO₂ and water vapor (H₂O) scrubber, fan, and gas/water heat exchanger. TCL technology development components included the SWME, pump, Thermal Control Valve (TCV), and Feedwater Supply Assembly (FSA). Whereas included in the technology development count are the ATCL Mini-Membrane Evaporator (Mini-ME) and Auxiliary FSA (AFSA), which are smaller versions of the TCL SWME and FSA, respectively, perhaps more important is the idea that the ATCL represents a technology development system and new way of handling select contingencies. The PLSS 2.0 CWCS, was also a notable first generation technology development prototype.

III. Portable Life Support System 2.0/Human-in-the-Loop Test System

A high level block diagram of the PLSS 2.0/HITL test configuration is presented in Figure 3, with major segments and associated interfaces identified. Major segments include the PLSS 2.0 and Mark III space suit, as well as the necessary ancillary equipment such as the DAQ, supplementary instrumentation, laboratory facilities, treadmill, fall protection safety hardware, and communication system. Photos in Figure 4 provide another test configuration overview by highlighting the PLSS 2.0, Mark III suit, and some support hardware.

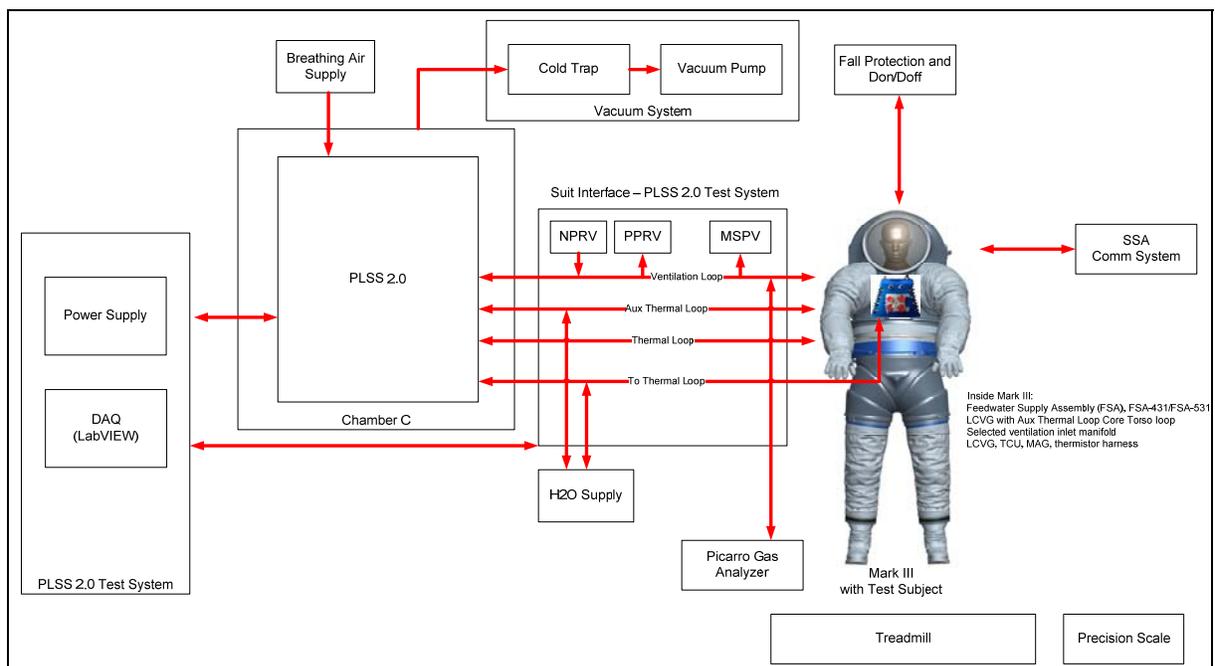


Figure 3. Overview Schematic of the Integrated PLSS 2.0/HITL Test Configuration

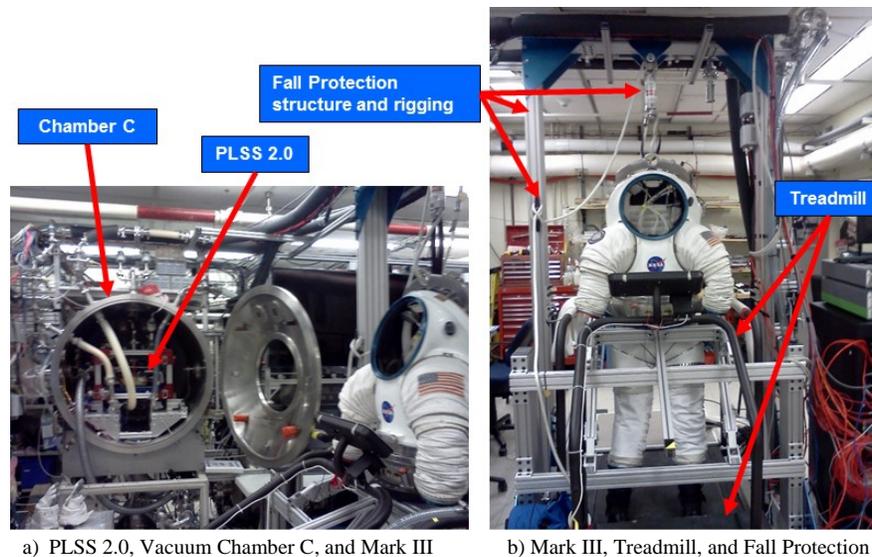


Figure 4. Photos of the Integrated PLSS 2.0/HITL Test Configuration

A. PLSS 2.0 Test System and PLSS Laboratory Equipment

The PLSS 2.0 Test System was composed of hardware and instrumentation to support testing operations, including a simulated vehicle thermal loop and extension of the OVL known as the Suit Interface to incorporate additional functional capabilities and instrumentation. The Suit Interface will be discussed further in the following sub-section. Other aspects of the PLSS 2.0 test system that were used for unmanned testing, including a space suit assembly simulator and human metabolic simulator, were replaced for the HITL test series by the Mark III suit and human test subject.

The PLSS 2.0 Test System also includes the DACS, labeled as DAQ in the PLSS 2.0/HITL block diagram in Figure 3, which was responsible for recording measurements from PLSS 2.0, the Test System, and ancillary instruments. In addition, it sent signals per PLSS operators or the DACS to PLSS 2.0 hardware controllers to command POR and SOR delta-pressure set-points, RCA bed switching, OVL fan speed, TCL pump speed, TCL TCV position, and SWME Back Pressure Valve (BPV) set-point.

Notable PLSS Laboratory equipment included the PLSS Lab Vacuum System, comprising Vacuum Chamber C, a dry rotary vacuum pump, and liquid nitrogen cold trap to increase pumping capability. For the duration of PLSS 2.0/HITL testing, the PLSS prototype was installed inside Vacuum Chamber C, but the chamber was isolated from the rest of the Vacuum System and was not operated at vacuum. PLSS 2.0 was exposed to ambient lab pressure (14.7 psia), with the following notable exceptions: 1) the RCA vacuum access port and SWME BPV were plumbed to the Vacuum System to enable CO₂/H₂O removal and cooling, respectively; 2) the ATCL Mini-ME BPV could not be plumbed to a vacuum source, so technology development fiber cartridges that had previously undergone performance testing were assembled, placed in a small vacuum chamber, and plumbed into the ATCL. Certified breathing air was supplied from K-bottles, with two new K-bottles used for each manned test run. PLSS 2.0 TCL and ATCL FSA recharge water containing 5ppm silver fluoride was stored in a Millipore can to enable pressurization. A Picarro gas analyzer was used primarily to monitor ammonia within the OVL, but also provided a backup carbon dioxide measurement.

B. Suit Interface

The Suit Interface features prominently in the high level PLSS 2.0/HITL block diagram (Figure 3) as a collection of interfaces between the PLSS 2.0 and Mark III space suit. The Suit Interface should be viewed as a term that refers to a collection of primary, secondary, and supplementary functionality required to effect PLSS 2.0/HITL testing and not a discrete assembly. For example, early analyses determined the need for a semi-open OVL configuration and purge flow rates to maintain oxygen concentrations at acceptable levels while achieving two hour EVA time test point durations. Subsequently, hardware implemented to provide controllable purge flows included a mass flow meter, hand operated valve, and oxygen sensor. The oxygen sensor was connected upstream of the Mark III suit to verify suit inlet oxygen concentrations were acceptable and the purge flow meter and hand valve were connected downstream of the suit. Given there was no other means to monitor and effect proper suit inlet oxygen concentrations, these components together form a primary functionality. An example of a supplementary functional capability is the booster fan that was included to extend the life of the PLSS 2.0 fan by reducing its work load. Preliminary testing showed the PLSS 2.0 could marginally achieve 6 actual cubic feet per minute (acfm), but at fan speeds and fan motor power well above its design point. These components are shown in the PLSS 2.0 Test System manned test configuration pneumo-hydraulic schematic (Figure 5).

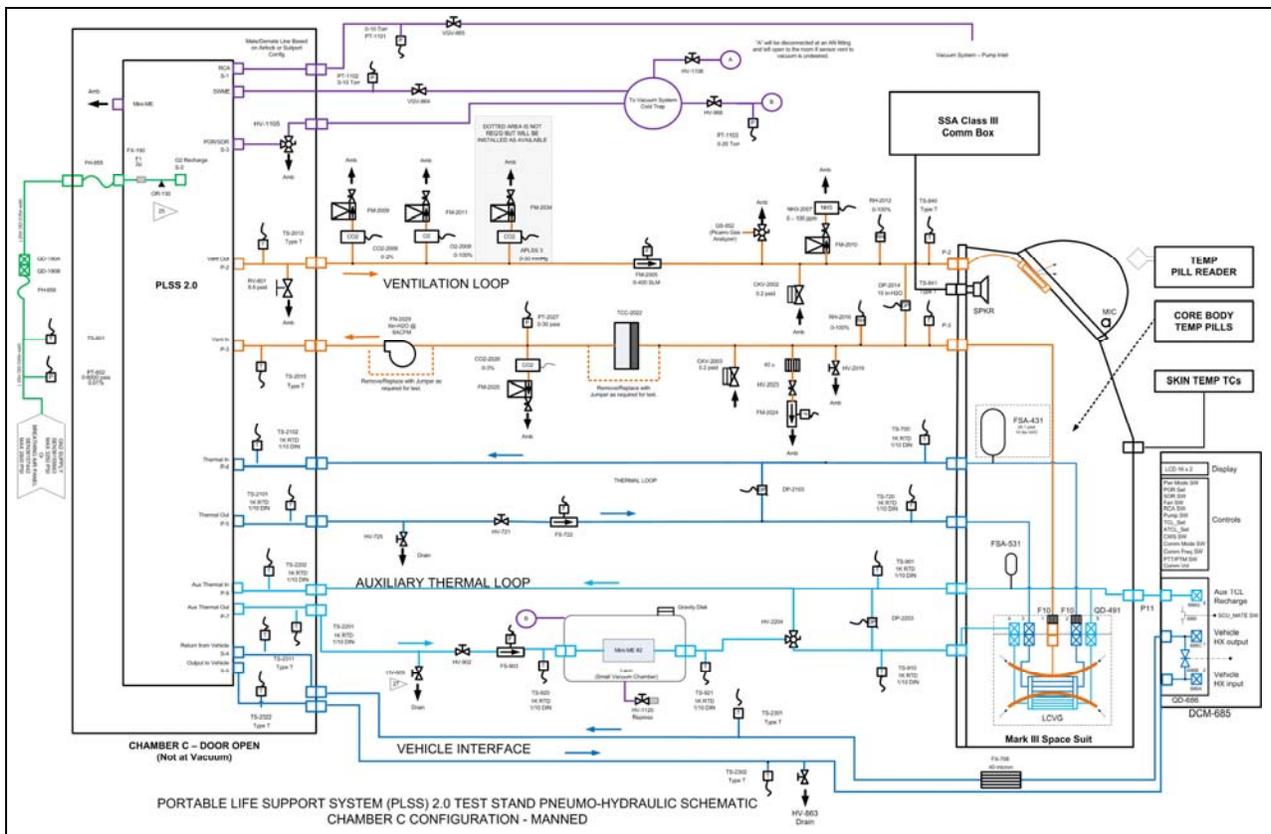


Figure 5. PLSS 2.0 Test System – Suit Interface

C. Mark III Space Suit and Support Hardware

The Mark III suit, shown in Figure 6, is a rear entry space suit prototype that combines rigid suit portions in the torso and hip areas with soft goods arms and legs. The Mark III suit is capable of manned superambient pressurized activity when breathing gas, cooling for the test subject, and a communication system are provided.

