

Thermal Performance Testing of EMU and CSAFE Liquid Cooling Garments

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Future exploration missions require the development of a new liquid cooling garment (LCG) to support the next generation extravehicular activity (EVA) suit system. The new LCG must offer greater system reliability, optimal thermal performance as required by mission directive, and meet other design requirements including improved tactile comfort. To advance the development of a future LCG, a thermal performance test was conducted to evaluate: (1) the comparable thermal performance of the EMU LCG and the CSAFE developed engineering evaluation unit (EEU) LCG, (2) the effect of the thermal comfort undergarment (TCU) on the EMU LCG tactile and thermal comfort, and (3) the performance of a torso or upper body only LCG shirt to evaluate a proposed auxiliary loop.

To evaluate the thermal performance of each configuration, a metabolic test was conducted using the Demonstrator Spacesuit to create a relevant test environment. Three (3) male test subjects of similar height and weight walked on a treadmill at various speeds to produce three different metabolic loads - resting (300-600 BTU/hr), walking at a slow pace (1200 BTU/hr), and walking at a brisk pace (2200 BTU/hr). Each subject participated in five tests - two wearing the CSAFE full LCG, one wearing the EMU LCG without TCUs, one wearing the EMU LCG with TCUs, and one with the CSAFE shirt-only. During the test, performance data for the breathing air and cooling water systems and subject specific data was collected to define the thermal performance of the configurations.

The test results show that the CSAFE EEU LCG and EMU LCG with TCU had comparable performance. The testing also showed that an auxiliary loop LCG, sized similarly to the shirt-only configuration, should provide adequate cooling for contingency scenarios. Finally, the testing showed that the TCU did not significantly hinder LCG heat transfer, and may prove to be acceptable for future suit use with additional analysis and testing.

Nomenclature

acfm	=	actual cubic feet per minute
BTU	=	british thermal unit
COTS	=	commercial-off-the-shelf
CO ₂	=	carbon dioxide
CSAFE	=	Constellation Suit Accommodations for Exploration
CSSS	=	Constellation Space Suit System
EEU	=	engineering evaluation unit
EMU	=	extravehicular mobility unit
EVA	=	extravehicular activity
EVA	=	ethylvinyl acetate
LCG	=	liquid cooling garment
LCVG	=	liquid cooling and ventilation garment
Met Rate	=	metabolic rate

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NASA = National Aeronautics and Space Administration
 O_2 = oxygen
 PLSS = portable life support system
 psi = pounds per square inch
 psid = pounds per square inch differential
 Q_{LCG} = total sensible heat transferred to the LCG
 q_{LCG} = sensible heat transfer rate to the LCG
 Q_{AIR} = total sensible heat transferred to the ventilation air flow
 q_{AIR} = sensible heat transfer rate to the ventilation air flow
 Q_{SWEAT} = latent heat transfer through moisture evaporation
 $q_{SWEAT-RAT}$ = latent heat transfer rate through moisture evaporation
 Q_{MET} = metabolic heat generated
 q_{MET} = metabolic rate
 Q_{STOR} = heat stored by the body
 $q_{STOR-RAT}$ = heat storage rate
 Q_{TOTAL} = total heat rejected
 RQ = respiratory quotient
 SMC = suit multiple connector
 SSA = space suit assembly
 SSC = suit support cart
 TCU = thermal comfort undergarment
 UA = overall heat transfer coefficient
 WHTM = Wissler Human Thermal Model

I. Introduction

This paper discusses a test that was conducted to evaluate the performance of various liquid cooling garment (LCG) configurations. The test was designed to evaluate three aspects of the LCGs: (1) the thermal performance of a CSAFE developed engineering evaluation unit (EEU) LCG compared to the extravehicular mobility unit (EMU) LCG configuration, (2) the effect of the thermal comfort undergarment (TCU) on the thermal performance of the EMU LCG, and (3) the performance of a torso or shirt-only LCG, intended to advance the design of an LCG with an auxiliary thermal loop.

The primary function of a Spacesuit LCG or liquid cooling and *ventilation* garment (LCVG) is to regulate core body temperature by removing metabolic heat. Metabolic heat is removed predominately by three mechanisms: sensible heat transfer to the LCG, latent heat transfer to the ventilation system, and the transfer of heat through the suit to the external environment. The LCG works with the physiological heat transfer mechanisms of sweat rate and blood flow to regulate the core body temperature. Thermal performance of the garments was tested by tracking the energy removed by the garment, by the ventilation system, and the body stored heat at various metabolic rates.

The current flight EMU LCVG (Figure 1, left) has 48 equal lengths of 1/16" EVA tubing, totaling approximately 255 feet for the "-05" size used in this test, passed through a two layer garment. The LCVG has an integrated vent tree and is commonly worn with TCUs underneath. Water is typically passed through the LCVG at 240 lb/hr and a typical temperature range of 40 °F to 90 °F. For this test the ventilation tree was removed from the LCVG and the LCG was tested with and without TCUs. TCUs are often worn underneath the EMU LCVG for tactile comfort, thermal comfort in cold environments, and to reduce biocontamination of the LCGs. However, the TCUs also reduce the heat transfer coefficient (UA) between the skin and the LCG.

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 (Figure 1, right) 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.



Figure 1: EMU LCG (left) and CSAFE EEU LCG (right) Configurations

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 a yet to be developed LCG. This test evaluates one concept of the auxiliary LCG, in which the additional auxiliary tubing is integrated into only the torso of the LCG.

II. Test Methodology

This evaluation included three test subjects – all male of similar age, stature, anthropometric profile and fitness level. Each was asked to prepare for the test by eating the same dinner of his choice the night before each test day as well as the same breakfast of his choice the day of the test. Testing occurred in mornings to make it easier for subjects to arrive at the test with adequate rest. These requirements ensured a reasonably consistent pre-test metabolic scenario for each individual.

Four LCG configurations were tested. The testing was conducted in a randomized order to reduce any order based factors. The first configuration was the CSAFE EEU LCG design which included a shirt and pants, each subject tested this configuration twice, to obtain a greater quantity of data for the new design. The second configuration was the CSAFE LCG EEU - shirt only. The third configuration was the EMU LCG without TCUs. The fourth configuration tested was the EMU LCG with TCUs. The TCUs used were Class 3 Patagonia Capilene 1.

The test matrix is shown in Table 1. The 5 x 3 matrix results in 15 data points.

