Model Correlation and Thermal Analysis of xEMU Boot at Lunar South Pole Temperatures

ICES-2026-153

July 14, 2026

Emma Quick, *Amentum, Johnson Space Center*

Noah Andersen, *HX5 LLC, Johnson Space Center*

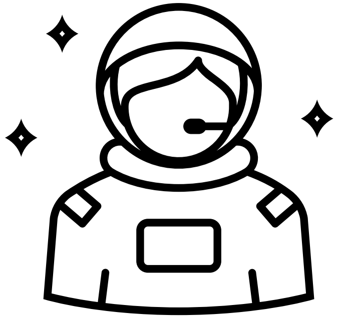
Ben Swartout, *Johnson Space Center*

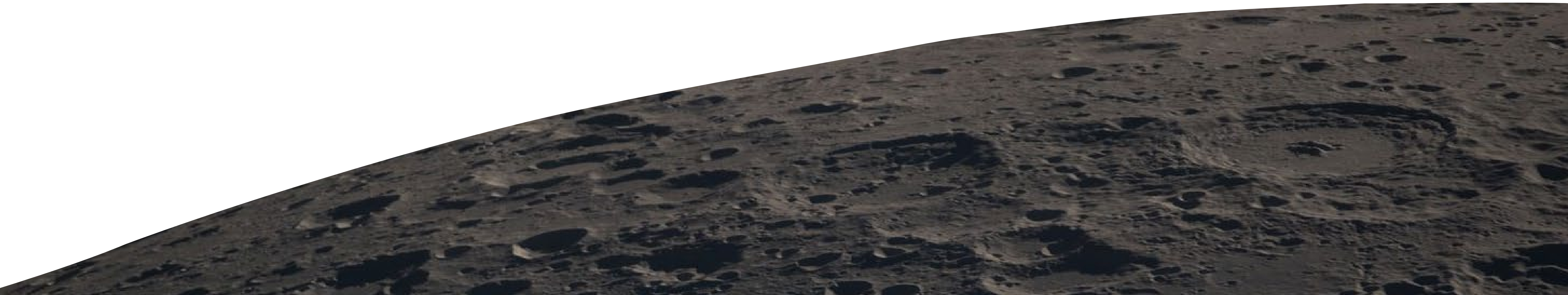
Shane McFarland, *KBR HHPC, Johnson Space Center*

Contents

Background & Objectives

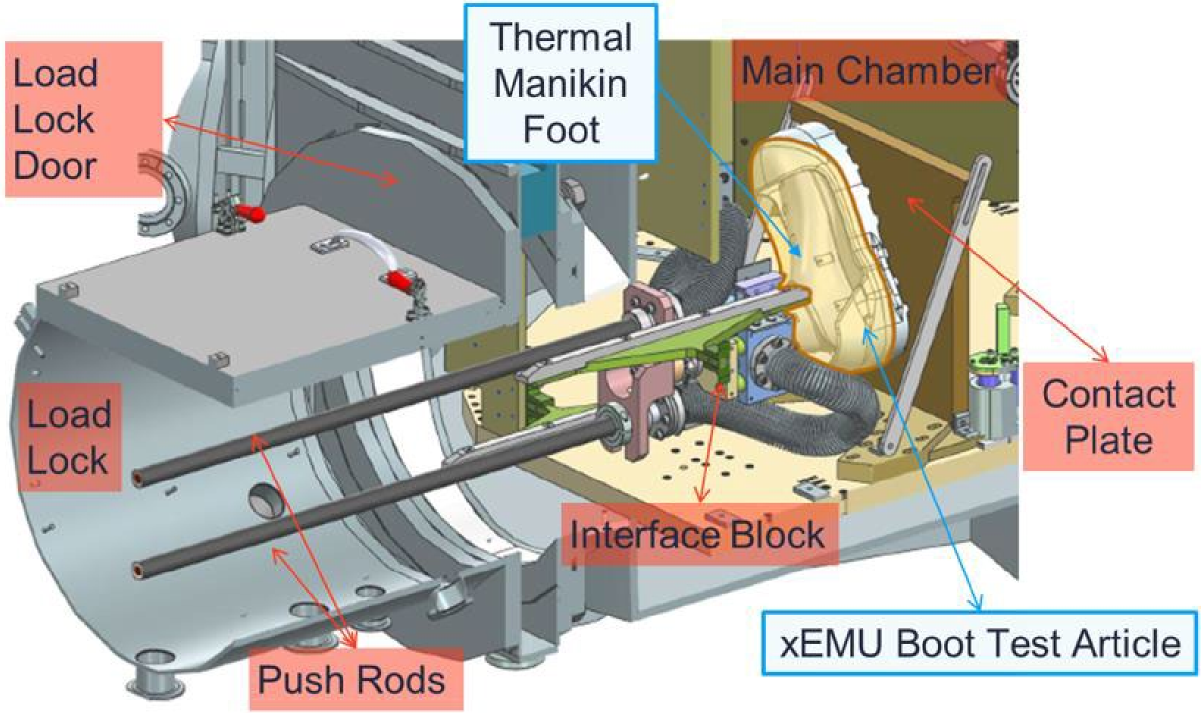
- **Upcoming Artemis missions will land astronauts on the moon at the south pole region**
  - Temperatures here can be as low as ~50 K
- **Exploration Extravehicular Mobility Unit (xEMU) boots will need to withstand these temperatures throughout extravehicular activity (EVA)**
  - Comprehensive thermal vacuum testing and subsequent thermal model correlation of the xEMU boot are essential to ensure crew safety
- **Test data was used to correlate the thermal model and predict lunar boot performance in permanently shadowed regions on the moon**
- **An uncertainty analysis was also performed to quantify which model inputs have the highest uncertainty and impact on results**





Test Setup, Instrumentation, and Conditions

- **CITADEL TVAC chamber at NASA JPL**
- **Thermal manikin foot outfitted with xEMU boot**
  - Water lines running through the foot maintain a skin boundary temperature
  - Thermocouples/RTDs on various layers of the foot+boot stack-up
    - 56 external and 16 internal TCs
  - Ventilation flow of 12.4 SLPM (1.5 ACFM) between the sock and bladder layers
  - Pressurization of boot to 4.3 psia
- **MiniShroud for environmental temperature control**
  - Aluminum stomp pad for boot to contact
  - Six environment TC coupons
- **Boot mounted on actuated push-rod system to simulate IVA to EVA transition**

