Performance Evaluation of Intravehicular Activity Spacesuit without the Use of a Liquid Cooling Garment

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Objective of Study

- The Orion Crew Survival Systems (OCSS) suit is equipped with safety technology that protects the crew during launch and re-entry and Intravehicular Activities (IVA).
- It was designed to be used with a Liquid Cooling Garment (LCG), an undergarment with tubes that circulate water to remove excess heat from a crewmember.
- The exclusion of the LCG from IVA suit architecture and relying solely on air cooling is worth evaluating if those crewmembers are exposed to more benign thermal environments during nominal and contingency operations.
- The objective of this study was to determine if the IVA Suit can be used without the LCG to maintain the crew within their heat storage requirements. It was completed in the following phases:

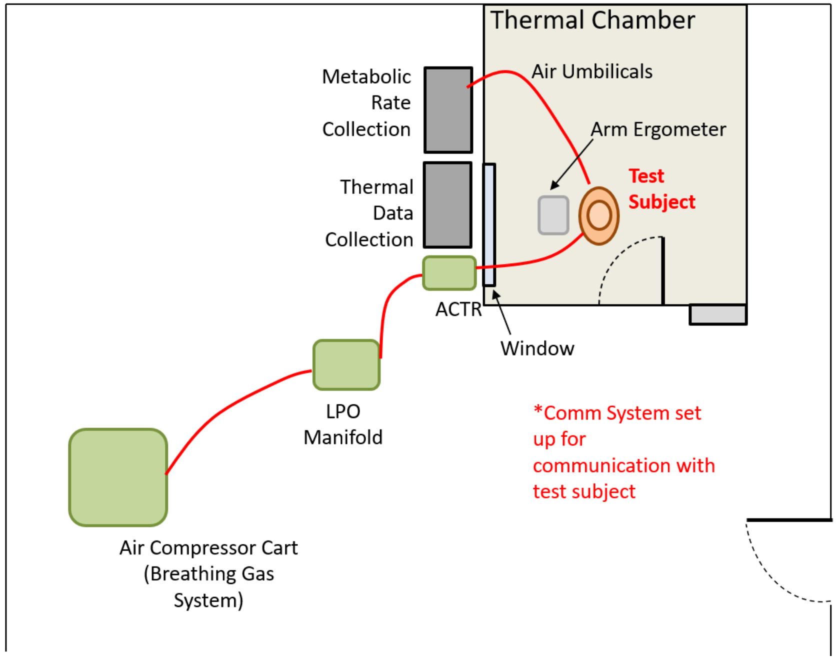
  1.) Execute a test series involving test subjects wearing IVA suits without LCGs in a thermal chamber.

  2.) Correlate the human thermal model to the test data and updating the model's intrinsic parameters for the use case of the IVA suit without an LCG.

Artemis II Crew Donning OCSS Suits

Test Series Overview

- To simulate heat loads and human performance within a crewed cabin, test subjects donned IVA Suits and were directed to operate an arm ergometer located in a temperature- and humidity-controlled thermal chamber.
  - Body core temperature measurements were transmitted via RF by a sensor-encapsulated pill.
  - Skin temperature measurements were logged on iButtonLink, LLC temperature sensors attached to the subject’s body with hypoallergenic tape.
  - Air flow rate to suit and CO2 concentrations at the suit outlet allowed for real-time metabolic rates to be estimated.
  - Arm ergometer speeds were adjusted to achieve target metabolic rates for various test points.
  - Four test subjects were recruited and were referred to with the following identifier: X_Y, where X denotes the suit size of the test subject, and Y is a unique test subject number starting at 1 for each suit size.
  - Hence, the four test subjects for this test series are referred to by the following identifiers: XS_1, M_1, L_1, and L_2.



Facility Layout

Test Series Case Matrix

	Test Point Number	Chamber Temperature [°F]	Chamber Humidity [% rH]	Inlet Breathing Air Temperature [°F]	Inlet Breathing Air Humidity [% rH]	Metabolic Rate [BTU/hr]	Suited Config.
HOT VEHICLE BOUNDARY CONDITIONS	1	86	80*	75	80*	800	Visors down
	2	86	80*	75	80*	1200	
	3	86	80*	75	80*	800	Visors up
	4	86	80*	75	80*	1200	
	5	86	80*	75	80*	800	Helmet/gloves off
	6	86	80*	75	80*	1200	
COLD VEHICLE BOUNDARY CONDITIONS	7	59	20**	55	≤20	600	Visors down
	8	59	20**	55	≤20	800	
	9	59	20**	55	≤20	600	Visors up
	10	59	20**	55	≤20	800	
	11	59	20**	55	≤20	600	Helmet/gloves off
	12	59	20**	55	≤20	800	
	13	59	20**	55	≤20	Resting	Visors up

*or as high as can be achieved, granted that the humidity does not go above 80%.

**or as low as can be achieved, granted that the humidity does not fall below 20%.

Heat Storage

- **Objective: Determine if an IVA suited crew member without an LCG stayed within required heat storage limits.**
  - **Nominal Operations:** Stay within the thermal comfort range of -0.8 ≤ Q_{store} ≤ 1.3 BTU/lb.
  - **Contingency Operations:** Stay within Cognitive Deficit Onset (CDO) limits -1.8 ≤ Q_{store} ≤ 2.0 BTU/lb.
- **Method: Calculate the heat storage using the skin temperature and core temperature.**
  - The skin and core temperature were determined with skin temperature sensors and a core temperature pill.
  - The reference temperature refers to the thermally comfortable temperature of the test subject, established at the start of each test day while the subject is in shirt sleeves.

$$Q_{store} = m * C_{pB} * (0.2\,(T_{skin} - T_{skin_{ref}}) + 0.8\,(T_{core} - T_{core_{ref}}))$$

$$Q_{store_{req}} = \frac{Q_{store}}{m}$$

- m = subject's mass
- C_{pB} = specific heat capacity of the human body
- T_{skin} = average skin temperature
- $T_{skin_{ref}}$ = reference average skin temperature
- T_{core} = core temperature
- $T_{core_{ref}}$ = reference core temperature
- Q_{store} = heat storage