Table 1: Test Matrix

Subject 1 EEU Shirt and Pants Run 1	Subject 1 EEU Shirt and Pants Run 2	Subject 1 EEU Shirt Only	Subject 1 EEU EMU LCVG w/ TCU	Subject 1 EMU LCVG w/o TCU
Subject 2 EEU Shirt and Pants Run 1	Subject 2 EEU Shirt and Pants Run 2	Subject 2 EEU Shirt Only	Subject 2 EEU EMU LCVG w/ TCU	Subject 2 EMU LCVG w/o TCU
Subject 3 EEU Shirt and Pants Run 1	Subject 3 EEU Shirt and Pants Run 2	Subject 3 EEU Shirt Only	Subject 3 EEU EMU LCVG w/ TCU	Subject 3 EMU LCVG w/o TCU

Data were collected at rest and two constant metabolic rates (Met Rates). The resting rate occurred with subjects at rest in a seated position at an estimated 300-600 BTU/hr metabolic rate. The low and medium rates were

achieved by subjects walking on a treadmill at approximately 1200 BTU/hr Met Rate and 2200 BTU/hr Met Rate, respectively. These rates were reached by varying the treadmill walking speed per individual requirements. On the Step 1-2 and Step 2-3 transitions, the timer began for the step once the subjects were within a few 100 BTU/hr of the target metabolic rate. All test subjects received the same predetermined cooling water flow rate (100 lbs/hr) and temperature (65°F) for each metabolic rate. This temperature and flow rate was chosen to stress the capabilities of the LCG and differentiate between the configurations. The temperature and flow rate also reduced the number of variables and simplified some aspects of the data analysis. Each metabolic cycle for each LCG configuration was a step-up and step-down test as shown in Figure 2. The duration of each step is shown in the figure. Room conditions were that of a typical laboratory environment.

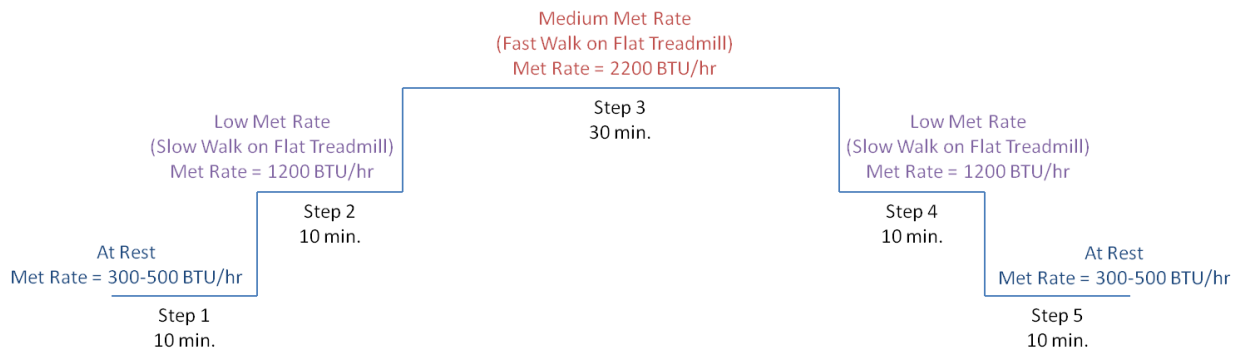


Figure 2: Metabolic Profile

A. Test Support Equipment

The Demonstrator Spacesuit was built by David Clark Company Incorporated for launch entry and abort, and contingency EVA operations. The bladder is a Gore-Tex tri-laminate which is moisture vapor permeable. The suit was built to be a mobile launch, entry, and abort suit at pressure and includes upper arm bearings, cable assisted shoulder and waist/hip, and convoluted elbows and knees. This suit was operated during this test with a bubble helmet and continuous gas flow of 6 acfm at vent pressure (≤ 0.8 psid). Flow is through an EMU style bubble helmet and out through the vent tree and the torso of the suit. Gloves were not worn for this test to allow pass through of the skin thermocouples and use of an OxyWatch. Wrist dams were used to enable most of the gas to return to the Suit Support Cart for analysis.

The suit support cart (SSC) provided breathing air and cooling water to the suit/LCG during testing. The SSC breathing air source was compressed, dry breathing air from a gas cylinder manifold. The SSC also provided a data acquisition system to record the following data:

1. Gas (Breathing Air):

- Flow Rate (acfm)
- Inlet and Outlet Pressure (psi)
- Inlet and Outlet Temperature (°F)
- Delta Pressure (psid)
- Inlet or Outlet % oxygen (O₂)
- Inlet or Outlet % cabondioxide (CO₂)
- Outlet % Humidity

2. Cooling Water:

- Flow Rate (lbm/hr)
- Outlet Pressure (psi)
- Delta Pressure (psid)
- Inlet and Outlet Temperature (°F)

3. Additional Performance Parameters:

- Thermocouple skin temperature data (°F)

- CorTemp Pill Data (°F)

The SSC maintained the water operating pressure (~12 psid), the water inlet temperature (65°F), and the water flow rate (100 lbs/hr) for each LCG. It also maintained the gas flow rate (6.0 acfm), the suit pressure (vent < 0.8 psid), the inlet gas temperature (50°F – 60°F), and the inlet composition (grade D breathing air).

Core temperature pills allowed for monitoring of the test termination criterion. According to ASTM 2300F-10 "Standard Test Method for Measuring the Performance of Personal Cooling Systems Using Physiological Testing" the acceptable core temperature range for human testing is minus 1°C (1.8°F) to plus 2°C (3.6°F) of the test subject's baseline core temperature reading.¹ The core temperature pill has an accuracy of ± 0.1°C.

The test subject's skin temperature was monitored and recorded using four Class 1 type T thermocouples positioned on the right side of the subject's body in four body locations – chest, bicep, thigh, and calf. The skin temperature sensors had an accuracy of ± 0.5°C.

The test subject's heart rate was monitored using a COTS Choicemmed OxyWatch W11 Pulse Oximeter. The unit was worn on the test subject's left wrist with a finger clip attached to their middle or ring finger tip. This device was worn outside the wrist dam and monitored real time by the suit tech.

An F80 Sole treadmill was used to exercise the subjects and elevate their metabolic rates.

B. Test Subject Data

The following data were recorded for each test subject:

- Test Subject Number
- Gender
- Age
- Height
- Weight (Pre-test nude, Post-test nude, & Pre- and Post-test Ancillary Equipment)
- Shoe Size
- Fitness Activity Level as provided to clinic during test subject physical
- Suit Sizing Adjustment Settings
- Preferred Ancillary Gear
- In-Suit Comfort Preferences such as boot inserts, moleskin, etc.
- 85% of Maximum Heart Rate (used as a test termination criteria)
- Baseline Core Temperature Reading (recorded each test day – also used for test termination)

The focus of the subjective comfort data was on thermal comfort, LCG next-to-skin comfort and LCG-to-suit integration comfort. The data collector asked comfort questions during each metabolic cycle in the test sequence. The Corlett & Bishop Discomfort Scale, shown in Figure 3, was used along with the body segment diagram to guide the test subject's response.