For the PLSS 2.0/HITL test series, the Mark III rear hatch penetrations to the Hard Upper Torso (HUT) enabled the separate TCL and ATCL lines from PLSS 2.0 to pass into the suit for connection with the FSA/AFSA and the LCVG. Additionally, because pressure relief protection for the suit was provided via the PLSS 2.0 test system, the suit relief valve port was reconfigured to serve as a pass-through for electronics cabling for thermistors used to measure test subject skin temperature. Inside the suit, test subjects wore a maximum absorbency garment (MAG), and either an EMU LCVG with a thermal comfort undergarment (TCU) or an RL-LCVG depending on the specific test objective.

For each test point, test subjects ingested a core body temperature sensor and wore a chest-strap heart rate monitor to enable measurement of physiological parameters. Additionally, 13 thermistors were affixed to the test subject's skin at particular locations including the abdomen, upper and fore arm, thigh, calf, back, and forehead. Skin temperatures were necessary to calculate the overall heat transfer coefficient (UA) for each LCVG and to correlate test data to the Wissler thermal model.



Figure 6. Mark III Suit in Fall Arrest Stand with Don/Doff Fixture

D. EMU and OSS Liquid Cooling and Ventilation Garments (LCVG)

Space suit LCVGs serve the function of crew thermal control and do so by facilitating TCL water and OVL gas flow over the crew body to acquire crew sensible and latent heat. Most crew heat is acquired by the TCL water that flows through many small, flexible water tubes woven through a garment, which is then worn by the crew (see Figure 7) such that the water tubes are in close proximity to the crew skin. LCVG OVL tubes are routed such that they encourage gas flow across the body, which in turn promotes the evaporation of sweat. The significantly larger LCVG ventilation tubes are easily seen in the photo of the EMU LCVG in Figure 7. While not a primary function of LCVG design, the OVL also acquires crew latent heat by carrying away exhaled water vapor.

Two LCVGs were used throughout the PLSS 2.0/HITL testing: the EMU LCVG and the OSS RL-LCVG (Figure 7). Pertinent features of each garment are shown in Table 1. The OSS RL-LCVG differs from the EMU LCVG by having two water loops, a primary one connected to the PLSS 2.0 TCL and a secondary one connected to the ATCL. This unique feature of a secondary circuit enabled testing of the ATCL concept during PLSS 2.0/HITL testing.

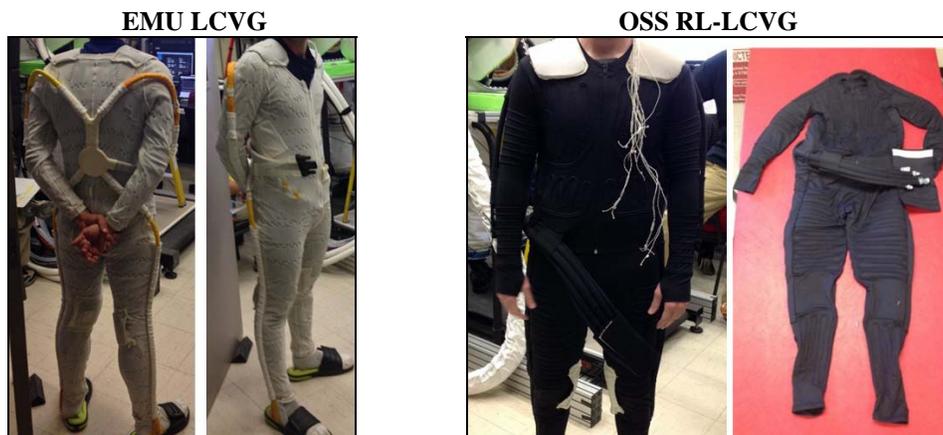


Figure 7. LCVGs Used in PLSS 2.0/HITL Testing

Table 1. Comparison of EMU LCVG and OSS RL-LCVG Features

	EMU LCVG	OSS RL-LCVG
TCL/ATCL water tube material	ethyl-vinyl acetate (EVA)	polyurethane
TCL/ATCL water tube inner and outer diameters	1/16 and 1/8 inches	1/16 and 1/8 inches
TCL water circuit tubing configuration	48 tubes in parallel	22 tubes in parallel
TCL total water tube length*	230-270 ft.	125-145 ft.
TCL average circuit tube length*	4.8-5.6 ft.	5.7-6.6
TCL water loop coverage	Torso, arms, legs	Torso, arms, legs
OVL gas pick up location	Extremity ends	Extremity ends and back to effect a flow split of 60% extremities and 40% torso
TCU worn with LCVG	Yes	No**
ATCL water circuit tubing configuration	N/A	10 tubes in parallel
ATCL total water tube length*	N/A	55-65 ft.
ATCL average circuit tube length*	N/A	5.5-6.5
ATCL water loop coverage	N/A	Torso & upper legs

* Range is due to variation dependent on LCVG size.

** The RL-LCVG has an integral garment made of hydrophilic textile material to promote moisture wicking away from the crew skin and to eliminate the need for the TCU.

IV. Testing Overview

PLSS 2.0/HITL testing, shown in Figure 8, was conducted on nineteen days from October 27 to December 18, 2014. The general plan for each test point (TP) was to execute a two hour EVA simulation that would address multiple specific objectives as well as add to the overall goal of building a valuable PLSS 2.0/HITL test dataset. Most test points simulated a nominal EVA, one that did not include contingency operations. However, three of the nineteen test points simulated a contingency mode denoted by the use of the ATCL.

Three metabolic profiles, labeled High, Low, and Low/ATCL, were used throughout PLSS 2.0/HITL testing and are presented in Figure 9. The high metabolic rate profile is characterized by several strenuous activity periods with a maximum metabolic rate of 3000 Btu/hr and a profile time weighted metabolic rate average of 1400 Btu/hr. The low metabolic rate profile yields an average of 840 Btu/hr with a peak exertion level of 1600 Btu/hr. The combined low/ATCL consists of an 800 Btu/hr average first hour of TCL operations followed by a 1200 Btu/hr average second hour of ATCL operations. Profile periods marked by the 500 Btu/hr metabolic rate represent resting periods in all metabolic rate profiles.



Figure 8. Photo of PLSS 2.0/HITL Testing

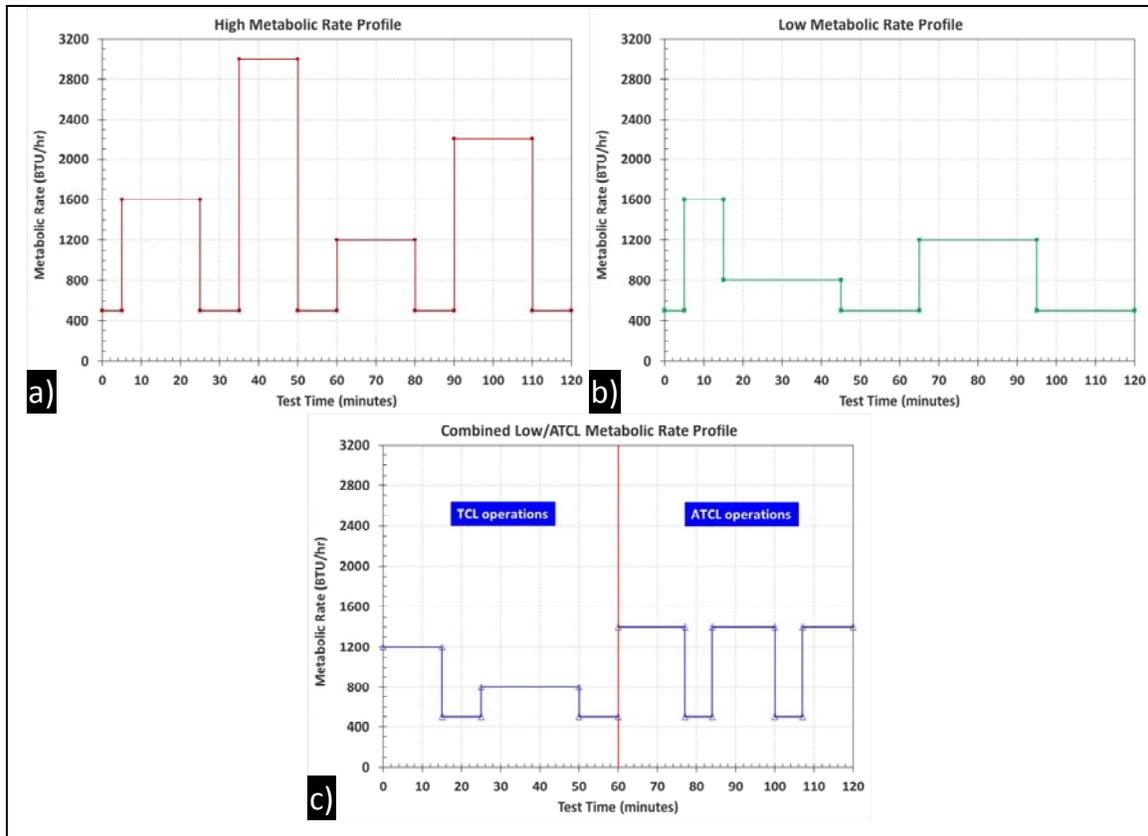


Figure 9. PLSS 2.0/HITL Metabolic Rate Profiles

In addition to metabolic profile, other primary test variables included the RCA control mode and RCA bypass valve configuration. For some test points, these variables were set in accordance with a schedule, defined in the detailed test procedures (CTSD-ADV-1156) and shown in Figure 10, that alternated RCA and bypass valve control modes in order to obtain test subject observations within a single test point. In CO₂ mode, RCA bed switching occurred at a suit inlet CO₂ partial pressure of 3 mm Hg. Eventually, test points were carried out with the RCA in CO₂ mode and the bypass valve disabled for the duration of nominal (non-contingency) EVA simulations, representing the preferred system configuration for flight operations due to resource management considerations.

Five fan noise evaluations were also carried out concurrent with or immediately after the end of the simulated EVA test point. These consisted of flowing OVL gas at 4.5, 5.5, and 6 acfm for five minutes each and noting test subject observations.

Original test plans called for evaluation of three modes of TCL operation: flow control, flow/temperature control, and auto-cooling. Ultimately, the auto-cooling control method was not tested due to limitations in algorithm maturity and hardware performance. Further, it was determined that only flow control would be assessed, as it was preferred over flow/temperature control due to its simplicity.

The combinations of variables selected for each test point evolved throughout PLSS 2.0/HITL testing as the test team learned about the performance of the integrated test system, to achieve particular objectives, and due to

Test Elapse Time (min)	RCA Control Mode		RCA Bypass Valve
	Mode	Setpoint (mm Hg, seconds)	
0	CO ₂	3	Enabled
5	Timed	<u>90</u>	
15			Disabled
35	CO ₂	3	Enabled
45			Disabled
60	Timed	<u>120</u>	Enabled
70			Disabled
90		<u>60</u>	Enabled
100			Disabled

Notes:
 1) Setpoint of 3 mm Hg means RCA bed switch occurs when suit inlet CO₂ partial pressure per CO₂-2006 reaches 3 mm Hg.
 2) Timed setpoint is half cycle time, that is the time each bed is exposed to either the OVL or vacuum. Full cycle time refers to the duration a bed is exposed to the OVL and vacuum or vice versa.

Figure 10. Schedule of RCA and RCA Bypass Valve Control per DTP (CTSD-ADV-1156)

logistical considerations. The final test point matrix, showing the parameters for each of the nineteen test points carried out during the PLSS 2.0/HITL test series, is shown in Table 2.

