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DEVELOPING A HYBRID SPACESUIT SIMULATOR AS A RESEARCH TOOL FOR ASSESSING EXTRAVEHICULAR ACTIVITY RELEVANT WORKLOAD

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Supported provided by: NASA Mars Campaign Office Exploration Capabilities

Outline



- Background/Motivation/Objectives
- Methodology
- Results
- Summary
- Future Work

Introduction [1/3] – Motivation

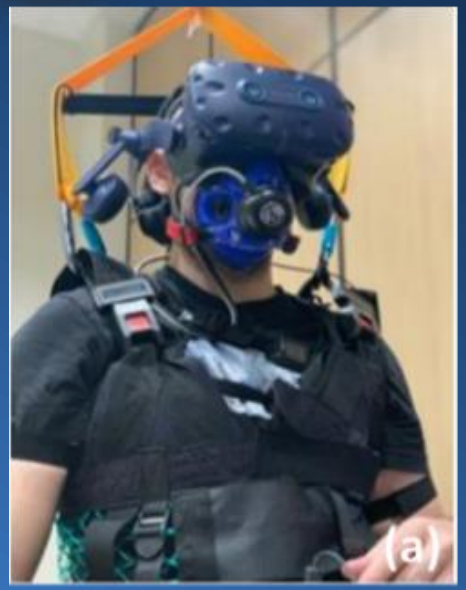
- **Historical Relevance:** Utilizing a space suit simulator is not a new concept (dating back to the Apollo era)

- **Motivation:** Access to NASA spacesuits (& mockups) is extremely limited and associated with strenuous cost/schedule. NASA needs a research tool to:
  - Provide human health and performance (HH&P) relevant workload simulations to aid in closure of critical HH&P knowledge gaps
    - Many HH&P objectives that DON'T require a full pressurized spacesuits
  - Meet the rapidly increasing Extravehicular Activities (EVA) testing and training needs for exploration missions



Photo Credit: NASA

Introduction [2/3] – Background













- **What are suit simulators ? Why do we need them ?**
- Types of Spacesuit simulators
  - a) Unsuited analog
  - b) Limited interface
  - c) Representative simulation
  - d) (and e) Unpressurized full-spectrum simulation
  - f) Pressurized spacesuits

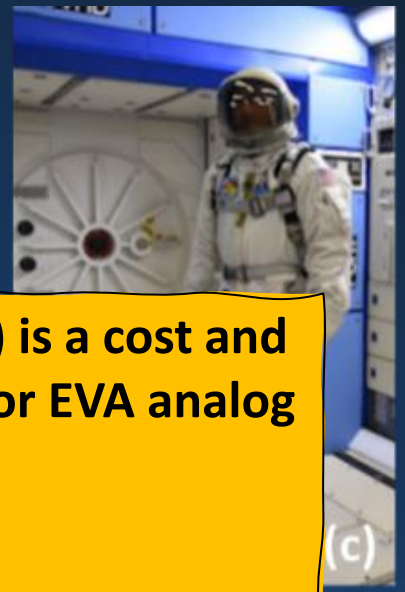
increasing cost and complexity

(a) Baughman, *et al.*, "Assessments of Physiology And Cognition in Hybrid-reality Environments (APACHE)– Physical Workload Approximation," ICES 2022.
(b) Apollo crew to conduct geological training (photo credit: NASA)
(c) Public affair team use suit (photo credit: NASA)
(d) NASA's xEMU suit by Atlas Devices (photo credit: Atlas Device Inc)
(e) Akin, *et al.*, "Field Analogue Simulations Investigating EVA/Robotic Collaboration in Lunar Exploration," ICES 2011.
(f) Davis *et al.* , "Testing of the NASA Exploration Extravehicular Mobility Unit Demonstration (xEMU Demo) Architecture at the Neutral Buoyancy Laboratory," ICES 2019.

Introduction [3/3] – Motivation





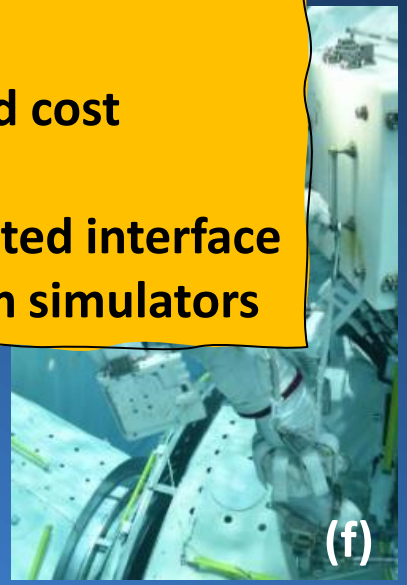


Hybrid Space Suit Simulator (HS3) is a cost and schedule-effective research tool for EVA analog testing:

- **Modular spacesuit simulator**
- **Simplifies and reduces overhead cost**
- **Simulation assets similar to limited interface and unpressurized full-spectrum simulators**







- Types of Spacesuit simulators
  - a) Unsuited analog
  - b) Limited interface
  - c) Representational simulation
  - d) (and e) Unpressurized full-spectrum simulation
  - f) Pressurized spacesuits

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Problem Definition

- **Problem Statement:** A cost/schedule effective unpressurized EVA physical and cognitive workload simulator is needed for EVA analog testing in support of NASA HH&P studies to close HH&P knowledge gaps for the evolving exploration missions.
- **Scope of this paper:** describes the design, development and subsequent technology demonstration of the HS3 during simulated EVAs.

