xEMU Spacesuit Boot Lunar South Pole Thermal Vacuum Testing

ICES-2026-600

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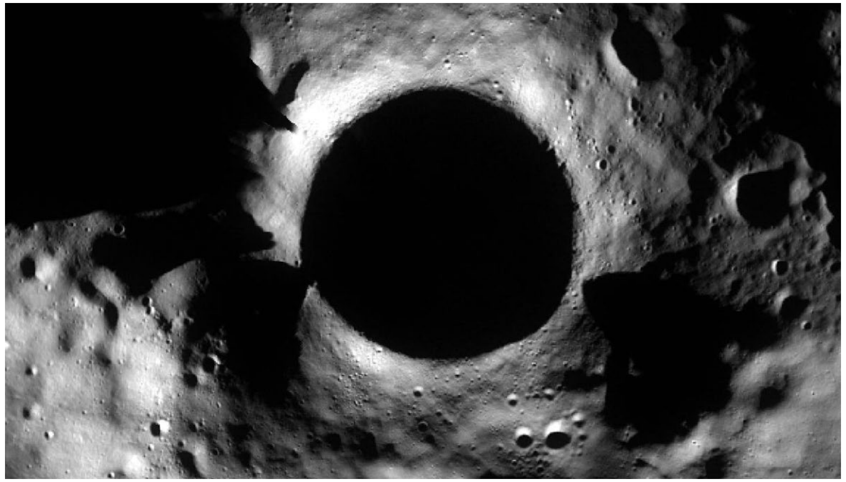
Presentation Outline

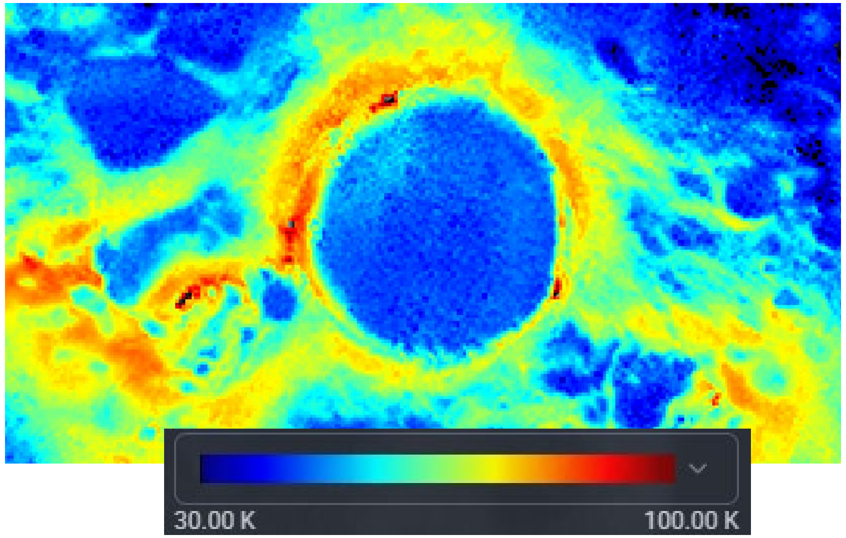
- **Background**
- **Hardware**
- **Test Results**
- **Potential Improvements**
- **Conclusions**

Background – Lunar South Pole Environment

- **Regolith surface temperatures at lunar south pole are expected to reach < 50K.**
  - In shaded regions, the expected radiative sink temperature will also drop down to these cold temperatures
- **Lunar boots are expected to exchange with the environment through:**
  - Conduction to the lunar regolith
  - Radiation to the sink temperature



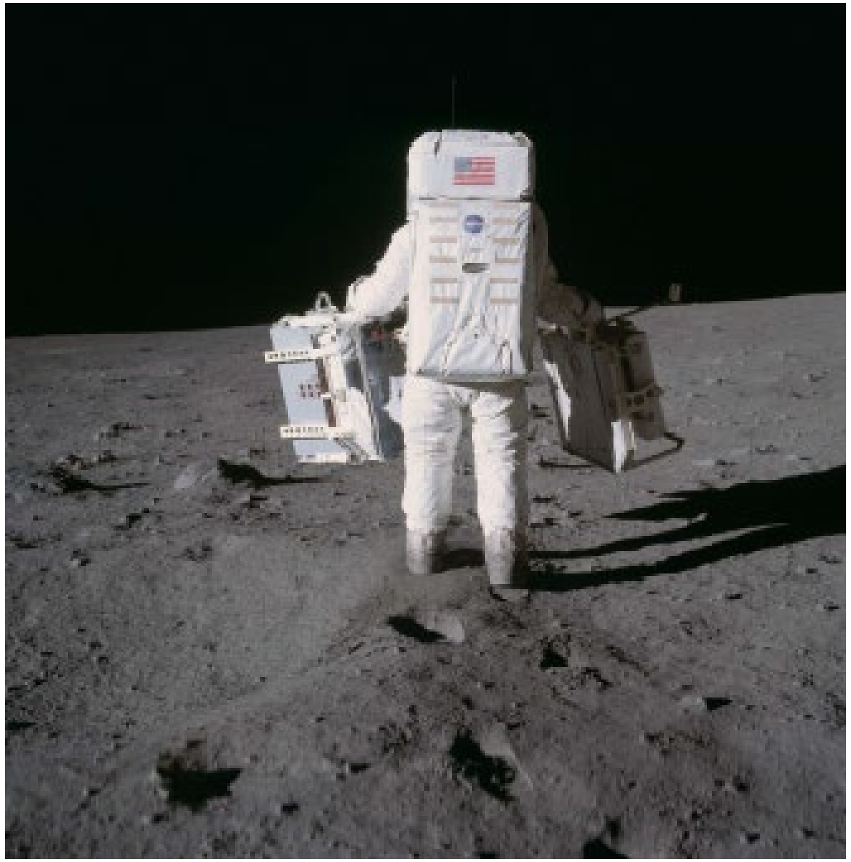
Global Minimum Surface Temperature at Shackleton Crater (K)



