xEMU Spacesuit Boot Lunar South Pole Thermal Vacuum Testing

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The Exploration Extravehicular Mobility Unit (xEMU) spacesuit lunar boot was evaluated in the Jet Propulsion Lab (JPL) CITADEL thermal vacuum chamber at lunar South Pole conditions. The JPL CITADEL chamber provides a radiation environment and contact plate temperature of 48K, simulating the temperature of a lunar Permanently Shadowed Region (PSR) at the South Pole of the Moon. The main objectives of the test series were: to evaluate the risk lunar PSRs pose to advanced spacesuit boots, validate the xEMU lunar boot thermal model, and develop a test methodology to evaluate lunar spacesuit boots. To simulate the thermal effects of a crewmember's foot inside the boot, a thermal manikin foot was developed to inject heat into the spacesuit boot. Thermal data was collected through a variety of sensors including thermocouples, thermistors, heat flux sensors, and infrared cameras. A test matrix was developed to investigate the variables of foot contact force, simulated skin temperature, external contact plate temperature, and ventilation flowrate. The JPL CITADEL chamber includes a loadlock (airlock) that afforded the ability to simulate the transition of the boot from a thermally neutral IVA condition to a cold EVA condition within seconds. This paper will document the test design, test objectives, success criteria, test support equipment, spacesuit boot to chamber interfaces, and configuration of the test article. Additionally, this paper will document the high-level results of the testing. More detailed test results will be presented in a different paper.

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Nomenclature

xEMU	=	Exploration Extravehicular Mobility Unit
TVAC	=	Thermal Vacuum
JSC	=	Johnson Space Center
CITADEL	=	Cryogenic Ice Transfer, Acquisition Development, and Excavation Laboratory
JPL	=	Jet Propulsion Laboratory
DVT	=	Design Verification Test
MLI	=	Multi-Layer Insulation
EVA	=	Extravehicular Activity
HITL	=	Human In the Loop
EMU	=	Extravehicular Mobility Unit
PSR	=	Permanently Shadowed Region
NASA	=	National Aeronautics and Space Administration
ACFM	=	Actual Cubic Feet per Minute
RTV	=	Room Temperature Vulcanizing
EPG	=	Environmental Protection Garment
TFS	=	Thermal Foot System
IVA	=	Intravehicular Activity
JWST	=	James Webb Space Telescope
PSIA	=	Pounds per Square Inch Absolute
PSID	=	Pounds per Square Inch Differential
SLI	=	Single-Layer Insulation
IR	=	Infrared
GN_2	=	Gaseous Nitrogen
LCVG	=	Liquid Cooling Ventilation Garment
xPLSS	=	Exploration Portable Life Support System
RV	=	Relief Valve
DOF	=	Degree of Freedom

I. Introduction

THE Artemis program strives to return Americans to the lunar surface of the Moon for the first time since the historic Apollo missions in the 1960s and 1970s. Spacesuit technology has evolved significantly over the past 50 years enabling Artemis astronauts to traverse farther in more extreme lunar environments than the Apollo astronauts. The past two decades of advanced spacesuit development have culminated in the government reference design Exploration Extravehicular Mobility Unit (xEMU), the highest fidelity advanced spacesuit prototype in the world. A significant thermal vacuum (TVAC) test of the xEMU was performed at Johnson Space Center's (JSC) Chamber B in 2023[1]. The results of this pioneering thermal vacuum test indicated further investigation was warranted for the thermal insulation architecture of the xEMU spacesuit boots[2].

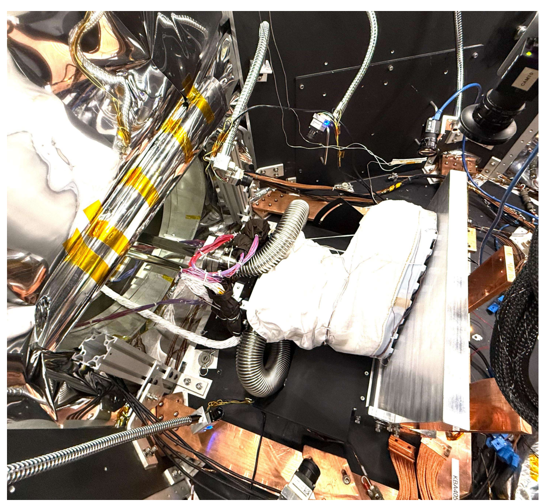

Figure 1: xEMU Spacesuit Boot in JPL CITADEL Thermal Vacuum Chamber.