Heat Exchange Mechanisms During EVA

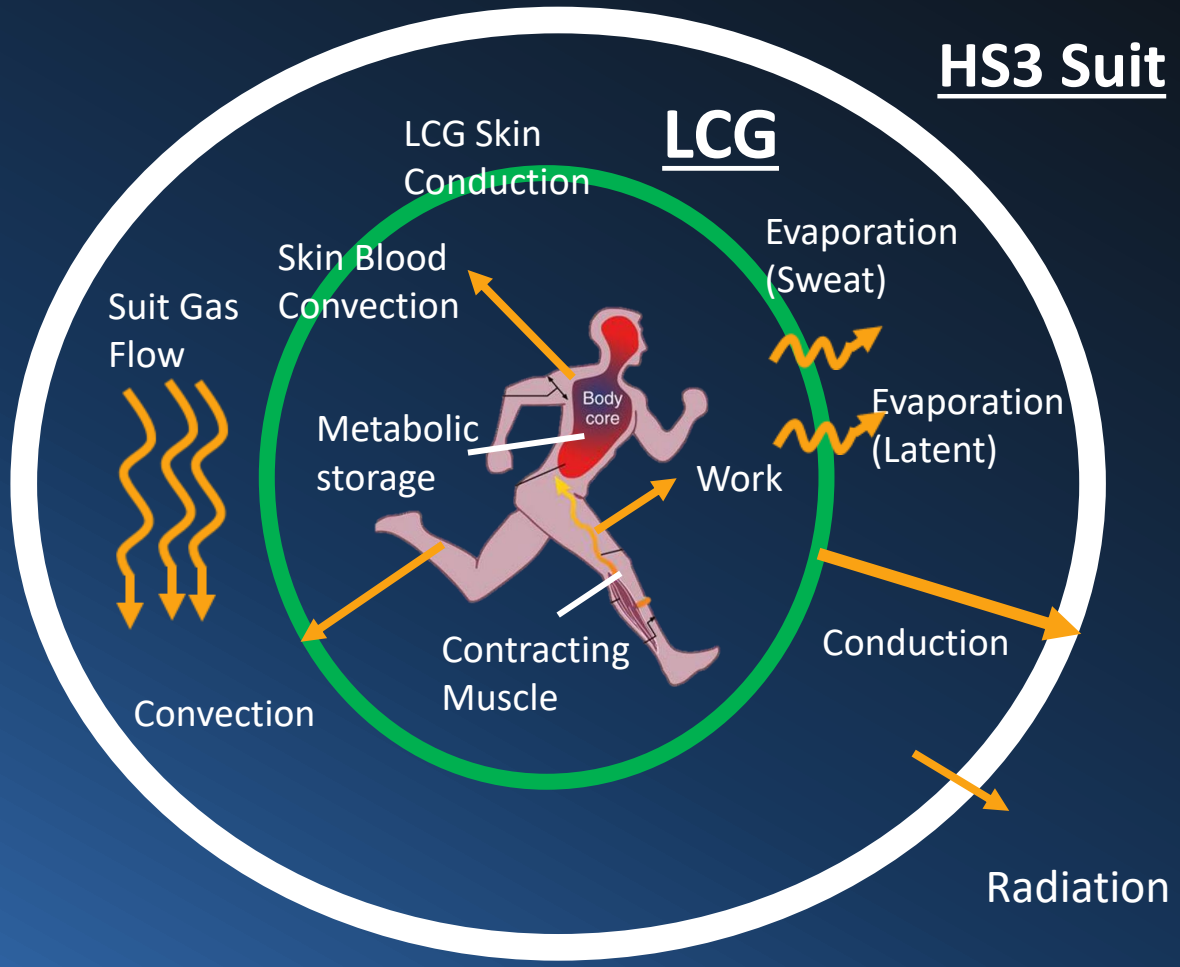
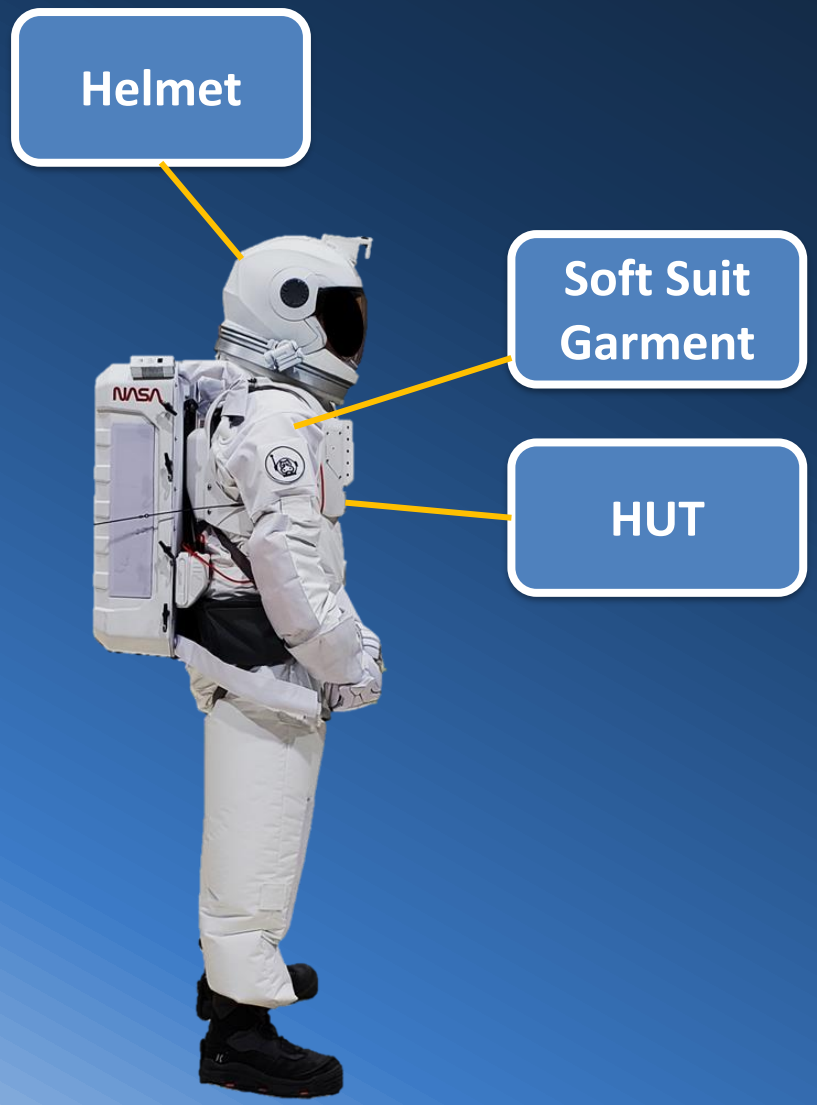


Diagram adopted from Hoffmann, et al., Human Thermal Assessment of Traverse and Geology Task Iterations During Simulated Lunar Extravehicular Activity. IEEE 2023.

Hardware Design/Implementation [1/2]



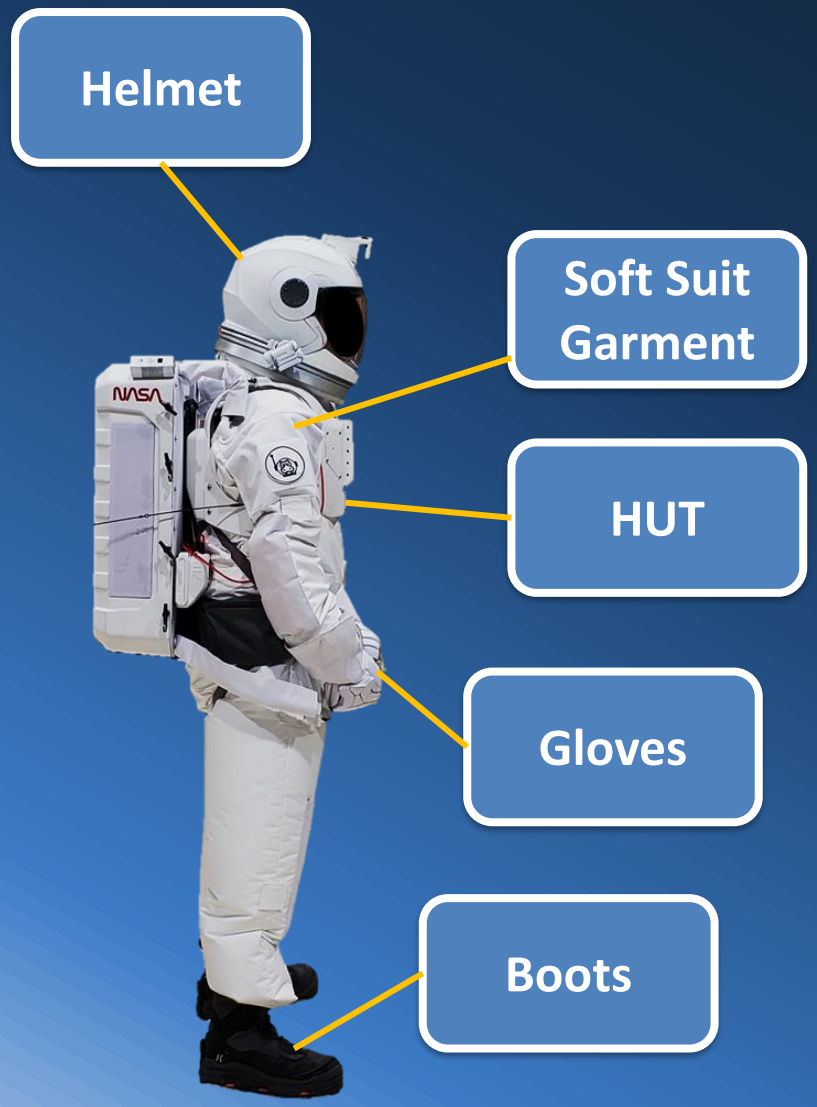






HUT = Hard Upper Torso
PLSS = Portable Life Support System
LCG = Liquid Cooling Garment