Data from LRO Diviner [1]: https://bit.ly/4elCSqS

Background – Comparison to Apollo Data

- **Apollo missions experienced different anticipated environments and requirements than Artemis missions**
- **Apollo missions were more focused on the hot environment due to landing site:**
  - Testing up to 394 K environment for 2 hours.
  - Some testing at cold condition (144 K) for short duration due to account for transition into shadowed region.
- **Artemis missions target landing on lunar south pole where temperature requirements are much colder.**



Test Objectives

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1. Characterize the government reference design xEMU spacesuit boot performance at Artemis surface conditions

2. Validate the government reference design xEMU spacesuit boot thermal model

Hardware – xEMU Boot

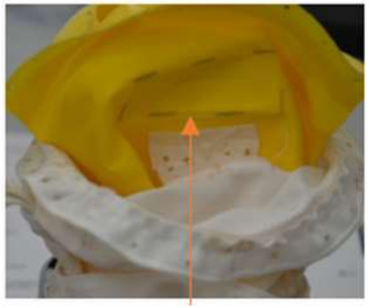
- **Boot was originally tested in Chamber B testing at NASA JSC [2]**
- **Modifications were made to MLI cover based on data from Chamber B testing**
- **Boot was instrumented with 72 sensors**
    - 56 external (outside pressure bladder)
    - 16 internal (inside pressure bladder)

xEMU Boot without MLI cover

xEMU Boot with MLI cover

Hardware – xEMU Boot

Sizing Insert



Bladder

Restraint

Frame

Internal

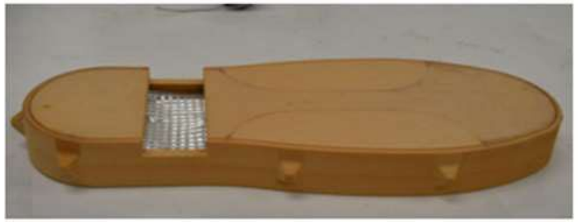
External

Cross Section View

EPG

Outsole

Thermal Insert

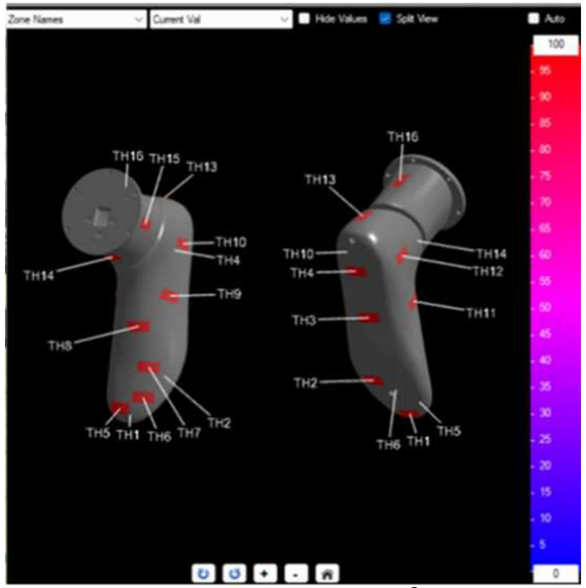


xEMU Boot Layers

Hardware – Thermal Foot System (TFS)

- **Goals of thermal foot system:**
  - Maintain an isothermal boundary condition in the boot
  - Measure the heat leak out of the foot/boot
- **Thermal foot system was designed for test series by Thermetrics [3].**
- **Temperature of foot is maintained through embedded fluid lines inside the foot**
  - Control box allows for direct control of the foot temperature
- **Foot is instrumented with 16 heat flux and temperature sensors**

TFS

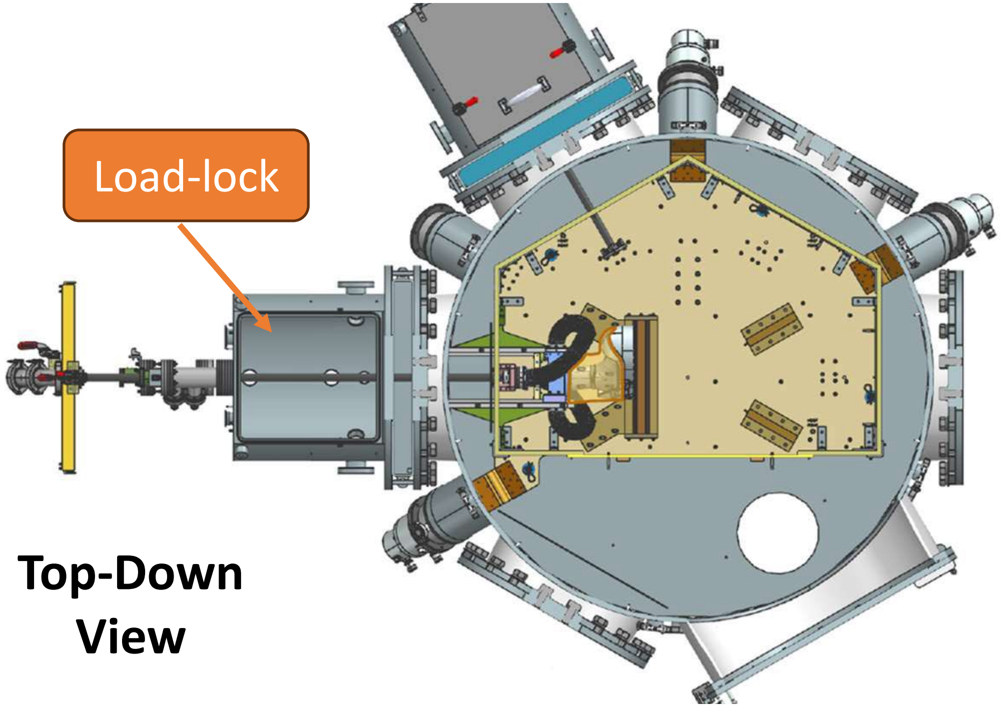


Sensor Locations

Control Box & “Chiller”