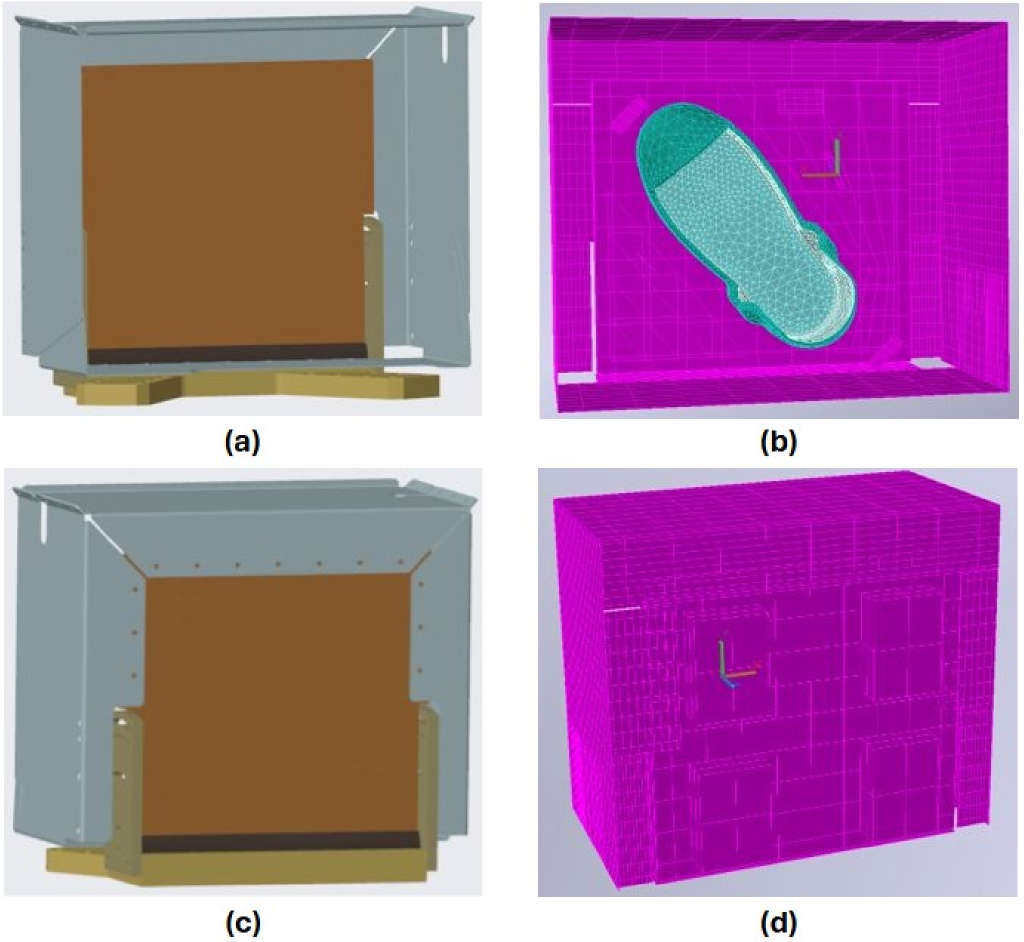


Test Parameters:

Variable Name	Levels	Units
Contact Pressure	0, 40, 100	lbf
Ventilation Flow	0, 1.5	ACFM
Foot Temperature	28, 33	°C

MiniShroud Model

- **It was necessary to build the MiniShroud model instead of using single external sink node for the boot**
  - In test, the MiniShroud did not provide a cold, isothermal environment
- **Model built from JPL CAD and includes stomp pad, top/side/bottom panels, copper bars, Teflon stomp pad coverings, and SLI curtain**
- **External MiniShroud environment simulated with sink temperature nodes on each face**
- **G10 spacers on bottom of MiniShroud were not explicitly modeled, but represented with a gap and low-conductance contactor**
- **Mechanical joints (screws, panel overlaps, interfaces) were modeled with face/edge contactors**
  - Conduction coefficients calculated based on screw count, conductivity, and contact area



Comparison of CAD file (.stp) and Thermal Desktop (TD) geometry. (a) CAD interior, (b) TD interior, (c) back of CAD, (d) back of TD.

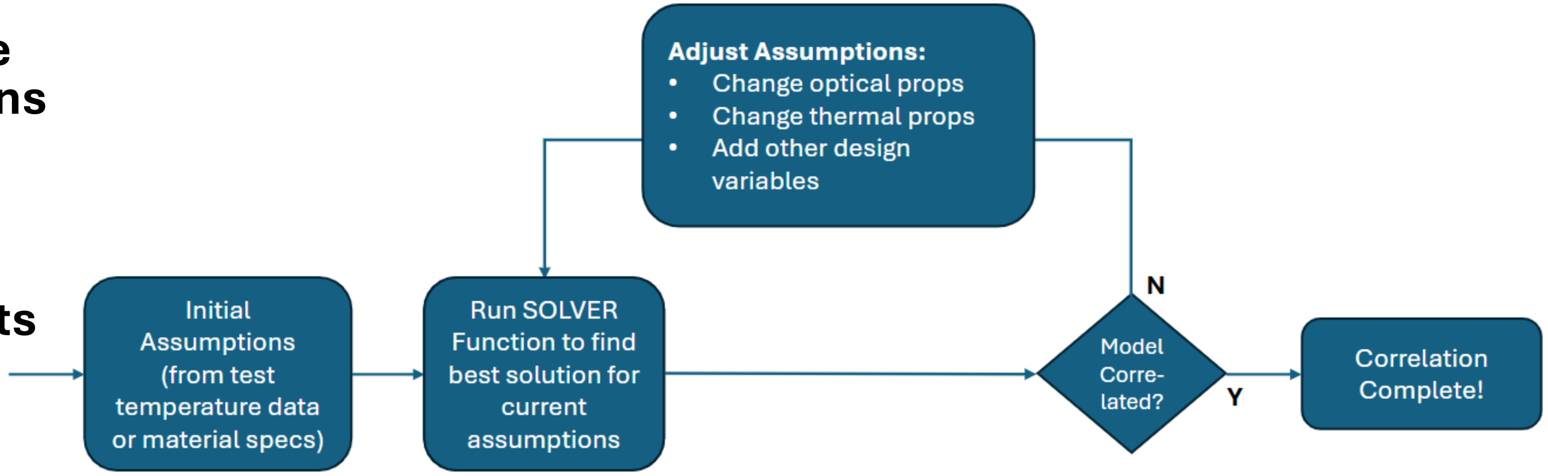
MiniShroud Model Correlation

- **The variables with highest uncertainty in the MiniShroud model were fed into Thermal Desktop SOLVER as design variables**
  - External environment sink temperatures, conductance from stomp pad to MiniShroud floor, conductance from bottom panels to the sides
- **Data from the test or from material specifications used as initial guesses in the model**
- **SOLVER iterates until objective function is minimized. The object is defined as follows:**

