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Experimentally determined overall heat transfer coefficients for spacesuit liquid cooled garments

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A Human-In-The-Loop (HITL) Portable Life Support System 2.0 (PLSS 2.0) test has been conducted at NASA Johnson Space Center in the PLSS Development Laboratory from October 27, 2014 to December 19, 2014. These closed-loop tests of the PLSS 2.0 system integrated with human subjects in the Mark III Suit at 3.7 psi to 4.3 psi above ambient pressure performing treadmill exercise at various metabolic rates from standing rest to 3000 BTU/hr (880 W). The bulk of the PLSS 2.0 was at ambient pressure but effluent water vapor from the Spacesuit Water Membrane Evaporator (SWME) and the Auxiliary Membrane Evaporator (Mini-ME), and effluent carbon dioxide from the Rapid Cycle Amine (RCA) were ported to vacuum to test performance of these components in flight-like conditions. One of the objectives of this test was to determine the overall heat transfer coefficient (UA) of the Liquid Cooling Garment (LCG). The UA, an important factor for modeling the heat rejection of an LCG, was determined in a variety of conditions by varying inlet water temperature, flowrate, and metabolic rate. Three LCG configurations were tested: the Extravehicular Mobility Unit (EMU) LCG, the Oceaneering Space Systems (OSS) LCG, and the OSS auxiliary LCG. Other factors influencing accurate UA determination, such as overall heat balance, LCG fit, and the skin temperature measurement, will also be discussed.

Nomenclature

CO_2	=	carbon dioxide
EMU	=	extravehicular mobility unit
EVA	=	extravehicular activity

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LCG	=	liquid cooling garment
LiCl	=	lithium chloride
LCVG	=	liquid cooling and ventilation garment
psia	=	pounds per square inch absolute
RH	=	relative humidity
SWME	=	Spacesuit Water Membrane Evaporator
TS		Test Subject

I. Introduction

The Portable Life Support System (PLSS) 2.0 is an integrated system test recently conducted at Johnson Space Center. It is the first packaged PLSS integrated test utilizing new technologies since the Apollo program. It has been evaluated through a series of functional tests using test systems to simulate a space suit and human. After successfully demonstrating PLSS 2.0 performance using a simulated suit and test subject, it was determined that integrating this test article with the Mark III Space Suit Assembly and using a human test subject would be an opportunistic evaluation that could influence the next iteration of PLSS development. The idea was to extend the long history of Mark III suit human testing to evaluation of the PLSS 2.0 (Figure 1). 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.

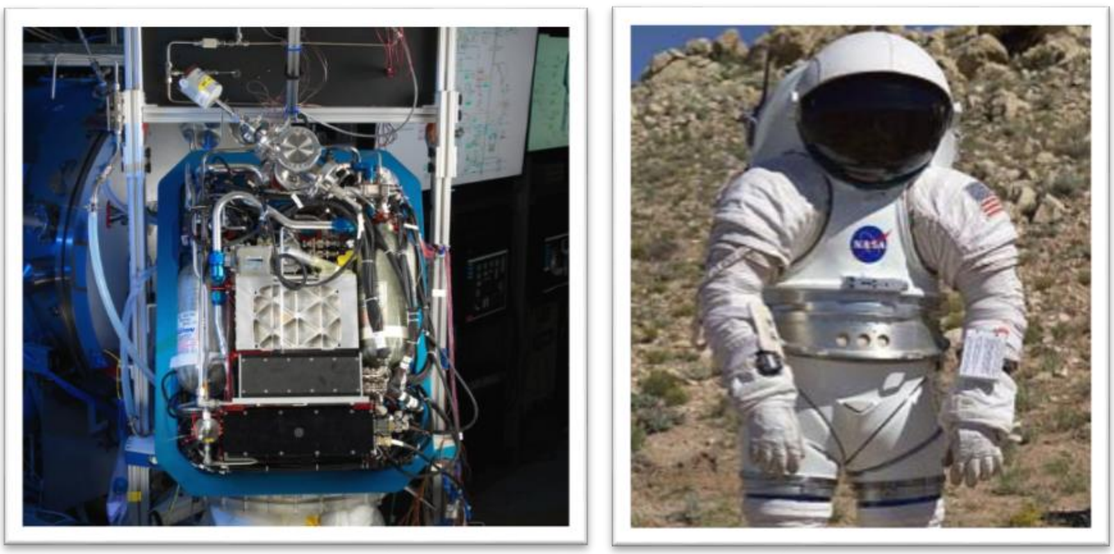


Figure 1. PLSS 2.0 Test Article and Mark III Space Suit Assembly

Three of the HITL objectives are the subject of this paper: 1) Extend the EMU LCG performance database beyond the limits of previously collected data (1600 Btu/hr) up to 3000 Btu/hr; 2) Evaluate the performance of the Oceaneering Space Systems (OSS) redundant loop OSS LCG across the full metabolic range of 0-3000 Btu/hr; 3) Evaluate the PLSS 2.0 auxiliary loop thermal control. The overall heat transfer coefficient (UA) between the LCG and test subjects for the three LCGs were calculated with the data collected and compared. These results will ultimately be correlated to the thermal desktop/Wissler model in a subsequent study.

JSC has been active in LCG development since the first Gemini spacewalk when it became clear that ventilation alone was insufficient for heat removal in most EVA activities. The Apollo LCG consisted of a network of tubes covering the torso, thigh, calf and uppers arms [1]. The Shuttle LCG differed slightly from the Apollo LCG in that cooling was extended to the forearms and vent ducting became integral to the garment [2], and had similar cooling efficiencies [3]. An early effort to improve the LCG was directed toward automatic control concepts [4]. A human-LCG thermal math model was used to define a comfort curve providing a control target relationship for the control algorithm based on inlet temperature and metabolic rate [5].

The empirical relationship of cooling efficiency to flow rate and inlet temperature of the Shuttle LCG was refined with regression analysis from test data [6,7], and was used to improve modeling accuracy. A new comfort curve was developed using the revised model for further automatic control development [8, 9]. These comfort curves were altered to reflect the comfort bias of crewpersons in subsequent testing with the EMU [10] and showed that with 240 lbm/hr coolant flow that above metabolic rates of 2000 Btu/hr inlet temperatures of 50 °F would be required.

Efforts to improve efficiency by supplying different coolant temperature to the torso, arms and legs were deemed unsuccessful [11]. An important phenomenon has also been demonstrated of condensation accumulating on the LCG tubes during high heat load resulted in overcooling by subsequent evaporation during low heat load periods [12]. Selective tubing placement and other innovations have resulted in a garment that weighs 45% less than the Shuttle LCG [13], yet performs better under certain conditions [14].

A new LCG was developed on the CSAFE contract with the intent of improved thermal and tactile comfort by using new advanced materials technology and a custom water loop design that allows for improved heat transfer and mobility for the subject. The CSAFE EEU LCG is a prototype two-piece (shirt and pants) design with 28 equal length tubes (14 on shirt and 14 on pants), totaling 250 feet, sandwiched in between two knit commercial-off-the-shelf (COTS) garments. The EEU LCG was tested in identical conditions with the EMU LCG and produced essentially equivalent performance in multiple subject trials with target metabolic rates as high as 2200 BTU/hr [15].

The EEU LCG was also tested in a shirt-only configuration to evaluate the performance of an auxiliary thermal loop concept. The current EMU PLSS relies on a secondary oxygen system to provide ventilation cooling in the case of a cooling or primary system failure. This reliance requires larger/higher pressure secondary oxygen tanks than necessary based on oxygen consumption alone. The in-development exploration PLSS instead relies on a completely redundant auxiliary liquid cooling loop, including an auxiliary LCG loop integrated into the primary LCG. This auxiliary LCG concept was evaluated with a shirt-only LCG configuration and showed favorable results [15].

Figure 2: EMU LCG (left), OSS LCG (center) with redundant loop (right)

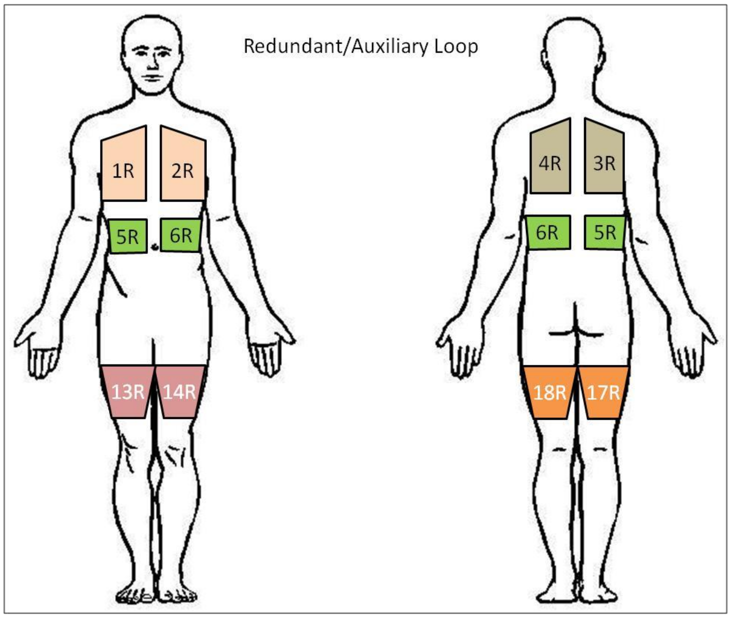
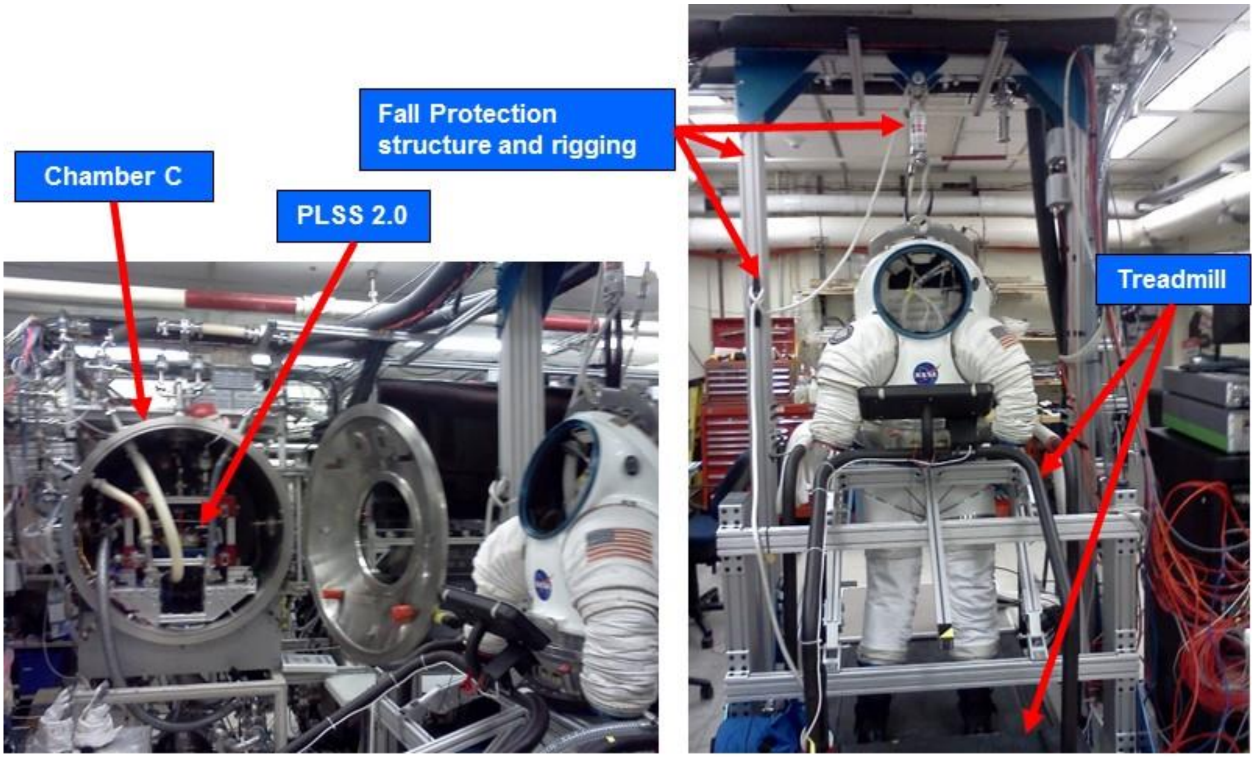