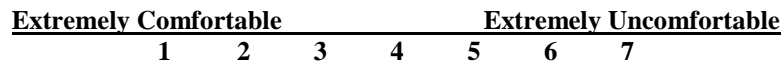


Figure 3: Corlett & Bishop Discomfort Scale

In addition to comfort comments, general comments made by Test Subjects, the Test Director, Data Collector and other observers were also recorded.

III. Results

Test subjects were selected based on three key attributes: (1) good suit fit, (2) similar stature and anthropometric profile, and (3) similar fitness level. However, there is still variability in suit fit and the amount of feedback the subjects provide. A large variation in response to LCG cooling even from individual to individual with similar physical characteristics, is known to exist, and the small number of test subject may not provide results that are representative of the entire population.

The metabolic rate (q_{MET}) calculations were made by measuring the % CO₂ out of the suit, the % O₂ into and out of the suit, and the total dry gas flow rate. The % CO₂ and the % O₂ change can both be used to calculate the metabolic rate using the Weir Equation.

The data collected are used to evaluate the suit heat balance and track the amount of heat removed by the key heat removal mechanisms. The key derived mechanisms are: the sensible heat removed by the LCG (q_{LCG}), the sensible heat removed by the air temperature change (q_{AIR}), the latent heat removed by moisture evaporation into the air (Q_{SWEAT}), and the heat stored in the body as measured by the core temperature and skin temperatures (Q_{STOR}).

The latent heat removed by moisture removal (Q_{SWEAT}), was measured by taking the difference between the pre-test subject nude weight, the post-test subject nude weight, and adding the moisture weight gain in the ancillary equipment.

In order to present an instantaneous heat balance throughout the test, Q_{SWEAT} was plotted as the latent heat rate (q_{SWEAT}) by linking the overall sweat loss to the air humidity out of the suit. Similarly, Q_{STOR} was continuously calculated based on the initial core temperature and a weighted average value of the skin temperatures², and the rate of change of Q_{STOR} , $q_{STOR-RAT}$ was used for the energy balance.

$$\begin{aligned}
 q_{LCG} &= \dot{m}_{H_2O} \cdot c_p \cdot \Delta T \\
 q_{AIR} &= \dot{m}_{AIR} \cdot c_p \cdot \Delta T \\
 Q_{SWEAT} &= m_{SWEAT} \cdot \Delta H_{vap} \\
 Q_{STOR} &= m_{Body} \cdot c_{p,Body} (0.2 \cdot \Delta T_{SKIN} + 0.8 \cdot \Delta T_{CORE}) \\
 q_{MET} &= 3.941 \frac{kcal}{lO_2} \cdot \dot{m}_{AIR} \cdot (\%O_2 In - \%O_2 Out) + 1.106 \frac{kcal}{lCO_2} * \dot{m}_{AIR} * \%CO_2 Out
 \end{aligned}$$

Due to the large quantity of data collected by the SSC for each test, it was necessary to reduce the raw data set. The sampling rate of the SSC was 10 samples/second. The data was averaged over 20 samples for a data rate of one per two seconds.

Additional processing, using a moving average, was used to minimize the noise produced in the $q_{STOR-RAT}$ and q_{MET} calculations as they were susceptible to very small changes in the associated measurements. Also, the core temperature data was fairly consistent, but due to infrequent loss of signal or movement of the pill within the body there were brief temperature movements, up or down approximately 0.5°F. These changes produced brief spikes or plateaus in the q_{STOR} data. Several speed changes on the treadmill were made during step 3 in order to maintain a fairly steady q_{MET} ; however, in some tests it proved easier than others to maintain a plateau. The durations of each step vary slightly between tests, as it took subjects varying amounts of time to reach the next metabolic rate.

The total heat removed from the system (Q_{TOTAL}) did not add up to the metabolic heat generation (Q_{MET}), and consistently showed a 400 - 600 BTU difference over the test period. The difference between Q_{MET} and Q_{TOTAL} is attributed to environmental loss and sensor uncertainty. This difference is consistent for all tests, allowing for a general comparison of the test configurations.

A. CSAFE EEU LCG

Figures 4-6 show representative results for the CSAFE EEU LCG configuration. Running each subject twice in this configuration has shown repeatability for the EEU LCG test setup. The testing shows that Q_{STOR} increases throughout step 3, with the $q_{STOR-RAT}$ peaking in the middle of step 3, and the total Q_{STOR} maxing out towards the end of step 3 (see Figure 3). The decrease $q_{STOR-RAT}$ is attributed to increased q_{LCG} and q_{SWEAT} . The maximum Q_{STOR} throughout this test, averaged across all test subjects for the CSAFE EEU test configuration was 249 BTUs.