Table 2. PLSS 2.0/HITL Test Point Matrix

LCVG	Test Subject	High Metabolic Rate Profile			Low Metabolic Rate Profile	Low/ATCL Metabolic Rate Profile	Fan Noise
		Flow/50°F	F-T/50°F	Flow/45°F	Flow/45°F	Flow/45°F/ATCL	
EMU	S1	Oct 27 ^{TE1}	Oct 30				Oct 30
EMU	S2	Oct 28	Oct 31				
EMU	S3	Nov 5			Nov 14		Nov 5
EMU	S4			Nov 10	Nov 19		Nov 10
EMU	S5			Nov 6	Nov 17		Nov 17
EMU	S6			Nov 12	Nov 20		Nov 20
OSS	S1					Dec 17	
OSS	S2	Dec 18		Nov 24*			
OSS	S3					Dec 11	
OSS	S4			Nov 25 ^{TE2}			
OSS	S6			Dec 9 ^{TE3}		Dec 15	

Key:
 Color denotes RCA and RCA bypass valve operated per CTSD-ADV-1156
 Color denotes RCA bed switch at suit inlet P_{CO2} of 3 mm Hg and RCA bypass valve disabled
 Flow/xx°F TCL control was LCVG flow control with SWME outlet temperature fixed
 F-T/xx°F TCL control was LCVG flow and SWME outlet temperature control with minimum outlet temperature listed
 ATCL Thermal control provided by Auxiliary Thermal Control Loop

Notes:
 TE1 Test point terminated early as precaution due to unexpected noise from Mark III suit hip joint
 TE2 Test point terminated early due to blister formation on test subject foot
 TE3 Test point terminated early due to concern regarding blister (test subject felt hot spot)
 * Test point with 30 minute duration 3000 Btu/hr metabolic rate exertion period

Finally, test subject evaluation of PLSS 2.0 performance was guided by questions posed on a scheduled basis and grouped per TCL and OVL emphasis. These questions are listed below:

TCL Questions:

A: Please rate your thermal comfort using the scale provided:

Extremely Too Cold	Moderately Too Cold	Slightly Too Cold	Neither Hot Nor Cold	Slightly Too Hot	Moderately Too Hot	Extremely Too Hot
1	2	3	4	5	6	7

B: Does your body feel equally hot/cold across all segments? If no, explain.

C: Do you believe that cooling adjustments (hotter or colder) were made in a timely manner? If no, explain.

D: Please rate your level of perspiration using the scale provided (intended to gauge LCVG moisture content):

No sweat at all	Just barely sweating	Slightly sweaty	Moderately sweaty	Very sweaty	Exceptionally sweaty	Drenched with sweat
1	2	3	4	5	6	7

OVL Questions:

A: Please rate your level of distraction or annoyance with the ventilation loop and swing bed using the scale provided:

Did not notice it at all	It did not bother me	It would be nice if it was less noticeable	It made the experience uncomfortable	It made being in the suit very unpleasant
1	2	3	4	5

B: Please describe what you noticed or experienced when the beds cycled or the bypass valve actuated:

C: Please rate your perception of odor in the suit using the scale provided:

Cannot Detect Odor		Odor Slightly Noticeable		Odor Moderately Noticeable		Odor Extremely Noticeable	
1	2	3	4	5	6	7	8

D: Please describe any odor detected (musty, dry, stale, acidic, ammonia, rubber, etc.).

E: Please rate your perception of ambient noise in the suit using the scale provided:

Quiet		Slightly Too Loud		Moderately Too Loud		Extremely Too Loud	
1	2	3	4	5	6	7	8

F: Does any sound stand out from the ambient noise? If yes, explain.

G: Is any one sound particularly distracting? If yes, explain.

V. Test Results

PLSS 2.0/HITL testing produced an extensive dataset consisting of over 220 instrument parameters (some instruments reported more than one measurement) at 1 Hertz or better for a total of 36 hours of simulated EVA time and more than 60 hours of testing time. In addition, over 880 test subject evaluation observations and ratings were obtained. The breadth and depth of the PLSS 2.0/HITL test dataset is considered extensive and, based on PLSS 1.0 unmanned testing experience, expected to yield valuable baseline measurements and guidance to ongoing and future PLSS system and component engineering efforts addressing design, requirements, operations, and testing. The following subsections will address several of the eight primary PLSS 2.0/HITL test objectives listed in Section I, specifically those for which results were deemed most informative. For the sake of brevity and because results were straightforward, results pertaining to Objective 3 (Fan Noise Evaluation) and Objective 4 (Evaluation of Perceptive Smells and Odors) will be summarized at a high level only:

- Objective 3 – Fan Noise Evaluation: Five fan noise evaluation test sequences were performed with noise ratings averaging 2 or less (see Appendix for ratings summary plot). A rating of 2 denotes “quiet”. Maximum ratings from all fan noise queries were 2 in all but one TP which included a 3 denoting “slightly too loud”. While this test served to positively identify the lack of noise related issues given the medium-fidelity test hardware, test configuration features that might have contributed to a non-conservative assessment included the long flexible hoses separating the PLSS 2.0 and Mark III suit probably attenuating noise levels and lack of structural transmission of vibrations, which would exist had the PLSS 2.0 been physically secured to the space suit back hatch.
- Objective 4 – Perceptive Smells and Odors Evaluation: Positive odor evaluations dominated PLSS 2.0/HITL testing and 15 of 19 test points yielded an average odor rating of 2 or less, denoting “cannot detect odor” (see Appendix for ratings summary plot). One test point yielded an average odor rating of 3, which denotes “odor slightly noticeable”. Interestingly, one test subject in three separate test points resulted in average odor ratings of 4, the upper half of the “odor slightly noticeable” designation. It is believed the odors that elicited the most comments were associated with the flexible tubing connecting the Mark III suit and PLSS 2.0 OVL.

A. Objective 1: Airlock Operations Evaluation with Emphasis on RCA Startup Ammonia Reduction

Original test plans called for evaluation of airlock operations with the Manual DCM. It was realized prior to PLSS 2.0/HITL testing that using the DCM in conjunction with the Mark III would be impractical, thus resulting in assignment of PLSS 2.0 hardware operations to test team personnel. This change, however, did not negate the value and experience gained from working towards performing an evaluation of airlock operations. Some particular lessons learned from this exercise included:

- Maturation and evaluation of ISS airlock operational concepts
- Consideration of logistics associated with RCA desorb protocol
- Maturation of PLSS controller operations (ex: how do SWME and TCV operate when Service and Cooling Umbilical is connected; how do SWME/TCV operate using different control schemes; how does RCA initialize valve position when RCA mode is changed)
- Development of acceptable human physiological limitation requirements, both for ground testing as well as flight operations (CO₂ exposure, heart rate, core temperature, NH₃ exposure, O₂ deprivation)

One of the critical issues PLSS 2.0/HITL testing sought to address was residual ammonia in the RCA that can enter the OVL. The amine used in the RCA is known to off-gas ammonia. To minimize off-gassing into the OVL, the RCA valve is put into an intermediate position during stowage that isolates each bed, thus limiting ammonia build up within the RCA bed volumes. However, the absolute quantity of ammonia building up within the RCA can be significant, as previous experience had shown, and easily result in extremely high concentrations (30 to 100 ppm) in a sealed OVL.

Four methods of RCA ammonia desorbing were tested prior to PLSS 2.0/HITL testing so that a successful protocol could be implemented in each HITL test point. Methodology and results from this investigation are summarized in Table 3 and show that the final protocol tested proved successful at maintaining OVL ammonia levels below the 3 ppm limit.

Table 3. Summary of Unmanned RCA Ammonia Desorb Protocol Testing

Method	Date	Methodology	Picarro NH ₃ Measurement Maximums (ppm)	
			30 second Average	Instantaneous
1	12/9/2013*	Do nothing	108	108
2	10/1/2014	Cycled each RCA bed once for 2 minute exposures to vacuum (one full cycle totaling two 2 minute half cycles), then turned fan on	8.3	9.7
3	10/6/2014	Cycled each RCA bed thrice for 2 minute exposures to vacuum (three full cycles totaling six 2 minute half cycles), then turned fan on	6.6	8.3
4	10/14/2014	Cycled each RCA bed twice for 2 minute exposures to vacuum (two full cycles totaling four 2 minute half cycles), then turned fan on and flowed through OVL with hatch open for free exchange of lab air	0.7	0.8

* Measurements taken during PLSS 2.0 PIA Section 14.1 testing - pre-HITL testing of this method was not performed due to previous experience with high concentration accumulation of NH₃ within the OVL

Confirmation of the chosen RCA desorb protocol was pursued by plotting instantaneous ammonia levels as measured by the Picarro G1103 gas analyzer for all nineteen PLSS 2.0/HITL test points. Figure 11 presents this plot showing ammonia concentrations ranged up to 1.3 ppm, well below the Institutional Review Board approved 3 ppm limit, for the entire duration of testing in all test points except TP 2. Furthermore, test subjects did not once report the smell of ammonia. Of course, TP 2 stands out as it experienced an ammonia spike upon startup prior to suit donning, although not shown, up to 108 ppm. Further investigation of TP 2 test data shows its ammonia concentration spike was caused by inadvertent fan operation at the start of the RCA desorb protocol. A momentary OVL flow pulse peaking at 2.5 acfm caused the displacement of ammonia from the RCA bed exposed to the OVL and subsequently picked up by the Picarro gas analyzer.

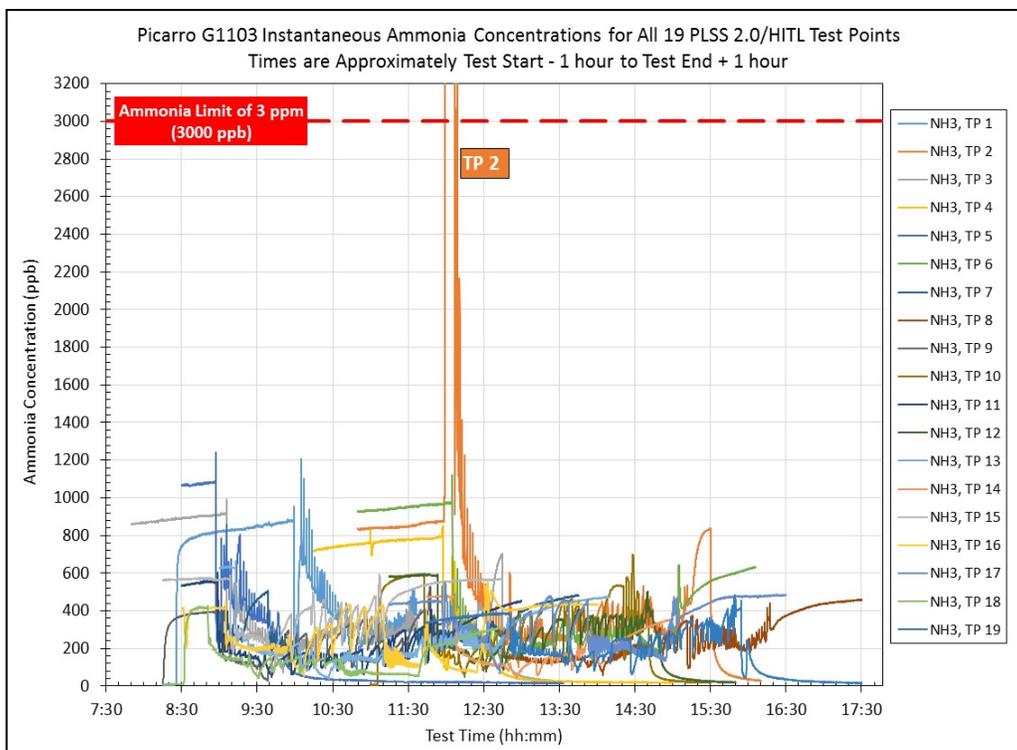


Figure 11. Instantaneous Ammonia Measurements for all Nineteen HITL Test Points

Finally, it should be noted that all of the aforementioned testing was performed without a Trace Contaminant Control (TCC) cartridge containing activated charcoal, which will be included in the final AEMU design. The inclusion of a TCC was deemed unnecessary for HITL testing as it was proven via analysis and testing that the semi-open loop OVL configuration adequately controlled trace contaminants to within acceptable limits.

B. Objective 2: RCA Swing Bed Operations Evaluation

Significant anticipation existed regarding this first opportunity for human evaluation of PLSS RCA swing bed operations. Some aspects of RCA swing bed operations were understood, but many questions remained. For example, in the absence of human feedback the RCA bypass valve was added to the AEMU PLSS schematic to address the flow interruption caused by the RCA valve. However, the additional complexity and failure modes introduced to the AEMU PLSS by the RCA bypass valve forces a sharp focus upon the need for the RCA bypass valve as it would be advantageous to omit it.