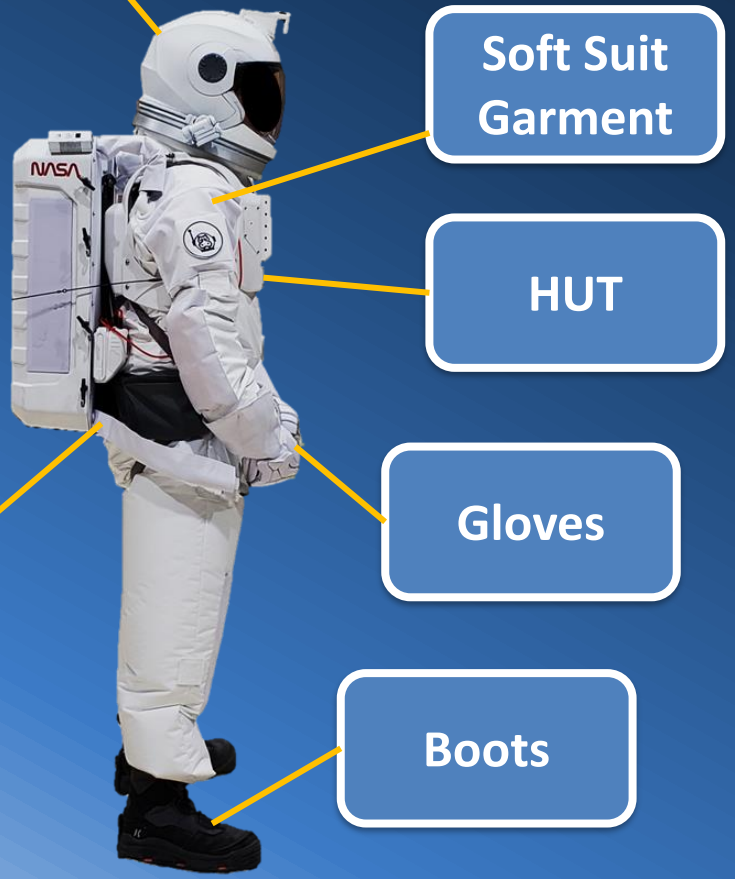
Hardware Design/Implementation [1/2]





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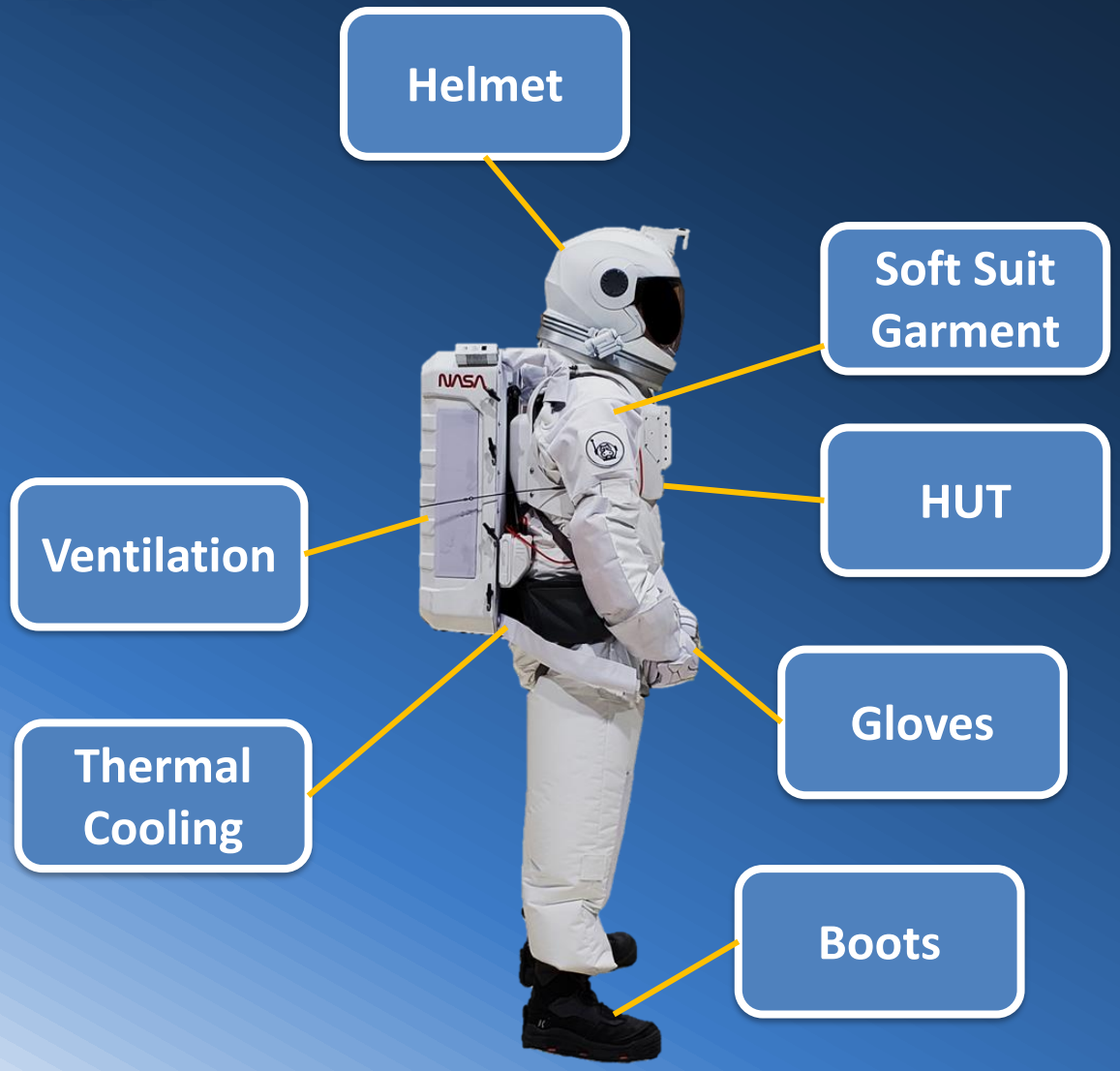






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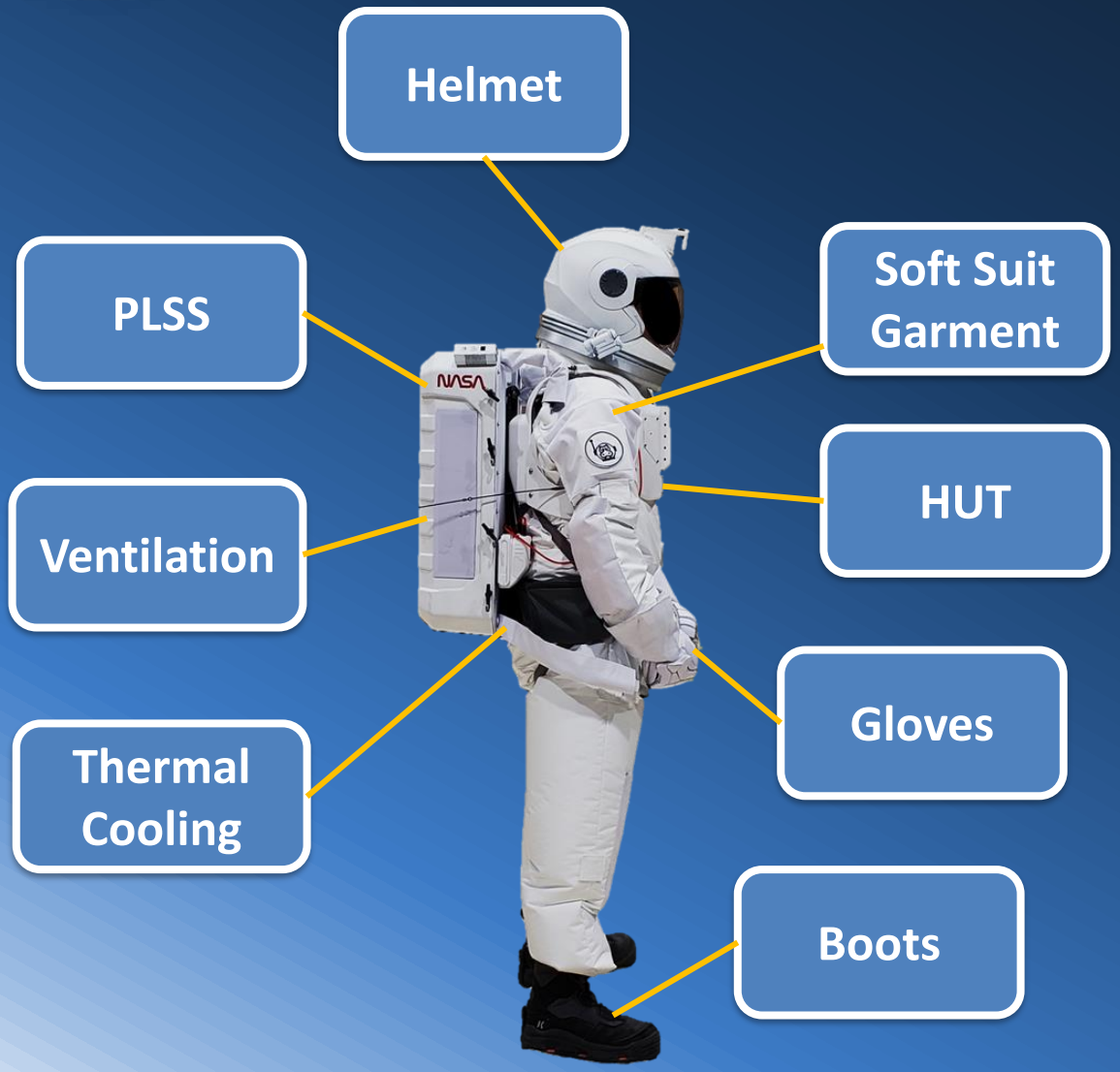