$$OBJECT = \sqrt{\sum\left(T_{model,i} - T_{test,i}\right)^2}$$

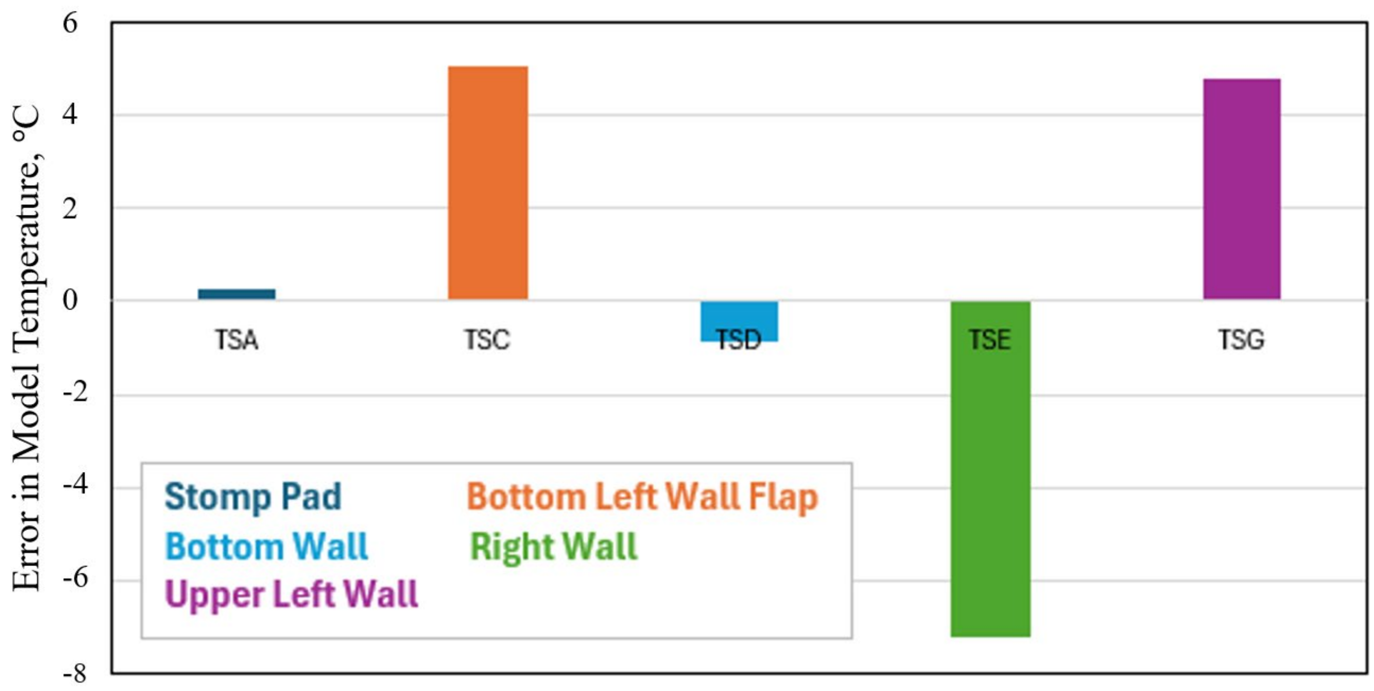
Where T represents temperatures at known TC locations on the walls of the MiniShroud

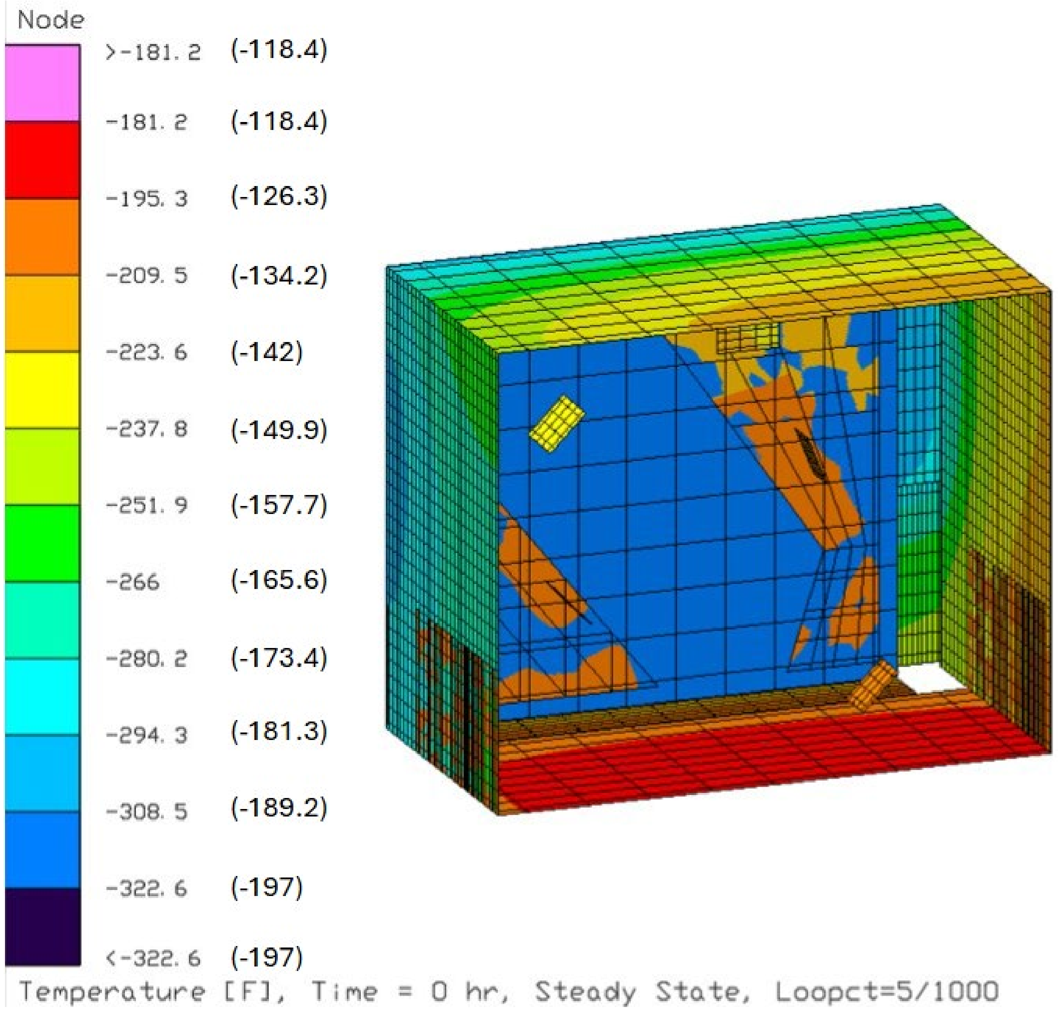
- **Optical and thermal properties were adjusted manually between iterations**
- **Model was correlated to 4 steady state radiation and contact test points separately since the temperature of the stomp pad affects the wall temperatures**