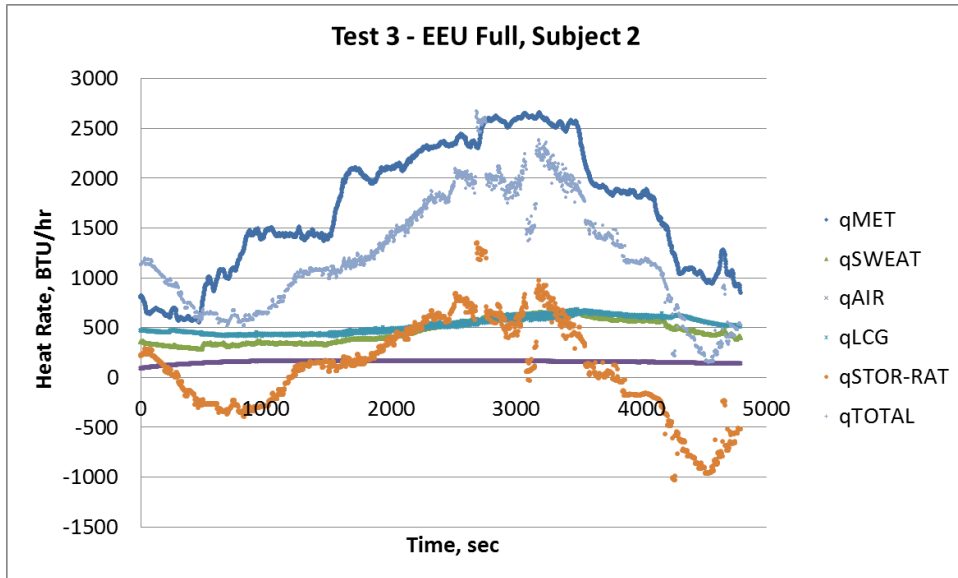


Figure 4: Energy balance for Test 3, EEU full configuration

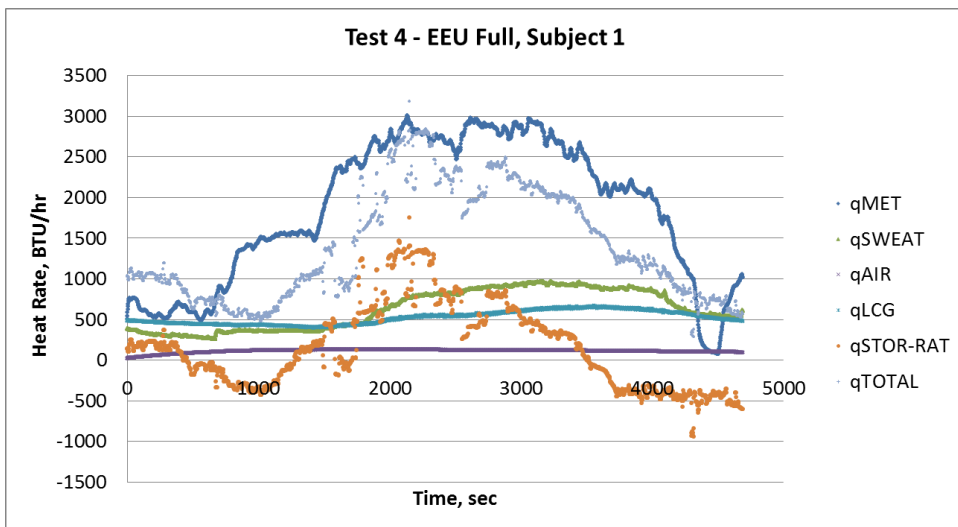


Figure 5: Energy balance for Test 4, EEU full configuration

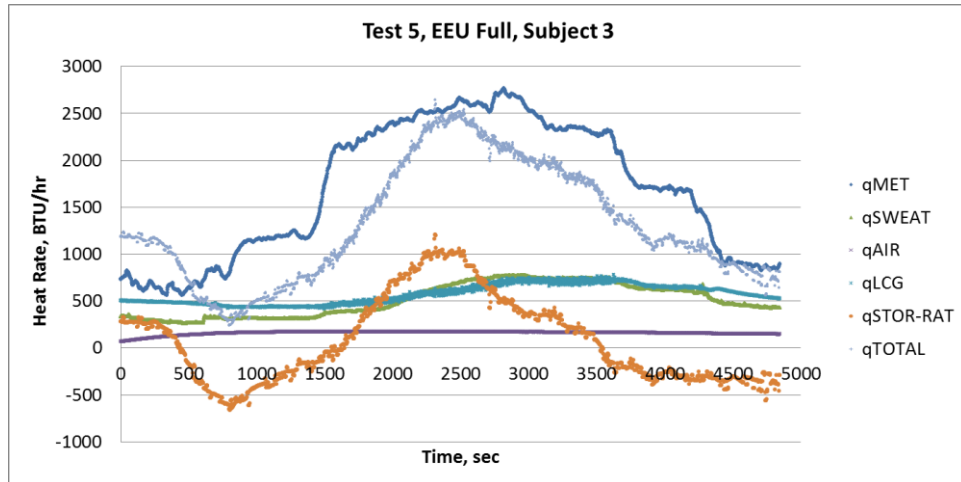


Figure 6: Energy balance for Test 5, EEU full configuration

B. CSAFE EEU Shirt Only

Figures 7 and 8 show representative results for the CSAFE EEU shirt-only configuration. The max %RH values for shirt only range from 85% to 90%, where the shirt and pants configuration is 70% to 75%. The leg temperatures, for the CSAFE shirt-only configuration, were typically higher than the upper body temperatures, where the inverse was true for the full EEU configuration testing. The maximum Q_{STOR} throughout this test, averaged across all test subjects for the EEU shirt-only tests, was 297 BTUs.

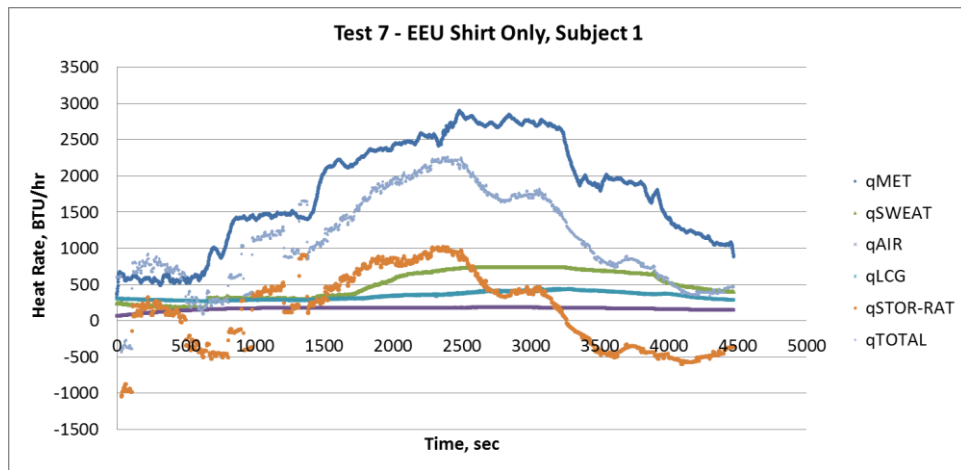


Figure 7: Energy balance for Test 7, EEU shirt-only configuration

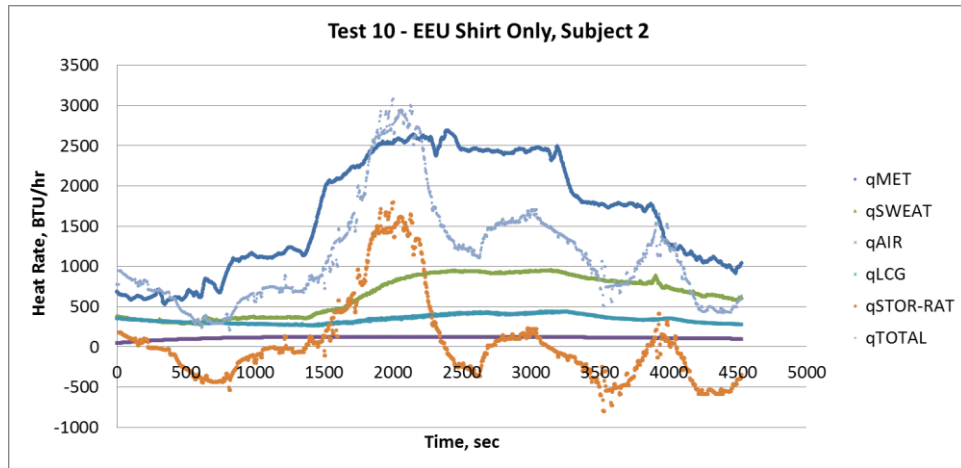


Figure 8: Energy balance for Test 10, EEU shirt-only configuration

C. EMU LCG with TCU

Figures 9 and 10 show representative results for the EMU LCG with TCU configuration. The maximum Q_{STOR} throughout this test, averaged across all test subjects for the three EMU LCG with TCU tests was 238 BTUs.