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Hardware Design/Implementation [1/2]

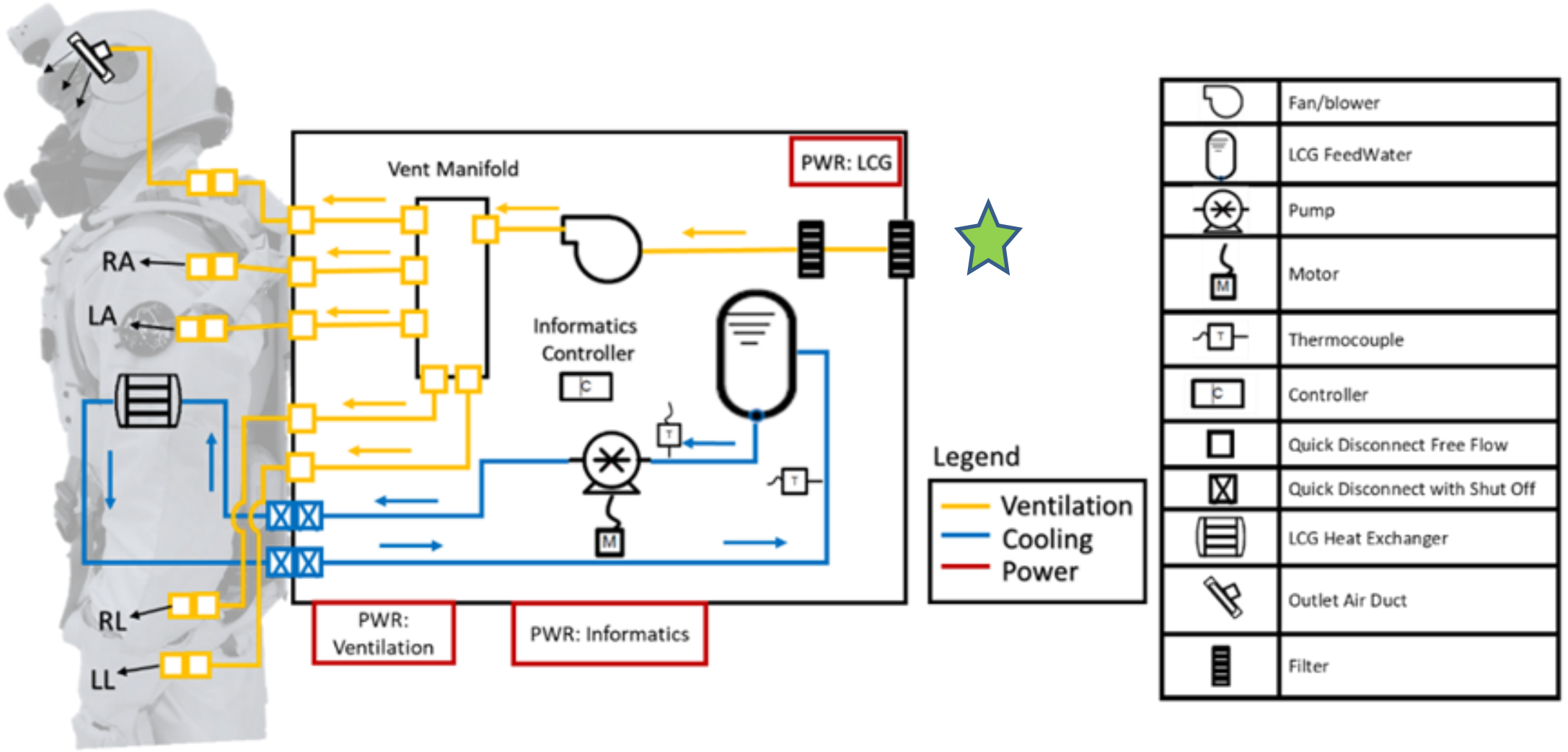






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Hardware Design/Implementation [2/2]



Methods [1/4]

- Evaluate HS3 hardware and capability
  - **2** healthy male subjects without suited experience
  - **3-hour** simulated EVA
  - EVA timeline (similar functional movements and exploration tasks from the Physical and Cognitive Exploration Simulations (PACES) procedures commonly used in HH&P testing [1])

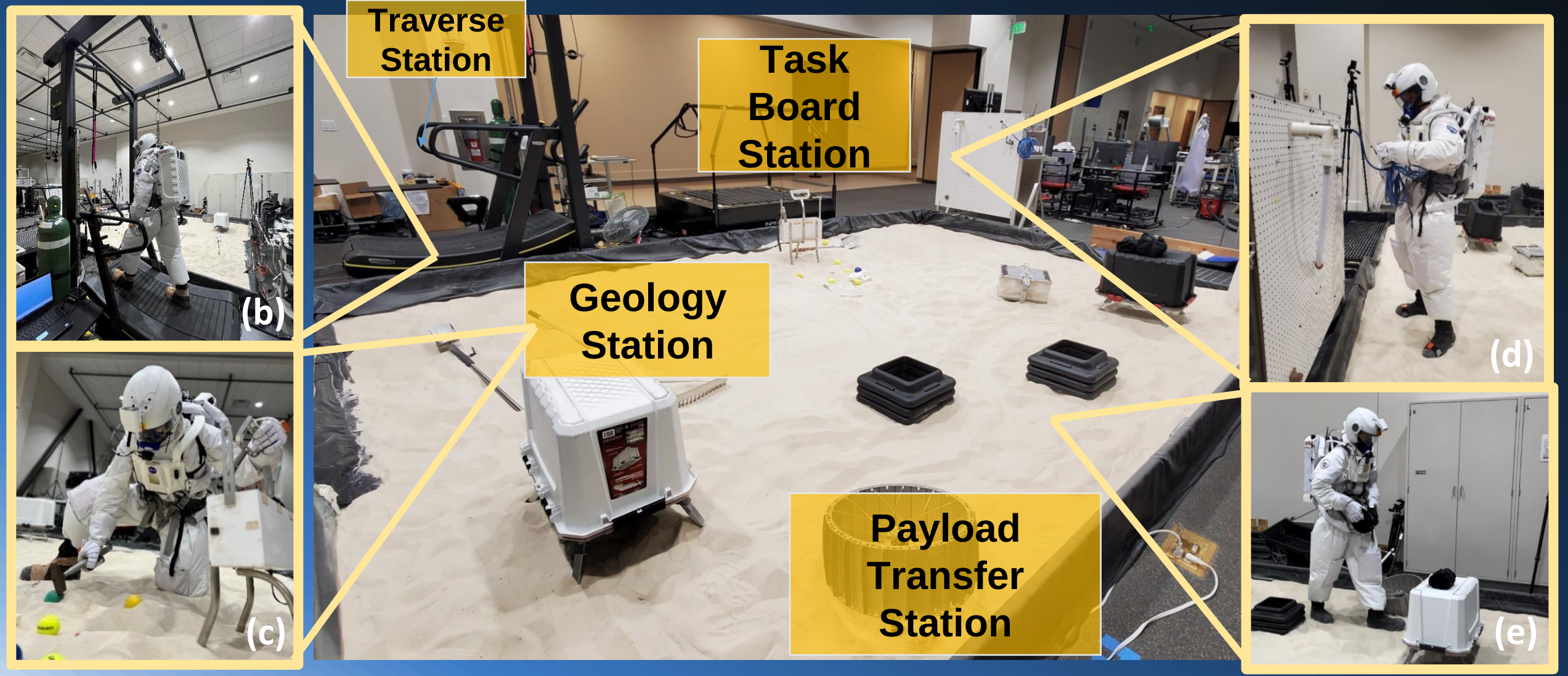
- HS3 system performance + human physiology data were collected
  - **3-minute breaks** (allow return to baseline)
  - Minimum of 5-minute (allow steady state)
  - Subjects monitored for 85% of age-calculated maximum heart rate for less than 2-minutes continuously.