Figure 3: OSS LCG redundant loop design scheme showing regions of auxiliary loop.

In this study the EMU LCG performance was compared to a fully integrated redundant loop LC, developed by Oceaneering Space Systems (OSS) and called the OSS LCG. The primary OSS LCG garment is based on the EEU prototype design but also incorporated a set of co-parallel tubes, the auxiliary LCG (Aux LCG), in the torso and the upper thigh area, fixed adjacent to primary tubes (Figures 2 and 3). These new comparison tests are fundamentally different from the previous study because the integrated redundant loops may impact the compliance of the garment system and thereby reduce the overall heat transfer coefficient (UA) of the each of the loops. Accordingly a series of test were conducted as a part of the PLSS 2.0 HITL to measure the UAs of the EMU LCG, OSS LCG and the Aux LCG to determine if redundant loop concept can meet the metabolic rate demand required for an exploration EVA.

II. Methods

Integrated PLSS 2.0/HITL testing was conducted in the PLSS Development Laboratory, Rooms 2005 and 2006, Building 7, NASA-Johnson Space Center from October 27 to December 18, 2014. The PLSS 2.0 system was mounted, front side down into Chamber C which was at ambient pressure for the HITL, with the vacuum dependent Rapid Cycle Amine (RCA), Spacesuit Water Membrane Evaporator (SWME) and Mini-Membrane Evaporator (Mini-ME) systems ported to vacuum sources (Figure 4). The Mini-ME consisted of two half-size systems connected in parallel to provide the full-size Mini-ME requirement of 1000 Btu/hr. The coolant system was operated at ambient pressure, 14.7 psi. The ventilation system and Mark III were operated at 4.3 psi above ambient. Test subjects performed metabolic challenges on a treadmill equipped with a fall arrest stand (Figure 4). The stand was equipped with a waist bearing capture ring to allow subjects to rest between metabolic challenges in an upright position with the treamill static.



a) PLSS 2.0, Chamber C, and Mark III b) Mark III, Treadmill, and Fall Protection

Figure 4: EMU LCG (left), OSS LCG (center) with redundant loop (right)

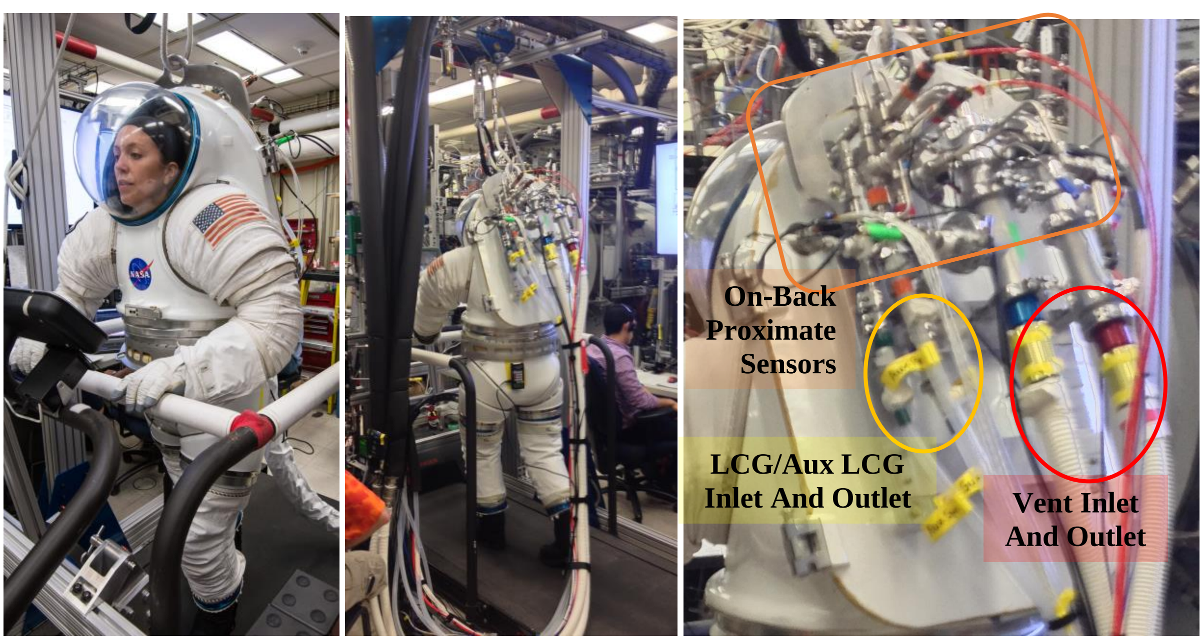


Figure 5. Test subject at work (left), Up-and-over coolant/vent/sensor umbilical (center), hatch plate closeup (right)

A. Instrumentation

Because PLSS 2.0 was not mounted on-back but within Chamber C, the coolant and ventilation tubes were routed from the chamber in a bundle up and over the Fall Arrest Stand to the back plate pass throughs. Accordingly, the temperature sensitive fluid stream measurements related to the UA determination, were obtained as close as possible to the test subject, specifically on the hatch of the Mark III suit (Figure 5). A list of key instrumentation is presented in Table 1.

Table 1. Key Instrumentation

Description	Sensor	Type	Make/Vendor	Model	Uncertainty
13 Skin Temperature Sensors	T1-T13	Thermistor	GE	MA100GG103A	0.09 deg F
Core Themperature Recorder	Core Temp	RS232	CorTemp	HT150016	0.18 deg F
Core Themperature	Core Temp	Pill	CorTemp	HT150002	0.18 deg F
CO2 Concentration, Suit, Inlet/Outlet	CO2-2006/-2026	NDIR	LiCor	Li840A	<1.5% of reading
Vent Flow Meter	Flow Meter		Teledyne Hastings	HFM-D-301	0.90%
Relative Humidity, Suit, Inlet/Outlet	Relative Humidity		Humicap/Vaisala	HMT338	1% RH
Vent Temperature, Suit, Inlet/Outlet	TS-840/TS-841	Type T T/C	Omega	TMQin-125U-6	1 deg F
Coolant Temperature, Suit, Inlet/Outlet	TS-720/TS-701	RTD, 1k ohm	Omega	P-M-1/10-1/4-6-0-P-15	0.1 deg F
Coolant Flow, Suit, Inlet	FS-722	Coriolis	MicroMotion	CMF025M319N8BAEZZZ	0.05%
Aux.-Coolant Temperature, Aux-LCG, Inlet/Outlet	TS-910/TS-901	RTD, 1k ohm	Omega	P-M-1/10-1/4-6-0-P-15	0.1 deg F
Aux.-Coolant Flow, Suit, Inlet	FS-903	Coriolis	MicroMotion	CMF025M319N8BAEZZZ	0.05%

Core temperature was assessed by a core temperature pill and recorder. The subjects were instructed to take the pill 2 hours before the scheduled beginning of the test. The recorder was located on the back side of the pelvic section of the Mark III. A total of 13 skin temperature thermistors were applied to the skin of the test subjects using 3M Transpore® surgical tape. Twelve of the thermistors are located underneath the LCG for UA determination these were grouped in pairs that were spaced at half-widths of the local tube spacing, ranging from 7mm to 13mm depending on location, and oriented in parallel with the direction of the tubing runs, which varied for each LCG type. The location of the six UA doublet thermistors are left abdomen, left bicep, left forearm, right thigh, right calf and right back (Figure 6). One forehead skin thermistor was also placed (not used for UA). This doublet system was used to average the skin temperature under the LCG, and helped to reduce uncertainty that there would be bias of distribution of singlet thermistors directly under tube compared to other tests where they might be disproportionately in-between tubes.