Given suit inlet P_{CO_2} and OVL gas flow rates are paramount to sustaining human life in a sealed space suit, they are plotted first in Figure 12 for a test point 6 period of 1200 Btu/hr metabolic rate exertion level where the RCA bypass valve was at first enabled and then disabled. Immediately notable are P_{CO_2} and flow rate (FM-2005) spikes that are a function of an enabled RCA bypass valve. RCA bypass valve operation allowed high P_{CO_2} from the suit to flow straight to the suit inlet where the magnitude of the suit inlet P_{CO_2} spikes were very close to the suit outlet P_{CO_2} , essentially equal for practical purposes. Not surprisingly, disabling the RCA bypass valve caused OVL gas flow rates to

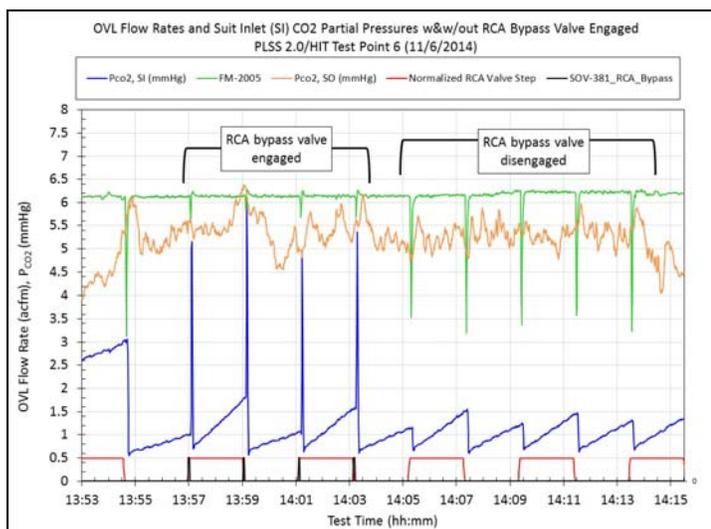


Figure 12. OVL Flow Rates and Suit Inlet CO_2 Partial Pressures with and without the RCA Bypass Valve

drop precipitously, up to 47%, and the suit inlet P_{CO2} exhibited no spikes as the RCA valve caused a momentary OVL flow path closure.

Figure 13 shows the suit pressure and OVL flow rate fluctuations during typical operation with the RCA bypass valve engaged and disengaged. With the RCA bypass valve engaged, typical suit pressure fluctuations were on the order of a 0.07 psi increase followed by a 0.16 psi decrease while a cursory look showed the maximum pressure decrease to be 0.25 psi. These values are well below the limits borrowed from Orion requirements of 0.6 psi and 30 psi/min for pressurization and 0.5 psi (no rate applied) for depressurization. It is believed the flow rate decrease is attributable to a momentary diversion of some POL supply breathing air to the new RCA bed that was originally at half the suit pressure. With the RCA bypass valve disengaged, typical suit pressure fluctuations were on the order of a 0.11 psi increase over one second at a rise rate of 6.6 psi/min, followed by a pressure decrease of 0.22 psi with 0.2 psi of it occurring in one second. The suit pressure fluctuation behavior shown in Figure 13 was observed in pre-HITL testing, which bounded the problem with testing at a significantly smaller volume and, thus, established expectations of meeting Orion specifications during HITL testing. A cursory review of HITL test data showed suit pressure increase due to RCA operations with the bypass valve disengaged reached 0.25 psi. These pressurization and depressurizations also fall well within the Orion specifications noted previously.

Test subject subjective responses indicated different sensations based on RCA bypass valve configuration. In

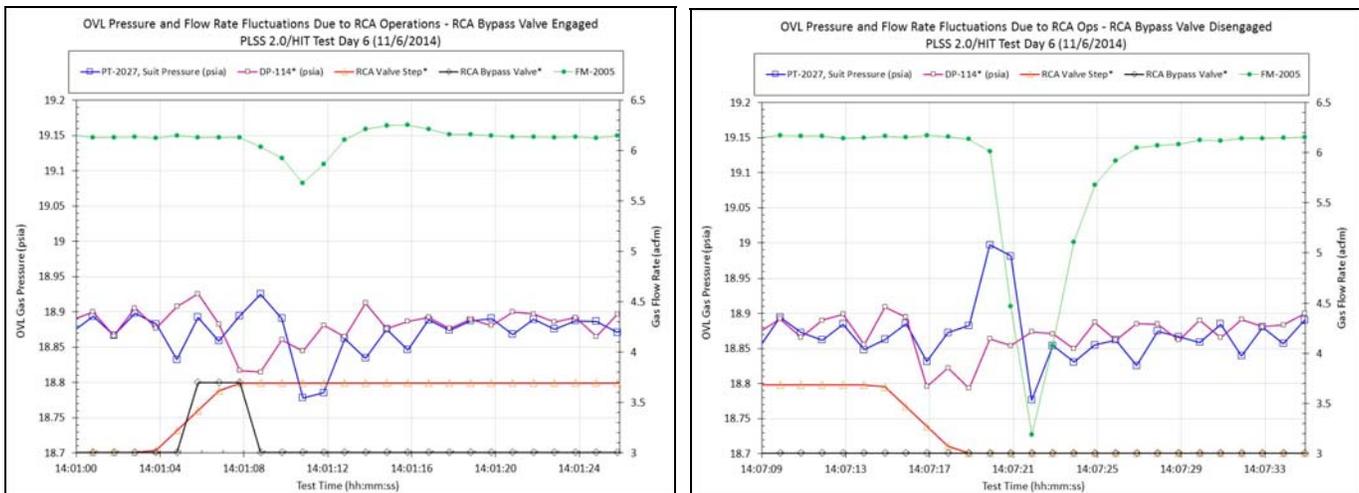


Figure 13. OVL Pressure and Flow Rate Fluctuations Due to RCA Operations, RCA Engaged and Disengaged

cases with the bypass valve engaged, the sensation of a pressure change was predominantly noted by test subjects, whereas disruption of flow was the principal observation when the bypass valve was disengaged. However, the numerical ratings of OVL/RCA operations were very similar between the two bypass valve configurations. Figure 14 shows test subjects' responses to OVL Question A ("Rate your level of distraction or annoyance with the ventilation loop and swing bed.") for all test points and Figure 15 shows a comparison of OVL Question A ratings for test points in which both RCA

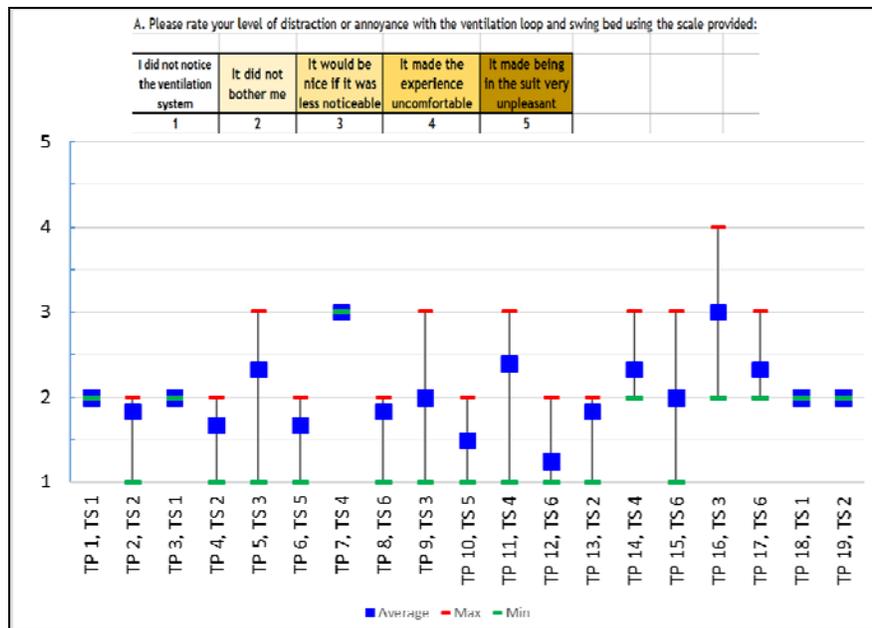


Figure 14. Summary of OVL Question A Ratings for all Test Points

bypass valve configurations were evaluated.

The first and most notable takeaway from this data is that perceptions of OVL/RCA operations were similar between configurations in which the bypass valve was engaged and disengaged. Thus, the RCA bypass valve did not significantly improve test subjects' perceptions of OVL/RCA operation and has therefore been eliminated from the advanced PLSS design. The second takeaway is somewhat more subjective: due to the OVL Question A Ratings, the JSC Advanced PLSS Team concluded that perceptions of pressure fluctuations were not sufficiently negative to warrant prioritization of system redesign to reduce the pressure perturbation at this time.

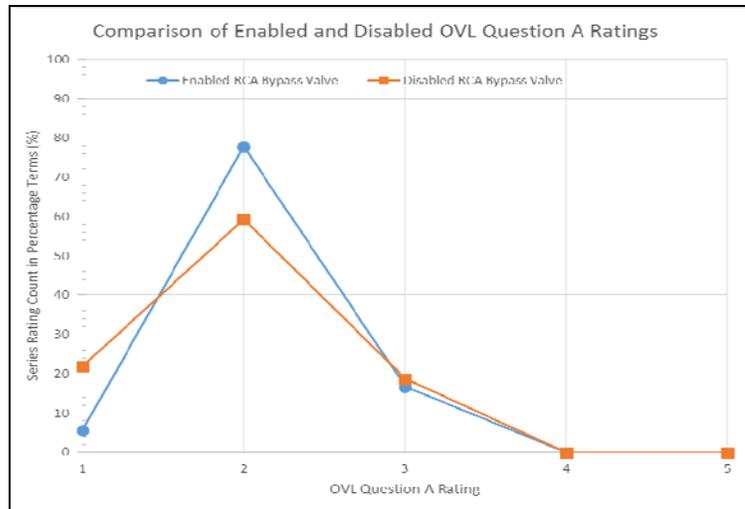


Figure 15. Comparison of OVL/RCA Ratings from Test Points with Engaged and Disengaged Bypass Valve Operations

C. Objective 5: Evaluation of TCL Control Schemes

Early in the HITL test series, high metabolic rate profile testing resulted in modifications to the test plans and operations in response to test subject preferences. The first purposeful change was implemented after the first five TPs by dropping the SWME outlet temperature target 8 °F to 42 °F to increase test subject cooling. Early testing demonstrated a ~3 °F temperature rise from the SWME outlet to the LCVG inlet due to environmental heat gain that would not be present in a flight configuration, hence the new SWME outlet target of 42 °F to supply 45 °F water to the test subject. A consideration worth mentioning is that the 3°F LCVG water flow temperature rise equates to an additional 170W of SWME heat load, or a load equal to 25% of its 700 W design heat load. The SWME outlet temperature target remained 42 °F until the final TP, TP 19, in which the outlet target was reverted back to 50 °F to engender a direct comparison to TP 2. Recall from the test point matrix table, Table 2, TP 3 and 4 objectives included testing the Flow-Temperature TCL control scheme. In actuality, the test subject in both TPs maintained constant LCVG flow and SWME outlet target temperature of 50 °F for thermal comfort reasons during these high metabolic rate profile TPs. Consequently, Flow-Temperature TCL control was not tested.

The second TCL related operational change, implemented after TP 8, was the introduction of the low metabolic rate profile to precipitate LCVG flow control functioning. In four of the first five TPs, test subjects chose to maintain constant full LCVG flow during their entire EVA time. In addition, lowering the SWME outlet target temperature did not necessarily engender LCVG flow control functioning as the TP 7 test subject maintained full LCVG flow and the TP 6 test subject reduced LCVG flow for only ~8 minutes during the resting period following the 1600 Btu/hr exertion period and then reverted back to full LCVG flow for the remaining EVA time.

Test subjects' responses to TCL Question A ("Rate your thermal comfort.") are presented in Figure 16, along with references to clarify SWME outlet target temperature, EMU LCVG/RL-LCVG, and metabolic rate profile, for all EMU LCVG and OSS RL-LCVG primary thermal loop test points. The data in Figure 16 shows that test subjects were generally warm for the high metabolic rate test points. In TP 1-5, when the LCVG inlet temperature was ~53°F, no subjective ratings below 4 ("Neither hot nor cold"), with one exception, were given and the average rating for thermal comfort was above 4. The exception of a rating of 3 ("Slightly too cold") on TP 5 occurred at the end of the test during the 500 BTU rest period. After TP 5, the LCVG inlet temperature target was lowered to ~45°F, but TPs 6 and 7 continued to indicate subjects felt warm in the test. The subject in TP 6 ran full cold through the run except for the rest period at the end and noted during the 1600 BTU/hr portion they would have taken more cooling if it were available. It is interesting and somewhat contradictory to note that the rating of 3 was given for the 2200 BTU section of the profile during which a cooling adjustment was made from TCV position 7 to 10 resulting in an increase in cooling. Again, these perceptions are relevant to the high metabolic profile EVAs, which had a profile time weighted metabolic rate average of 1400 Btu/hr and a peak metabolic rate of 3000 Btu/hr.