Table 1. Detailed test timeline of HS3 assessments.

EVA Timeline Tasks	Planned Task Time
Sensor Setup	0:25
Suit Donning	0:25
Baseline Data Collection/Mounting	0:05
Traverse station 1: 500m (Resistance 3/4)	0:10
3-minute Break + Surveys	0:03
Task Board Station	0:05
3-minute Break + Surveys	0:03
Traverse station 2: 500 m (Resistance 7/8)	0:10
3-minute Break + Surveys	0:03
Geology Station 1: Trenching	0:05
3-minute Break	0:03
Geology Station 2: Chip Sample hammering)	0:05
3-minute Break	0:03
Geology Station 3: Raking	0:05
3-minute Break + Surveys	0:03
Traverse station 3: 500m (Resistance 5/6)	0:10
3-minute Break + Surveys	0:03
Payload transfer station: 10lb Large, rocks	0:05
3-minute Break + Surveys	0:03
EVA cleanup	0:05
Suit Doffing	0:30
Total Planned time:	**2:49**

[1] Bekdash, *et al.*, "Physical and Cognitive Exploration Simulations: Development and Testing of Exploration Activity Modules," International Conference on Environmental Systems, Lisbon, Portugal, 2020, pp. 1-12.

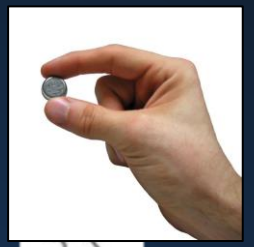
Methods [2/4]

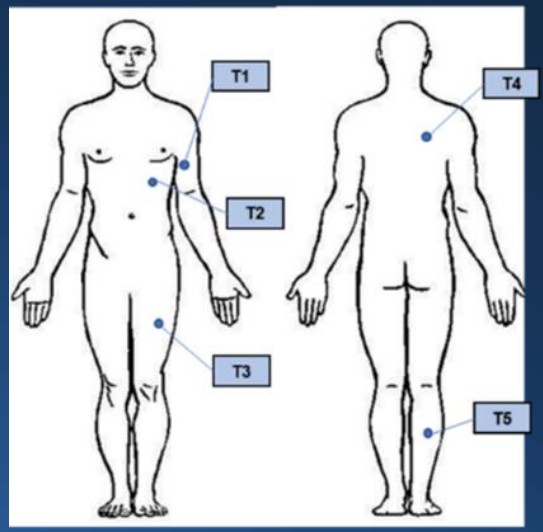

Traverse Station
Task Board Station
Geology Station
Payload Transfer Station
(b)
(c)
(d)
(e)

Methods [3/4]

- Dependent Variables
  - Physical Workload:
    - Metabolic Rate and Heart Rate (COSMED K5)
    - Heart rate max is based on age predicted value.
  - Thermal:
    - Skin temperature and humidity x6 (iButtons)
    - LCG inlet/outlet temperature (Resistive Temperature Detector)
    - PLSS temperature and humidity (Vaisala HMP7)
  - Subjective surveys: commonly used EVA analogs
    - Simulation quality rating, simulation task acceptability, Rating of Perceived Exertion (RPE), NASA Task Load Index (TLX), comfort, thermal acceptability, and fatigue scales.
    - Access physical and cognitive workloads









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Methods [4/4] - Analysis

- Metabolic Rate calculation was completed using the Péronnet Formula [1] (Eq. 1):

$$Energy\ Expenditure\ \left(\frac{kcal}{hr}\right) = 60 * \left(\frac{4.039 * VCO_2}{RER} + 1.157 * VCO_2\right) \quad (1)$$

- Mean Skin Temperature was calculated via the Ramanathan method [2] (Eq. 2):

$$Ts = 0.3 * (Chest + Bicep) + 0.2 * (Quadricep + Calf) \quad (2)$$

- Task Averages were calculated over the task blocks to view overall changes in:
  - Mean skin temperature
  - HS3 LCG delta temperature (between inlet and outlet)
  - PLSS temperature and humidity

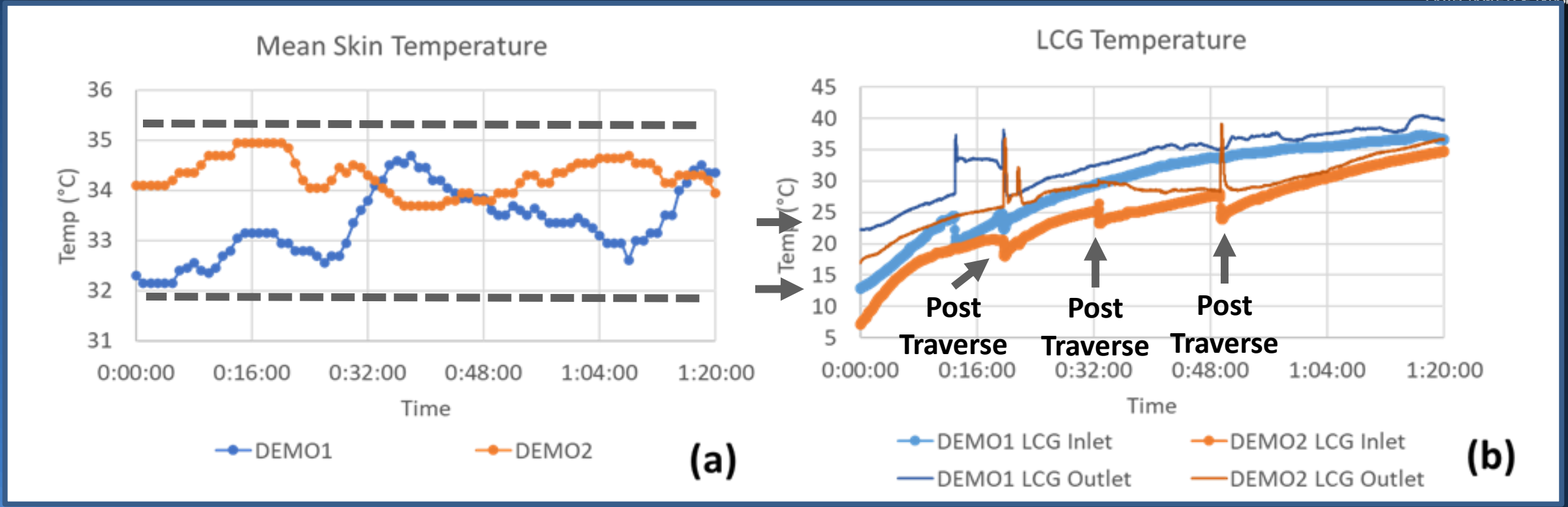
[1] F. Péronnet and D. Massicotte, "Péronnet F, Massicotte DTable of nonprotein respiratory quotient: an update. Can J Sport Sci 16:23-29," *Can. J. Sport Sci. J.*, 1991.
[2] D. Mitchell and C. H. Wyndham, "Comparison of weighting formulas for calculating mean skin temperature," *J. Appl. Physiol.*, 1969