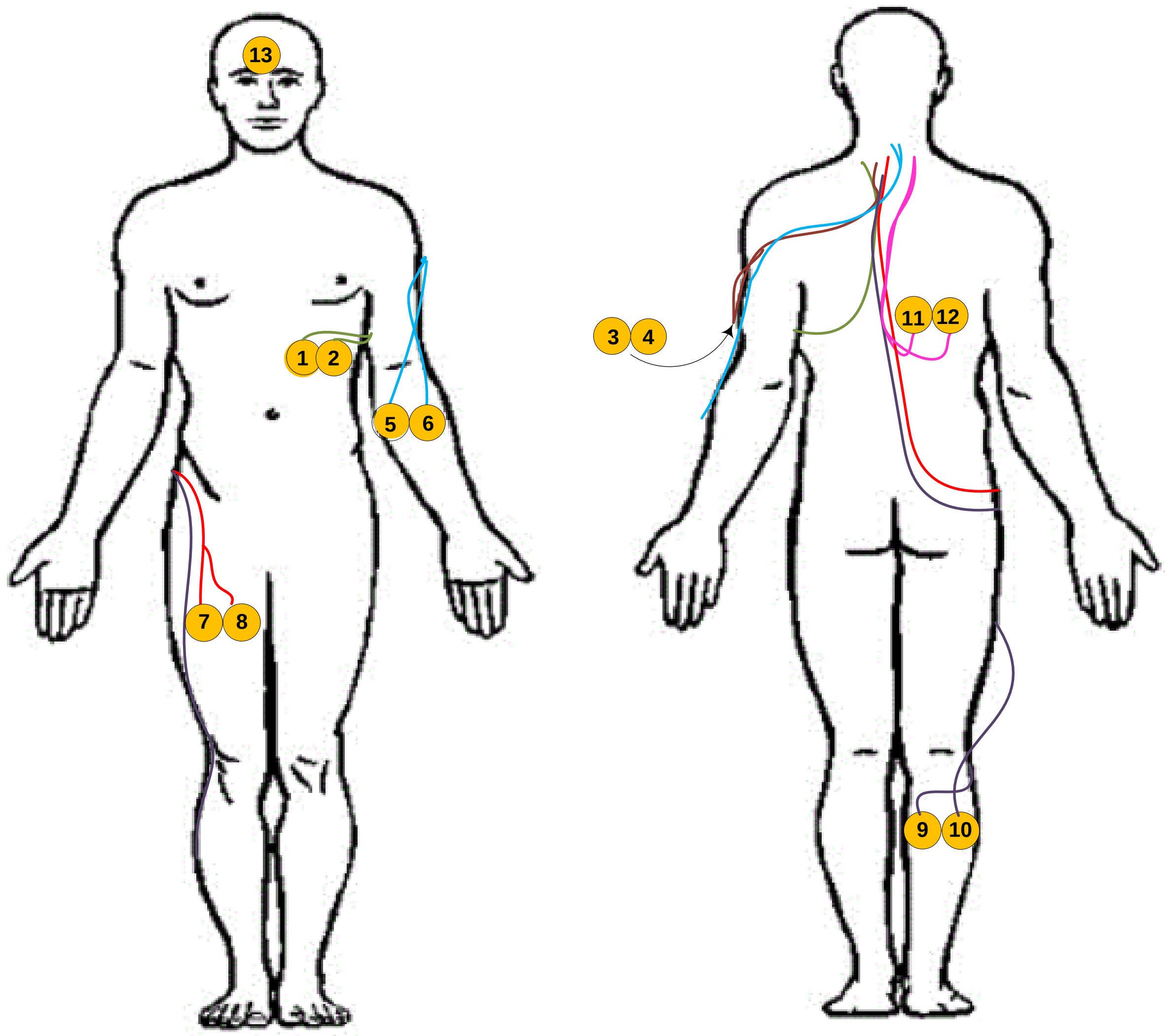


Figure 6. Skin temperature location for UA determination (1-12) and 1 forehead placement (13).

B. Determination of Key Parameters

The average skin temperature was taken as a area weighted average of the 13 skin temperature measurements from the following relation:

$$\overline{T}_{SKIN} = 0.26T_{13} + 0.06\overline{T}_{5,6} + 0.1\overline{T}_{3,4} + 0.17\overline{T}_{7,8} + 0.15\overline{T}_{9,10} + 0.26\left(0.45\overline{T}_{1,2} + 0.55\overline{T}_{11,12}\right) \quad (1)$$

where $\overline{T}_{SKIN}$ is the average skin temperature of the test subject, and the seven terms on the right are, in order, location 13—the forehead skin temperature distributed to all uncovered areas of the skin, the head, neck, hands and feet, location 5,6 average—left forearm temperatures distributed to both lower arms, location 3,4 average--left bicep temperatures distributed to both upper arms, location 7,8 average—right thigh temperatures distributed to both upper legs, location 9,10—right calf temperatures distributed to both lower legs, location 1,2 average—left abdomen temperatures distributed to front torso and location 11,12 average—right back temperatures distributed to back torso. This relation was used to determine the average body temperature for each test subject (TS) from the relation:

$$\overline{T}_{TS} = 0.2\overline{T}_{SKIN} + 0.8T_{CORE} \quad (2)$$

where T_{CORE} is the body core temperature from temperature pill. Another similar skin temperature average uses all but the forehead skin temperature, for the purposes of determining the average skin temperature under the LCG:

$$\overline{T}_{SKIN,UA} = 0.081\overline{T}_{5,6} + 0.135\overline{T}_{3,4} + 0.23\overline{T}_{7,8} + 0.203\overline{T}_{9,10} + 0.351\left(0.45\overline{T}_{1,2} + 0.55\overline{T}_{11,12}\right) \quad (3)$$

where the area distributions are normalized to the LCG total area.

The relation for the overall heat transfer coefficient follows from an energy balance of internal flow system with constant surface temperature[16]:

$$q_{conv} = \overline{h} A_s \Delta T_{lm} \quad (4)$$

where ΔT_{lm} is the log mean temperature difference:

$$\Delta T_{lm} \equiv \frac{\Delta T_o - \Delta T_i}{\ln\left(\Delta T_o - \Delta T_i\right)} \quad (5)$$

and $\overline{h}$ is the average convection coefficient, A_s is the area of the constant temperature surface--the product of these terms is the overall heat transfer coefficient UA:

$$\mathrm{UA} \equiv \overline{h} A_s \quad (6)$$

For the UA of the LCG, q_{conv} is the heat transfer to the LCG which was determined from:

$$q_{LCG} = \dot{m} c_p \left(T_{LCG,out} - T_{LCG,in}\right) \text{ (Btu/hr)} \quad (7)$$

Where $\dot{m}$ is the mass flow of the LCG (lb/hr), c_p is the specific heat of water (1 Btu/lb-°F) and the bracketed term is the rise in LCG coolant temperature (°F) from the LCG inlet to the outlet, as measured in test. Applying Equations (3)-(7) for the case of a human wearing an LCG and rearranging terms to solve for UA, the result is:

$$UA_{LCG} = \dot{m} c_p \ln\left(\frac{T_{SKIN,UA} - T_{LCG,in}}{T_{SKIN,UA} - T_{LCG,out}}\right) \text{ (Btu/hr-°F)} \quad (8)$$

The carbon dioxide (CO_2) concentration was measured at the inlet and outlet legs of the vent loop. The difference between the two stream, together with the vent flow measurement, was used to deterning the instantaneous CO_2 production rate (lbm/hr). This was used to estimate the oxygen (O_2) consumption rate using the following [17]:

$$\dot{m}_{O_2,consumed} = \frac{\dot{m}_{CO_2,prod}\left(\frac{32.0}{44.0}\right)}{R_{resp}} \text{ (lbm/hr)} \quad (9)$$

where 32.0/44.0 is the ratio of the molecular weights of O_2 to CO_2 and R_{resp} is the respiratory quotient assumed to be 0.9. The resulting instantaneous metabolic rate was determined from the following relation [17]:

$$q_{MR} = \frac{\dot{m}_{O_2,consumed}}{2.0265x10^{-4} - 4.5055x10^{-5} R_{resp}} \text{ (Btu/hr)} \quad (10)$$

The measured q_{MR} was influenced by the lag effect of the circulating vent volume. This was noticeable especially with the RCA system cycled. While instantaneous q_{MR} is displayed on plots, averages over intervals of interest, encompassing multiple RCA cycles to reduce lag transients when interpreting results.

Body heat storage (Btu) was determined instantaneously for each test subject from body core and skin temperatures of using the following equation:

$$E_{TS} = m_{TS}\bar{c}_{p,TS}\bar{T}_{TS} \text{ (Btu)} \tag{11}$$

where E_{TS} is the test subject enthalpy (Btu), m is the mass (lbm), $\bar{c}_{p,TS}$ is the average specific heat (0.839 Btu/lbm-°F) and $\bar{T}_{TS}$ is the average body temperature (°F) per Equation (20). An average heat storage value, $\bar{E}_{TS}$, was determined for every second using the previous 90 measurements and subsequent 90 measurents, and was used in determining the instantaneous storage rate:

$$q_{STOR} = \frac{\bar{E}_{TS}(t_i) - \bar{E}_{TS}(t_{i-1})}{t_i - t_{i-1}} \text{ (Btu/hr)} \tag{12}$$

where $(t_i - t_{i-1})$ is the sampling interval in hours.

The vent latent heat was determined from relative humidity, temperature measurements at the inlet and outlet, and vent flow to the Mark III and converted to water vapor mass production rates:

$$q_{LATENT} = (\dot{m}_{H2O,out} - \dot{m}_{H2O,in})h_{fg} \text{ (Btu/hr)} \tag{13}$$

where q_{LATENT} is the latent heat rate (Btu/hr) and h_{fg} is the latent heat of fusion for water (1048 Btu/lbm).

The total test subject heat rate, q_{TOT} (Btu/hr) was determined instantaneously for performance plots:

$$q_{TOT} = q_{LCG} + q_{STOR} + q_{LATENT} \text{ (BTU/hr)} \tag{14}$$

where the right side terms are as defined in Equations (7), (12) and (13). Vent sensible was negligible because of the long tube runs from PLSS 2.0 and the Mark III that resulted in only small temperature differences amounting to about 10 Btu/hr or less. Heat loads leaving the suit through radiation and convection were also assessed using an infrared camera. Tests showed good agreement (~3 °F) with the scoped targets of the suit and adjacent thermocouple readings. There was little difference (~3 °F) between the test facility air temperature and the external parts of the suit. Therefore radiation and convective heat leak out of the system was deemed negligible. Metabolic rate measured in test, and assumed to be heat generated within the control volume of the suit, but instead ending up as work done on the environment, was also considered. The only outlet for such work was deemed to be on the suit bearings. The IR camera showed some slight heating in localized regions of the bearings, but this was also determined not to be significant [18]. The heat balance of the system was assessed by averaging the metabolic rate, q_{MR}, and the total test subject heat rate, q_{TOT}, over the entire test duration.

C. Metabolic Rate Profiles

Three metabolic rate profiles, "High," "Low," and "Aux," each 120 minutes in length, were devised to test different aspects of the PLSS 2.0, and were all useful for UA and LCG evaluations (Figures 7, 8, and 9, respectively).

The High metabolic profile has four metabolic challenge segments, 1600 Btu/hr, 3000 Btu/hr, 1200 Btu/h and 2200 Btu/hr each lasting 15-20 minutes, with 5-10 minute rest intervals of 500 Btu/hr between the challenge segments. The average target metrate for this profile is 1400 Btu/hr (Figure 7).

The Low metabolic profile is primarily to test for control of comfort with flow control that is tested with a 10 minute 1600 Btu/hr segment that steps down to a 30 minute 800 Btu/hr segment, and then down again to 20 minutes at 500 Btu/hr. A second test is a 1200 Btu/hr 30 minute segment followed by a 25 minute 500 Btu/hr segment. The average target metrate for this profile is 840 Btu/hr (Figure 8).

The Auxiliary profile, or Aux profile (Figure 9) begins with a low metabolic rate conditioning profile (blue lines) with the full garment, to simulate a transition to the Aux cooling system after 1-hour of EVA. The nominal EVA portion is set to a low metabolic rate to prevent sweat accumulation on the garment that might improve the Aux LCG performance. The last hour of the profile (red lines) begins with a transition to the Aux system, and has three 1400 Btu/hr of 17, 17 and 12 minutes in length, separated by two 500 Btu/hr rest periods of 7 minutes each. This targets an averge metabolic challenge of 1190 Btu/hr for 1 hour.