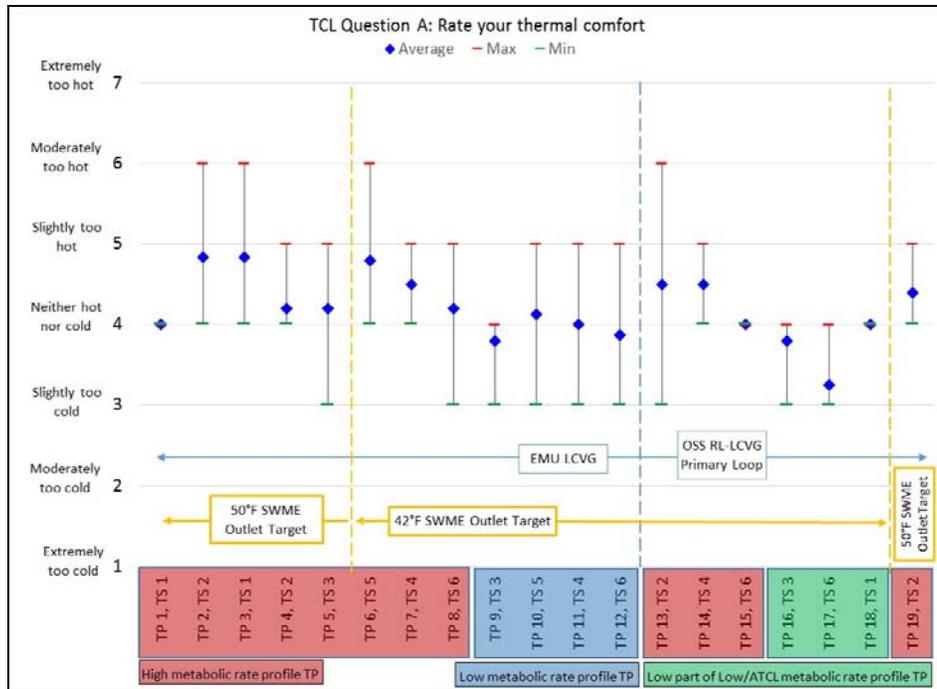


Figure 16. Test Subject Evaluation TCL Question A Data with Min, Max, and Average Ratings for all EMU LCVG and OSS RL-LCVG Primary Loop TPs

For the low metabolic rate profile, with a profile time weighted metabolic rate average of 840 Btu/hr and peak metabolic rate of 1600 Btu/hr, the results in Figure 16 show that test subjects ranged from slightly too hot to slightly too warm, but that average ratings near 4 indicated average thermal neutrality. In the Low portion of the Low/Aux test points, test subjects reported ranging from slightly too hot to slightly too cold, with one exception noted during TP 13. The maximum rating of 6 (“Moderately too hot”) reported during TP 13 occurred during a 1200 Btu/hr portion of the metabolic rate profile that followed a five minute rest period subsequent to the 15 minute 3000 Btu/hr section.

D. Objective 6 – Extension of EMU LCVG Performance Database to 3000 Btu/hr Metabolic Rates

Test points 2-8 successfully completed the two hour high metabolic rate profile and generated the dataset used for evaluation of the EMU LCVG high metabolic rate performance. Figure 17 summarizes EMU LCVG performance by plotting instantaneous UAs for TPs 2 through 8.

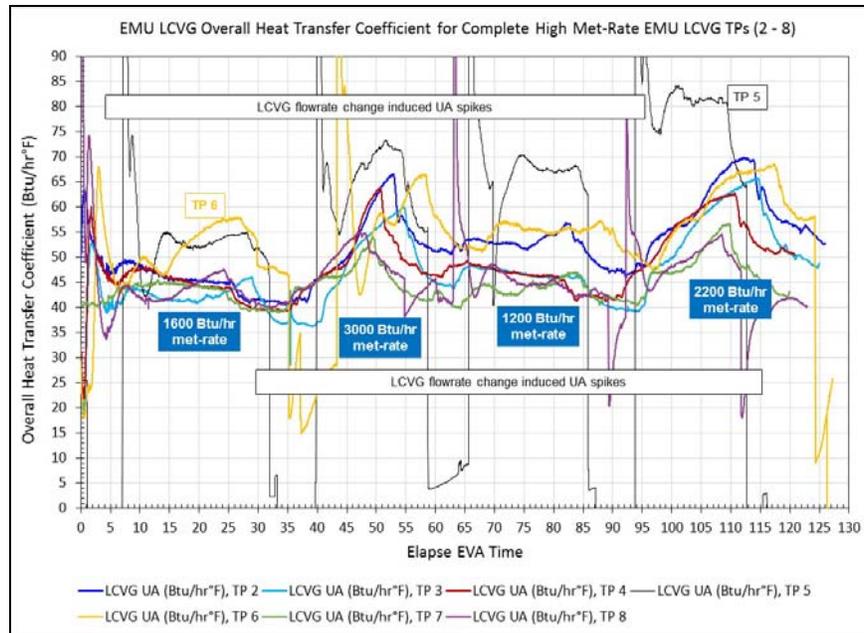


Figure 17. Summary Plot of EMU LCVG/Test Subject Overall Heat Transfer Coefficients for TPs 2/8

Many features of test UAs in Figure 17 stand out and elicit multiple considerations that are presented below:

- TP 5 UA values that were consistently higher than those of other test points, relatively steady during much of the 3000 Btu/hr period, and significantly higher during the 2200 Btu/hr period relative to its 3000 Btu/hr values. TP 5 test UA values and trends, especially during the second hour of testing, pose the challenge of uniqueness and being out of family with respect to the trends the other TPs followed. Several theories exist to explain TP 5 LCVG/UV behavior, including LCVG fit and test operations variations, but ultimately the cause remains unknown.
- UAs generally trended similarly during the 3000 Btu/hr exertion periods with a steep rise followed by an initially precipitous decline and then a relatively less steep decline. This behavior, especially the precipitous decline, and initial hand calculations type analysis suggests the high metabolic rate exercise causes a significant lowering of the thermal resistance between the LCVG tube outer surface and test subject skin.
- Peak UAs during the 2200 Btu/hr exertion period were comparable to peak 3000 Btu/hr period UAs with some slightly lower and some slightly higher and again excepting TP 5. UA values comparable to their 3000 Btu/hr counterparts suggest there is a limit to reducing the skin to tube outer surface thermal resistance. Also, the role of sweat and condensate enhancing performance has to be addressed.
- Peak UAs in the 2200 and 3000 Btu/hr exertion periods were higher than 1200 and 1600 Btu/hr exertion period peak UAs. This general trend was expected.
- UAs during the 1200 Btu/hr exertion period were relatively flat after an initial rise as expected given the moderate rate of exertion.
- Resting period UAs exhibit a general increase from the one prior to the 3000 Btu/hr exertion period to the one after and then a general decrease to the next resting period in between the 1200 and 2200 Btu/hr exertion periods. LCVG moisture (sweat, condensate) levels probably explain this phenomenon as it is known that a wet LCVG better transfers heat by reducing the skin to tube outer surface thermal resistance.

The primary source of historical EMU LCVG UA data is EMU performance verification testing performed in the NASA-JSC 11 foot vacuum chamber in 1994-1995. A thermal math model correlation effort noted in Ref. 4 compared model results to test UA for three test runs with test subjects exercising at metabolic rates ranging from 200 to 1800 Btu/hr. Figure 18 presents historical EMU LCVG test UA for two test runs showing test UAs ranged from 10 to 44 Btu/hr°F with most testing experiencing a more narrow range from 22 to 30 Btu/hr°F. LCVG water flow rates for these test points were a constant 240 lbm/hr. Test UA spikes correspond to sudden changes in sublimator flow through and reflect rapid temperature changes.

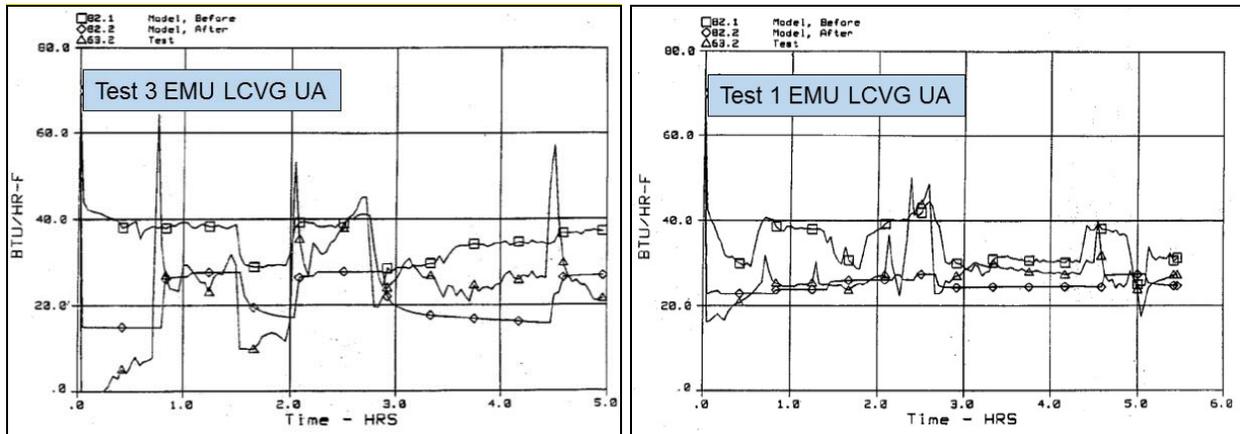


Figure 18. Historical EMU LCVG Test UA from 11 Ft Vacuum Chamber Test Runs Model Correlation Report – Test UA Marked by Triangles in both Plots

Comparing PLSS 2.0/HITL 1600 Btu/hr exertion and resting periods test UAs, which ranged from 36 to 46 Btu/hr^{°F}, to the historical data (10-44 Btu/hr^{°F}) indicates appreciable differences in test configurations. Analysis of PLSS 2.0/HITL EMU LCVG thermal performance data calculated high metabolic rate (3000 & 2200 Btu/hr) LCVG UA ranging from 54 to 80 Btu/hr^{°F}, well above the historical maximum UA of 44 Btu/hr^{°F}. The most likely difference is the use of a thicker TCU in the 11 foot chamber test runs compared to the thinner TCUs used in PLSS 2.0/HITL testing. A thicker TCU would decrease the water tube outer surface to skin UA and reduce overall heat transfer coefficients. Another possible contributor was differences between the space suits and test configurations where the Mark III suit in the air-conditioned laboratory testing behaved like a constant temperature boundary condition adding heat into the LCVG whereas the EMU used in the 11 foot chamber tests at vacuum would have provided significant heat transfer resistance. It is also possible some of the difference can be explained by differences in instrumentation configuration, in particular temperature measurements, as it is known that small temperature differences can yield large UA differences.

E. Objective 7 – Evaluation of the OSS Redundant Loop LCVG Primary Loop Performance

There are two stated parts to objective 7 with the first to perform an evaluation of the OSS RL-LCVG primary loop performance over the entire range of metabolic rates and the second to correlate results to a detailed Thermal Desktop/Wissler thermal/human model. There is a third objective implied by the test plan and that is to compare OSS RL-LCVG primary loop UA performance to EMU LCVG UA performance. It is the evaluation of OSS RL-LCVG primary loop performance and comparison to EMU LCVG test results that are the topics of this section. The model correlation remains a long term, future task.

High metabolic rate profile OSS RL-LCVG test results are summarized in Figure 19 by plotting RL-LCVG primary loop test UAs and flow rates for TPs 13, 14, 15, and 19. TP 13 UAs stand out since it was the TP with an extended 3000 Btu/hr exertion period and a maximum peak UA of 64 Btu/hr^{°F}. The TP 13 2200 Btu/hr exertion period peak UA was 61 Btu/hr^{°F}, close to its 3000 Btu/hr peak UA. One interesting feature of TP 19 is the relatively narrow band of UA values, 42 to 46 Btu/hr^{°F}, exhibited during most of the TP, and perhaps indicative of early onset of LCVG saturation with moisture. As expected, TP 19 UAs rose during the 3000 and 2200 Btu/hr exertion periods with peak UAs of 53 and 59 Btu/hr^{°F}, respectively. The lower UA values exhibited in TP 14 results are considered reasonable given that the test log notes RL-LCVG poorly fit the test subject. TP 15 1200 Btu/hr exertion period UAs ranged from 40 to 42 Btu/hr^{°F} with 53 lbm/hr LCVG water flow and close to TP 19 UAs of 45-46 Btu/hr^{°F}, which had 200 lbm/hr of water flow.