Results – HS3 System Characteristics

- **Weight** = 40 lbs
- **Electrical system**: 6 isolated battery power systems integrated in PLSS
  - Average power consumption < 30W (average battery life of 2 to 2.5 hours)
  - Battery hot swap allows battery life extension to 5-8 hours
- **Communication range**: 60'(COTS wireless earbuds) or 100' (integrated motorcycle headset)
- **Ventilation System**: 30 L/min

Power Systems	Main Load	Power (W)	Battery Life (hr)	Battery Type
A	HRM, Thermocouples for LCG	6.52	12	DeWalt 203 Li-ion rechargeable battery pack (80Wh)
B	LCG	1.63	10	Rechargeable battery (16.8Wh)
C	Ventilation	16.0	2.5	DeWalt 203 Li-ion rechargeable battery pack (40Wh)
D	COSMED K5	5.58	4	Rechargeable battery pack (22.3Wh)
E	Communication & lighting	·	6-7	Rechargeable battery pack, disposable alkaline batteries (light)
F	Thermal (iButton)	·	10 years	Single-use battery
Total		29.7		

Results – Thermal Performance

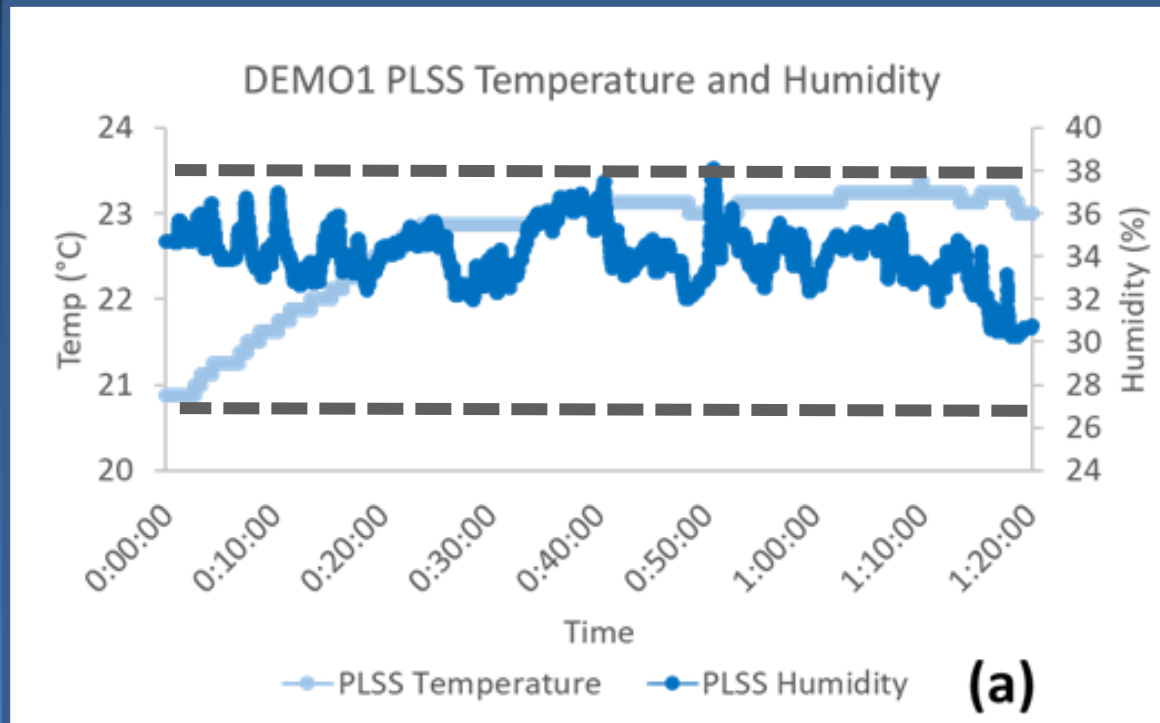


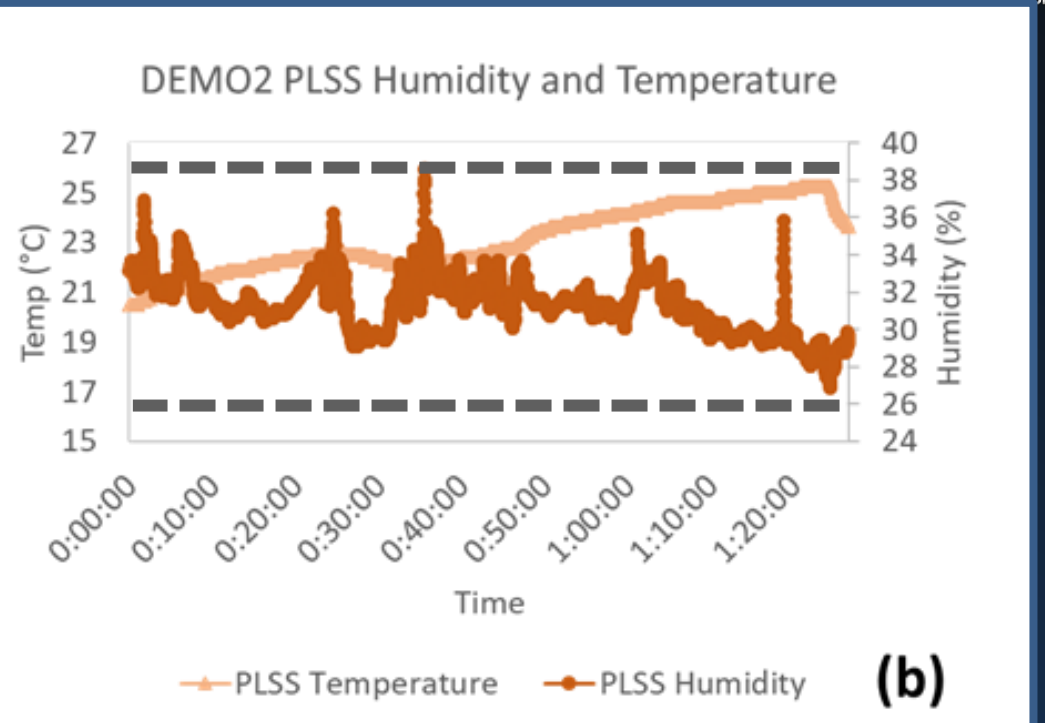
General cooling effectiveness of the LCG (offload of 3 to 4 °C) → Stable mean skin temp