D. Test Matrix

The test consisted of 19 planned subject trials, with 3 of these be terminated early for hardware and data acquisition issues. There were six subjects 5 males and 1 female, between 22 and 35 years of age, weighing between 145 and 175 lbm with body surface areas ranging between 1.78 m^2 and 2.0 m^2. A fit check test and dry run was performed with each of the subjects. All subjects were deemed be a good fit with the EMU LCG. Two sizes of the OSS LCG were provided, and the smallest subject was determined to be a better fit in the small size while the rest were other subjects wore the larger size. Table 2 is a matrix of the 19 test days, indicating the LCG test (EMU, OSS or Aux), test subject (S1-S6), metabolic profile (High, Low or Aux), and LCG target inlet temperature (53 °F, 50 °F or uncontrolled for Aux). Four major areas of interest were planned for the test data represented by the four "Data Usage" columns: 1) Compare the performance of the OSS LCG to the EMU LCG, 2) determine the sensitivity of UA on small changes in supply temperature, 3) determine if the 3000 Btu/hr challenge of the High profile improves the subsequent performance of the LCG's through residual sweat accumulation, and 4) prove out the concept of the redundant garment for the Auxiliary cooling system. Comparisons within a column are denoted in green and amber shades, for example the EMU LCG (green) is the counterpoint to the OSS LCG (amber), or the 53 °F

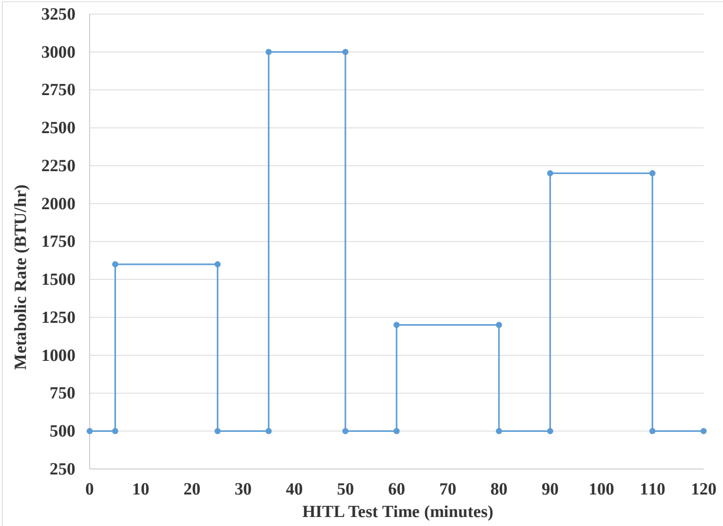


Figure 7. High Metabolic Profile

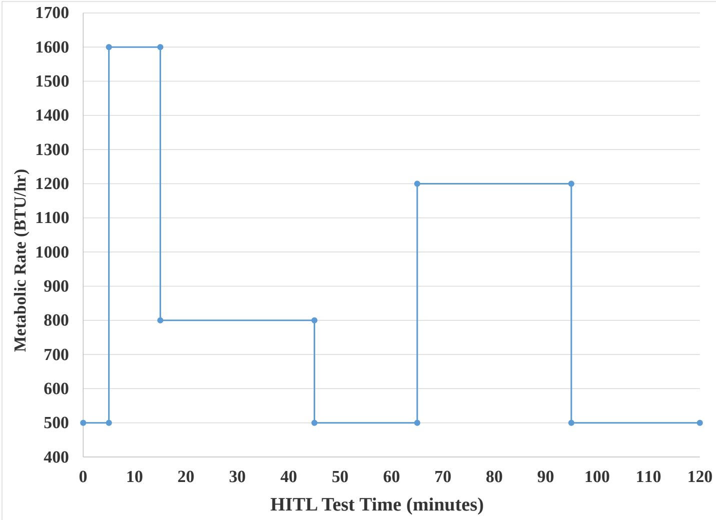


Figure 8. Low Metabolic Profile

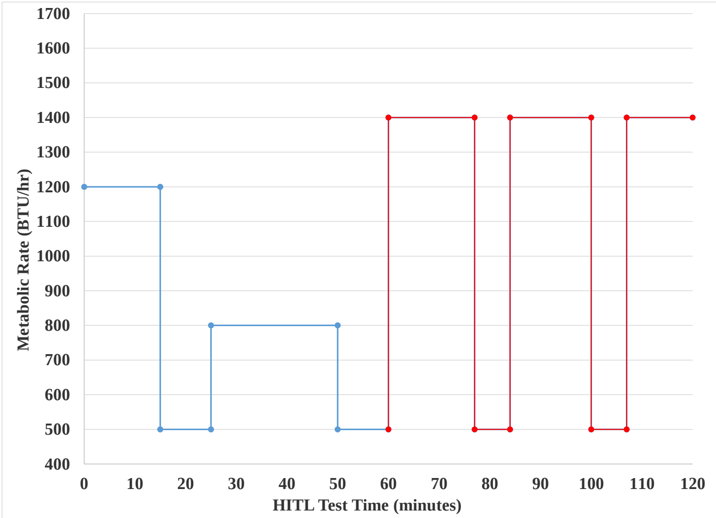


Figure 9. Auxiliary Metabolic Profile with 60 minutes conditioning

target inlet temperature subject trials (green) are the comparison trials to the 50 °F target inlet temperature subject trials (amber). Many of the subject trials were used for more than on purpose.

Table 3. Test Day Matrix

							Data Usage			
Test Date (2014)	**Day #**	**LCG**	**Test Subject**	**Metabolic Profile**	**LCG Target Inlet Temp (°F)**	**Not used**	**EMU/OSS LCG Comparisons**	**Effect of Inlet Temperature**	**Lag Effect of High Metrate**	**Auxilary Thermal System**
10/27	1	EMU	S1	High	53	x				
10/28	**2**	EMU	S2	High	53		x	x		
10/30	**3**	EMU	S1	High	53		x	x		
10/31	**4**	EMU	S2	High	53		x	x		
11/05	**5**	EMU	S3	High	53		x	x		
11/06	**6**	EMU	S5	High	50		x	x	x	
11/10	**7**	EMU	S4	High	50		x	x	x	
11/12	**8**	EMU	S6	High	50		x	x	x	
11/14	**9**	EMU	S3	Low	50				x	
11/17	**10**	EMU	S5	Low	50				x	
11/19	**11**	EMU	S4	Low	50				x	
11/20	**12**	EMU	S6	Low	50				x	
11/24	**13**	OSS	S2	High	50		x	x		
11/25	14	OSS	S4	High	50	x				
12/09	15	OSS	S6	High	50	x				
12/11	**16**	Aux	S3	Aux	N/A					x
12/15	**17**	Aux	S6	Aux	N/A					x
12/17	**18**	Aux	S1	Aux	N/A					x
12/18	**19**	OSS	S2	High	53		x	x		

III. Results

A. Comparison of the OSS LCG and the EMU LCG

Table 4 show the UA's for each of the High profile metabolic rate targets. With exception of the Day 3 trial for the 1600 MR target, the OSS LCG slightly underperformed the EMU LCG UA's in all other test points. Note that the Day 2, Day 4 and Day 19 are the same subject, so the differences cannot be ascribed to be due to subject differences. The actual metabolic rates (under the MR columns) are all within 200 Btu/hr of the target metabolic rates except the 3000 Btu/hr target for Day 3 that was limit by heart rate according to test protocol. A summary of key parameters taken over the complete High metabolic profile of the five subject trials under consideration for the LCG comparison are listed in Table 5. With exception of the Day 5 S3 trial, all other trials had full LCG flow rates. Day 5's S3 was the smallest subject, at 145 lbm with the other subjects all between 170 lbm and 175 lbm, and has less muscle mass. Even though the metabolic rates were proportionally

Table 4. OSS/EMU LCG Comparison of UAs (Btu/hr-°F) for High metabolic rate profile targets (Btu/hr) with 53 °F LCG inlet temperature

Day	TS	LCG	1600		3000		1200		2200	
			UA	MR	UA	MR	UA	MR	UA	MR
2	S2	EMU	45.78	1410	58.72	2938	53.44	1210	63.89	2199
4	S2	EMU	45.37	1480	55.21	3068	47.23	1161	57.71	2152
19	S2	OSS	43.13	1512	49.86	3208	45.80	1272	53.66	2221
3	S1	EMU	42.59	1612	53.44	2411	46.65	1091	58.67	2082
5	S3	EMU	53.13	1521	70.04	2854	66.49	1146	81.07	2165

Table 5. OSS/EMU LCG Key parameters for High profile trials with 53 °F LCG inlet temperature

Day	TS	LCG	LCG Flow (lbm/hr)	Tin,LCG (°F)	Tout,LCG (°F)	Tskin,LCG (°F)	UA (Btu/lbm-°F)	LCG Heat (Btu/hr)	Max LCG Heat (Btu/hr)	TS Total Heat Rate (Btu/hr)	MR (Btu/hr)	Starting Core (°F)	Ending Core (°F)	DT Core (°F)	Mean Core (°F)	Energy Balance Δ %
2	S2	EMU	186.05	53.27	59.25	77.84	52.10	1112	1487	1286	1263	99.05	99.31	0.26	98.94	-1.8
4	S2	EMU	184.74	52.94	58.87	78.75	48.26	1241	1467	1260	1325	99.4	99.41	0.01	98.77	5.0
19	S2	OSS	193.27	53.31	58.69	77.84	48.14	1064	1277	1202	1279	99.48	99.69	0.21	99.36	6.0
3	S1	EMU	185.73	53.20	59.00	79.20	47.02	1077	1487	1237	1258	100.3	99.94	-0.36	99.80	1.71
5	S3	EMU	132.23	54.52	62.09	78.13	48.85	957	1566	1198	1173	97.89	97.8	-0.09	97.90	-2.1

higher, S3's higher surface area to mass ratio may have resulted in higher UA's during the target MR's and maintain low core temperatures relative to the other subjects, and therefore had to reduce flow rate. The test series average UA's for the five trials were within a narrow range. Core temperatures were maintain within acceptable bounds for all subjects. By this measure, in this challenging High profile, it is clear that the OSS LCG met the requirements of the test in the same way as the EMU LCG. It cannot be concluded that the presence of the redundant loop has had a dramatic effect on the performance of the primary loop.