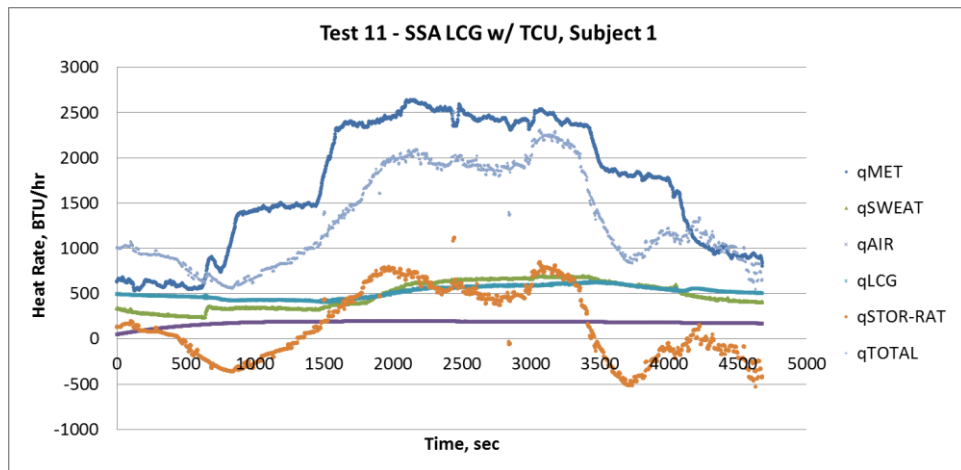


Figure 9: Energy balance for Test 11, EMU LCG with TCU configuration

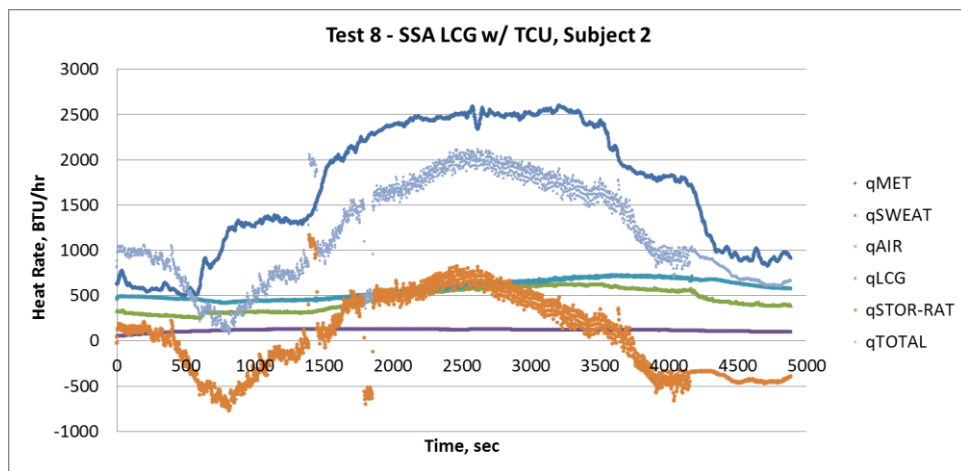


Figure 10: Energy balance for Test 8, EMU LCG with TCU configuration

D. EMU LCVG without TCU

Figures 11 and 12 show the results for the EMU LCG without TCU. Even though the Met Rate profiles were very similar, subject 1 (Figure 12) had relative humidity values similar to those for the EEU shirt-only configuration. While this configuration produced the highest maximum q_{LCG} , it also had the largest difference for max q_{LCG} across subjects, a difference of 128 BTU/hr. The maximum Q_{STOR} throughout this test, averaged across all test subjects for the EMU LCVG with TCU test configuration was 223 BTUs.

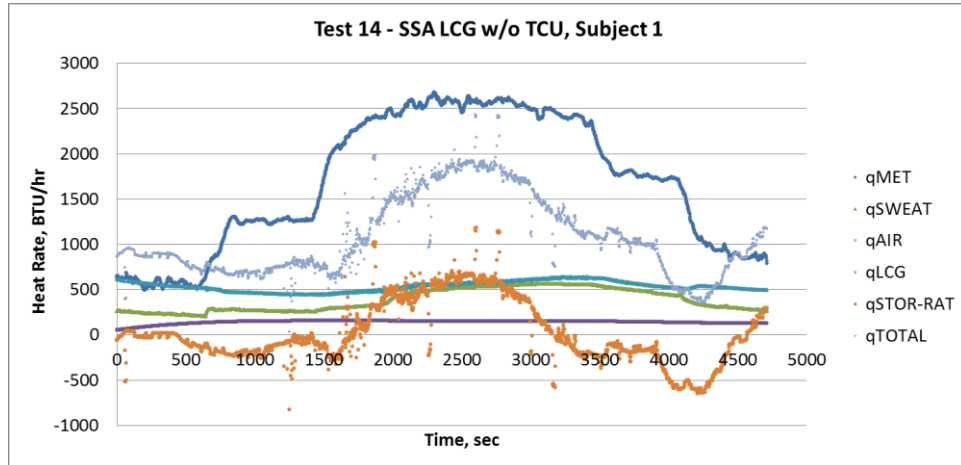


Figure 11: Energy balance for Test 14, EMU LCG without TCU configuration

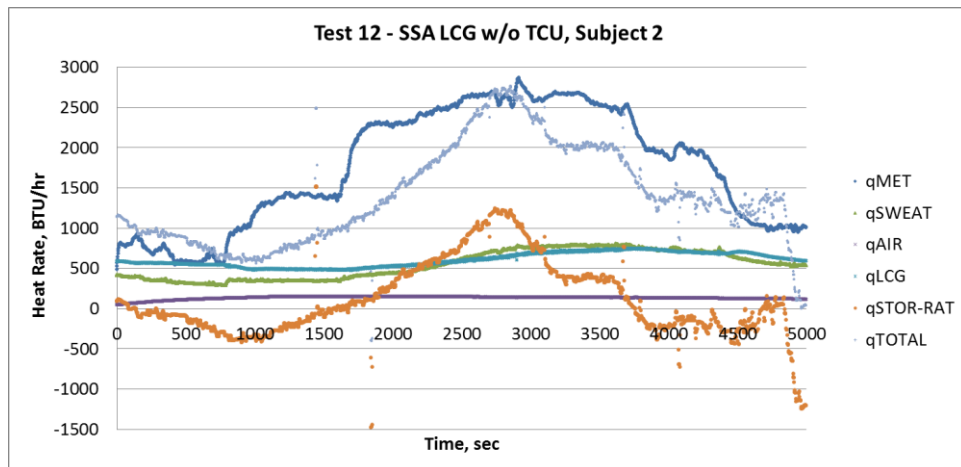


Figure 12: Energy balance for Test 12, EMU LCG without TCU configuration

E. Temperature Data

The plots shown earlier do not show the details of the temperature gradients, so this section provides a more refined temperature plot. The same general trends can be seen for all the LCG configurations, but the relative order of skin temperature locations from highest to lowest changes with subject. The skin temperature and core body temperature values were used to estimate the amount of stored heat, as outlined above.