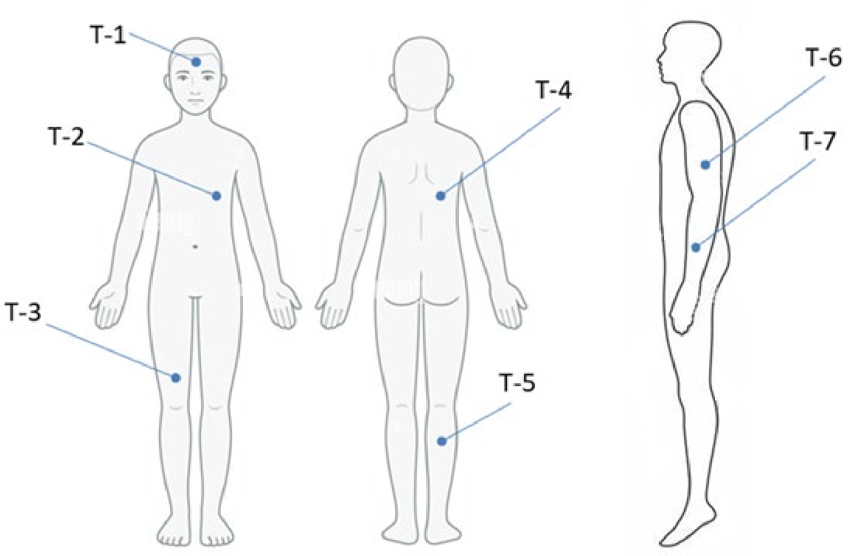
Determining Average Skin Temperature

- **Objective: Find average skin temperature.**
  - The average skin temperature was the area-weighted average of the temperatures measured at the head (*T1*), chest (*T2*), right thigh (*T3*), shoulder blade (*T4*), right calf (*T5*), left upper arm (*T6*), and left lower arm (*T7*).

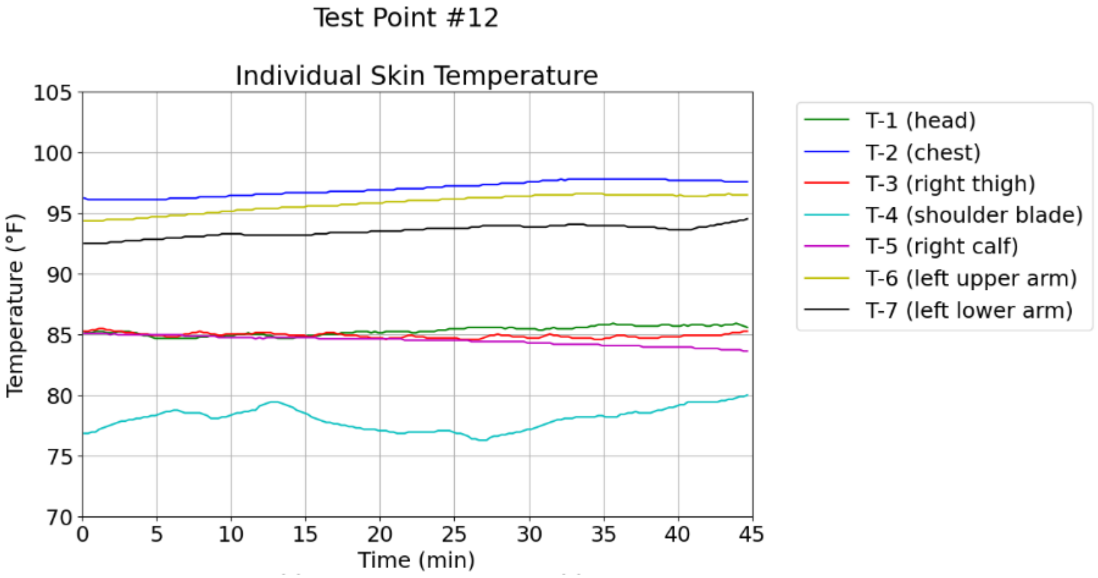
$$T_{skin} = 0.26 * T1 + 0.06 * T7 + 0.1 * T6 + 0.17 * T3 + 0.15 * T5 + 0.26 * (0.45 * T2 + 0.55 * T4)$$

- **Modification for test subject L_1 during test point 12:** The shoulder temperature sensor may have shifted since it was showing the temperature of ~77 °F while the rest of the sensors were at 85 – 97 °F; the modified equation was used.

$$T_{skin} = 0.26 * T1 + 0.06 * T7 + 0.1 * T6 + 0.17 * T3 + 0.15 * T5 + 0.26 * T2$$



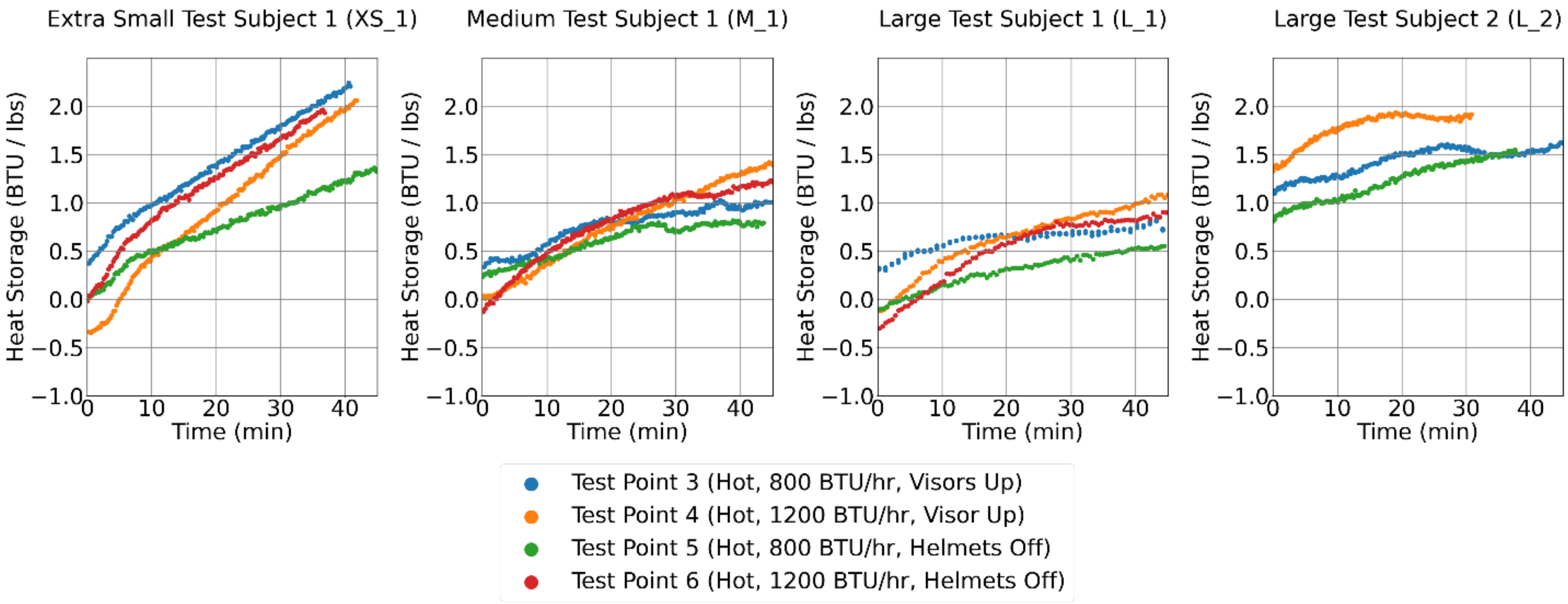
Skin Temperature Sensor Locations [6]



Lower T-7 Temperature for Subject L_1 during Test Point 12.