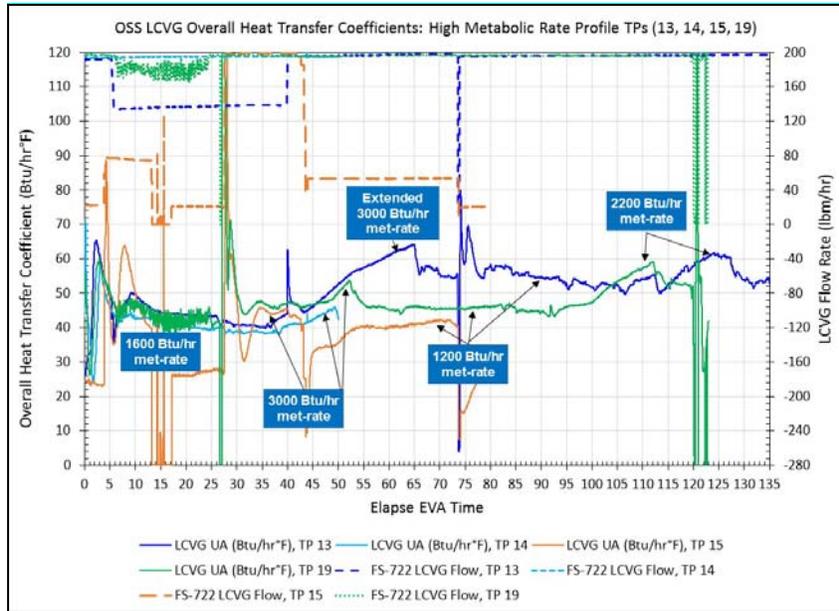


Figure 19. OSS RL-LCVG UAs During High Metabolic Rate Profile Test Points (13, 14, 15, 19)

The final TP of the PLSS 2.0/HITL testing series, TP 19, was a high metabolic profile TP using test subject 2 and the OSS RL-LCVG. These parameters were chosen to facilitate a direct comparison between the OSS RL-LCVG and EMU LCVG, which was worn by the same test subject executing the same high metabolic rate profile in TP 2. Heat gains plotted for both LCVGs in Figure 20 are the first measures of performance and show EMU LCVG heat gains were consistently higher than OSS LCVG heat gains, except for the TP 19 resting period in between the 1200 and 3000 Btu/hr exertion periods. EMU and OSS LCVG peak heat gains in the 3000 exertion periods were 1500 and 1250 Btu/hr, respectively, and 1390 and 1240 Btu/hr in the 2200 Btu/hr exertion periods. In relative terms, the EMU peak heat gains were 20 and 12% greater, respectively, and very interesting since the EMU LCVG total water tube length was 75% greater. The appreciable differences between relative heat gains and LCVG total tube areas suggest the OSS RL-LCVG has a lower tube outer surface to test subject skin thermal resistance. Excluding the pre-3000 Btu/hr resting period in which the higher OSS LCVG heat gains were a result of its test interruption, EMU LCVG low metabolic rate heat gains ranged from 5 to 11 % higher than comparable OSS LCVG heat gains.

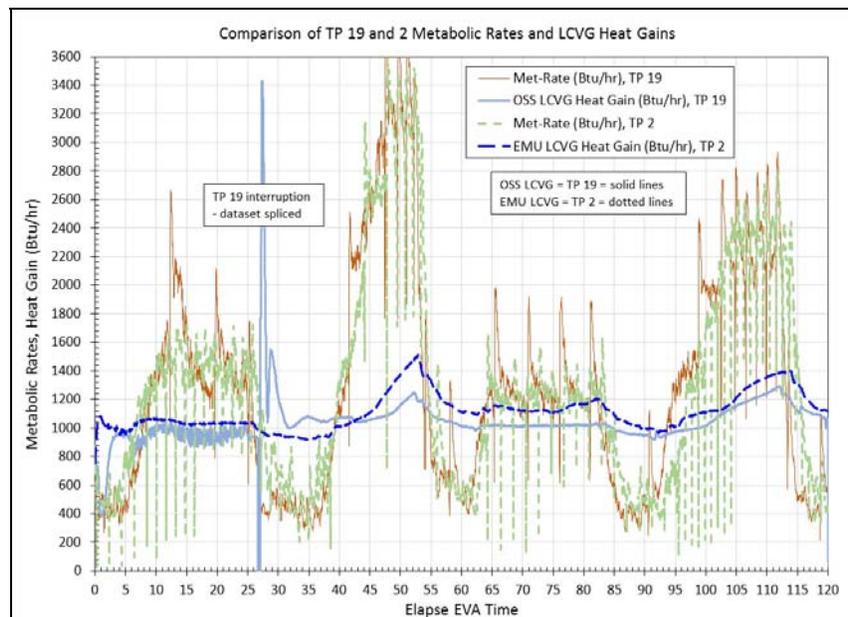


Figure 20. Comparison of TP 19 and 2 Metabolic Rates and OSS RL-LCVG and EMU LCVG Heat Gains

UAs for the EMU and RL-LCVG are plotted in Figure 21 along with OVL suit outlet dewpoint, LCVG in/outlet water, and test subject average skin temperatures. Similar to LCVG heat gains, EMU UAs were typically higher than OSS UAs. Peak UAs from the 3000 and 2200 Btu/hr exertion periods were 54 and 59 Btu/hr°F in TP 19,

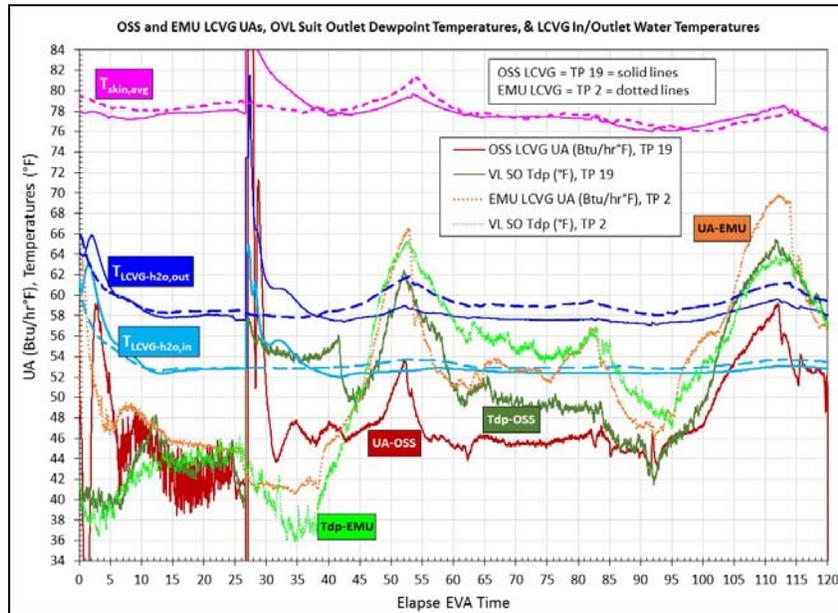


Figure 21. OSS and EMU LCVG UAs and Corresponding LCVG In/Outlet Water, OVL Suit Outlet Dewpoint, and Test Subject Average Skin Temperatures

respectively, and 66 and 69 Btu/hr°F, in TP 2, respectively. Test subject average skin temperatures proved very similar between the two test points with the notable difference being the TP 2 greater rise during the 3000 Btu/hr exertion period. It is differences of LCVG water temperatures, especially the outlet, that best underscore the differences between the OSS and EMU LCVG heat gains and UAs. The TP 2 outlet water temperature was consistently 1 °F higher or more than the TP 19 outlet temperature after the second rest period. The slight persistent temperature difference between LCVG inlet temperatures starting after the second rest period is curious mainly from a SWME operations perspective and not a large contributor to UA differences.

With internal flow heat transfer characterized, it is possible to calculate tube internal forced convection UA, UA₁, and tube wall conduction heat transfer UA, UA₂, from theory and then calculate the tube wall outer surface to skin UA, UA₃, using the first two series UAs (UA₁, UA₂) and test overall heat transfer coefficient, UA. Results of these calculations are presented for the first test result of interest, peak 3000 Btu/hr period UAs, in Table 4. Calculated OSS LCVG UA₁ and UA₂ are 308 and 110 Btu/hr°F, respectively, and 40 and 27% lower than respective EMU UAs. This result is not surprising as both are linear functions of total tube length. Given OSS and EMU LCVG peak UAs of 54 & 66 Btu/hr°F, calculated UA₃ for each is 162 and 152 Btu/hr°F, respectively. The fact the OSS UA₃, the tube outer surface to test subject skin thermal conductance, is slightly greater than the EMU UA₃ in spite of having 42% less tube surface area is quite remarkable.

Table 4. OSS RL-LCVG and EMU LCVG UA Analysis

UA Analysis	LCVG Data and Calculations		RL-LCVG/EMU LCVG Ratio
	RL-LCVG Primary Loop	EMU	
<u>Peak UA from 3000 Btu/hr Period (Btu/hr°F)</u>	54	66	<u>0.82</u>
Water to Tube UA, UA ₁ (Btu/hr°F)	308	513	0.60
Tube Wall UA, UA ₂ (Btu/hr°F)	110	151	0.73
Skin to Tube Outer Wall UA, UA ₃ (Btu/hr°F)	161.6	152.4	1.06
<u>Skin to Tube Outer Wall Heat Transfer Coefficient (Btu/hrft²°F)</u>	<u>107.0</u>	<u>58.5</u>	<u>1.83</u>
RL-LCVG Length Required to Attain UA = 66 Btu/hr°F	177		

To put the comparable peak 3000 Btu/hr period UA_3 results in proper perspective, each UA_3 is divided by its respective tube planar area (total length times tube outer diameter) to calculate an effective tube wall outer surface to test subject skin heat transfer coefficient ($h_{\text{eff,tube-TS}}$). The OSS LCVG $h_{\text{eff,tube-TS}}$ is 107 Btu/hrft²°F and 87% greater than the EMU LCVG $h_{\text{eff,tube-TS}}$ of 59 Btu/hrft²°F. The significantly greater OSS LCVG $h_{\text{eff,tube-TS}}$ clearly shows the OSS RL-LCVG effects a stronger heat transfer path between the tube outer surface and the test subject skin.

There are numerous factors that could influence the relative performance of the EMU LCVG and the OSS RL-LCVG. The OSS RL-LCVG is worn without a separate undergarment, which heat transfer theory and experience indicate could play a very important role in reducing interface thermal resistances by the elimination of an interface that the EMU LCVG and TCU share. In addition, it is possible the absence of a separate TCU allows location of the water tubes closer to the skin, thus reducing conduction heat transfer resistances through the garment material, still air filled voids, and sweat when present. There could be other mechanisms inherent to the OSS RL-LCVG that play an important role such as its garment elasticity and ability to conform the flexible water tubes to the body, its garment hydrophilic property and potential ability to improve the conduction heat transfer path to the tubes by filling voids with water, the pliability of the polyurethane water tubes to effect a broader skin contact area, and lateral conduction improvements.

Finally, the comparison between the OSS and EMU LCVG PLSS 2.0/HITL test results should address subjective test subject feedback in response to thermal comfort questions (see Appendix). For a direct comparison, average thermal comfort ratings were 4.4 and 4.8 for the OSS and EMU LCVG, respectively, remaining in between the ratings of “neither hot nor cold” (4) and “slightly too hot” (5). While the OSS LCVG average is slightly lower than the EMU LCVG, these averages demonstrate both LCVGs performed adequately during challenging metabolic rate profile TPs. High metabolic rate OSS RL-LCVG TPs experienced one 5 and one 6 maximum thermal comfort rating while EMU LCVG high metabolic TPs experienced four 5 and three 6 maximum ratings. A rating of 6 denotes “moderately too hot”. Given the OSS maximum thermal comfort rating of 6 occurred in the extended 3000 Btu/hr period, it is possible a lower maximum rating of 5 would have occurred had the nominal high metabolic rate profile been followed. This possibility is mentioned because it leads to speculation regarding an interesting contrast. That contrast is that while the OSS LCVG heat acquisition was consistently lower than the EMU LCVG in the one to one comparison, the OSS LCVG exhibited slightly better average thermal comfort ratings and potentially better maximum thermal comfort ratings, meaning closer to 4.