MiniShroud Model Correlation Results

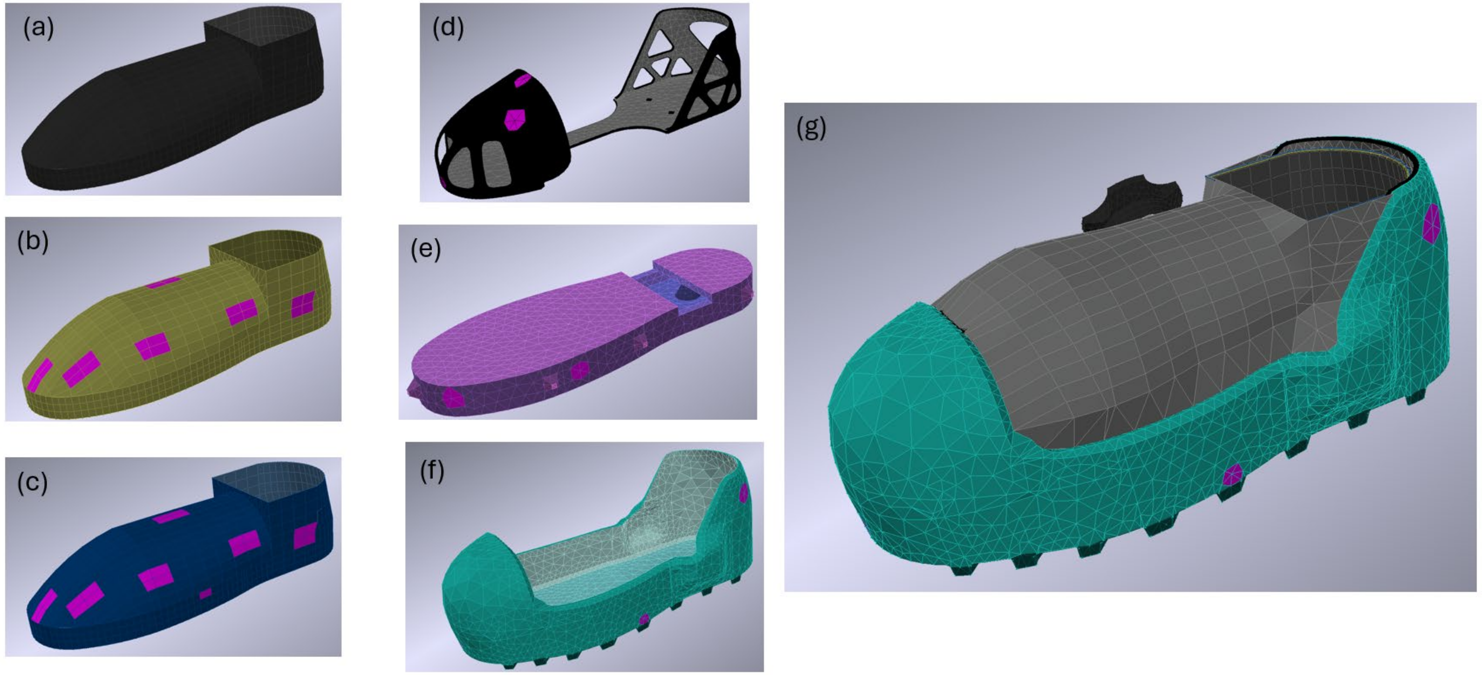
Design Variable	All Radiation Test Points	Contact, 48-60 K setpoint	Contact, 100 K setpoint	Units
Tchambersink_floor	255.8	272.0	264.2	K
Tchambersink_left	284.9	279.8	282.9	K
Tchambersink_right	255.4	255.4	255.4	K
Tchambersink_top	309.1	289.2	299.2	K
Tload	292.0	294.8	294.7	K
StompPad2Bottom	16.139	21.276	25.297	$W/K/m^2$
Flap2SideScrew	0.100	0.129	0.100	W/K





Boot Model

- **Built from CAD of xEMU boot model**
- **Layer material properties such as conductivity, specific heat, and optical characteristics match actual hardware**
- **Foot is represented with boundary nodes to match manikin's isothermal behavior**
  - Full human foot model not available
- **Linear conductors and contacts capture internal heat transfer paths**
- **External heat transfer paths include radiation and outsole conduction**



Thermal Desktop Boot Model: (a) sock, (b) pressure bladder, (c) restraint layer, (d) frame, (e) thermal insert, (f) outsole, and (g) full assembly. Magenta regions represent TC locations.

- **EPG regions had adjustable effective emissivity for tuning purposes**
- **Stomp contact could be modeled with just the tread tops (hard flat surface) or the entire outsole (granular regolith)**

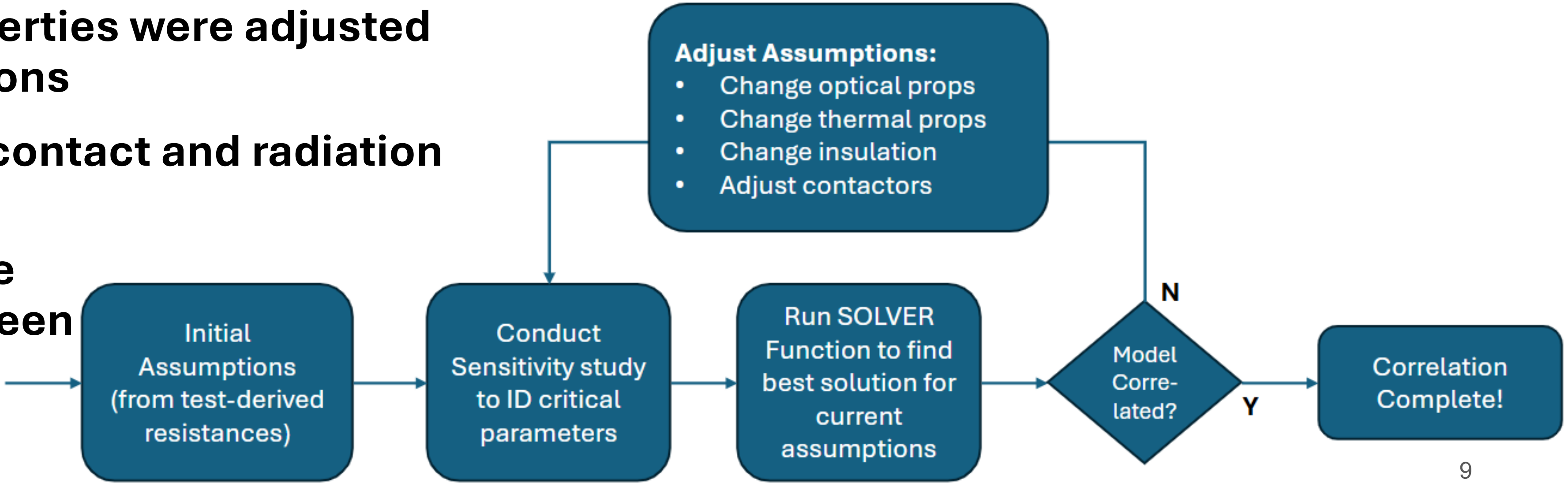
Boot Model Correlation

- **The variables with highest uncertainty in the MiniShroud model were fed into Thermal Desktop SOLVER as design variables; sensitivity analysis performed to determine design variables**
  - Thermal contactors/conductors between boot layers, thermal and optical properties, and insulation performance
- **Data from the test (calculated conductances) used as initial guesses in the model**
- **SOLVER iterates until objective function is minimized. The object is defined as follows:**

$$OBJECT = \sqrt{\sum \left(T_{model,i} - T_{test,i}\right)^2 + K \cdot \sum \left(q_{model,i} - q_{test,i}\right)^2}$$

Where T represents temperatures at known TC locations on the boot and q represents the heat leak out of the boot