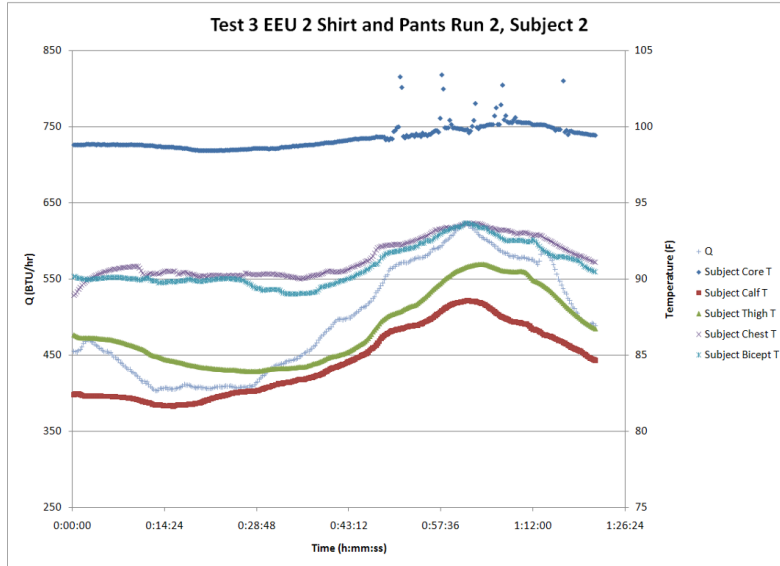


Figure 13: Test 3 EEU LCG Run 2, Subject 2 Temperatures

F. Subjective Data

Subjective data was collected for LCG thermal comfort, LCG to skin comfort, and LCG to suit comfort. Figures 14, 15, & 16 show the results for LCG thermal comfort. The baseline data were taken prior to the start of the test but after donning the LCG and suit. The discomfort ratings higher than 1 for a baseline and at the end of step 1 were due to being cold. The water temperature and flow rate were selected to stress the capabilities of the LCG configurations. These parameters were kept constant throughout the test to eliminate some variability.

The discomfort ratings for step 2 (not shown) revealed that the water temperature and flow rate worked well at the 1200 BTU/hr Met Rate for all the LCG configurations. Even though two of the three subjects gave ratings of 1 for the shirt only configuration, they all commented on their legs feeling a little warmer.

Halfway through step 3 and at the end of step 3 (Figure 16) a marked increase in discomfort due to increased core temperatures can be seen for all LCG configurations; however, the variability between subjects can also be seen. There was no correlation between LCGs and location of discomfort (upper or lower body).

The ratings slowly decrease in step 4 and 5 (Figure 17) as the Met Rates and the core temperatures decrease; the heat transfer of the LCG is able to keep up with heat produced by the subject. Again, ratings above 1 for step 5 (rest) were due to being cold.

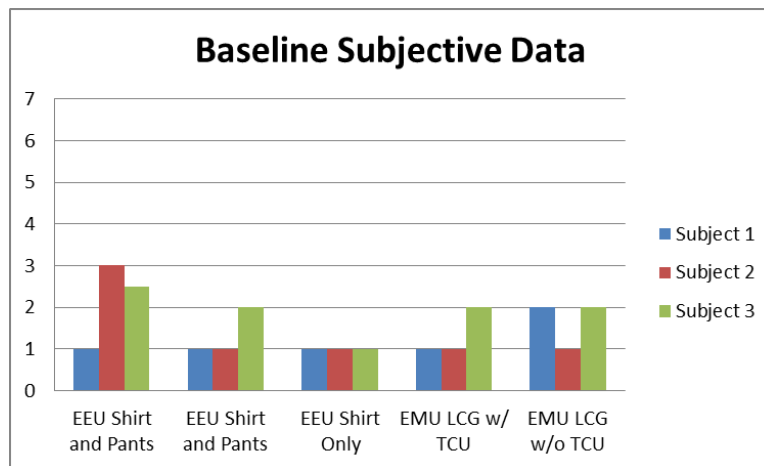


Figure 14: Baseline Subjective Data for LCG Thermal

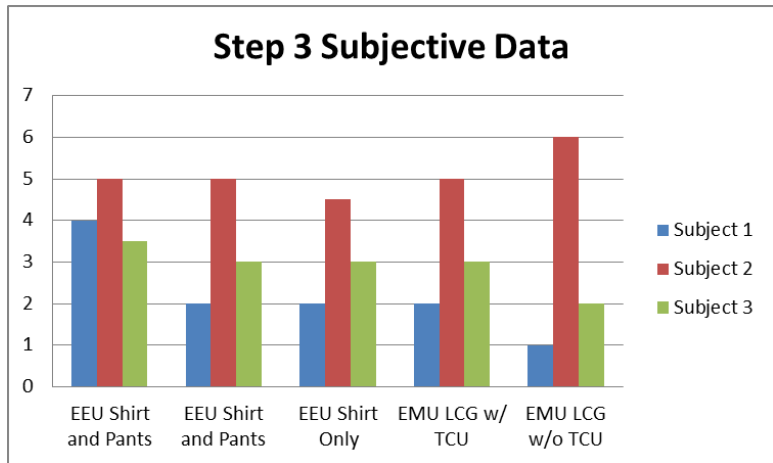


Figure 15: Step 3 Subjective Data for LCG Thermal

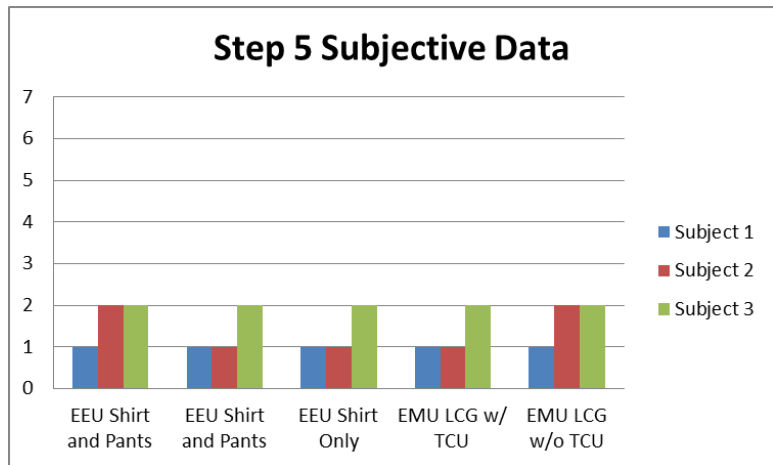


Figure 16: Step 5 Subjective Data for LCG Thermal

Figure 17 shows the results of the LCG to skin subjective data. Only step 3 is shown because all other steps show a similar trend. Subjects 2 and 3 commented that they could feel the EEU 2 manifold on their hip. They also commented that the EMU LCVG without the TCU was scratchy and abrasive, revealing the tactile comfort value of the TCU for the EMU LCG design during this type of operation.