The energy balance for all five subjects is within bounds of the accuracy of the instrumentation (last column of Table 5, ranging from -1.8 to 6 %. Another way to explain this is that the test subject's significant modes of heat rejection and storage by the test subjects, the TS Qtot in Equation (14) was roughly equal to the heat generation rate, the average metabolic rate. What was apparent in most of the subject trials is that when the two terms were expressed as a running average (the blue and red dashed lines in Figure 10), that initially there was not good agreement. As the trials approached completion the Δ% of the energy balance got smaller. This may be due to a lag effect in the core temperature measurement relative to the metabolic rate measurement. The core temperature pill being in the upper GI tract has more lag in warming than the CO2 production in response to increase metabolic rate.

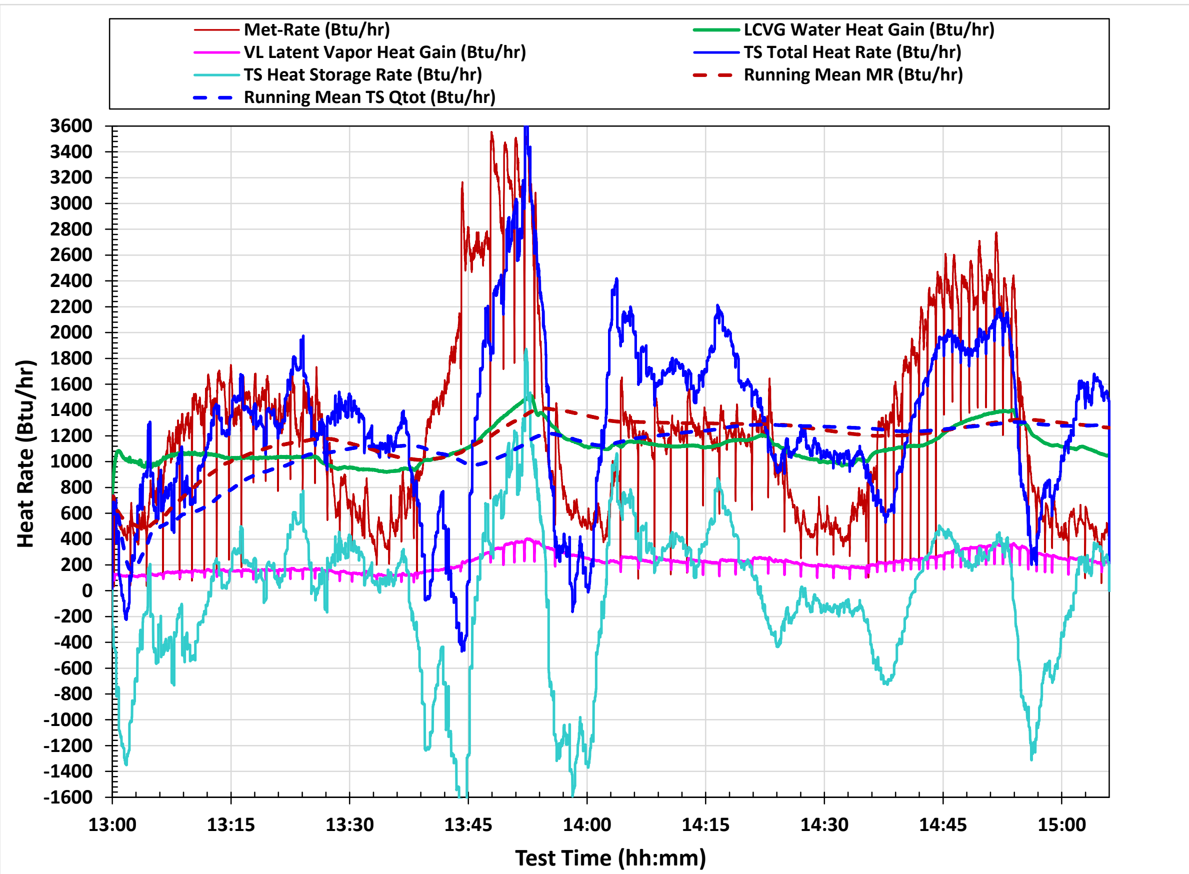


Figure 10. Test Subject Heat Balance Parameters, Day 2, S2, High Profile, 53 °F LCG Inlet Target

S3 in particular, had less Δ% energy balance Δ% over the entire course of the trials compared to the other subjects. This may be due to smaller muscle mass and more rapid turnover of blood return to the core from the muscles in response to increased metabolic rate.

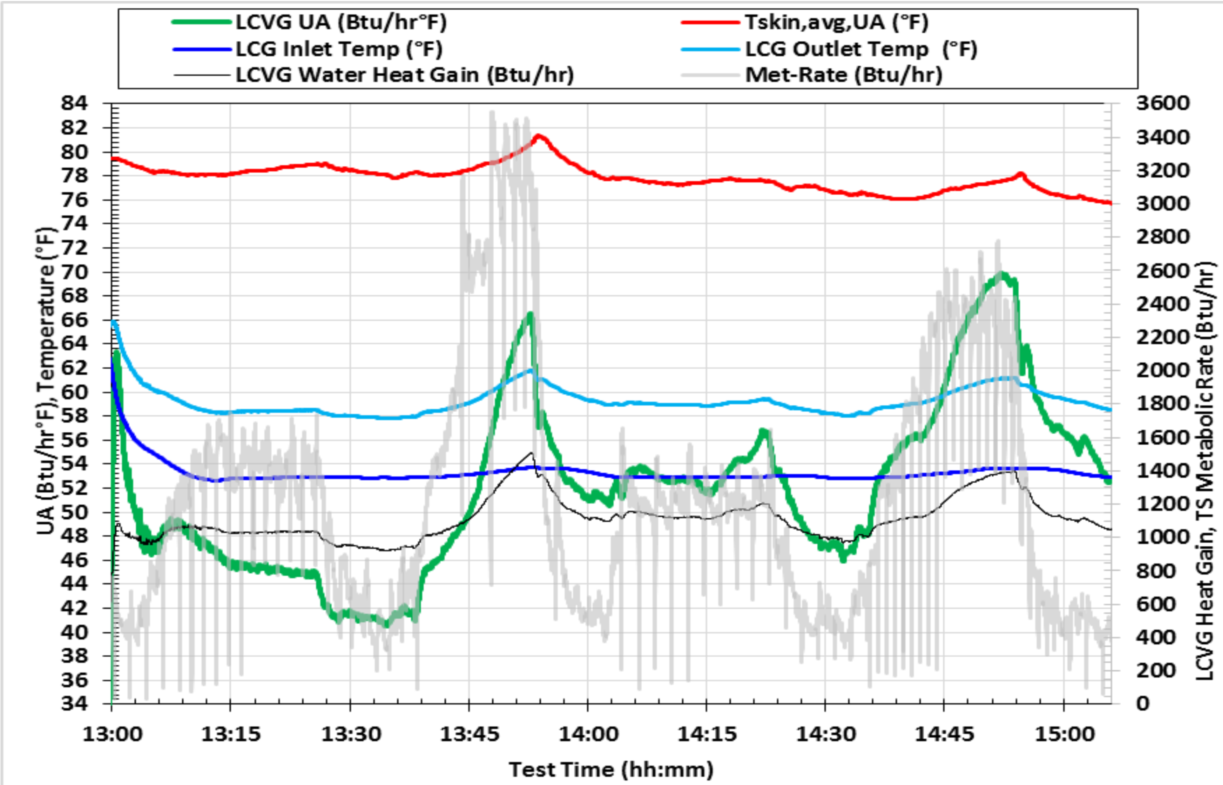


Figure 11. Transient UA parameters, Day 2, S2, High Profile, 53 °F LCG Inlet Target

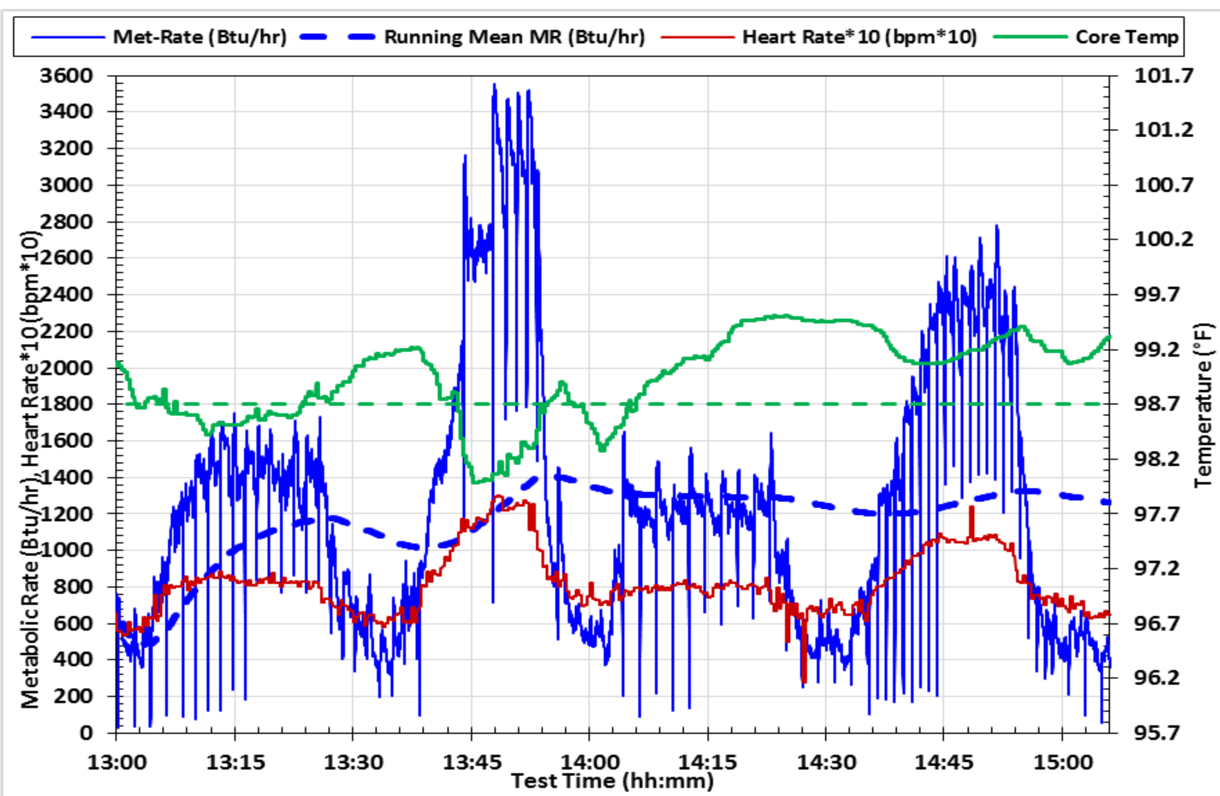


Figure 12. Test subject critical parameters

A transient TS profile shows the instantaneous UA calculated in response to the metabolic rate, skin temperature under the LCG and the LCG inlet and outlet temperatures and resulting heat gain by LCG (Figure 11). The spikes on the metabolic rate profile shows the lag response of vent stream flow to the CO_2 sensors with the RCA swing bed cycles owing to the large circulating volume in the test configuration. For the 1600 Btu/hr and 1200 Btu/hr metabolic rate segments the UA has steadied out. This is reflected by the LCG temperatures and heat gain, and the LCG skin temperatures. At the higher metabolic rate challenges of 3000 Btu/hr and 2200 Btu/hr, the UA is sharply increasing, a reflection of the relative constancy of the LCG inlet temperature relative to the outlet temperature and underlying skin temperature. It is clear that the UA's would continue to rise if the high metrates were sustained. The 10 min rest segments following the high metrates do not show complete recovery of the UA and the underlying parameters. The transient LCG response characteristics noted for Day 2 (Figure 11) are typical for all the subjects. In contrast to the responsiveness of the UA to increases in metrates, the core temp pill response lags by about 10 to 15 minutes (Figure 12). The lag is reflected in the running mean for TS Qtot relative to that of the metabolic rate (Figure 10). The lag responses are largely dampened out by the end of the 2 hour trial.