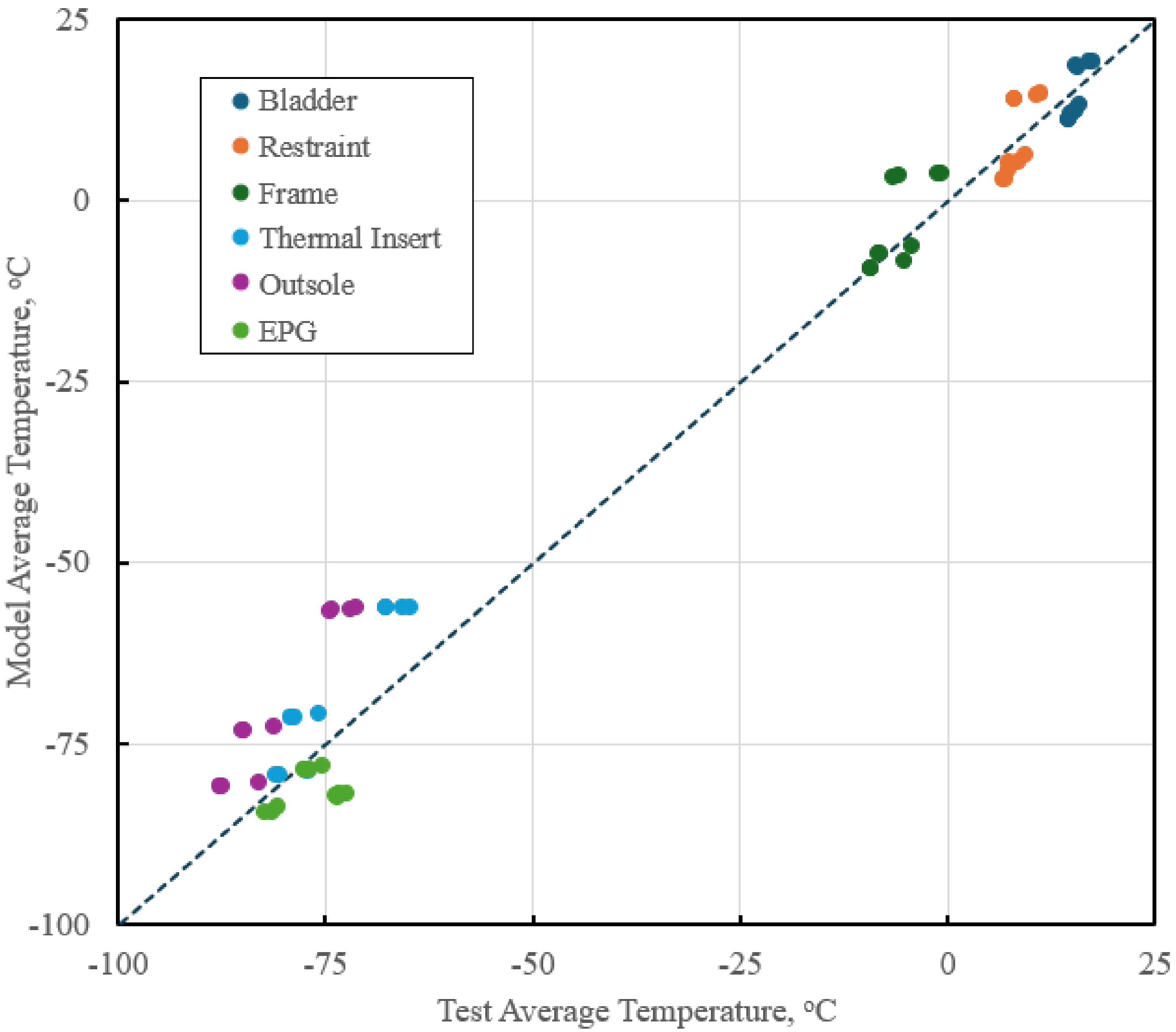
- **Optical and thermal properties were adjusted manually between iterations**
- **Model was correlated to contact and radiation cases separately**
- **Foot to sock conductance was allowed to vary between flow and no flow cases**



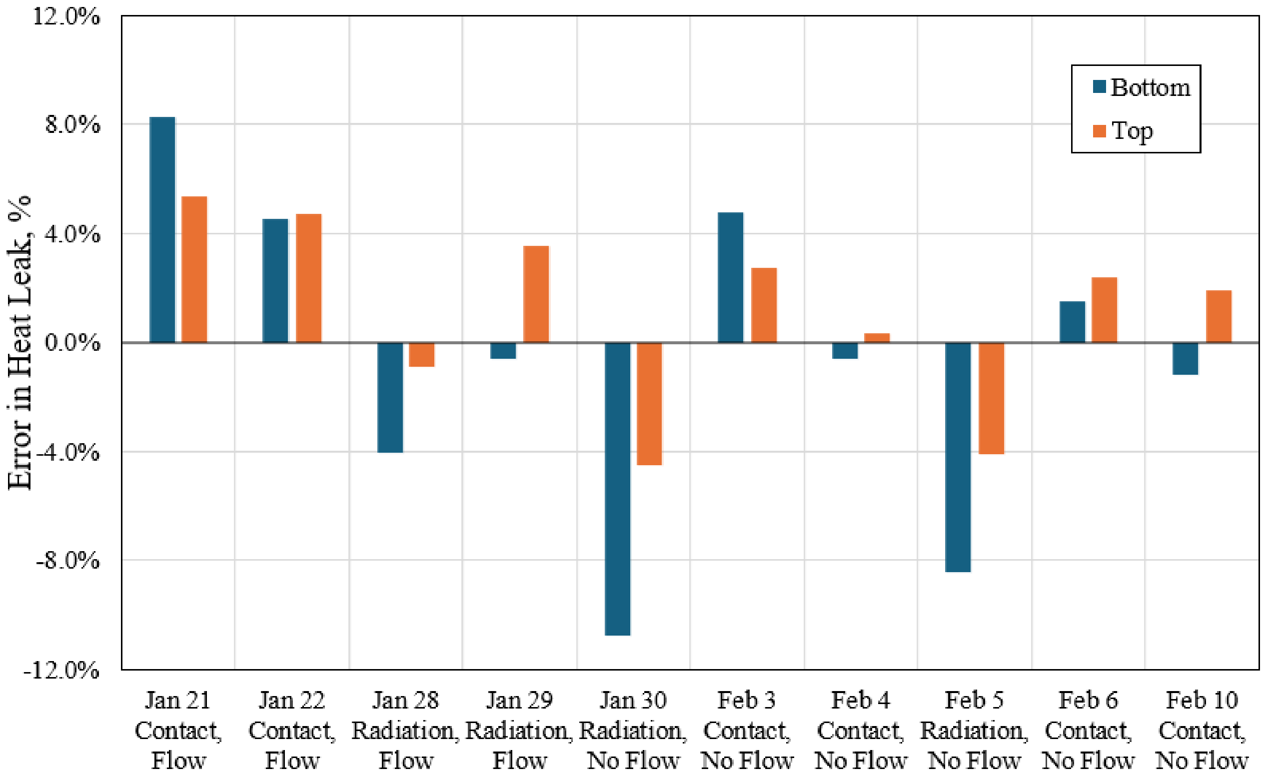
Key Adjustment to Boot Model

- **The effective emissivity of the EPG increased from 0.06 to 0.10 to correct excessive predicted heat loss through the sole**
  - Justified by the complex geometry of coverage and layer compression effects
- **The thermal insert conductivity was decreased by an order of magnitude**
  - Accounts for combined effects of geometry, material properties, multi-layer insulation (MLI) distribution, and dimple contact on heat transfer
- **The stomp pad emissivity was increased from 0.2 to 0.5 to correct overly warm outsole temperature predictions**
  - Supported by the Teflon layers (emissivity ~0.9) covering most of the stomp pad surface
- **The contactors between the pressure bladder and restraint were adjusted to represent a toe that does not have perfect contact with the toe of the boot**
  - In contact cases, the restraint and bladder in the toe regions were consistently colder in test than predicted by the model, likely due to a higher resistance from the toes to the pressure bladder and restraint
- **Outsole-to-stomp pad conduction was allowed to vary between contact cases to align with TC data**
  - Supported by probable inconsistency or nonuniform contact with the stomp pad from case to case