Hardware – Test Facility

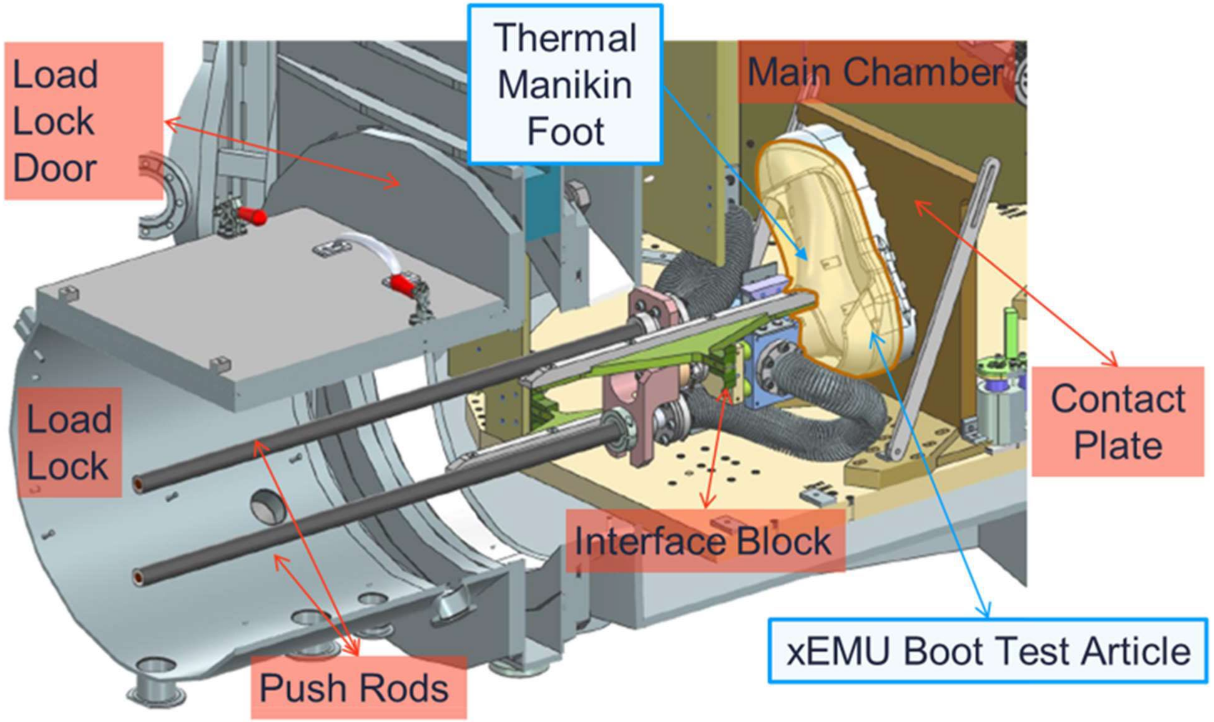
- **Boot was tested at JPL in the CITADEL (Cryogenic Ice Testing, Acquisition Development, and Excavation Laboratory) chamber**
  - Rough dimensions: 1.2 m tall x 1.5 m wide
- **Test facility capabilities:**
  - Temperature conditioning down to 50 K
  - Load-lock for simulation of IVA to EVA transition