Recommendation: pre-chill water and adding backup feedwater bladders

LCG outlet temperatures corresponded to high workload activities

Results – Thermal Performance

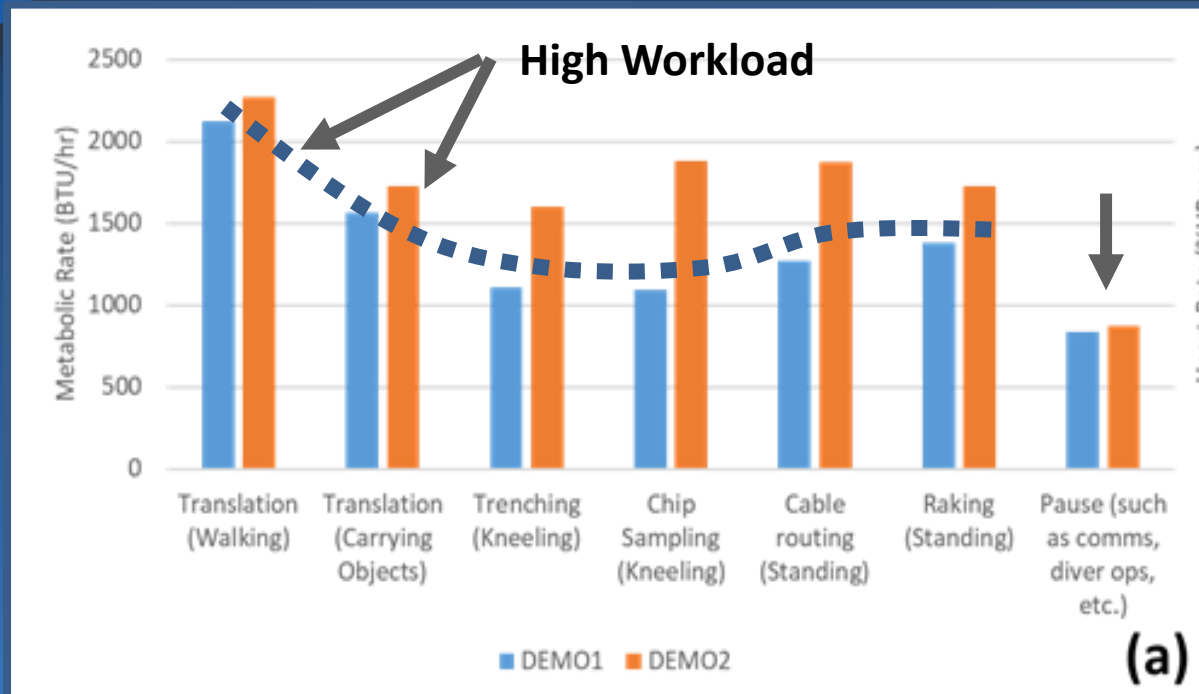


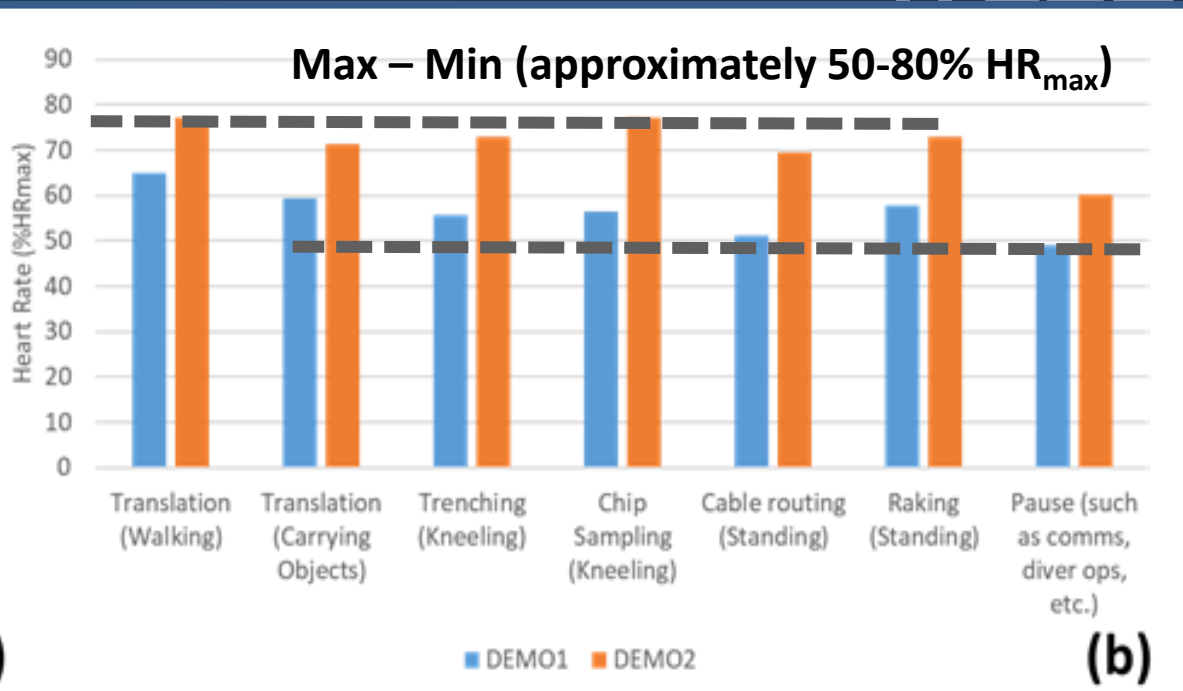


Stable at room temperature and humidity stayed between 31-38%

Temperature rose during through the EVA → pre-chilled LCG feedwater progressively warming, and hot swap

Results – Metabolic and Heart Rate





Category	DEMO1		DEMO2	
	Percent of HR_{max}	Avg Metabolic Rate (BTU/hr)	Percent of HR_{max}	Avg Metabolic Rate (BTU/hr)
Translation (Walking)	65% ± 8	2124 ± 549	77% ± 8	2269 ± 717
Translation (Carrying objects)	59% ± 2	1563 ± 215	71% ± 1	1723 ± 262
Trenching (Kneeling)	56% ± 2	1108 ± 221	73% ± 1	1597 ± 149
Chip Sampling (Kneeling)	56% ± 3	1092 ± 170	77% ± 2	1881 ± 272
Cable Routing (Standing)	51% ± 5	1268 ± 241	70% ± 4	1870 ± 289
Raking (Standing)	58% ± 3	1379 ± 216	73% ± 2	1724 ± 153
Pause (Resting, Standing)	49% ± 6	836 ± 327	60% ± 7	869 ± 203

Binned EVA task categories → showing highest metabolic driver in traverse task (consistent results with other analogs)

HS3 is able to adjust/capture physical workload.

Results – Cognitive Workload and Subjective Surveys

- **Range of motion** is limited with restrictive field of view
- **Acceptable simulation quality** - no/minor limitation to data validity with possible feasibility of EVA immersion
- **Cognitive workload** (geology and task board):
  - average effort (10% to 50%) on TLX scale
  - 2 to 3 (low workload) for Bedford scale





Summary

- This paper demonstrated HS3 as a **modular space suit simulator** with an integrated suite of human **physiology sensors** as a **new research tool** for ground-based EVA simulation and evaluation.

- This paper is a **technology proof of concept demonstration**.

- Metabolic rate, heart rate, mean skin temperature, and suit thermal metrics were successfully collected using the integrated sensor platform during 3-hour simulated EVAs.

- HS3 represents a new research tool to provide physical and cognitive workload simulation during simulated EVA with the following benefits

  - Customizable and modular use to address study specific aims
  - Cost and schedule effective
  - Provide immersion

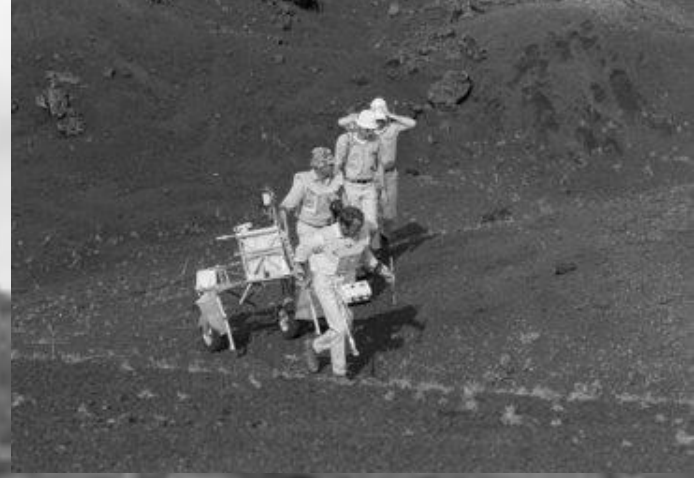
Future Work

- FY2023 (to be completed by September 2023)
  - **Characterization Study:** characterize the physical and cognitive workload simulation during EVA simulation for a larger cohort of subjects in the 1-g APACHE environment
    - Baseline HS3's operational characteristics (e.g., communication, power, and thermal)
    - Characterize core temperature, range of motion, field of view, biomechanics, and immersion
    - Subjects with pressurized-suit experience to comment on HS3's simulation characteristics
  - **Computational EVA simulations:** use HS3 as a platform for software testing and quality assurance procedures would be carried out.
- FY2024 and beyond:
  - Comparing the relevancy of HS3 to existing analog space suits
  - Comparing previous datasets of spacesuit testing in a simulated partial gravity environment
  - Applicability of HS3 configurations for different EVA scenarios

Acknowledgments

- *NASA Exploration Capabilities for funding this work*
- *Human Physiology, Performance, Protection and Operations Team (H-3PO)*
  - Kyoung Jae Kim
  - James Stoffel
  - Patrick Estep
  - Taylor Schlotman
  - Alex Baughman
  - Alex Garbino
  - Brett Siders
  - Andrew Abercromby





Thank you.