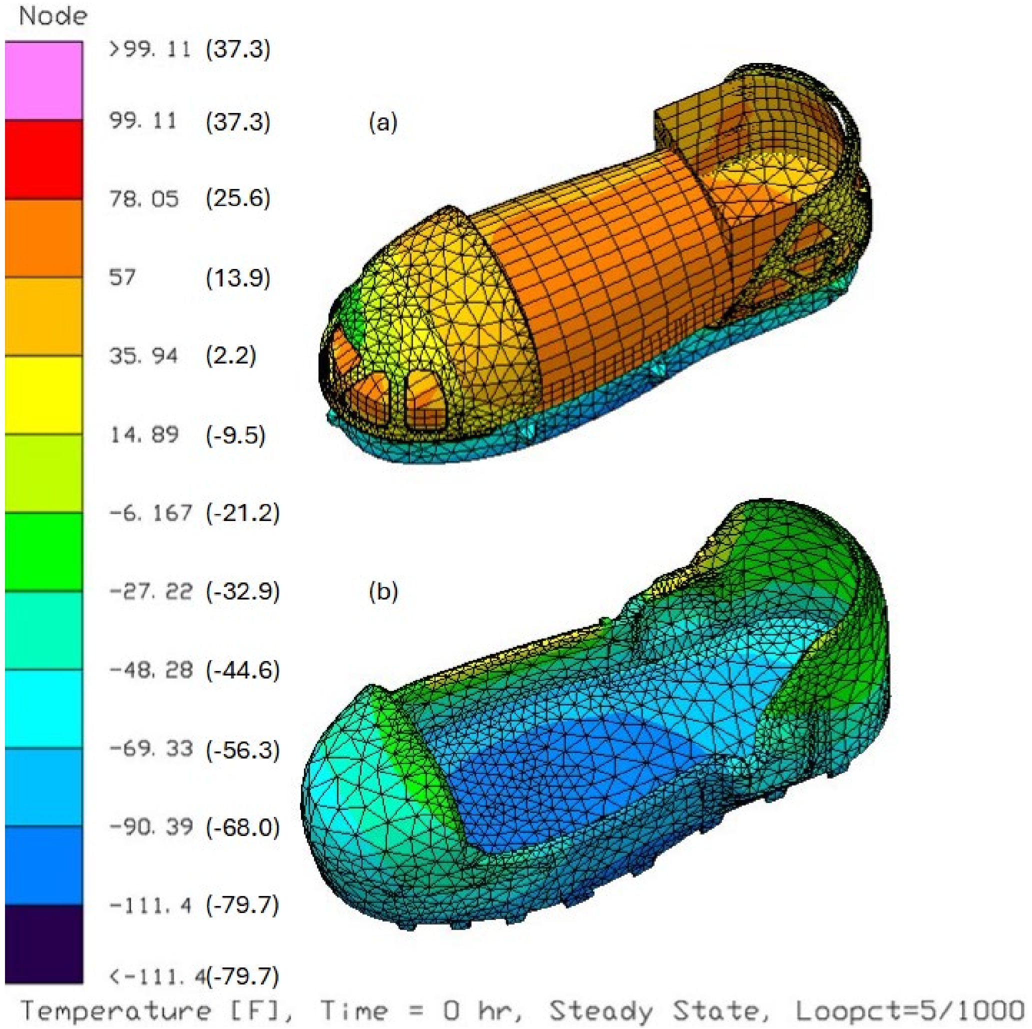
Boot Model Correlation Results



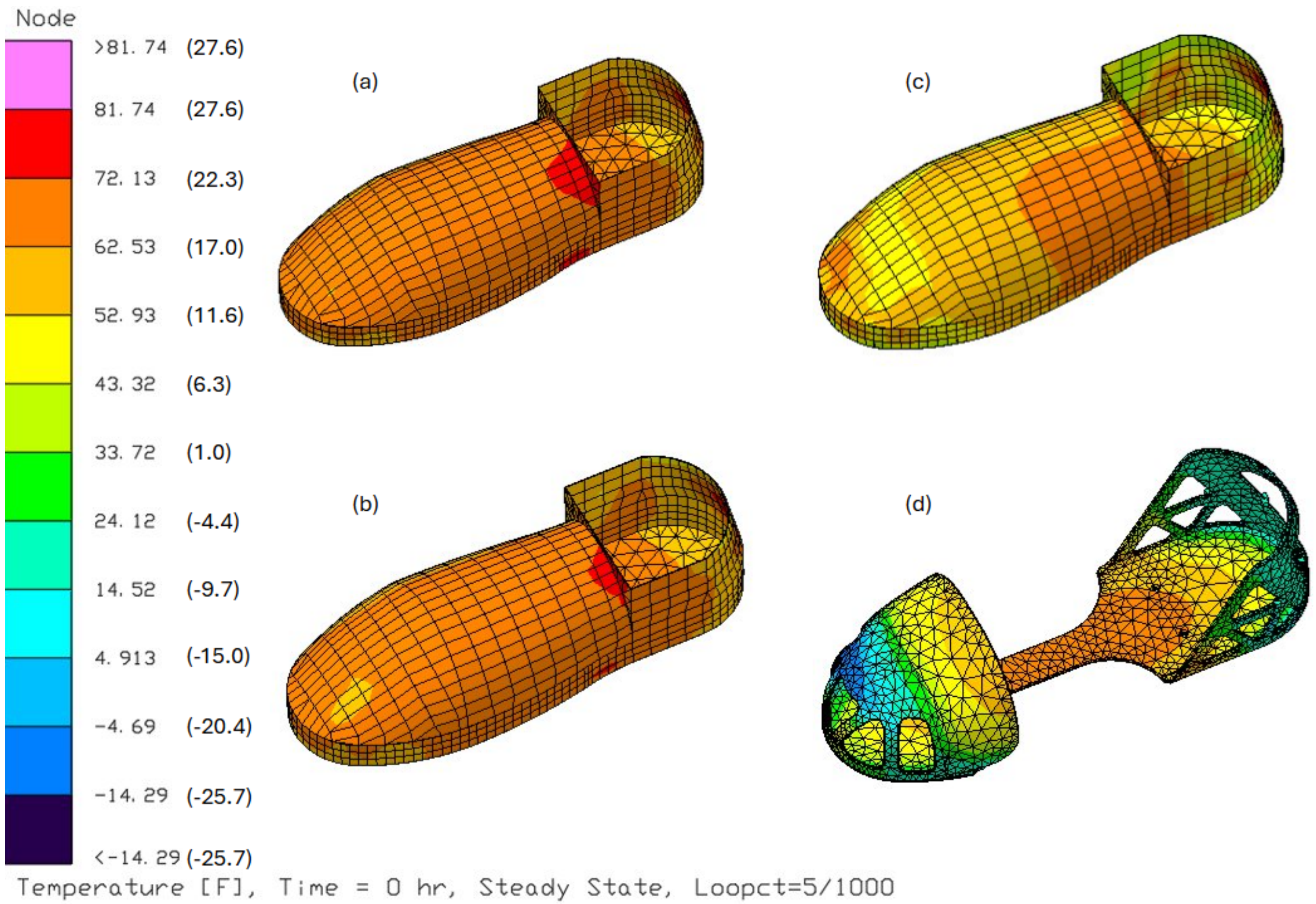
In general, the model is slightly conservative for contact cases (overpredicting heat leak) and slightly non-conservative for radiation-only test points.



Boot Model Thermal Performance



Radiation case temperature gradients between layers of the boot. (a) restraint, frame, and thermal insert; (b) outsole. Temperatures in Celsius are provided in parentheses.