Test Heat Storage Visor-Up and Helmets Off Hot Environment (86 °F) Test Points 3-6

- **Test Conditions:** Each test subject has a subplot with the hot environment (86 °F) visor up configuration (test point 3 and 4) and helmet off configuration (test point 5 and 6); the target metabolic rates are 800 and 1200 BTU/hr.
- These represent the most demanding hot scenarios due to elevated metabolic rates in a warm environment.
- The XS_1 test subject exhibits the steepest rate of increase.
- Subjects with larger size and higher thermal capacitance require more time to heat compared to smaller ones.
- Test Subject L_2 did not complete test points 1, 2, 6, 7, 8, 9, 10, and 12 because they were not local to the test facility area.



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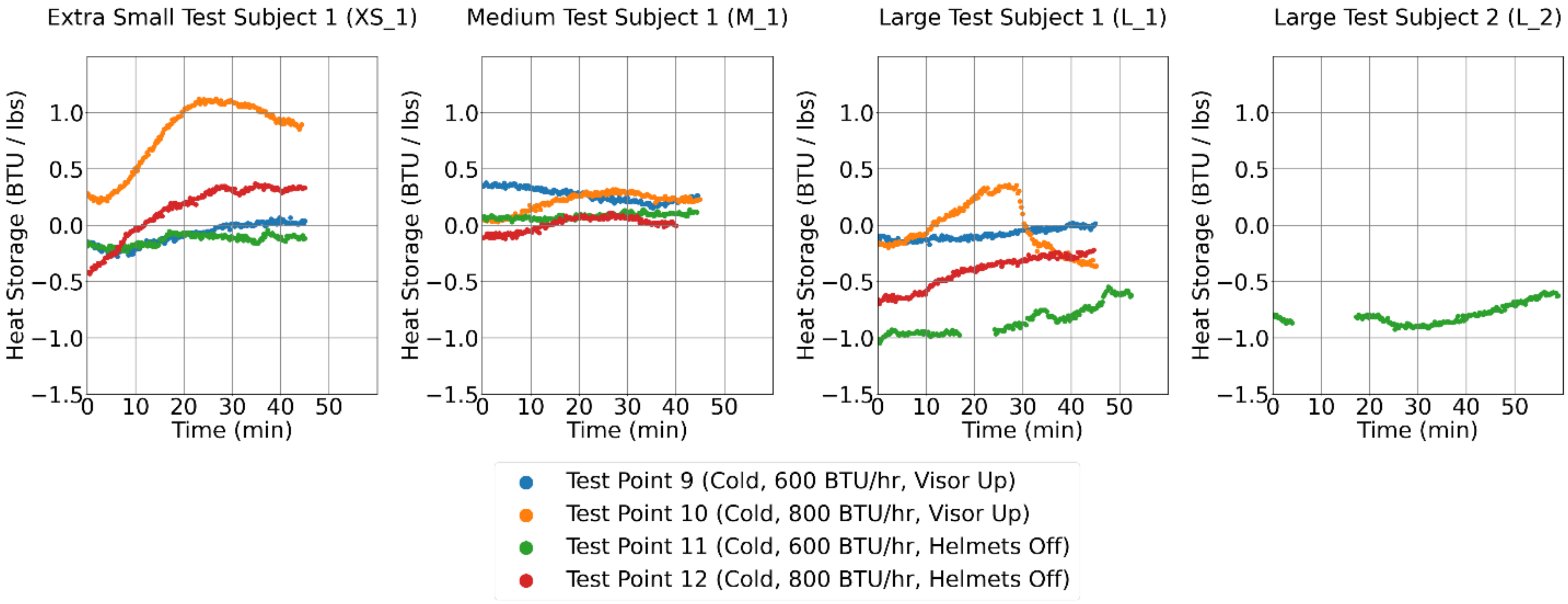
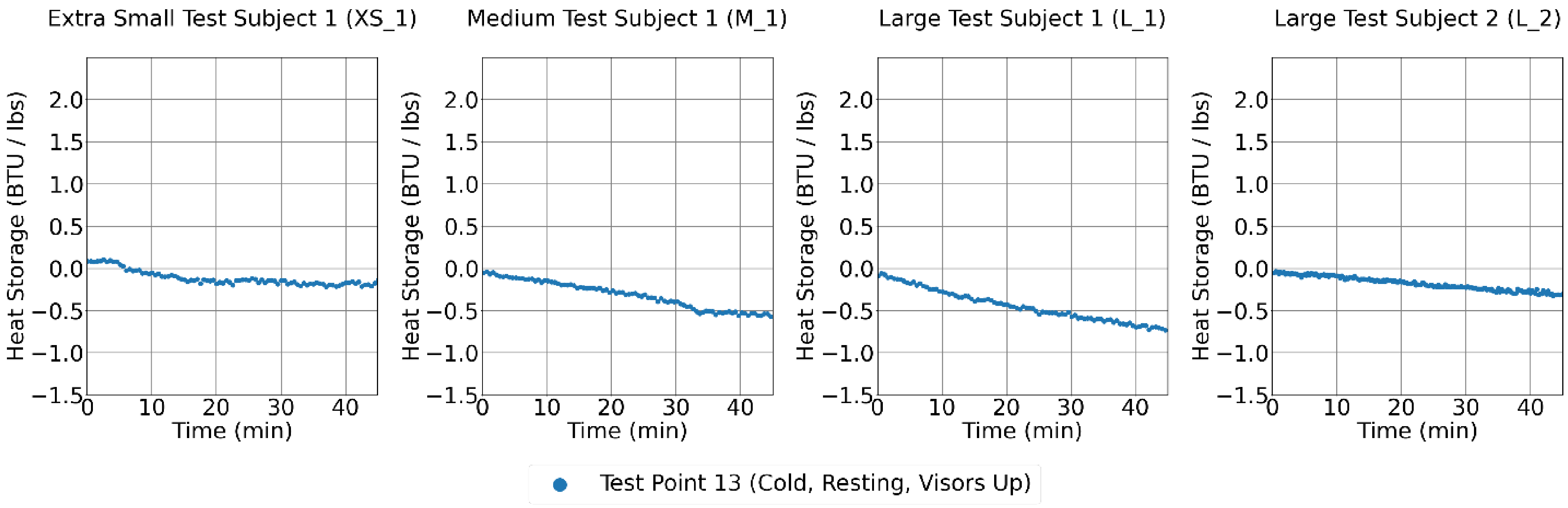
Test Heat Storage Visor-Up and Helmets Off Cold Environment (59 °F) Test Points 9-12

- The test subjects were exposed to a cold environment (59 °F) while maintaining moderate metabolic rates (600 and 800 BTU/hr), which provided a reasonably comfortable condition for them.
- Throughout most test points, heat storage shows a slight increase over the 45-minute duration of the test.
- At test point 11 (green) for both L_1 and L_2, there were data interruptions, but the overall active test time was 45 minutes.
- For test subject L_1 at test point 10, the heat storage initially increasing, followed by a sharp decreases could be caused by the subject’s slower digestion of the core temperature pill, as water consumption affects core temperature measurements.