A second series of tests was performed with both the EMU LCG and the OSS LCG that were done at slightly lower LCG inlet temperatures. The Day 13, S2 trial with the OSS LCG differed in the High profile by increasing the 3000 Btu/hr profile from 15 to 30 minutes. In this series the OSS LCG performance for the non-resting portions of the High profile are within the high and low trials for the EMU LCG for each metrate (Table 6). When key parameter are compared for the entire profile the OSS LCG performance is indistinguishable from that of the EMU LCG. The metrate average for OSS LCG trial was significantly higher than the EMU LCG trials, but this was mainly due to the extra 15 minutes at 3000 Btu/hr. When adjusted to account for the longer peak interval, the average was reduced to 1295 Btu/hr. The mean core temperatures of all subjects showed that core temperature was well regulated in spite of the challenging profile (Table 7).

Table 6. OSS/EMU LCG comparison of UAs (Btu/hr-°F) for High metabolic rate profile targets (Btu/hr) with 50 °F LCG inlet temperature

Day	TS	LCG	1600		3000		1200		2200	
			UA	MR	UA	MR	UA	MR	UA	MR
6	S5	EMU	52.94	1758	61.11	2852	55.69	1181	64.13	2029
7	S4	EMU	44.09	1587	48.58	2630	44.35	1166	52.17	2105
8	S6	EMU	51.08	836	65.32	1673	46.63	1218	50.92	2197
13	S2	OSS	44.16	1613	55.25	3116	55.57	1217	59.66	2332

Table 7. OSS/EMU LCG key parameters for High profile trials with 50 °F LCG inlet temperature

Day	TS	LCG	LCG Flow (lbm/hr)	Tin,LCG (°F)	Tout,LCG (°F)	Tskin,LCG (°F)	UA (Btu/lbm-°F)	LCG Heat (Btu/hr)	Max LCG Heat (Btu/hr)	TS Total Heat Rate (Btu/hr)	MR (Btu/hr)	Starting Core (°F)	Ending Core (°F)	DT Core (°F)	Mean Core (°F)	Energy Balance Δ %
6	S5	EMU	189.57	51.44	57.81	76.55	52.65	1217	2768	1301	1253	99.79	99.34	-0.45	99.57	-3.8
7	S4	EMU	200.44	48.89	54.15	75.29	44.46	1069	1320	1183	1166	98.77	98.41	-0.36	98.41	-1.4
8	S6	EMU	178.29	49.28	55.78	76.42	45.17	1073	1383	1182	1144	99.63	99.14	0.26	99.37	-3.3
13	S2	OSS	181.27	51.04	57.43	76.45	52.01	1190	1690	1349	1498	98.39	98.89	0.5	98.66	10.0

When the trials from both the 53 °F LCG inlet temperature and 50 °F LCG inlet temperature series are averaged and compared by LCG type similar results are obtained (Table 8). From these comparisons it can be said that both LCG types met the high metabolic rate demands of the High profile. The presence of a redundant loop on the OSS LCG has not diminished the primary loop performance. To prove a significant differents between the two LCG types, more subject trial would need to be performed.

Table 8. OSS/EMU LCG UA averages for High profile trials (Btu/hr-F)

LCG	1600	3000	1200	2200	High Profile
EMU	47.9 ± 3.9	58.9 ± 5.6	51.5 ± 6.0	61.2 ± 7.3	48.4 ± 2.4
OSS	43.6 ± 0.5	52.6 ± 2.7	50.7 ± 4.9	56.7 ± 3.0	50.1 ± 1.9

B. Effect of LCG Inlet Temperature

Day 1-5 trials with the EMU LCG were conducted with the SWME outlet temperature setpoint at 50 °F. Because of the long tube lengths between the PLSS 2.0 and the suited subject, the temperature had warmed to ~53 °F. To see if the slightly higher than intended inlet

Table 9. LCG UA averages (Btu/hr-°F) for High profile trials at different inlet temepratures

LCG Inlet T	1600	3000	1200	2200	High Profile
53 °F	46.0 ± 2.9	57.5 ± 5.5	51.9 ± 6.4	63.0 ± 7.6	48.9 ± 1.3
50 °F	49.4 ± 3.5	58.3 ± 6.5	48.9 ± 4.5	55.7 ± 5.6	48.6 ± 3.8

coolant temperature was an important limiting effect on high metabolic rate LCG performance, as had been suggested by previous analysis [10], the setpoint of the SWME was reduced to 47 °F for all but the last trial. With such a small diffence in inlet LCG coolant temperature in the two cases, it is not surprising that there is no significant difference between the two cases (Table 9). With a limited number of subject trials, to show an impact on LCG performance the inlet temperature difference would need to be larger.

C. Comparison of High and Low metabolic rate profiles

The current baseline LCG thermal control advanced PLSS is flow modulation with constant temperature. This offers advantages for the PLSS avionics providing a constant temperature environment, but also confers advantages to the crew. For example, if a crew member is performing a low metabolic task in a cold environment, zero LCG flow could be chosen, similar to the LCG bypass in ISS EMU. The LCG and underlying skin temperatures would tend to warm up during this task and during subsequent higher metrate activity an increase in flow would result in very high transient UA spikes that aid in cooling. If the PLSS and its heat generating avionics is allowed to float warmer during a temperature control scheme, then additional lag will occur with cooling demand as the PLSS mass adds stored heat to the coolant. The pure flow control results in a thermal system that is pre-cooled to the target level producing no on-back mass thermal inertia to overcome. The High profiles trials presented in the Sections A and B of the Results in this paper were almost exclusively run at full flow. This was chosen by the test subjects because of the thermal demands of the High profile. Therefore as part of the plan of the test, in order to assess the feasibility of pure flow control for thermal comfort, a series of trials using the Low metabolic profile (Figure 8) were conducted. An example of the flow control response is shown in the next three plots (Figures 13-15). The Low profile generates a small imbalance between the running mean metabolic rate and the running mean Qtot, the test subject heat storage and heat rejection, that only occurs with the 1600 Btu/hr metrate at the beginning (compare the blue and pink dashed lines in Figure 13). Thereafter there is good balance. Aside from the initial jump to 1600 Btu/hr, the transient UA, and related parmeters are more stable than with the High profile (compare Figure 14 to Figure 11). Core temperature is well regulated (see Figure 15). This was typical of all four of the subject trials. Subjective thermal responses from the four test subject ranged from "3" (slightly cool) to "5" (slightly warm) on a 7 point comfort scale.