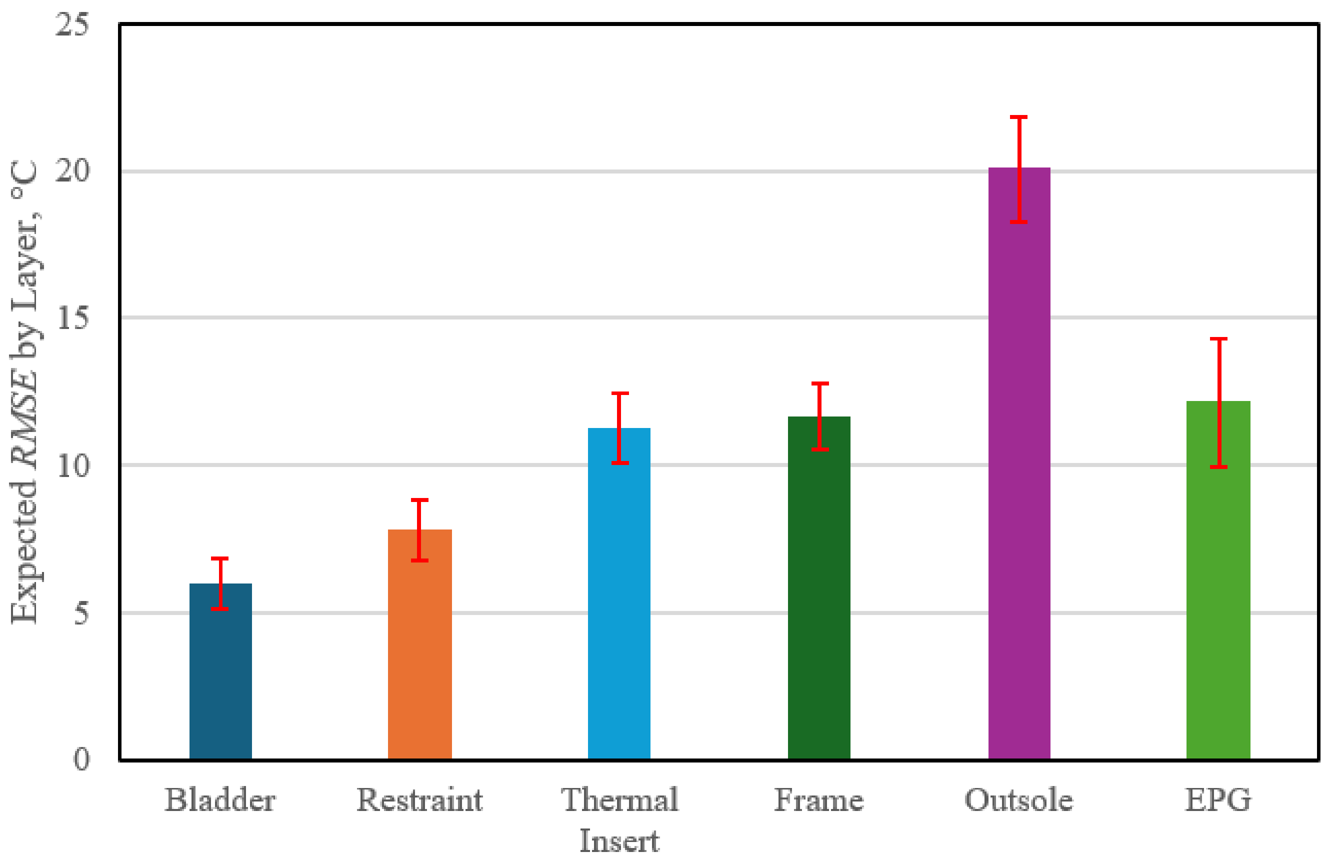


Radiation case temperature gradients throughout individual layers of the boot. (a) sock, (b) pressure bladder, (c) restraint, (d) frame. Temperature in Celsius are provided in parentheses.

Boot Model Predictions (RMSE)

$$RMSE_i = \sqrt{\frac{\sum_{i=1}^{N}\left(T_{model,i} - T_{test,i}\right)^2}{N}}$$

Analysis showed that sensors closest to the foot exhibit the lowest error, while sensors near the outsole and EPG have higher variability due to large thermal gradients and positional uncertainty.



Heat leak predictions were highly accurate which can be attributed to the deliberate modeling strategy of prioritizing the heat loss correlation accuracy

Location	Expected RMSE (W)	Uncertainty on RMSE (W)
Bottom of Foot	0.101	+0.042 / -0.033
Top of Foot	0.076	+0.021 / -0.018