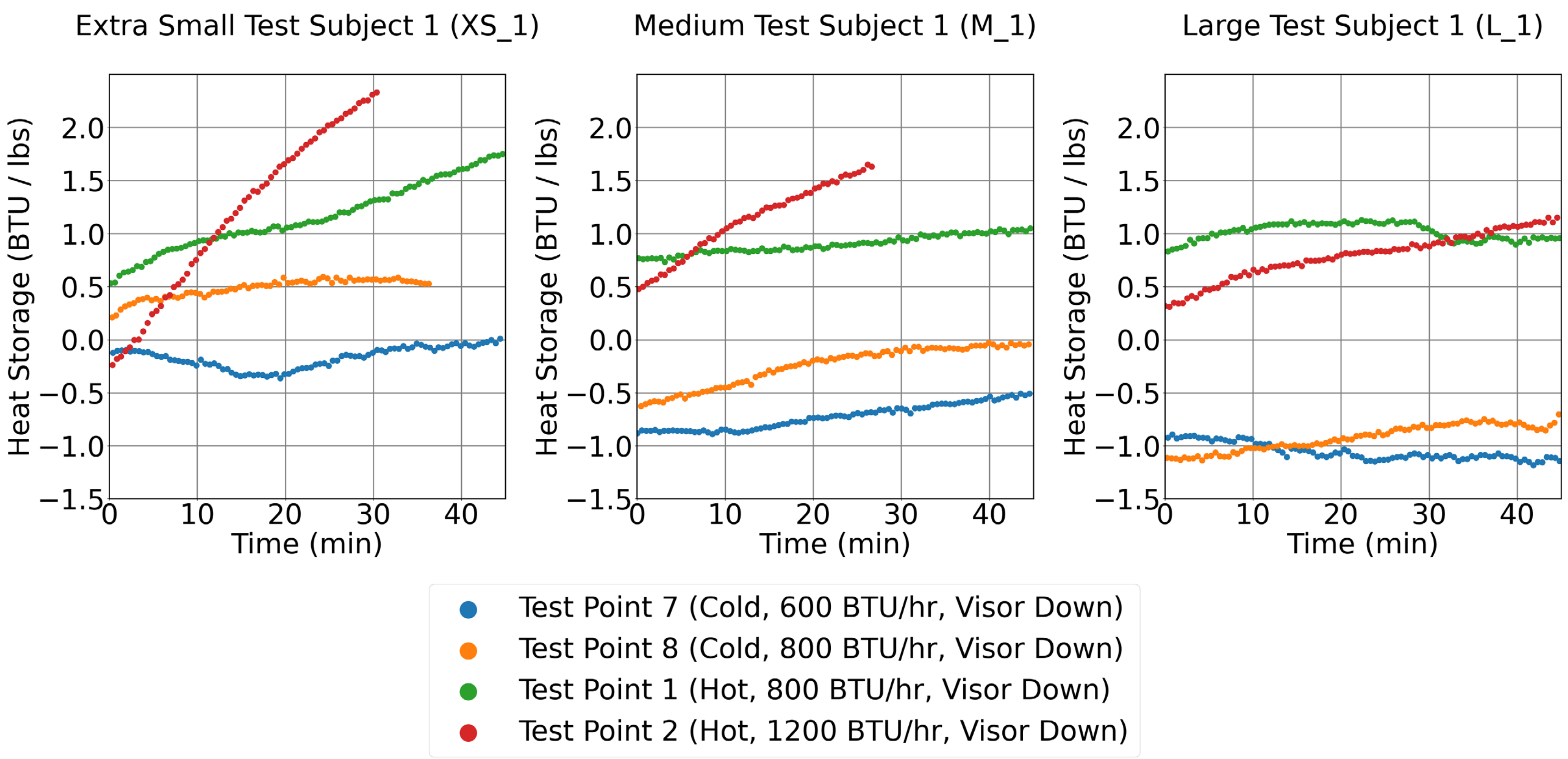
Test Heat Storage Visor-Up, Cold Environment Test Points 13 (59 °F)

- This resting metabolic rate case is the most straining cold environment case since test subject are inactive.
- Here the metabolic rate ranges between 253 - 332 BTU/hr.
- The heat storage decreases slowly over the 45-minute test.
- Given that the test subjects are resting with low metabolic rates, their heat storage is understandably negative and decreasing.



Test Heat Storage Visor-Down Cold and Hot Environment Test Points 1, 2, 7, 8

- For the visor-down cases, the hot (86 °F) and cold (59 °F) cases have been plotted together with target metabolic rates at 600, 800, and 1200 BTU/hr.
- The largest heat storage increase occurs in test point 2 when the test subjects are at the highest metabolic rate, 1200 BTU/hr.
- Most visor-down cold environment cases show a slight increase in heat storage.
- The heat storage is less for visor-down cases compared to visor-up/helmet off cases because the cool air is contained to the suit.
- The small test subject is more prone to overheating shown in test point 3, 4, 6 and 2 reached or surpassed 2.0 BTU/lb.