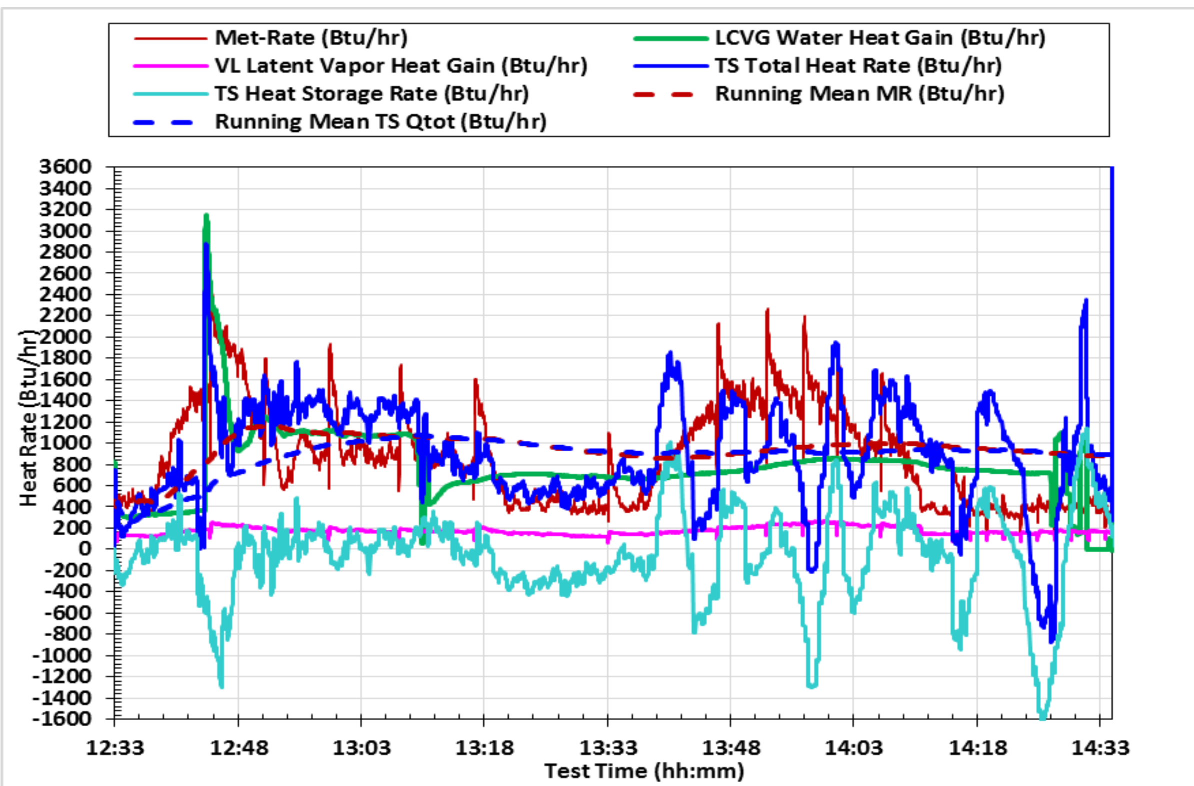


Figure 13. Test Subject Heat Balance Parameters, Day 12, S6, Low Profile

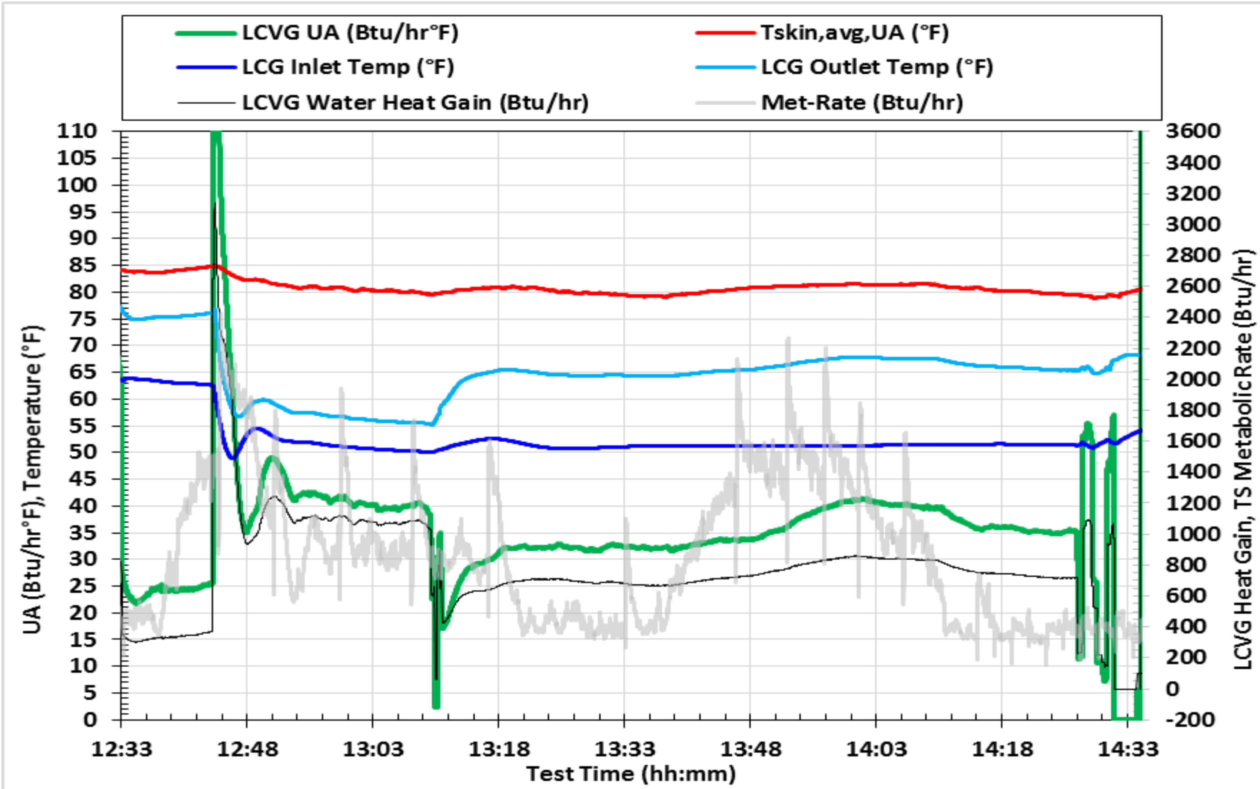


Figure 14. Transient UA parameters, Day 12, S6, Low profile

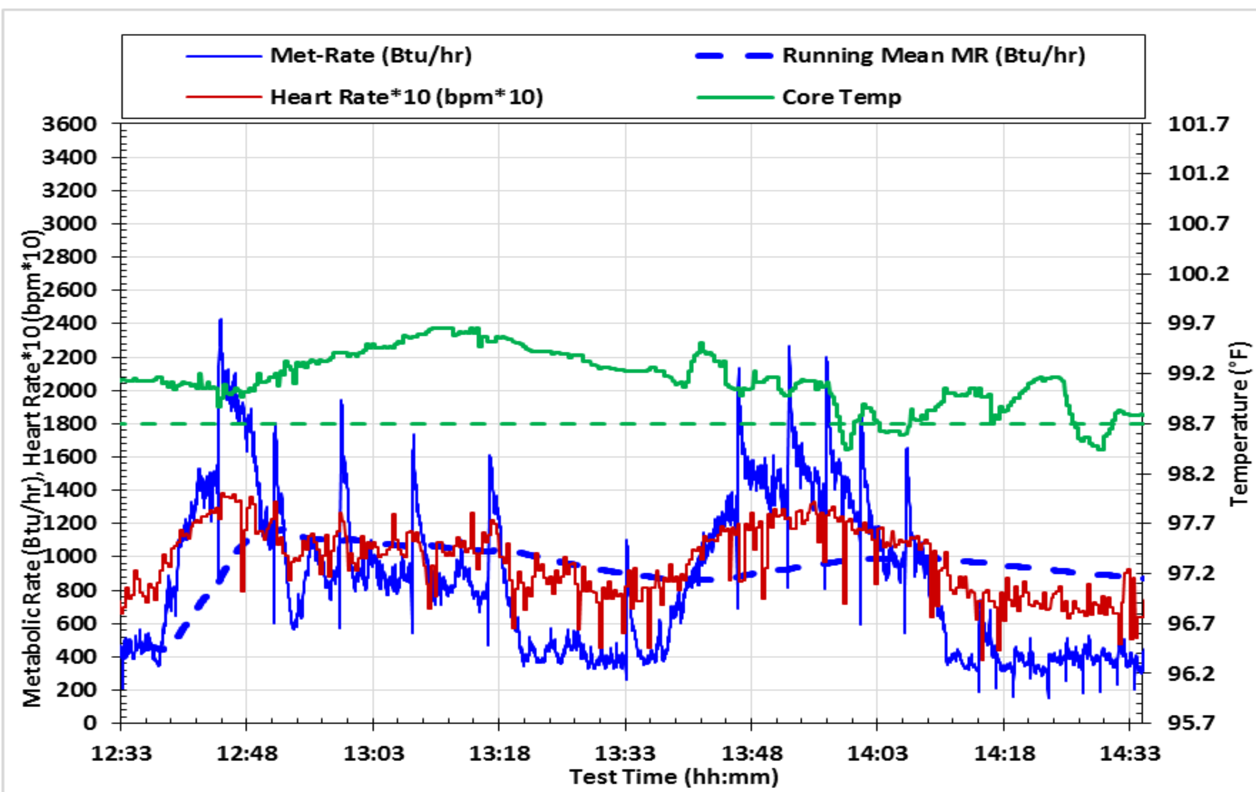


Figure 15. Critical test subject parmeters, Day 12, S6, Low profile

Table 10. Low profile subject UA (Btu/hr-°F), metabolic rate (Btu/hr) and LCG Flow (lbm/hr)

Day	TS	1600			800			1200			Low Profile		
		UA	MR	LCG Flow	UA	MR	LCG Flow	UA	MR	LCG Flow	UA	MR	LCG Flow
9	S3	59.25	1718	108	33.62	1001	39	59.82	1283	159	28.43	862	60
10	S5	48.66	1616	199	44.14	1045	157	53.95	1235	154	42.99	873	120
11	S4	44.14	1582	200	35.69	842	107	43.66	1423	116	36.82	809	121
12	S6	54.43	1885	199	36.39	967	154	38.03	1350	51	35.36	874	80

Flow rates varied considerably among the four subjects, within each metabolic rate and for the overall trial (Table 10). Core temperatures were well controlled, with means ranging from 98.29 °F to 99.71.

UA's in the Low profile tended to be proportional to metabolic rate whereas in the High profile UA's tended to be higher following the 3000 Btu/hr challenge. This was most noticeable in the 2200 Btu/hr challenge at the end of the High profile (Table 11). In eight of the nine High profile trials the TS average UA of the 2200 Btu/hr segment exceeded that of the 3000 Btu/hr segment. A warm up effect is probably involved, as the onset of exercise moves increases the blood volume in the muscles. Residual sweat accumulation occurring during the rest after the 3000 Btu/hr activity may also increase the thermal contact between the skin and the LCG tubes in the subsequent 2200 Btu/hr activity.

Table 11. UA (Btu/hr-°F) Lag effect for 2200 Btu/hr test point following 3000 Btu/hr test point

Day	TS	LCG	3000	2200
			UA	UA
2	S2	EMU	58.72	63.89
4	S2	EMU	55.21	57.71
19	S2	OSS	49.86	53.66
3	S1	EMU	53.44	58.67
5	S3	EMU	70.04	81.07
6	S5	EMU	61.11	64.13
7	S4	EMU	48.58	52.17
8	S6	EMU	65.32	50.92
13	S2	OSS	55.25	59.66
		mean	57.50	60.21

D. Auxiliary LCG Performance

Three subjects tested the Aux LCG following the Aux profile which is subdivided into two one-hour segments (Figure 16): A conditioning period of moderate metabolic rate using the primary loop, followed by