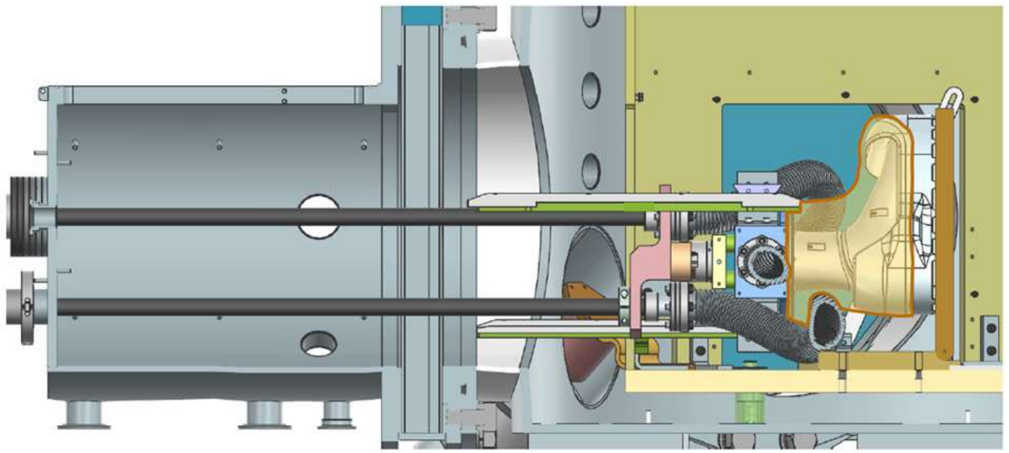


Top-Down View

Hardware – Test Facility

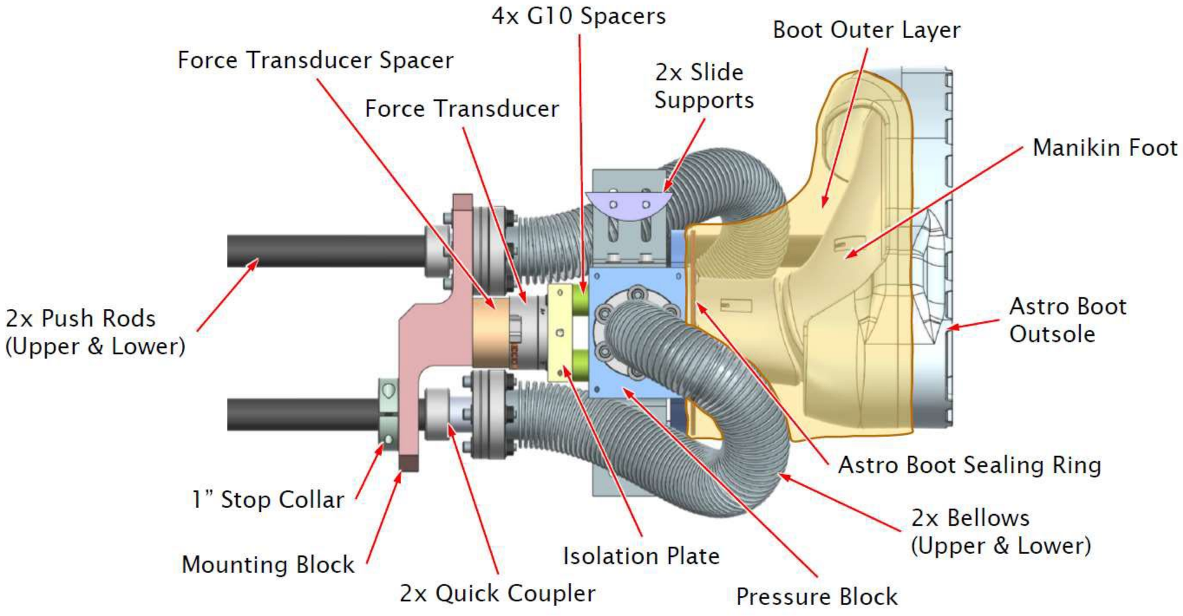
- **Load lock assembly enables testing that simulates transition from IVA to EVA conditions.**
  - Thermal environment in load-lock is near ambient conditions (~293 K)
  - Door between main chamber and load lock can enable re-pressurization of load lock while maintaining vacuum in main chamber.
- **Push rod system enables transition of boot into main chamber.**
  - Nitrogen (for boot pressurization), water lines for TFS, and wiring for instrumentation pass through the push rods.
  - Locking system enables a constant contact force between boot and contact plate





Hardware – Boot Interface System and Pressure System

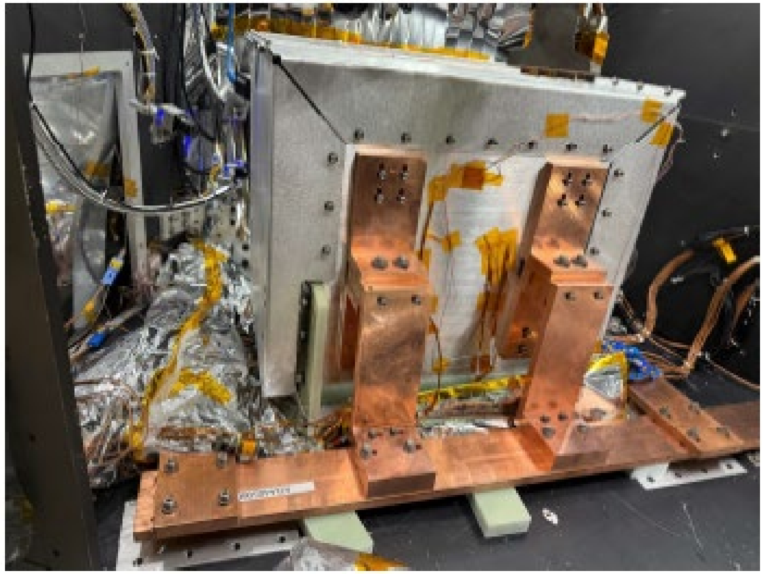
- **Boot interface system connected the push rods to the boot assembly**
  - Mounted with boot using a compatible bolt hole pattern
  - Measure contact force between boot and contact object
- **Pressure system was design to pressurize the boot to 29.7 kPa (4.3 psia) while providing 42.5 LPM (1.5 ACFM)**
  - Nitrogen was used as pressurizing fluid
  - System was designed with relief valves to avoid over-pressurization
  - System prevented flow from relief valve from entering the main chamber
    - Lesson learned from glove testing