F. Objective 8 – PLSS 2.0 Auxiliary Thermal Control Loop Evaluation

Testing of this new contingency water loop was successfully completed in three PLSS 2.0/HITL TPs in which the ATCL was operated for one hour during a challenging 1200 Btu/hr average metabolic rate profile. One objective of the ATCL is to offload crew cooling requirements, which currently drive the ISS EMU DCM contingency purge flow requirements, and would allow the AEMU to specify contingency purge flow rates that address CO₂ washout only. These purge flow rates are expected to be lower than contingency flow rates required to address CO₂ washout and crew cooling. Using an oronasal CO₂ measurement mask, OVL flow rates were dropped from an initial 6 acfm to steady ATCL operation values ranging from 2.8 to 3.8 acfm. Being a contingency system, the ATCL heat rejection capability was sized to safely cool the crew while allowing a certain amount of crew positive heat storage.

At the designated test elapsed time, ATCL water flow was set to achieve ~100 lbm/hr and then Mini-ME cooling was initiated. Once done, OVL operations were performed including initiating RCA timed control at 60 seconds half cycle, adjusting OVL flow rates per oronasal P_{CO₂} measurements, and setting the overboard purge flow to at least 25 slm. The objective of the OVL flow rate adjustments was to find the minimum flow rate that would yield oronasal P_{CO₂} measurements of 20 mm Hg or less.

Because the ATCL was sized for contingency operations, it was assumed and shown by analysis (Ref. 5) that the limited ATCL heat rejection would result in a net positive test subject heat storage. Test subject enthalpies were calculated by taking the product of the test subject mass, assumed human body specific heat of 0.829 Btu/lbm°F, and test subject average temperature weighted 80% core and 20% skin. Note in this approach the zero enthalpy reference corresponds to 0 °F. Figure 22 presents calculated test subject enthalpies for TP 16, 17, and 18 showing a rise of 221, 248, and 348 Btu, respectively, thus following trends as expected. The TP 16 test subject enthalpy rise calculation deducted the 80 Btu rise experienced during the TP interruption.

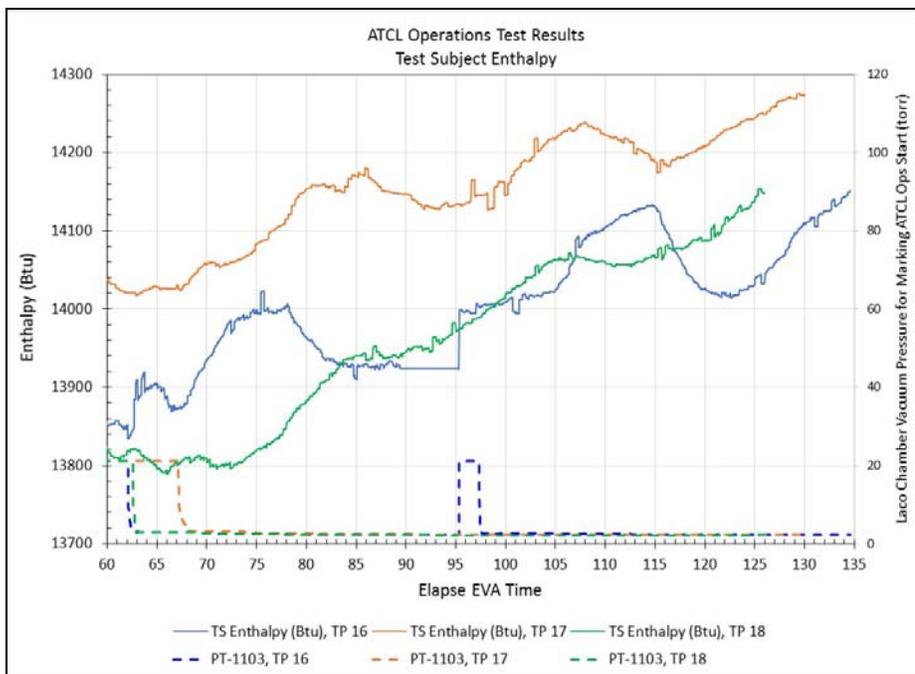


Figure 22. Text Subject Enthalpies During ATCL Operations

Subjective thermal comfort ratings for the ATCL portions of TPs 16, 17, and 18 ranged from 3 (“slightly too cold”) to 6 (“moderately too hot”), with average ratings from 4.3 to 4.8 where a rating of 4 represents “neither hot nor cold” and 5 represents “slightly too hot” (see Appendix). The subjective thermal comfort ratings coupled with enthalpy data consistent with model predictions clearly show that the OSS RL-LCVG redundant loop performed adequately during ATCL operations even with its water tubes covering a limited part of the test subject including the torso and upper legs.

VI. Conclusions and Recommendations

Integrated PLSS 2.0/HITL testing was conducted on nineteen days from October 27 to December 18, 2014 in the Advanced PLSS Development Laboratory at the NASA Johnson Space Center with the goal of each test day to perform a single two hour EVA simulation. All nineteen EVA simulations (test points) experienced orderly execution with sixteen test points successfully completing their prescribed two hour EVA simulation and three test points terminated early due to minor issues with test subject comfort or space suit hardware. PLSS 2.0/HITL EVA simulation testing, denoted EVA time, totaled 36 hours while test time that included pre and post-EVA time activities in addition to EVA time testing totaled over 60 hours. The testing produced an excellent dataset of PLSS 2.0 performance data and test subject evaluation observations. In general, PLSS 2.0/HITL testing proved successful and did not identify any significant issues regarding the advanced PLSS design that would necessitate major modifications. In addition, PLSS 2.0/HITL testing proved the viability of a new approach to select contingencies encapsulated by the Auxiliary Thermal Control Loop.

The summary of PLSS 2.0/HITL test results presented below highlights key findings:

- Objective 1 – Evaluate Airlock operations
 - A pre-EVA RCA IVA ammonia desorb protocol was demonstrated successfully throughout all nineteen test points. Ammonia levels remained well below 1 ppm throughout suit donning and throughout all manned test time.
- Objective 2 – Evaluate PLSS 2.0 RCA operations with the RCA bypass valve enabled or disabled
 - Perceptions of RCA operations with and a without bypass valve were not significantly different, thus subsequent advanced PLSS design iterations will not include an RCA bypass valve.
 - Perceptions of RCA induced OVL pressure fluctuations were not sufficiently negative to warrant prioritization of system redesign to reduce the pressure perturbation at this time.
- Objective 3 – Evaluate airflow based noise

- Fan noise did not present a problem and was generally reported to be “quiet”. It should be noted that PLSS/suit interfaces were not flight-like and future testing will be required to evaluate in-suit noise associated with a higher fidelity hardware configuration.
- Objective 4 – Evaluate perceptive smells in the OVL during all operational phases
 - Odor did not present a problem. It is believed that the most notable odors were due to test system tubing.
- Objective 5 – Evaluate TCL cooling schemes
 - Test subjects generally reported being warm during high metabolic rate test points with 53°F water at the LCVG inlet.
 - Test subjects generally reported ranging from slightly too cold to slightly too warm for high metabolic rate test points with 48°F water at the LCVG inlet.
 - Test subjects generally reported being warmer during high metabolic rate test points and cooler during low metabolic rate test points.
- Objective 6 - Extend measured EMU LCVG performance to metabolic rates up to 3000 Btu/hr
 - The EMU LCVG performed adequately with test subject metabolic rates up to 3000 Btu/hr.
 - At high metabolic rates of 3000 and 2200 Btu/hr, the EMU LCVG overall UA ranged from 54 to 80 Btu/hr°F; for reference, the historical maximum from previous testing was 44 Btu/hr°F. It is believed that thicker TCUs worn during the previous testing increased thermal resistance between the skin and LCVG tubing, thereby resulting in a lower UA.
- Objective 7 – Evaluate the OSS RL-LCVG to metabolic rates up to 3000 Btu/hr
 - The OSS RL-LCVG performed adequately with test subject metabolic rates up to 3000 Btu/hr.
 - At high metabolic rates of 3000 and 2200 Btu/hr, the OSS RL-LCVG overall UA attained a maximum of 64 Btu/hr°F.
 - EMU LCVG heat gains and overall UAs were consistently higher than those of the OSS RL-LCVG, but not proportional to the EMU LCVG’s significantly greater water tube total length. The OSS RL-LCVG exhibited more effective heat transfer between the water tubes and the skin per unit area compared with the EMU LCVG, likely due in part to the lack of a separate TCU worn with the OSS RL-LCVG in accordance with its design, as well as the conformal fit of the OSS RL-LCVG.
- Objective 8 - Evaluate the PLSS 2.0 ATCL
 - The ATCL performed adequately during simulated contingency operations with average target metabolic rate of 1200 Btu/hr.

Appendix

The following charts showing test subjects’ subjective responses to inquiries are provided for reference.

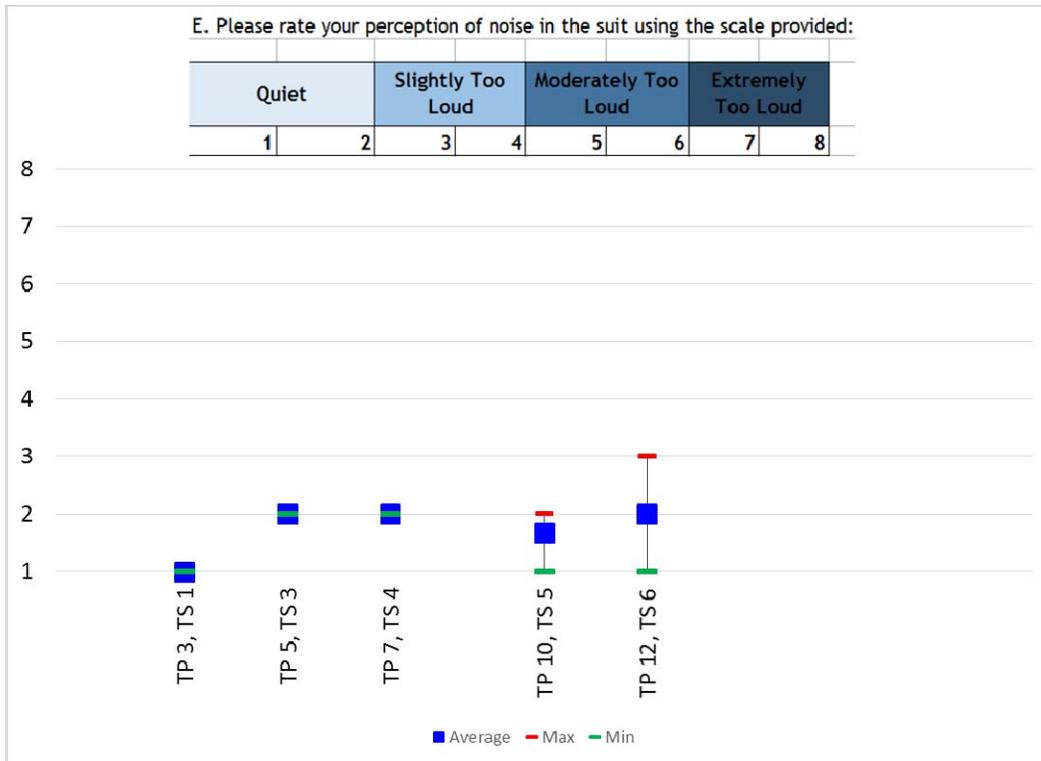


Figure 23. Noise Ratings Summary from Fan Noise Test Points (Test Objective 3)