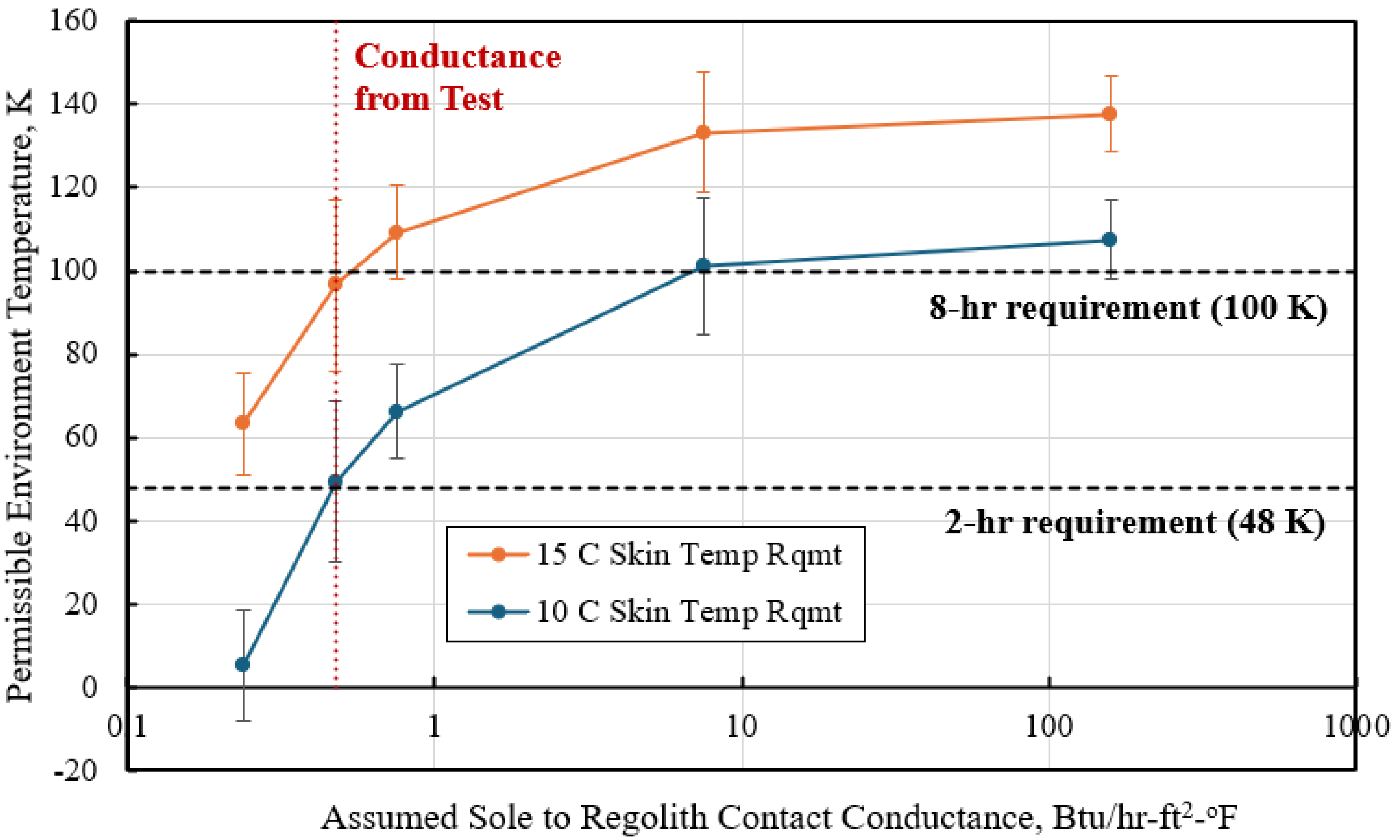
Lunar Operation Modeling

- **Gaps identified for accurate representation of lunar operation**
  - Unknown outsole-to-regolith thermal conductance
  - Lack of high-fidelity metabolic foot model
  - No dynamic gait modeling such as flexion and compression
- **Updates to model:**
  - Outsole contact increased to include tread valleys that would be filled by granular regolith
  - Initial conductance assumed came from test-derived outsole-to-stomp pad value of 2.703 W/m^2K
  - Foot represented with the upper and lower nodes as well as a new third node representing the toes, since this area was colder throughout testing
- **Permissible Heat Flux Criteria:**
  - Used to assess safety since model does not resolve detailed foot anatomy
  - Limits derived from EMU glove testing which used high-fidelity metabolic hand model
    - Thumb tip used as analog for toe heat flux requirement
  - Skin temperature thresholds were identified and the heat flux leaving the test article that resulted in the skin temperature hitting that threshold was calculated
    - 10°C (50°F) threshold → 120.8 W/m^2 heat flux
    - 15°C (59°F) threshold → 111.4 W/m^2 heat flux

Lunar Operation Heat Flux Predictions

Heat flux at the toe was evaluated for varying environment temperatures between 48 K and 120 K and outsole-to-regolith contact conduction between 0.24 Btu/hr/ft2/°F (1.36 W/m2/K) and 159.2 Btu/hr/ft2/°F (904 W/m2/K), assuming foot temperatures of 10 °C (50 °F) and 15 °C (59 °F), such that the heat leak calculated would model the heat leaving the toes when the skin temperature limit is reached.

When applying a 10 °C skin temperature limit, the boot is likely safe for 8-hour operation down to ~100 K, but performance at 48 K is inconclusive (and not feasible for any conductance at the stricter 15 °C limit), with exposure limits at 48 K requiring transient analysis that the current model cannot provide.



Error bars represent the standard error for the model, as computer using a Monte Carlo Simulation.

Results are highly dependent on the sole to regolith contact conductance, impacting pass/fail outcome

Lunar Operation Temperature Predictions

- **Assumes a constant foot temperature of 10 °C**
- **Addresses outsole-to-regolith contact conductance uncertainty and inherent model uncertainty**

Layer	Minimum Permissible Temperature	Minimum Expected Temperature at 48 K (with 95% confidence)	Minimum Expected Temperature at 100 K (with 95% confidence)
Bladder	-34.4 °C	-37.2 to -5.0 °C	-34.0 to -3.3 °C
Upper Frame	N/A	-109.0 to -37.0 °C	-96.6 to -30.2 °C
Outsole	N/A	-225.2 to -157.7 °C	-173.2 to -126.4 °C

- **Derived from contact conductance range of 0.24 Btu/hr/ft^2/°F to 159.2 Btu/hr/ft^2/°F**
- **Model uncertainty incorporated by adding RMSE error to this range, 2 times RMSE yields a 95% confidence interval**
- **Temperature ranges for all layers large**
  - Due to uncertainty in contact conductance
  - Methods for reducing ranges:
    - Additional testing to better characterize outsole-to-regolith conductance
    - Refinement of model correlation with emphasis on specific temperatures
    - Narrowing confidence interval

Conclusions

- **Successfully correlated lunar boot thermal model using extensive, repeatable steady-state data obtained across 10 test points including contact and radiation cases**
  - Achieved heat leak accuracy within 0.1 W
- **Used bootstrapping and Monte Carlo methods to quantify model uncertainty for both test and operational conditions**
- **Outsole-to-regolith contact conductance identified as the dominant driver of heat flux and temperature variability**
  - Bounded its impact and defined permissible environmental temperatures with parametric studies
- **Future improvements needed in regolith contact fidelity, colder/more uniform radiation environments, and human in the loop testing to validate a high-fidelity metabolic, transient, foot model**

References

[1] B. Swartout, "xEMU Spacesuit Boot Lunar South Pole Thermal Vacuum Testing," in *International Conference of Environmental System*, Rio Grande, Puerto Rico, 2026.

[2] B. Swartout, "Exploration Extravehicular Mobility Unit (xEMU) Lunar Boot Chamber B Thermal Vacuum Testing Results," in *International Conference on Environmental Systems*, Louisville, 2024.

[3] B. C. Conger, "Thermal Analysis of the EMU Boot with Foam Insert Removed," CTSD 1404, 1992.

[4] T. Durrant, "Orlan Spacesuit Boot Thermal Model," HDID-2G41-1132, 1999.

[5] J. V. Iovine, "EMU Boot Thermal Analysis for ISS EVA," HDID-2G41-954, 1998.

[6] J. V. Iovine, "Thermal Analysis of the EMU Boot Pressure Bladder," CTSD862, 1990.

[7] W. Lee, "Thermal Analysis Results of Stand-Alone Shuttle Boot Model for the Thermal Vacuum Chamber B Test for STS-37 Mission Hardware," CTSD454, 1989.

[8] T. Nguyen, "The Thermal Effect of a Newly Designed Aluminum Piece Attached to the Heel of the EMU Boot," 20977, 1984.

[9] D. Ochoa, "Thermal Design and Analysis of Constellation Space Suit System Boot Options for Lunar Missions," ESCG-4470-09-TEAN-DOC-0110, 2009.

[10] D. G. Gilmore, Spacecraft Thermal Control Handbook: Volume 1: Fundamental Technologies, The Aerospace Press, 2002.

[11] "fitgeotrans," Mathworks, [Online]. Available: https://www.mathworks.com/help/images/ref/fitgeotrans.html.

[12] "imwarp," Mathworks, [Online]. Available: https://www.mathworks.com/help/images/ref/imwarp.html.

[13] Z. Fester, S. McFarland, N. Andersen, E. Quick, D. Green, T. Jaimes and D. Morris, "xEMU Boot TVAC Final Report," NASA, CTSD-ADV-2272.

[14] N. L. Langston and V. Margiott, "EMU Phase VI Glove Thermal Vacuum Test and Analysis Final Report," CTSD-SS-1621, 1998.

[15] M. B. Abney, R. J. Jones, S. R. Wilson, T. K. Brady and N. L. Andersen, "Lunar Glove Thermal and Durability Analysis, Test, and Failure Mitigation," NESC-RP-21-01722, 2024.

[16] NASA, "NASA Spaceflight Human-System Standard Volume 1, Crew Health," 2023.

Acknowledgements / Questions

The authors would like to acknowledge the CITADEL test team at JPL for their hard work conducting test points and compiling data files.

Thank you!

Questions?

Further inquiries may be sent to the following:
Emma Quick: emma.j.quick@nasa.gov
Noah Andersen: noah.l.andersen@nasa.gov