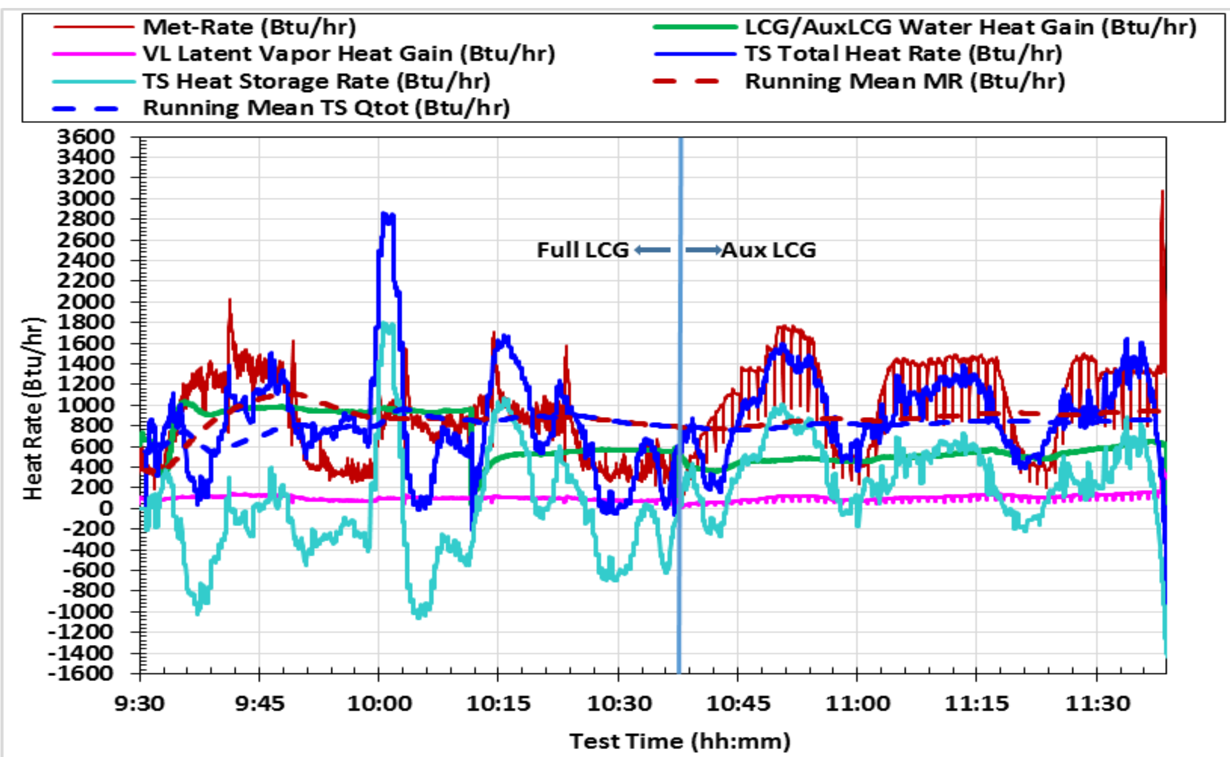


Figure 16. Critical test subject parameters, Day 18, S1, Aux profile

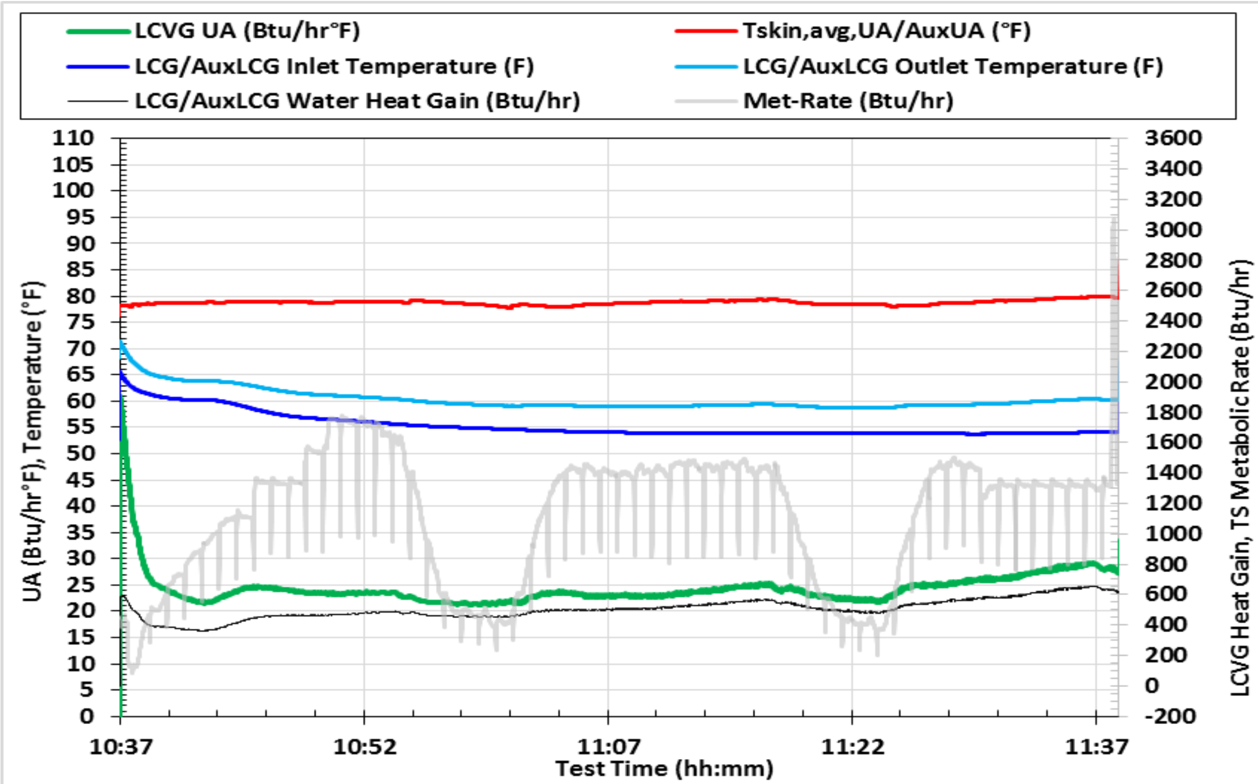


Figure 17. Transient UA parameters, Day 18, S1, Aux profile

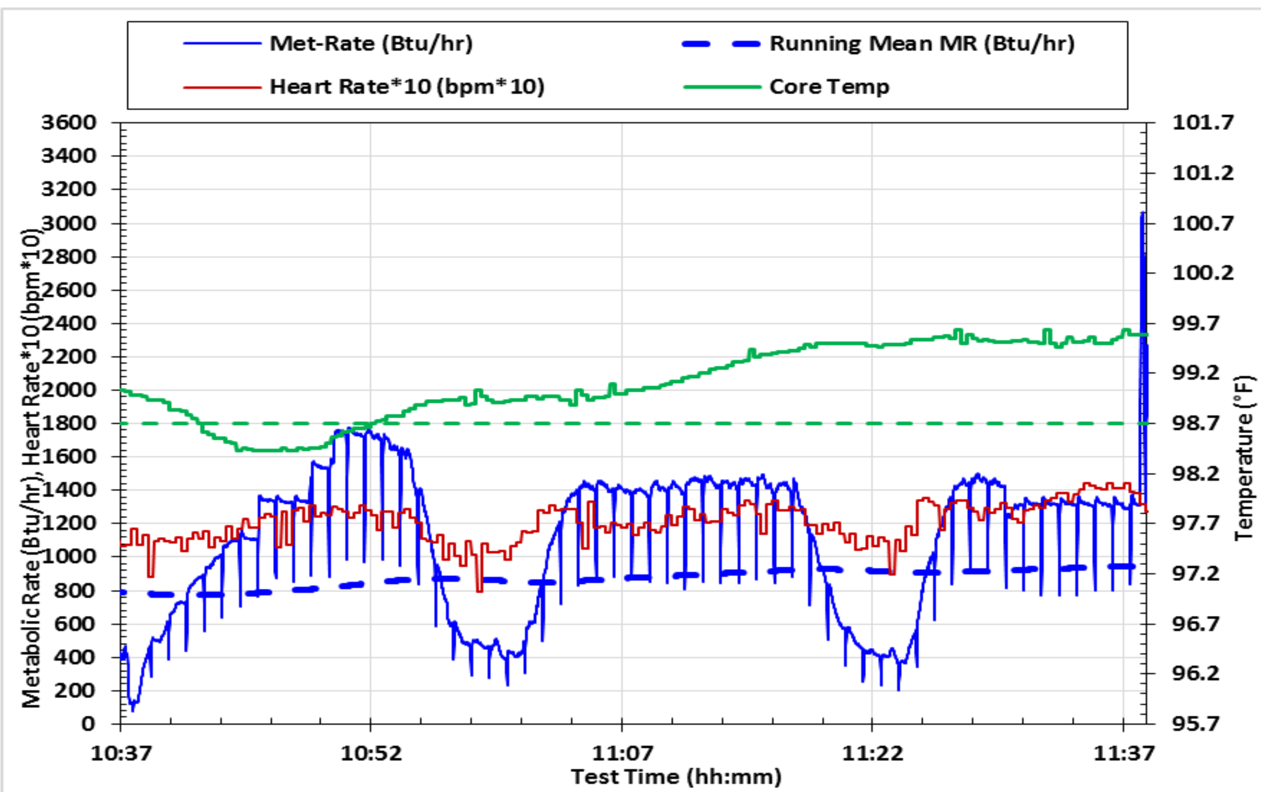


Figure 18. Critical test subject parameters, Day 18, S1, Aux profile

Table 12. Aux LCG key parameters for Aux profile trials

Day	TS	LCG	LCG Flow (lbm/hr)	Tin,LCG (°F)	Tout,LCG (°F)	Tskin,LCG (°F)	UA (Btu/lbm-°F)	LCG Heat (Btu/hr)	Max LCG Heat (Btu/hr)	TS Total Heat Rate (Btu/hr)	MR (Btu/hr)	Starting Core (°F)	Ending Core (°F)	DT Core (°F)	Mean Core (°F)	Energy Balance Δ %
16	S3	Aux.	100.98	68.38	72.13	81.60	23.95	522	631	970	1077	99.87	100.24	1.02	100.06	9.9
17	S6	Aux.	102.07	57.77	63.50	82.83	26.53	585	705	1048	1121	99.29	100.31	1.02	99.85	6.6
18	S1	Aux.	101.98	55.39	60.34	78.78	24.40	514	654	938	1121	99.02	99.59	0.57	99.11	16.3

a transition to the Aux loop. The requirement for the Aux thermal system is to support an average metabolic rate of 1200 Btu/hr for a period of 30 minutes while maintaining the core temperature below 100.5 °F. In these trials, each of the test subjects exhausted the auxiliary feedwater system. At the end of the trials the metabolic rates and core temperature requirements were met, and the duration requirements were exceeded the requirement by 100%. Figure 17 shows that the start the Aux portion of the trial the Aux LCG temperatures were slightly elevated, between the underlying skin temperatures and the adjacent, now stagnant, primary LCG loop temperatures. The auxiliary cooling system, the Mini-Membrane Evaporator, or Mini-ME, brought the Aux LCG temperature down while increasing the UA. At the end of the trial, the Aux LCG heat gain had reach a maximum heat gain of 631 Btu/hr (Table 12). Figure 18 shows that the core temperature is essentially ever increasing. The peak core temperature of the three trials was 100.31. The average UAs was about 25 Btu/lbm-°F. These tests proved that the redundant loop concept is viable for both primary and auxiliary loop.

IV. Conclusions

The OSS LCG with redundant loops was compared to the EMU LCG in multiple trials in the Mark III suit pressurized to 4.3 psi over ambient and a performing treadmill exercise protocol for 2-hours at a metabolic rate that averaged 1400 Btu/hr, and included a 15 minute 3000 Btu/hr segment and a 20 minute 2200 segment. The SWME in the PLSS 2.0 system, provided cooling at the specified flowrates and temperatures during the protocol. Both the OSS LCG and EMU LCG were able to support the test subjects during these metabolic challenges while keeping core tempertures well regulated. Heat generated, stored and rejected by the test subjects were shown to balance within the bounds of the instrumentation uncertainty. The UA's of the two garment were essentially equivalent for each of the metrate challenges and for the overall profile. The test showed that the redundant loop in the OSS LCG did not interfere with the heat transfer to the primary loop.

Conversely, the auxiliary loop exceeded its requirements and proved out the redundant loop concept.

Flow control was used throughout the subject trials. A low metabolic profile was also tested with multiple subjects and was shown to be adequate for maintaining comfort with variable low metabolic rates.

The redundant loop concept with pure flow control should be tested further in on-back PLSS chamber tests in the future.

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