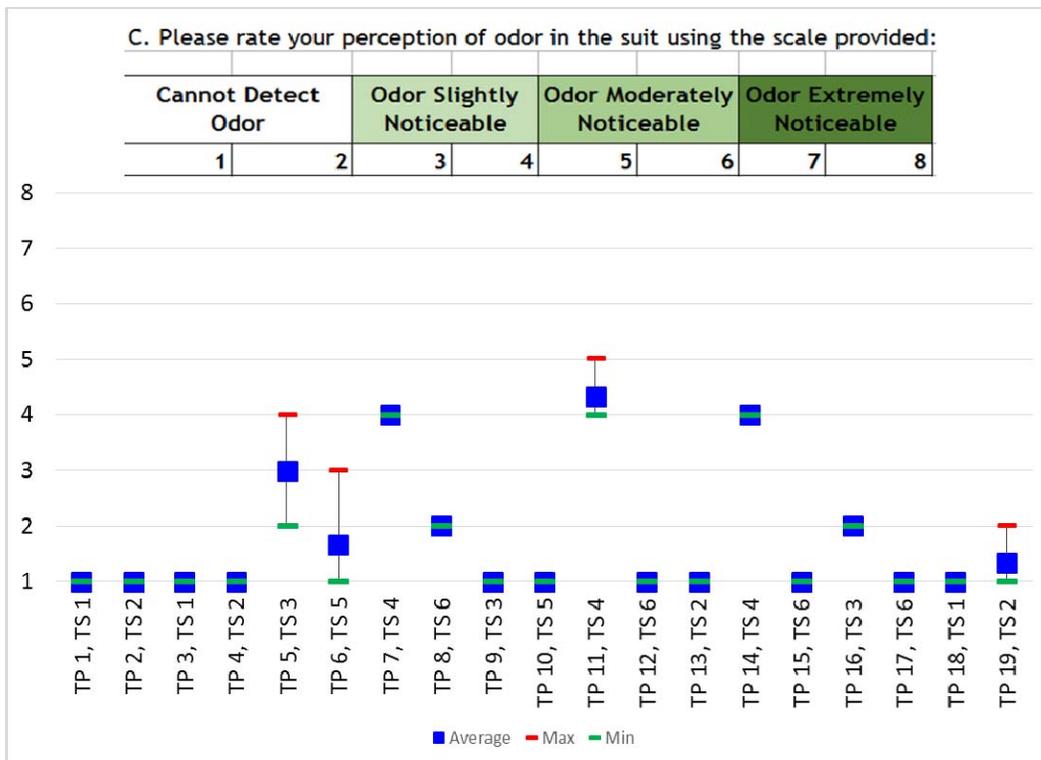


Figure 24. Odor Ratings Summary (Test Objective 4)

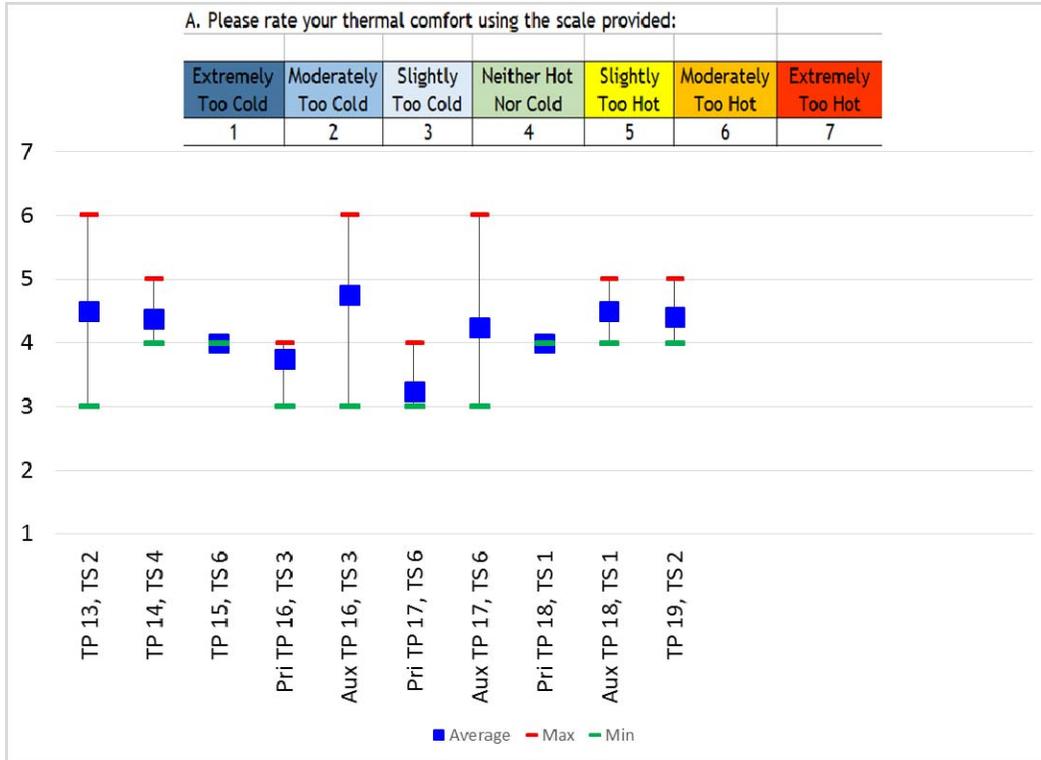


Figure 25. Thermal Comfort Ratings Summary, OSS RL-LCVG (Test Objective 7)

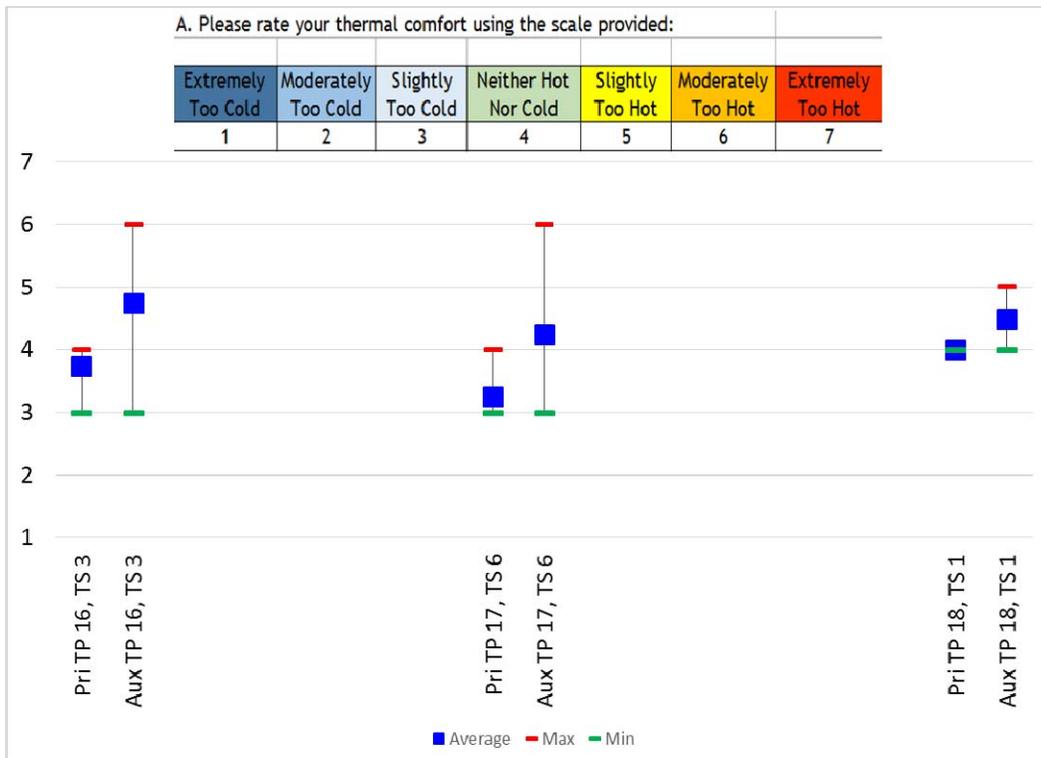


Figure 26. Thermal Comfort Ratings Summary, Low/ATCL TPs (Test Objective 8)

Acknowledgments

PLSS 2.0/HITL testing was a complicated test series involving significant hardware integration, test operations execution, and logistics management. The testing could not have been achieved without the noteworthy contributions from many JSC Advanced PLSS and Space Suit Assembly team members, including: Lindsay Aitchison, Ian Anchondo, Omar Bekdash, Colin Campbell, Cinda Chullen, Bruce Conger, Marlon Cox, Kevin Ehlinger, Eric Falconi, Kevin Groneman, John Harris, Adam Korona, Bill Lynch, Janice Makinen, Pete Meeh, Ian Meginnis, Jason Norcross, Russell Ralston, Richard Rhodes, Amy Ross, Ria Sadik, Nate Smith, Dana Valish, Walt Vonau, Gregg Weaver, and David Westheimer.

References

- ¹Anchondo, I., Cox, M., Watts, C., Westheimer, D., and Vogel, M., "Space Suit Portable Life Support System (PLSS) 2.0 Pre-Installation Acceptance (PIA) Testing," ICES-2016-86, *46th International Conference on Environmental Systems*, International Conference on Environmental Systems, Inc., July 2016. (submitted for publication)
- ²Campbell, C., "Advanced EMU Portable Life Support System (PLSS) and Shuttle/ISS EMU Schematics, a Comparison," AIAA-2012-3411, *42nd International Conference on Environmental Systems*, AIAA, July 2012.
- ³Watts, C., Campbell, C., Vogel, M., and Conger, B., "Space Suit Portable Life Support System Test Bed (PLSS 1.0) Development and Testing," AIAA-2012-3458, *42nd International Conference on Environmental Systems*, AIAA, July 2012.
- ⁴Iovine, J., "Extravehicular Mobility Unit (EMU) SINDA Model Verification Upgrades Report," HDID-E40D-547, NASA-JSC, 1995.
- ⁵Rhodes, R., Bue, G., Meginnis, I., Hakam, M., and Radford, T., "Thermal Performance Testing of EMU and CSAFE Liquid Cooling Garments," AIAA-2013-3396, *43rd International Conference on Environmental Systems*, AIAA, July 2013.
- ⁶Bue, G., Makinen, J., Cox, M., Watts, C., Campbell, C., Vogel, M., Colunga, A., and Conger, B., "Long-Duration Testing on a Spacesuit Water Membrane Evaporator Prototype," AIAA-2012-3459, *42nd International Conference on Environmental Systems*, AIAA, July 2012.
- ⁷Bue, G., Watts, C., Rhodes, R., Anchondo, I., Westheimer, D., Campbell, C., Vonau, W., Vogel, M., and Conger, B., "Experimentally Determined Heat Transfer Coefficients for Spacesuit Liquid Cooled Garments," ICES-2015-330, *45th International Conference on Environmental Systems*, International Conference on Environmental Systems, Inc., July 2012.
- ⁸Campbell, C. "Shuttle/ISS EMU Failure History and the Impact on Advanced EMU Portable Life Support System (PLSS) Design," ICES-2015-327, *45th International Conference on Environmental Systems*, International Conference on Environmental Systems, Inc., July 2012.
- ⁹Mosher, M. and Campbell, C., "Design and Testing of a Variable Pressure Regulator for a Flexible Spacesuit Architecture," AIAA-2010-6064, *41st International Conference on Environmental Systems*, AIAA, July 2010.
- ¹⁰Paul, H., Jennings, M., and Waguespack, G., "Requirements and Sizing Investigation for Constellation Space Suit Portable Life Support System Trace Contaminant Control," AIAA-2010-6065, *40th International Conference on Environmental Systems*, AIAA, July 2010.
- ¹¹Papale, W., Nalette, T. and Sweterlitsch, J., "Development Status of the Carbon Dioxide and Moisture Removal Amine Swing-Bed System (CAMRAS)," AIAA-2012-3411, *40th International Conference on Environmental Systems*, AIAA, July 2009.
- ¹²Steele, J., Quinn, G., Campbell, C., Makinen, J., Watts, C., and Westheimer, D., "Advanced Space Suit PLSS 2.0 Cooling Loop Evaluation and PLSS 2.5 Recommendations," ICES-2016-239, *46th International Conference on Environmental Systems*, International Conference on Environmental Systems, Inc., July 2016. (submitted for publication)
- ¹³Swickrath, M., Watts, C., Anderson, M., Vogel, M., Colunga, A., McMillin, S., and Broerman, C., "Performance Characterization and Simulation of Amine-Based Vacuum Swing Sorption Units for Spacesuit Carbon Dioxide and Humidity Control," AIAA-2012-3461, *42nd International Conference on Environmental Systems*, AIAA, July 2012.
- ¹⁴Watts, C., Anchondo, I. and Vogel, M., "Space Suit Portable Life Support System (PLSS) 2.0 Unmanned Vacuum Environment Testing," ICES-2016-88, *46th International Conference on Environmental Systems*, International Conference on Environmental Systems, Inc., July 2016. (submitted for publication)