To further evaluate the xEMU spacesuit boots, a cryogenic thermal vacuum test was conducted within the Cryogenic Ice Transfer, Acquisition Development, and Excavation Laboratory (CITADEL) Chamber[3] at the Jet Propulsion Laboratory (JPL) to simulate environmental conditions representative of the lunar South Pole. The test article for this evaluation was a Design-Verification-Test (DVT) fidelity xEMU spacesuit boot. This test campaign utilized a single spacesuit boot test article. An instrumented thermal manikin foot was placed inside the boot to simulate a crewmember's foot, enabling the measurement of resultant heat loads and skin temperatures. A variety of test support equipment was developed to pressurize the spacesuit boot, force gas flow through the boot, measure the contact force of the boot against a simulated lunar surface, and collect data from the numerous sensors. The integrated system's performance was then evaluated against the xEMU boot performance requirements and used to improve a lunar boot thermal model.

Evaluating the thermal performance of a spacesuit boot has some unique challenges compared to other spacesuit components.

1) *Heat Transfer:* In most space systems, radiation heat transfer is the dominant heat transfer mechanism and is relatively simple to insulate against with multi-layer insulation (MLI). However, spacesuit boots experience all three heat transfer mechanisms simultaneously: radiative heat transfer with top and sides of the boot and the space environment, convective heat transfer between the astronaut foot and the inside of the spacesuit boot, and conductive heat transfer between the astronaut foot, spacesuit boot, and lunar surface.

2) *Lunar Regolith:* Another challenge with evaluating planetary spacesuit boot thermal performance is the thermal capacity of lunar regolith and the interaction of the regolith and spacesuit boot. If an astronaut were to stand still on loosely packed regolith, the regolith would quickly (on the order of magnitude of minutes) approach the temperature of the external surfaces of the spacesuit boot. However, it is expected that much of a lunar extravehicular activity (EVA) would consist of walking, where an astronaut is constantly stepping on a new, cold spot of regolith. An additional complexity of lunar regolith is the surface area between the spacesuit boot and lunar regolith where conductive heat transfer can occur. If the regolith is loosely packed, an astronaut's boot would likely sink into the regolith by ~25-50 mm (1-2 inches). Should this occur, regolith would then contact the sides of the outsole, not just the bottom tread of the spacesuit boot. This would increase the surface area in which conductive heat transfer could occur and potentially increase the heat leak from the spacesuit boot. However, given the significant challenges with simulating lunar regolith for a thermal vacuum test, the project decided to pursue grounding the spacesuit boot thermal model on a single measured thermal conductance between the spacesuit boot and contact plate, and then using model results to predict permissible environmental temperatures given a variety of assumed regolith thermal conductance values.

3) *Mechanical Properties at Cryogenic Temperatures:* Little information exists for the mechanical properties of materials below 117K (-250°F). It is expected during a lunar EVA that astronauts would spend time walking to and from locations on the Moon that are of scientific interest. During ambulation, the spacesuit boot softgood components would be flexed and extended, leading to localized areas of increased stress on the spacesuit boot softgoods. While extensive testing and analysis has confirmed positive structural margins for 1G human in the loop testing (HITL) at ambient temperature[6], it is unknown if spacesuit boot structural failures would occur if the spacesuit boot materials were to approach lunar South Pole temperatures. Flexion and extension of spacesuit boot softgoods are difficult to test and not addressed by the test protocol developed in this testing campaign.

II. Comparison of Apollo and Artemis Thermal Environments

With Apollo being the only program to land humans on the lunar surface, much can be gained by studying the test and flight data from the Apollo program. The Apollo missions intentionally landed near the lunar equator, where hot thermal environments were expected. Apollo missions also did not occur during lunar nighttime where colder thermal environments would be present. Therefore, much of the testing focus during the Apollo era focused on the hot environments expected to be encountered during the Apollo missions.

Contrasting with the Apollo program, the Artemis program strives to land at the lunar South Pole, where much colder thermal environments are expected than at the lunar equator. The landing location, and resulting thermal environment, is a major difference between the Apollo and Artemis programs.

Figure 2: Apollo 11 Bootprints.

While some lunar nighttime testing was performed on the Apollo EMU, where test environment temperatures could reach below 144K (-200°F), most of the cold environment testing focused on a short sortie into a lunar shadow, only lasting around an hour in duration. Transitioning from a hot environment, where the Apollo spacesuit would be heated up, into a cold lunar shadow for an hour duration is not enough time for the well-insulated Apollo spacesuit boots to reach low temperatures. Qualification testing for the Apollo G (Apollo 11) mission did not perform any cold lunar nighttime thermal vacuum testing for the Apollo spacesuit boots.

A final notable difference is the delta between the human foot skin temperature and the respective thermal environment in Apollo and Artemis. In the Apollo missions, the maximum allowable foot skin temperature was 319K (115°F) and the maximum tested thermal environment was 394K (250°F) for approximately a 2-hour hot soak duration. In the Artemis missions, the minimum foot skin temperature requirement is 283.15K (50°F) with exposure to 117K (-250°F) thermal environments for up to 8 hours. It is important to consider that the delta temperature between the foot skin temperature and thermal environment for Apollo missions is 330K (135°F), while for Artemis missions the temperature delta between the foot skin temperature and thermal environment is much greater at 422K (300°F). While both Apollo and Artemis missions share the architecture of having a suited crewmember perform a planetary lunar EVA, the thermal environments the spacesuit must protect against are much more extreme for Artemis missions.