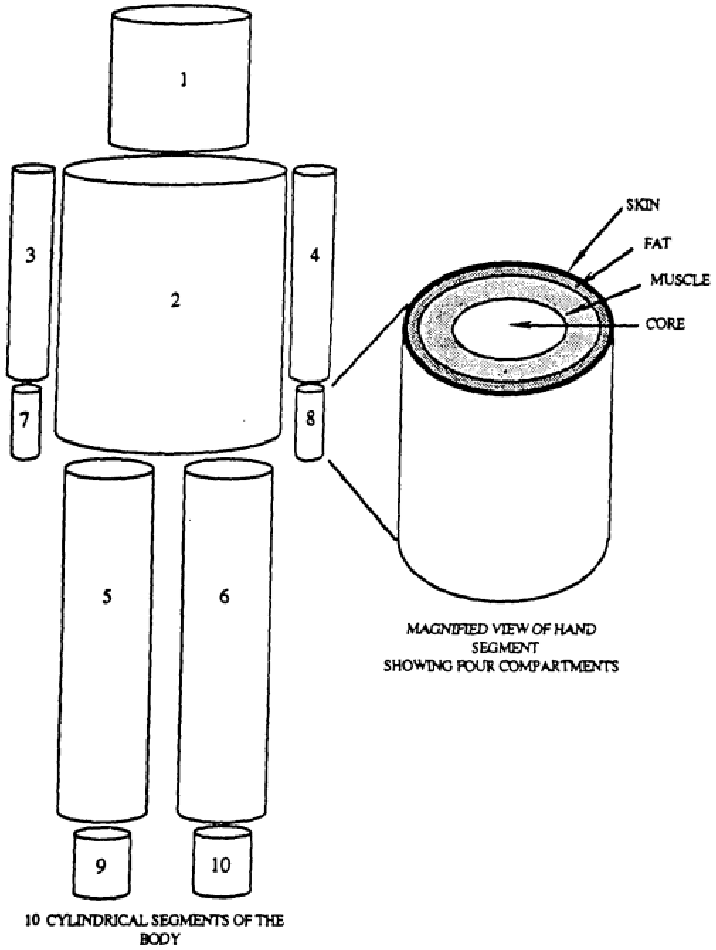


METMAN Model

- METMAN is a 41-node Fortran human thermal model that simulates the heat transfer within a crew member's body and from a crew member to the surrounding environment.
- **Inputs:**
  - Since there was no LCG, the undergarment insulation thickness was reduced from 0.0141 ft to 0.00141 ft because effective thickness was previously correlated to similar testing with the LCG present.
  - LCG water flowrate was set to 0 to turn the LCG off.
  - Adjusted Body Surface Area was used for the METMAN based on subject's weight.

Test Subjects	Weight (lb)	Body Surface Area (ft^2)
M_1, L_2	~170-180	21.3
L_1	~200	24.00
XS_1	~115	15.72

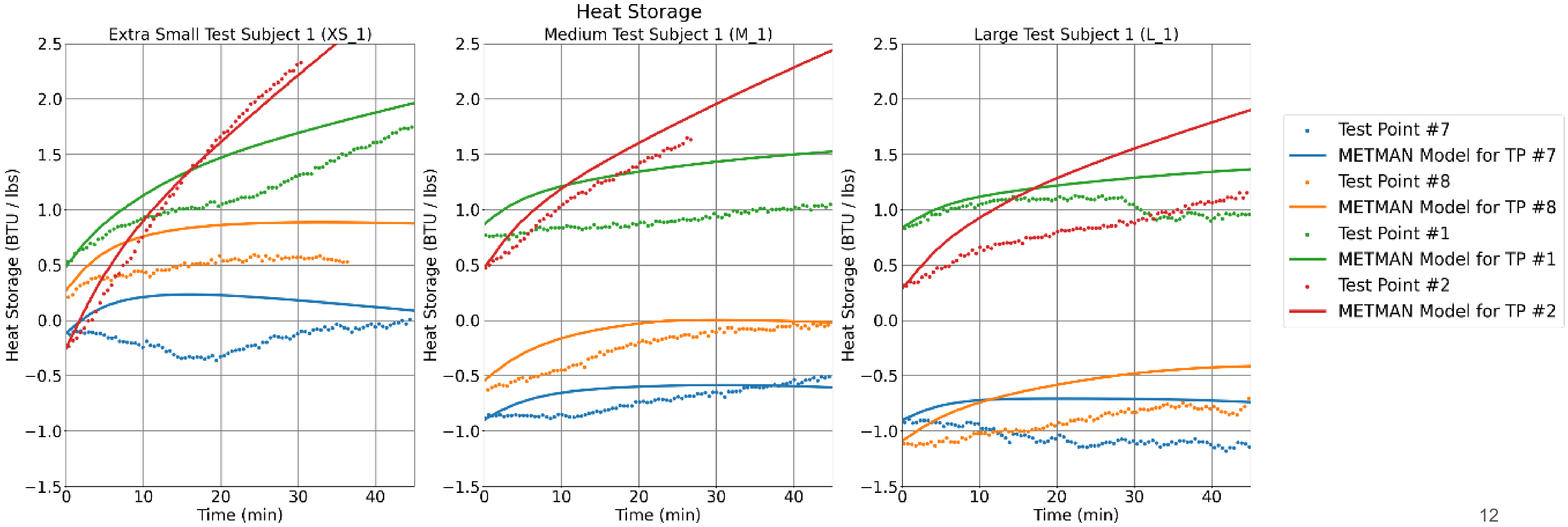
  - Sensor averages of the chamber temperature, chamber dewpoint, suit temperature, suit dewpoint, metabolic rate, and air flow rate were used as inputs.
- **For Visor-Up and Helmets Off cases:**
  - **Suit inlet airflow:** Modified since air from the neck ring would escape to the cabin
  - **Suit inlet dewpoint:** Used the dewpoint corresponding to the average cabin and suit water vapor pressure
  - **Suit inlet temperature:** Used the average cabin and suit inlet temperature.