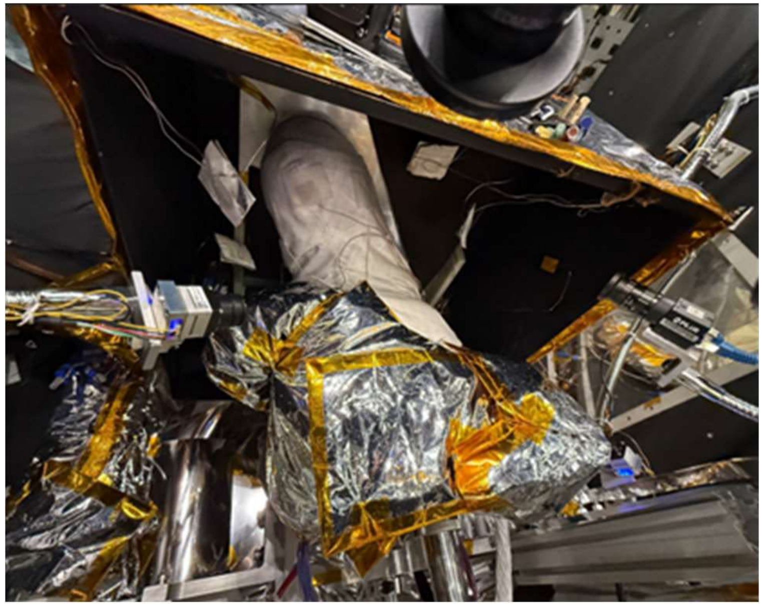
Boot Interface System

Hardware – Thermal Environment Simulation “Mini-shroud”

- **Thermal environment simulation was achieved through implementation of a smaller “mini-shroud”**
  - Insulated metal box inside of the main chamber
  - Directly tied to cold-heads through copper bars
- **Radiative thermal environment was measured with 6 coupons**
- **Mini-shroud was significantly smaller than the main chamber which allows for quick conditioning periods.**
- **Challenges with maintaining a cold enough radiation environment were observed – these are addressed in detail in ICES-2026-153 [4].**



Back side of Mini-shroud



Inside of Mini-shroud

Available Parameters for Testing

- **Stomp Pad Contact Force**
  - Contact force could be adjusted manually to enable radiation test points (no contact force), 178 N (40 lbf) contact, and 445 N (100 lbf contact).
  - Greater contact force is expected to reduce contact resistance at interfaces, resulting in larger heat leak from boot.
- **Environment Temperature**
  - Temperature of “Mini-shroud” could be adjusted to simulated different radiative and contact environments.
  - Targeted 48 and 100 K test points
- **Foot Temperature**
  - TFS enables different foot temperatures which act as internal boundary condition
- **Ventilation Flowrate**
  - Pressure system enables different ventilation flowrates to investigate the potential impact of flow in the boot on thermal performance.