Questions?

Monica.hew@nasa.gov

Photo Credit: NASA

Traverse Station

- Curved, passive treadmill (Skillmill Connect, Technogym, Italy)
- Each subject: x3 traverses of 500 m in a 10-minute window
- The different resistance levels were chosen to mimic the percent grade incline levels used in the H-3PO ARGOS metabolic rate characterization study traverses.

Table 2. Comparable passive treadmill resistance levels to the percent-grade incline at the ARGOS motorized treadmill based off gait. *All passive treadmill resistances are at 2 mph.*

Passive Treadmill Resistance Level	Motorized Treadmill % Grade at ARGOS
3/4	0%
5/6	10%
7/8	20%

Heart Rate Monitoring

- For subject safety, heart rate measurements were monitored throughout the EVA to avoid subjects operating at above 85% of their age-calculated maximum heart rate (HRmax¬) for longer than 2-minutes continuously. The HRmax¬ was estimated by age using Eq. (1). [1]

$$HR_{max} = 208 - 0.7\ x\ age \quad (1)$$

- Subjects' heart rate zone can then be computed by evaluating the measured heart rate and the percentage of HRmax using Eq. (2). The %HRmax can be used to assess the physical workload of the subject.

$$\%HR_{max} = \frac{HR}{HR_{max}}\ x\ 100\% \quad (2)$$

[1] Tanaka, H., Monahan, K. D., and Seals, D. R., "Age-predicted Maximal Heart Rate Revisited," *Journal of the American College of Cardiology*, Vol. 37, No. 1, 2001, pp. 153-156.

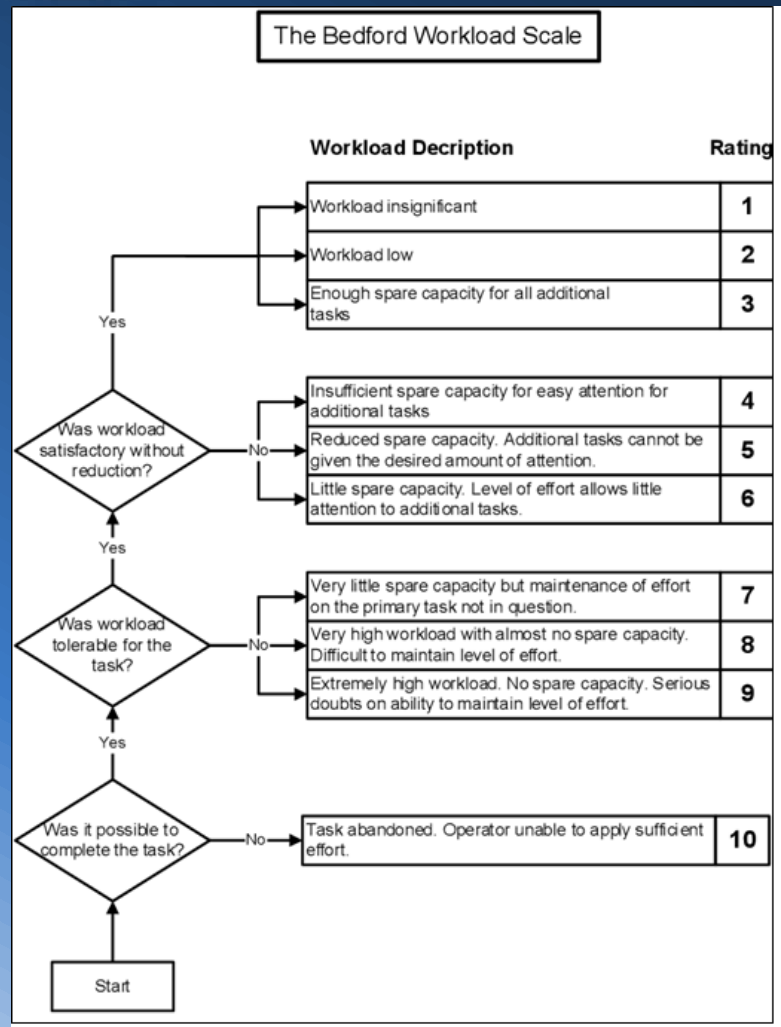
Thermal Results

Table 4. HS3 Sensor Data Summary

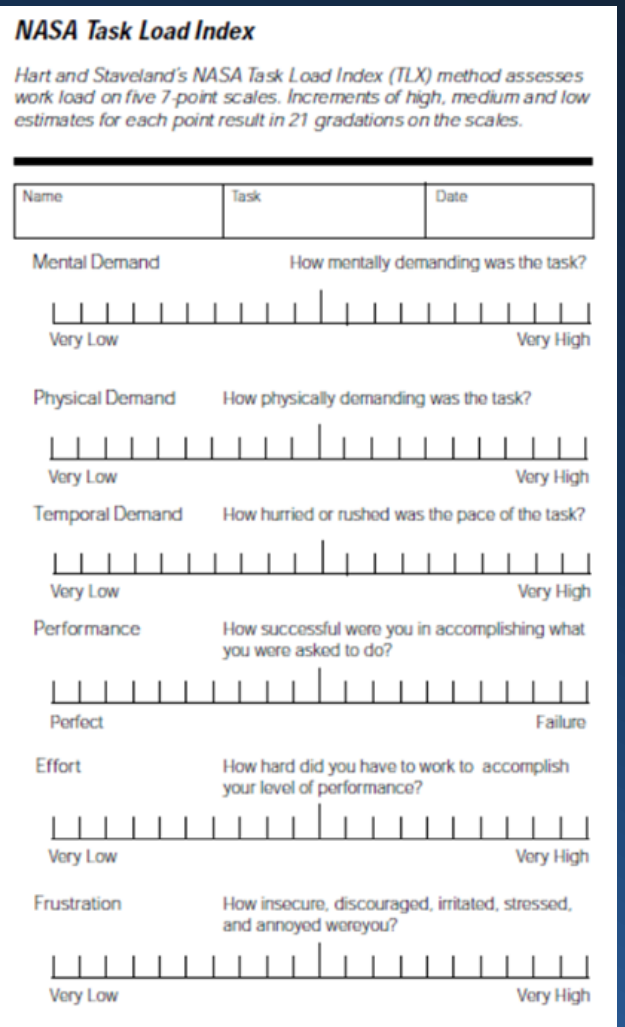
HS3 Sensor Data		
Suit Outputs	**DEMO1**	**DEMO2**
LCG Inlet Temperature (°C)	29.57 ± 6.62	25.63 ± 6.48
LCG Outlet Temperature (°C)	33.53 ± 6.62	29.21 ± 4.79
PLSS Temperature (°C)	22.71 ± 0.68	23.11 ± 1.32
PLSS Humidity (%)	34.06 ± 1.35	31.32 ± 1.51
Mean Skin Teamperature (°C)	32.75 ± 0.94	34.04 ± 0.71

Data are presented as mean ±standard deviation

Bedford Workload Scale & NASA task load index (TLX)



a.)



b.)

- **Bedford workload rating:** a uni-dimensional rating scale designed to identify operator's spare mental capacity while completing a task
- **NASA task load index (TLX):** a tool for measuring and conducting a subjective mental workload (MWL) assessment while they are performing a task

Credit: NASA