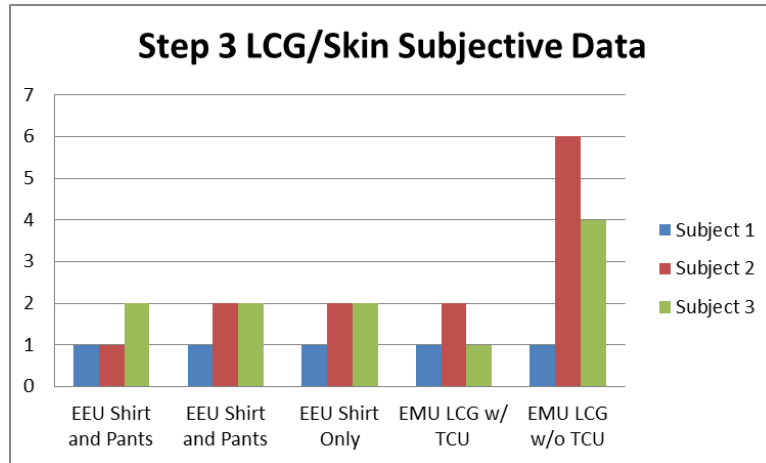


Figure 17: Step 3 Subjective Data for Tactile Comfort

The comments provided during the LCG to suit discomfort ratings were just related to hot spots in the suit, for example: tightness at the top of the boots, pressure on the back of the thigh, and pressure from the Suit Multiple Connector (SMC).

IV. Discussion

An effective LCG works efficiently with the body’s physiological heat transfer mechanisms to remove metabolic heat and regulate core body temperature. Although, there are several sources of error with any manned testing, and the Q_{MET} generated isn’t completely accounted for, the testing highlights the difference between each of the configurations and how they work with the body.

Figure 18 shows the amount of heat transferred by each energy transfer mechanism, normalized for the total heat removed (Q_{TOTAL}), during Step 3 of the test. Although the test conductors attempted to maintain fairly constant metabolic rates at each test step, there were variabilities between the test points. As a result, the mechanism of heat rejected is shown as a ratio to the total heat rejected (Q_{TOTAL}) to increase comparability. The data shows that the EMU LCG without TCU had the lowest Q_{STOR} , the lowest Q_{SWEAT} , and the highest Q_{LCG} . The LCG worked effectively enough that sweating was minimized and little energy was stored. Alternately, the EEU shirt-only configuration had the lowest Q_{LCG} and the highest Q_{STOR} . The Full EEU and the EMU LCVG with the TCU showed similar results to each other, lying somewhere between the two extremes.

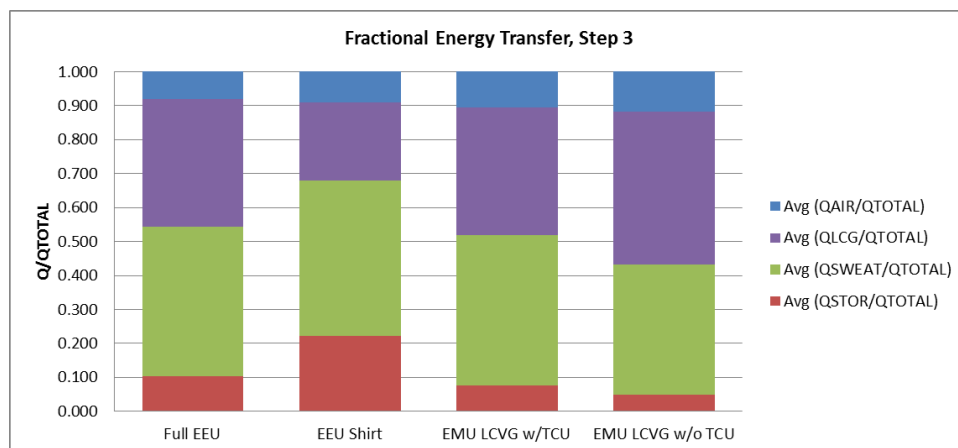


Figure 18: Ratio of energy transfer mechanism, during Step 3

A. EMU LCG with TCU vs. CSAFE EEU LCG

The CSAFE EEU LCG was evaluated in comparison to the EMU LCG with a TCU because the CSAFE EEU has an integrated wicking layer that functions like a TCU. The two configurations have roughly the same tube length and should have roughly the same heat transfer coefficient (UA) based on the types and thicknesses of materials. The similarities were confirmed based on the comparatively similar heat removal performance.

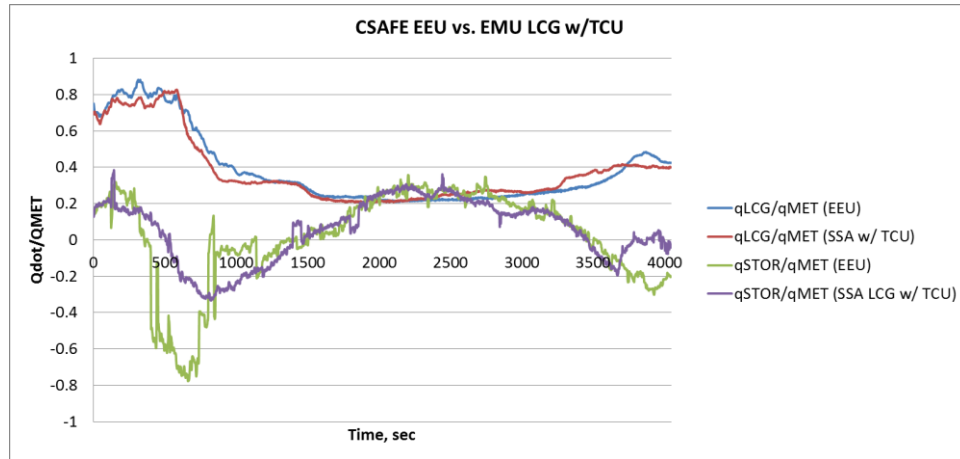


Figure 19: Comparison of EEU and EMU LCG with a TCU

The major difference between the configurations lies in the location of the tubes, fidelity of the construction and water manifolding, and improved materials. These differences were reflected in the subjective feedback, as some subjects commented on hotspots from the large EEU manifolds. The feedback was expected and not intended to be a part of the evaluation as it could be easily addressed with further engineering.