Geometric Representation of METMAN

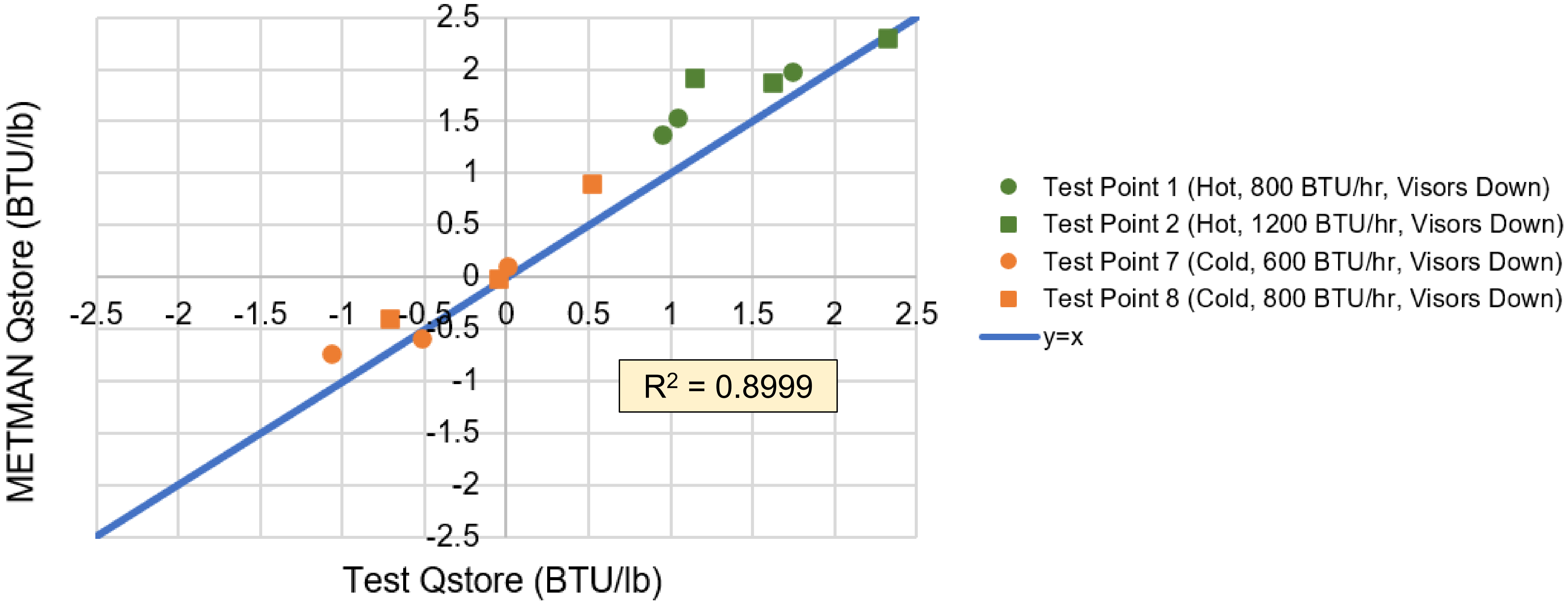
Test Heat Storage Visor-Down Vs. METMAN Model

- The transient METMAN heat storage (line) data is graphed with the test data (scatter).
- **Hot environment (test point 1 and 2):** METMAN tends to be conservative, typically predicting that the test subject reach the upper heat storage limit faster than the test data—except at XS_1 test point 1.
- **Cold environment (test point 7 and 8):** Heat storage prediction is sometimes higher and sometimes lower than the test data.
- **Conclusions:**
  - The transient METMAN and the test data could differ because the **average** test values were used as inputs to METMAN.
  - Although there were some fluctuations in the test data, the overall heat storage by the end of the test was similar.



Visor-Down: Q_{store} Test vs. METMAN Model at the End of Test Duration

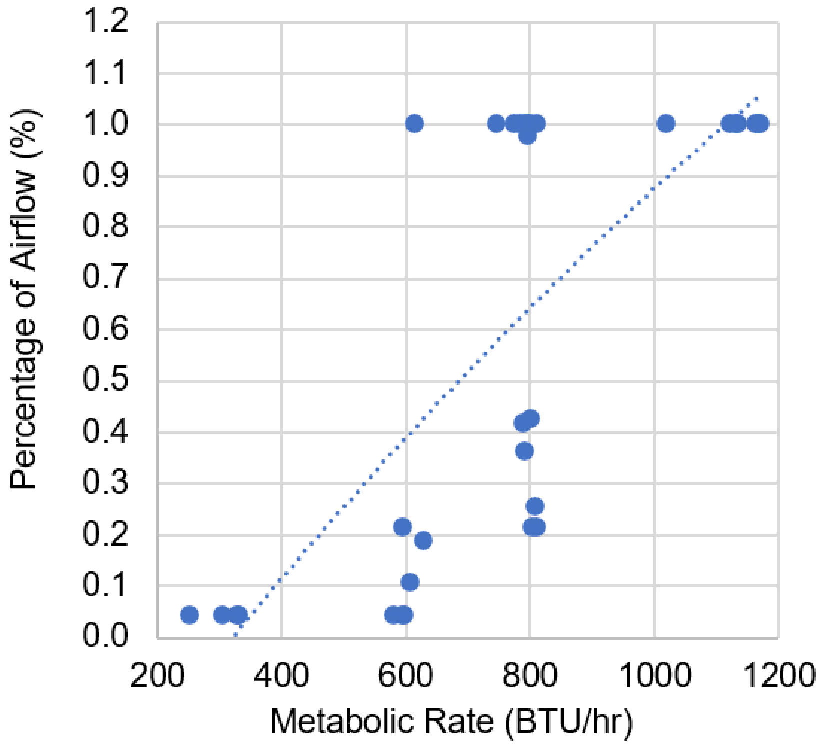
- To examine the heat storage levels from the various test subjects on one graph, the heat storage at the end of the test duration was plotted with the corresponding heat storage from METMAN.
- The y=x line would represent a perfect correlation and the R^2 is 0.8999 for x = y line, which shows good agreement.
- The data is plotted so that the same configuration = same color, ● = lower met rate, ■ = higher met rate.



Air Flowrate into Suit Based on Metabolic Rate

- **Objective: Modify the suit inlet airflow since some air from the neck ring would escape to the cabin.**
  - Ergometer Arm Movements instigated air flow out of suit into the cabin when the suit was deformed.
  - Metabolic rate was a measure of arm movements.
  - Higher metabolic rate = more arm movements.
- **Method: Create a relationship between metabolic rate and flowrate.**
  - The suit inlet airflow parameter in METMAN was decreased until the model and test data heat storages were similar.
  - Reduced suit inlet airflow / total flowrate = percentage of flowrate.
  - **Scatter Plot:** Metabolic rate vs. the percentage of flowrate.
  - **Second order polynomial curve fit:** Generalized the relationship between air flowrate and metabolic rate.