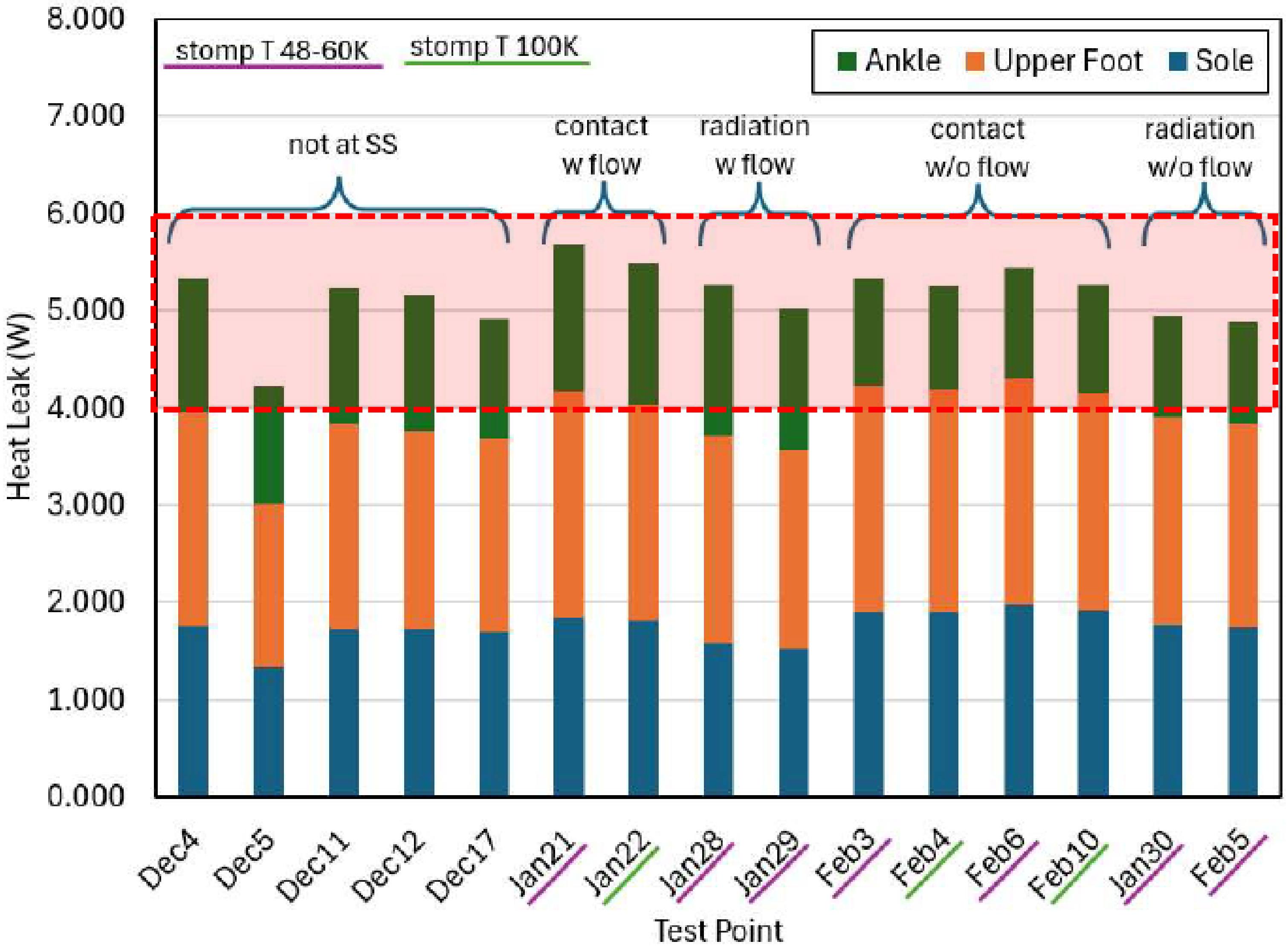
Test Matrix

Test Matrix

Test Day	Vent Flowrate (SLPM)	Case Type	Contact Pressure (N)	Foot Temp Setpoint (K)	Measured Foot Temp (K)	Stomp Pad Temp Setpoint (K)	Measured Stomp Pad Temp (K)	Measured Coupon Environment Temps (K)
Dec 4	12.4	Contact	445	306.15	304.01	100	73.15	180.75
Dec 5	12.4	Radiation	0	306.15	304.27	100	85.98	188.05
Dec 11	12.4	Contact	178	306.15	304.77	48-60	63.20	181.29
Dec 12	12.4	Contact	178	306.15	304.83	100	87.38	186.45
Dec 17	12.4	Contact	445	301.15	299.94	48-60	63.65	180.37
Jan 21	12.4	Contact	445	306.15	304.69	48-60	67.40	180.01
Jan 22	12.4	Contact	445	306.15	304.73	100	94.28	186.69
Jan 28	12.4	Radiation	0	306.15	304.78	48-60	66.30	180.03
Jan 29	12.4	Radiation	0	306.15	304.82	48-60	66.38	180.31
Jan 30	0	Radiation	0	306.15	304.85	48-60	66.25	179.99
Feb 3	0	Contact	445	306.15	304.77	48-60	66.7	180.09
Feb 4	0	Contact	445	306.15	304.80	100	93.83	185.73
Feb 5	0	Radiation	0	306.15	304.86	48-60	66.60	180.37
Feb 6	0	Contact	445	306.15	304.77	48-60	66.55	179.09
Feb 10	0	Contact	445	306.15	304.76	100	92.8	184.73

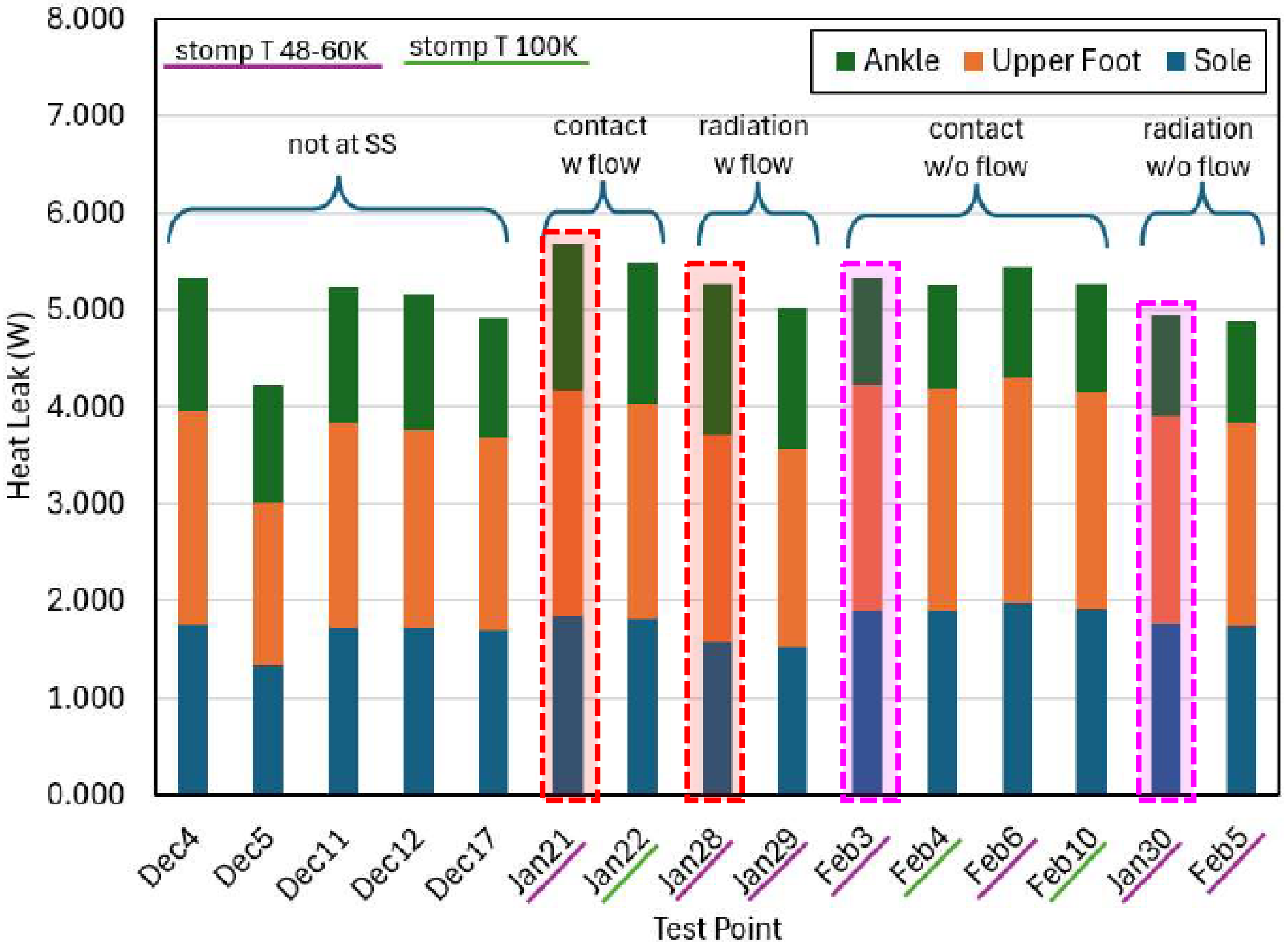
Test Results – Heat Flux

- **For all cases, the total heat leak falls between 4 and 6 W.**



Test Results – Heat Flux

- **For all cases, the total heat leak falls between 4 and 6 W.**
- **Contact cases has a slightly higher heat leak than the radiation test points, particularly in the sole.**