B. Auxiliary Thermal Loop – Shirt-Only EEU

The auxiliary cooling loop in the Advanced EMU PLSS represents a substantial departure from the design of the backup cooling system in the current EMU. The current EMU uses a high pressure (6000 psi) secondary oxygen purge tank, to provide gas cooling, metabolic oxygen and maintain suit pressure for a period of 30 minutes. The tank was sized to provide sufficient cooling during that period. The downside of this system for an exploration mission is that once the secondary oxygen purge is deployed, the system must be replaced requiring ground servicing, effectively precluding the further use of the PLSS for the mission. For this reason, a backup cooling system was sought that would be fully reusable within a mission. With a backup cooling system of fully independent components, namely the Miniature Spacesuit Water Membrane Evaporator (called the mini-ME), the auxiliary feedwater supply, the auxiliary pump, the auxiliary battery and the auxiliary LCG, cooling could be provided to the crew to support a metabolic rate of 1200 BTU/hr for 30 minutes, and perhaps longer. Margin will be added to the system if the water temperature can be lowered below 65°F. Together with a secondary O₂ loop having fully interchangeable O₂ tanks with the primary system, all the needs provided by the primary system could be met for 30 to 60 minutes regardless of the mode of primary system failure.

The auxiliary LCG needs to be fully redundant for the backup system, to cover the event of a leak in the primary system that interrupts flow. This does not require a separate LCG per se; rather, it requires that a subset of cooling tubes be added to the existing garment, and that the tubes flow in parallel to the primary tubes but are not connected to the primary system. The tubing density of the LCG would need to be increased, perhaps doubled, in certain regions. One design concept calls for doubling the LCG tube density in the shirt only resulting in a 50% increase in tubes. Another limits the added tubes to the torso only, resulting in a 40% increase in tubes, and has the advantage of avoiding additional tubes, located in the arm, that would be more ergonomically sensitive around the joint areas.

Thermal analysis was performed in the past year to assess the torso-only version of this LCG using the Wissler Human Thermal Model (WHTM).³ Two heat transfer coefficients (UA's) for the LCG were adopted from previous studies with a SINDA EMU models, that use the 41-Node Metabolic Man (MetMan) to simulate human thermoregulation.⁴ The first is the baseline in the MetMan model from the certification thermal vacuum tests wherein the LCG tubes rested directly on the skin. The second study involved suited subjects in vacuum chamber tests in 1995, where the SINDA EMU UA was derated to 45% of the baseline to account for the impact of wearing a

TCU.⁵ With the derated LCG UA, the MetMan and Wissler models both predicted heat storages levels of 503 BTU and 466 BTU, respectively, after 1 hour in ambient conditions at 1600 BTU/hr metabolic rate. WHTM analysis with these two studies showed that for the torso-only auxiliary LCG modification, sufficient heat could be removed only in the case without the TCU.

Because of the importance of the auxiliary cooling system to the Advanced EMU PLSS development for exploration missions and the uncertainty of the TCU impact, this study evaluates the margin of cooling provided by a shirt-only LCG. Showing stability of the core temperature at metabolic rates at or above 1200 BTU/hr, with acceptable thermal comfort, helps to establish the acceptability of a shirt-only auxiliary LCG configuration. Any margin in these cases would suggest that a torso-only configuration could provide acceptable cooling.

The maximum Q_{STOR} for the three EEU shirt-only tests, averaged across the 3 test subjects, was 297 BTUs with the peak Q_{STOR} value occurring towards the end of Step 3, however the $q_{STOR-RAT}$ begins to decrease in the middle of step 3 and continues to decrease towards zero, nearing steady state, towards the end of Step 3.

C. TCU vs. No TCU

The TCU was introduced (in the EMU program) as an ancillary crewmember option to address problems with extreme thermal cold conditions, the sanitary reuse of LCGs on orbit, and the abrasiveness of the EMU LCVG inner liner and discomfort of tubes. However, the TCU negatively impacts the heat transfer with the LCG. Analysis, previously mentioned, has shown that this could drive the size of the ancillary cooling loop of an exploration LCG.

Based on subjective feedback from testing and heat storage values, there was not a marked impact on the subject's thermal comfort with and without the TCU. We do not see the 45% UA derating that was used for the SINDA model. The thermal performance data did show that the LCG without the TCU was able to remove heat at a slightly higher rate, but the subjective feedback showed that TCU may be necessary for tactile comfort. Further analysis is required to correlate the test results with the analysis conducted, identify the appropriate UA of an LCG with a TCU.

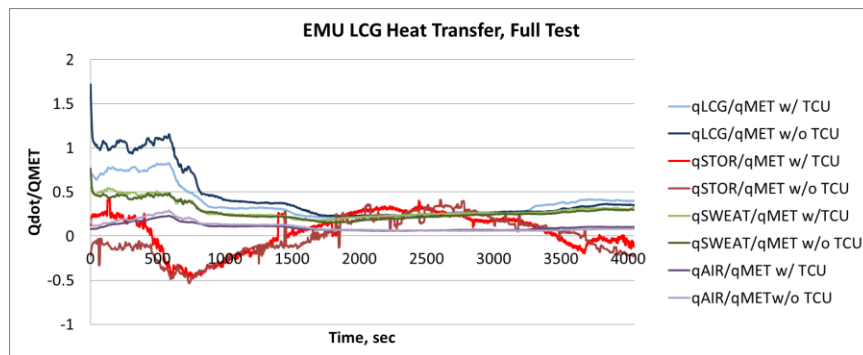


Figure 20: EMU LCG Heat transfer with and without a TCU throughout the test

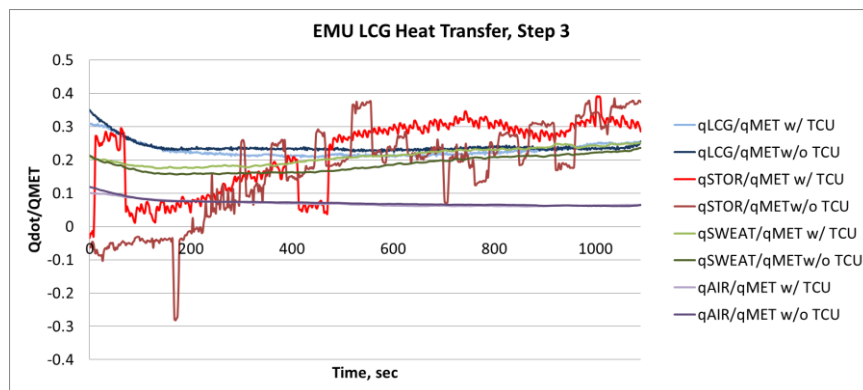


Figure 21: EMU LCG Heat transfer with and without a TCU during step 3

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