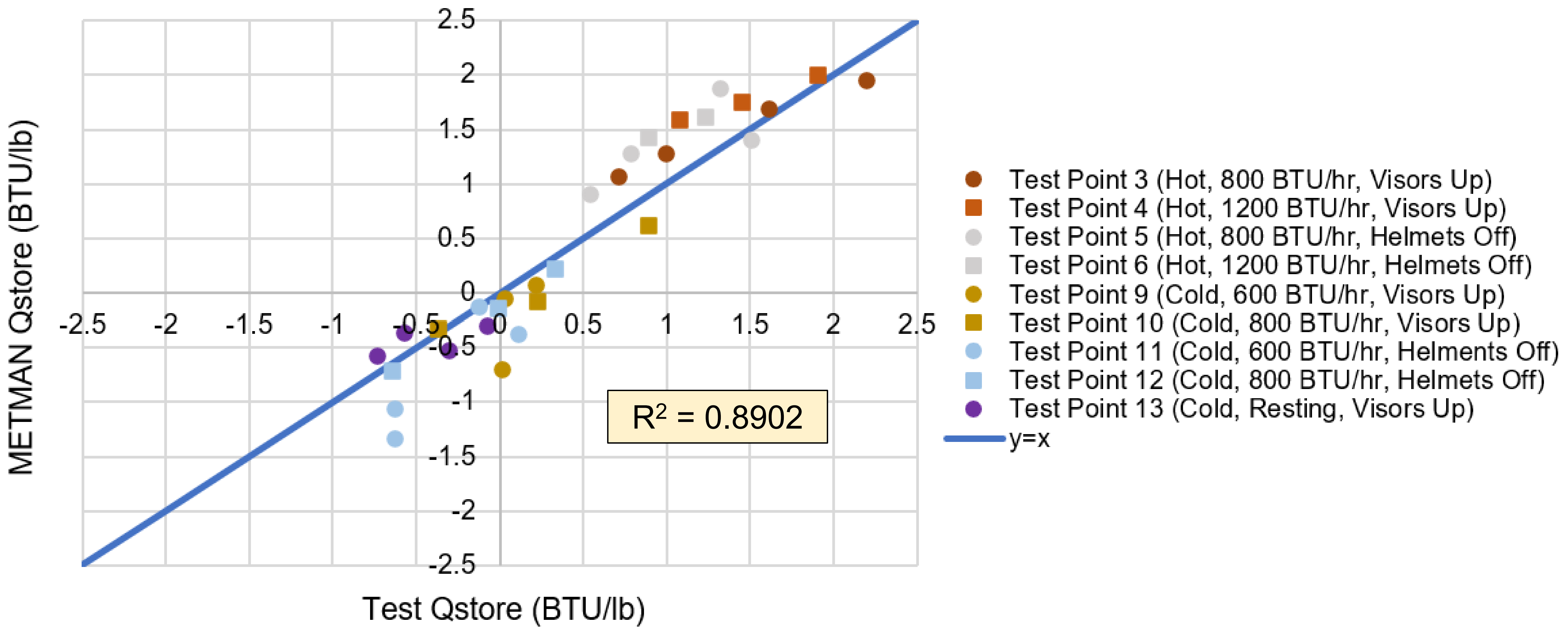
$$\%\ flowrate = -2.58 * 10^{-7}(MR)^2 + 1.63 * 10^{-3}(MR) - 4.94 * 10^{-1}$$



- The visor-up and helmet off cases were re-run using the curve fit percentages multiplied by the measured total flowrate.

Visor-Up and Helmet Off: Q_{store} Test vs. METMAN Model at the End of Test Duration

- The METMAN data is usually conservative, shown with hot cases above the line and cold cases below the line.
- The y=x line would represent a perfect correlation and the R^2 is 0.8902 for x = y line, which shows good agreement.
- The data is plotted so that the same configuration = same color, ● = lower met rate, ■ = higher met rate.



Conclusion

- The model predictions had good agreement with the test data, further substantiating METMAN in characterizing IVA Suit Pressure Garment Assembly thermal performance.
  - **R^2 = 0.8902** for visors-up and helmet-off configurations.
  - **R^2 = 0.8999** for visors-down configurations.
  - The model is even conservative in its predictions.
- The novel approach uncovered in this study will allow the community to assess crewmember heat storage in multiple suited configurations.
- Future considerations of this model correlation include conducting more testing to further validate this methodology.

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Backup

Visor-Up and Helmet Off: METMAN Suit Inputs Converting Average Water Partial Pressure to Dewpoint

- Since the air is mixing for the visor-up and helmet off cases, the average chamber and suit inlet temperatures are used for the METMAN suit inlet temperature.
- In addition, the METMAN suit dewpoint is adjusted to the corresponding dewpoint to the average chamber and suit water vapor pressure.
- Relative humidity of the suit and chamber are measured and can be converted to dewpoint temperatures.
- Then, the dewpoint temperatures (T_{dp}) are converted to vapor pressure (P_{SAT} in psia), where they can be averaged.
- The average chamber and suit vapor pressure (p_v in inHg) is converted back into dewpoint temperature using the T_{dp} equation

$$PSAT = 0.4912\, e^{\frac{-G-(G^2-4FH)}{2F}}$$

F = $-7.09 * 10^{-2}$
G = $1.63 * 10^{-3}\left(T_{dp}\right) - 1.0$
H = $-4.29 * 10^{-6}\left(T_{dp}\right)^2 + 3.53 * 10^{-2}\left(T_{dp}\right) - 2.52$
T = Dewpoint Temperature (°F)
PSAT = Vapor pressure (psia)

$$T_{dp} = \frac{-G + (G^2 - 4FH)}{2F}$$

F = $-4.29 * 10^{-4}$
G = $1.63 * 10^{-3}\,(\ln p_v) + 3.53 * 10^{-2}$
H = $(ln\, p_v)(-7.09 * 10^{-2}\,(ln\, p_v) - 1.0) - 2.52$
Pv = partial pressure of water vapor (in Hg)
TSAT = Saturation temperature (°F)

Visor-Up and Helmets Off Test Data for Hot Environments
Test Point 3-6

Test Subject	Test Point	Average Metabolic Rate [BTU/hr]	Limit Core Temp [°F]	Limit Skin Temp [°F]	Limit Heat Storage [BTU/lb]	Average Inlet Breathing Gas Temperature [°F]	Average Flow Rate [ACFM]	Average Inlet Breathing Gas Humidity [%]
XS_1 116.05 lb $T_{core_{ref}}$ = 98.89 °F $T_{skin_{ref}}$ = 91.51 °F	3	791.3	100.5	98.4	2.2 (max)	74.0	4.7	37.4
	4A‡	1162.2	99.7	97.9	1.6 (max)	73.4	4.7	41.0
	4B‡	981.0	100.2	98.4	2.1 (max)	73.7	4.7	40.3
	5	791.0	99.5	97.1	1.4 (max)	73.8	4.7	36.8
	6	1163.6	100.3	97.6	2.0 (max)	73.7	4.7	41.8
M_1 175.1 lb $T_{core_{ref}}$ = 99.66 °F $T_{skin_{ref}}$ = 89.93 °F	3	799.8	99.7	96.1	1.0 (max)	74.6	4.8	39.5
	4A	1188.1	99.8	96.1	1.1 (max)	74.1	4.8	40.6
	4B‡	1007.5	100.2	96.4	1.5 (max)	74.4	4.8	39.3
	5	810.7	99.6	95.1	0.8 (max)	74.1	4.8	40.9
	6A‡	1197.6	99.9	95.6	1.1 (max)	74.0	4.8	40.8
	6B‡	1001.7	100.1	95.6	1.2 (max)	74.2	4.7	41.1
L_1 See Table 4	3	746.7	98.8	96.1	0.8 (max)	73.9	4.7	56.7
	4	1168.3	99.1	96.7	1.1 (max)	74.0	4.7	55.6
	5	799.0	98.7	94.1	0.5 (max)	74.0	4.7	58.0
	6	1170.2	98.8	95.6	0.9 (max)	74.1	4.6	58.0
L_2 178.8 lb $T_{core_{ref}}$ = 99.4 °F $T_{skin_{ref}}$ = 84.4 °F	4	1019.4	99.3	96.0	1.3 (max)	73.8	4.7	38.1
	3	775.0	99.5	93.7	1.6 (max)	74.3	4.6	37.4
	5	785.4	99.3	93.9	1.5 (max)	74.1	4.7	49.5