Test Results – Heat Flux

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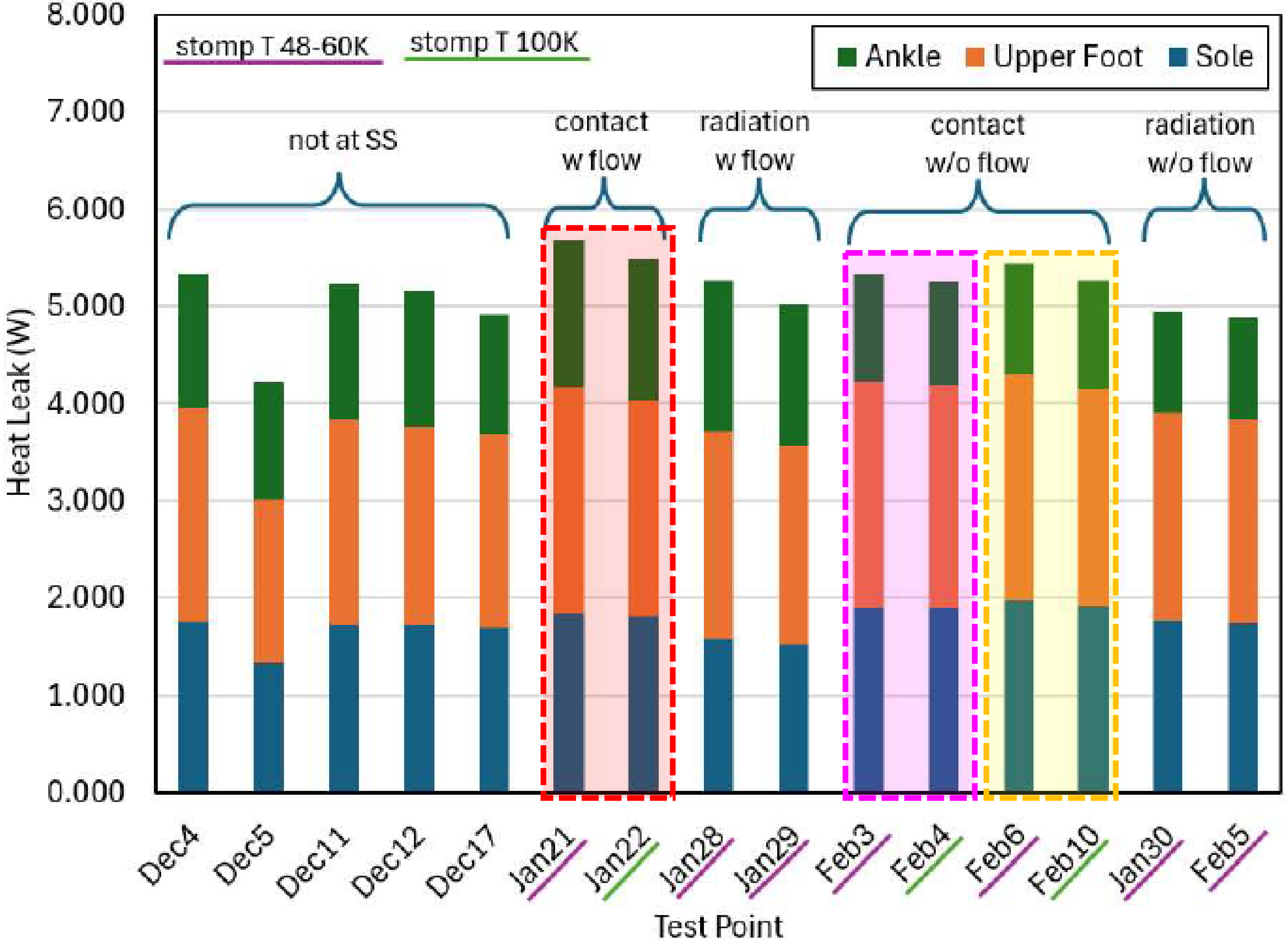
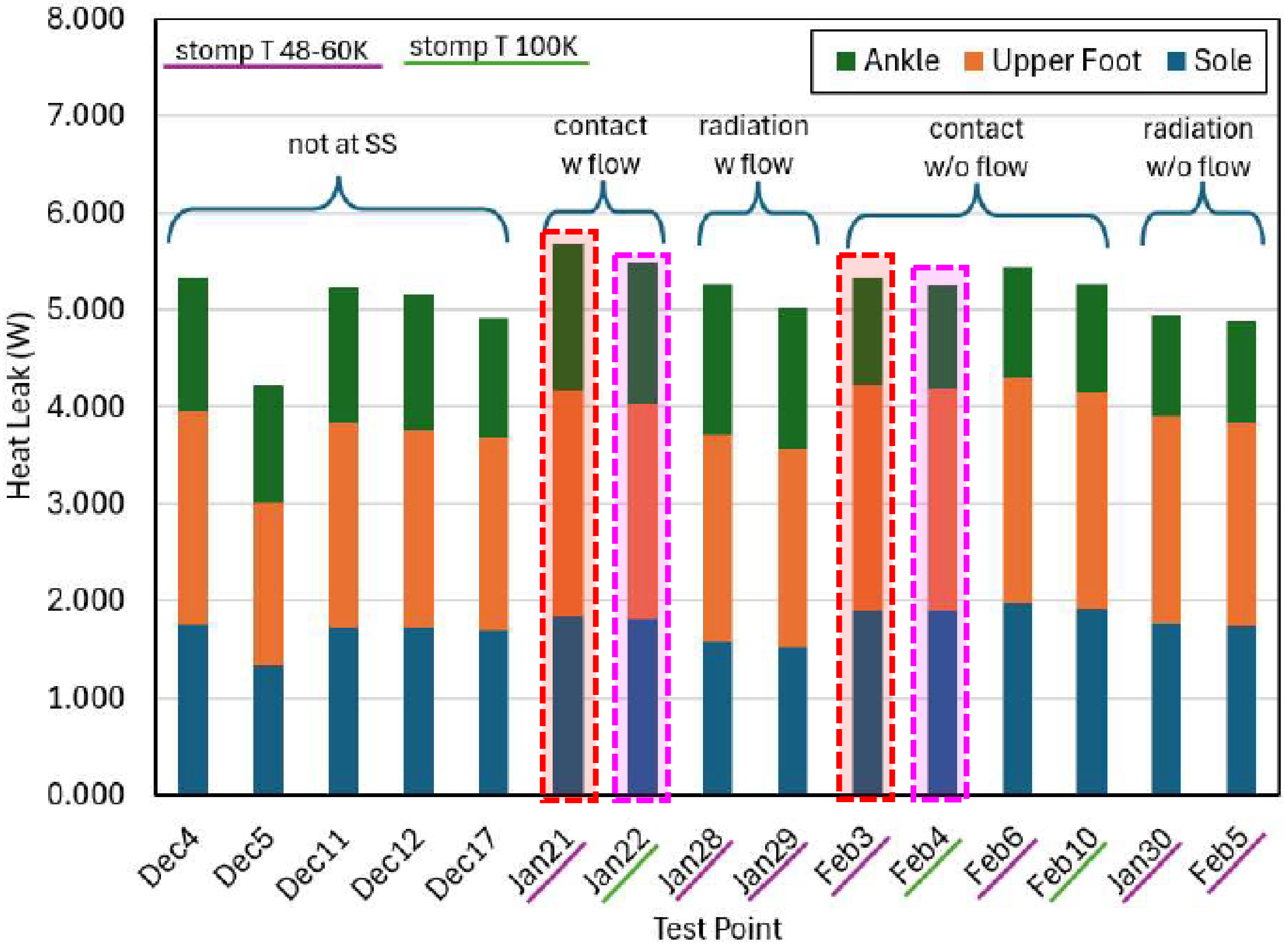
- **Contact cases has a slightly higher heat leak than the radiation test points, particularly in the sole.**
- **Warmer stomp pad temperatures result in slightly lower heat leak**