Case	Weight [lbs]	Tref, core [°F]	Tref, skin [°F]
L_1 3&4	198.1	98.76	91.54
L_1 5&6	196.7	98.55	91.38

‡ In these test points, the goal metabolic rate dropped from 1200 BTU/hr (351.7 W) in part A to 1000 BTU/hr (293.1 W) in part B because the subject's heart rate exceeding 85% of the age-predicted maximum for 2 continuous minutes. Later, the transient metabolic rates for these changes were captured in the METMAN correlation to make a one-to-one comparison between cases.

Visor-Up and Helmets Off Test Data for Cold Environments Test Point 9-12

Test Subject	Test Point	Average Metabolic Rate [BTU/hr]	Limit Core Temp [°F]	Limit Skin Temp [°F]	Limit Heat Storage [BTU/lb]	Average Inlet Breathing Gas Temperature [°F]	Average Flow Rate [ACFM]	Average Inlet Breathing Gas Humidity [%]
XS_1 115.65 lb $T_{core_{ref}}$ = 99.09 °F $T_{skin_{ref}}$ = 89.01 °F	9	627.9	98.9	88.1	-0.3 (min)	55.4	4.8	5.2
	10	809.7	99.8	93.0	1.1 (max)	55.5	4.7	5.1
	11	614.8	99.1	87.6	-0.2 (min)	55.4	4.8	5.0
	12	801.2	98.7	88.1	-0.4 (min)	55.6	4.7	5.0
M_1 172.00 lb $T_{core_{ref}}$ = 98.89 °F $T_{skin_{ref}}$ = 91.07 °F	9	594.9	99.6	99.6	0.4 (max)	55.8	4.7	5.2
	10	804.1	99.1	90.4	0.0 (min)	55.9	4.7	5.1
	11	606.9	99.5	88.9	0.0 (min)	56.1	4.7	5.1
	12	810.5	99.2	89.1	-0.1 (min)	56.1	4.7	5.0
L_1 207.00 lb $T_{core_{ref}}$ = 98.71 °F $T_{skin_{ref}}$ = 91.46 °F	9	579.9	98.6	89.7	-0.2 (min)	55.3	4.8	5.3
	10	797.5	98.3	90.1	-0.4 (min)	55.3	4.8	5.2
	11	594.3	97.7	88.4	-1.0 (min)	55.7	4.7	5.1
	12	790.1	98.0	89.3	-0.7 (min)	55.5	4.8	5.0
L_2 178.2 lb $T_{core_{ref}}$ = 98.9 °F $T_{skin_{ref}}$ = 88 °F	11	598.1	98.2	85.5	-0.9 (min)	55.4	4.7	5.3

Visor-Up, Resting Test Data for Cold Environments
Test Point 13

Test Subject	Test Point	Average Metabolic Rate [BTU/hr]	Limit Core Temp [°F]	Limit Skin Temp [°F]	Limit Heat Storage [BTU/lb]	Average Inlet Breathing Gas Temperature [°F]	Average Flow Rate [ACFM]	Average Inlet Breathing Gas Humidity [%]
XS_1	13	253.4	98.9	88.9	-0.2 (min)	56.5	4.7	5.8
M_1	13	328.3	98.7	90.4	-0.6 (min)	55.9	4.6	5.9
L_1	13	332.2*	97.7	89.0	-0.7 (min)	55.8	4.6	5.6
L_2	13	306.0	98.7	86.9	-0.3 (min)	55.9	4.6	5.3

* Test subject L1’s metabolic rate, ventilation, and Tidal Volume were averaged to 190.4 BTU/hr, 6.15 L/min, and 0.41 L, respectively. These values were below what was expected and could have resulted in a leak between the mask and test subject’s face. Therefore, an average of the Mifflin-St. Jeor [15] and Harris-Benedict [14] equations were used to calculate expected resting metabolic rate, 332.2 BTU/lb (74.1W). This method was applied to all resting test points. Since there was good agreement with the measured metabolic rate and average of the predicted resting metabolic rate for the other test points, this was deemed an acceptable method for calculating L_1’s resting metabolic rate.

Visor-Down Test Data for Hot and Cold Environments
Test Point 1, 2, 7 and 8

Test Subject	Test Point	Average Metabolic Rate [BTU/hr]	Limit Core Temp [°F]	Limit Skin Temp [°F]	Limit Heat Storage [BTU/lb]	Average Inlet Breathing Gas Temperature [°F]	Average Flow Rate [ACFM]	Average Inlet Breathing Gas Humidity [%]
XS_1 115.65 lb $T_{core_{ref}}$ = 99.09 °F $T_{skin_{ref}}$ = 89.01 °F	7	615.7	98.7	88.9	-0.4 (min)	56.0	4.7	5.8
	8	813.5	99.6	91.1	0.6 (max)	56.1	4.7	5.7
	1	805.4	99.8	97	1.7 (max)	73.8	4.7	56.2
	2	1151	100.4	98.3	2.3 (max)	73.8	4.7	56.1
M_1 172.00 lb $T_{core_{ref}}$ = 98.89 °F $T_{skin_{ref}}$ = 91.07 °F	7	609.4	98.4	89.5	-0.9 (min)	56.1	4.7	5.8
	8	811.8	98.6	90.5	-0.6 (min)	56.3	4.7	5.7
	1	797.5	99.8	95.5	1.0 (max)	74.6	4.6	57.4
	2	1214.3	100.3	97.3	1.7 (max)	74.4	4.7	54.9
L_1 207.00 lb $T_{core_{ref}}$ = 98.71 °F $T_{skin_{ref}}$ = 91.46 °F	7	590.6	97.2	88.5	-1.2 (min)	56.0	4.7	5.3
	8	782.3	97.1	89	-1.1 (min)	56.3	4.7	5.2
	1	776	98.7	96.1	1.1 (max)	73.9	4.6	53
	2	1173.5	99.1	96.2	1.2 (max)	74.8	4.7	55