Test Results – Heat Flux

- **For all cases, the total heat leak falls between 4 and 6 W.**
- **Contact cases has a slightly higher heat leak than the radiation test points, particularly in the sole.**
- **Warmer stomp pad temperatures result in slightly lower heat leak**
- **Flow inside of the boot results in a slightly higher heat leak**
- **Significantly more detailed analysis of results is presented in ICES-2026-153 [4]**



Test Series Future Improvements

- **Radiation environment condition (as measured by coupons) was too warm**
  - Mitigation: Redesign of the mini-shroud for future testing to include:
    - (1) thicker metal walls
    - (2) more contact with cold copper bars
    - (3) improved thermal blanket surrounding the mini-shroud and protecting from load lock
    - (4) adjustment of stomp pad emissivity
- **Contacting regolith is different from contacting a metal contact plate.**
  - Mitigation: Future testing should consider quantification of the contact resistance from the boot to regolith
- **Testing was static and did not consider impacts of walking**
  - Mitigation: Future testing that looks a moving the boot off/on of the contact object to investigate:
    - (1) transient thermal performance
    - (2) impact of cryogenic temperatures on softgood flexion risk
- **Testing only investigated the cold condition**
  - Mitigation: Update mini-shroud design to allow for simulation of both hot and cold environments.

Conclusions

- **A repeatable test protocol was developed to evaluate spacesuit boots at lunar South Pole temperatures**
- **Quick look at results shows that in general, the thermal performance of the boot is relatively unsensitive to:**
  - Contact pressure
  - Flowrate inside the boot
  - Small variations in thermal environment
- **Data generated from this test series enabled correlation of model (discussed in ICES-2026-153 [4])**
- **Numerous future improvements to the test series were identified to improve characterization of lunar boot performance.**

References

1. J.-P. Williams, et. Al. , "Seasonal polar temperatures on the Moon," *Journal of Geophysical Researc: Planets*, 125, 2505-2521, 2019.
2. B. Swartout, D. Westheimer, & Z. Fester, "Exploration Extravehicular Mobility Unit (xEMU) Lunar Boot Chamber B Thermal Vacuum Testing Results," *International Conference on Environmental Systems,* Louisville, KY, 2024.
3. Burke, R., et. Al., "Development and Validation of a Novel Instrumented Thermal Hand Manikin for the Evaluation of Lunar Gloves", *International Conference on Environmental Systems,* Prague, 2025.
4. Quick, E., Andersen, N., Swartout, B., McFarland, S., "Model Correlation and Thermal Analysis of xEMU Boot at Lunar South Pole Temperatures", *International Conference on Environmental Systems*, Rio Grande, Puerto Rico, 2026.