III. Test Objectives

The primary objective of this test campaign was to develop a test protocol for evaluating planetary Extravehicular Activity (EVA) boots in lunar South Pole environments, including permanently shadowed regions (PSR). Prior to this testing campaign, little test data existed for planetary EVA boots operating in the sub-liquid nitrogen temperature range (less than 117K (-250°F)). The xEMU spacesuit boots were designed to meet thermal environment requirements from 93K (-292°F) for a cold location on the lunar South Pole to 378K (+220°F) for a hot lunar crater. The driving thermal requirement for the xEMU spacesuit boots is a 2-hour exposure in a lunar PSR, where temperatures can reach 48K (-373°F). The goal of this test protocol is to design a repeatable test that would evaluate the thermal performance of EVA boots, that both NASA and our commercial spacesuit partners can use in the future. Secondary objectives of this test campaign include:

1) Characterizing the government reference design xEMU spacesuit boot performance at Artemis mission surface conditions.
2) Validating the government reference design xEMU spacesuit boot thermal model.

After years of developing the xEMU spacesuit boot thermal architecture, it is critical to test the thermal insulation design and prove out the performance of that design. While future spacesuit boot designs may evolve beyond the government reference design, the fundamental questions surrounding contact pressure effects on spacesuit boot thermal conductance, forced convection thermal effects on spacesuit boot heat leak, and feasibility of the thermal insert design are critical to investigate ahead of the Artemis III mission.

As planetary EVA boots are thermally complex systems, there were several test parameters that were able to be varied.

1) *Stomp Pad Contact:* Test points were planned with and without the boot contacting the stomp pad representing the cold lunar surface. These "contact" and "radiation only" test points gave a direct comparison of the spacesuit boot heat leak through the bottom of the spacesuit boot with and without the conduction pathway to the simulated cold lunar surface. These test points were critical in understand the thermal performance of the thermal insert providing conductive thermal insulation for the bottom of the spacesuit boot.
2) *Environment Temperature:* There are two main environmental thermal requirements for planetary spacesuit boots: an 8-hour exposure in a 93K (-292°F) nominal, lower bound, cold lunar South Pole location and a 2-hour exposure in a 48K (-373°F) lunar permanently shadowed region. Testing operations were planned at both of these environmental temperatures.
3) *Thermal Foot Temperature:* Another major requirement of the spacesuit boot is to maintain a minimum crewmember foot skin temperature of 283.15K (50°F). To enable the spacesuit boot thermal model validation, the thermal foot temperature was set to a constant boundary temperature, with most test points at 283.15K (50°F) and some at 288.15K (59°F) to evaluate the effect of the simulated crewmember foot skin temperature on the spacesuit boot heat leak. In reality, the crewmember's foot skin temperature will not be a constant value. Foot skin temperature will vary based on a variety of factors including heat leak out of the

spacesuit boot, crewmember metabolic rate, and physiological factors including cardiovascular health, genetic pre-disposition to high/low blood circulation in the extremities, and fat/muscle distribution in the feet. These complex factors are too complicated to easily replicate in this thermal vacuum testing protocol. A constant boundary temperature was set for the thermal foot with a known thermal conductance of the foot.

4) *Spacesuit Boot Gas Ventilation Flow Rate:* During the design of the xEMU spacesuit boot, significant thermal modeling work was performed to investigate the effect of forced convection through the spacesuit boot. While forcing warm gas through the spacesuit boot could potentially increase the foot and bladder temperatures, incorporating a mechanism to force gas flow through the spacesuit boot would add additional complexity to the spacesuit boot design, with significant implications for spacesuit boot indexing capabilities. Previous thermal modeling work predicted that during a 2-hour exposure to lunar PSR conditions, the foot and bladder would stay warm enough without forced convection. This testing campaign investigated this hypothesis by executing test points with and without 12.4 SLPM (1.5 ACFM) of gas flow through the spacesuit boot.

5) *Spacesuit Boot Contact Force:* It is known that human skin thermal conductance increases with greater contact forces. Increasing contact force can compress soft tissue, thereby increasing the skin density and conductive heat transfer efficiency, can increase surface area between the skin and touch object, and can reduce air gaps between the skin and touch object. With the spacesuit boot made from mostly compliant materials, uncertainty existed whether the spacesuit boot heat leak would be significantly impacted by contact force. Adding complexity to this area of investigation is that while the spacesuit boot materials, like the RTV outsole, may be compliant at room temperature, when exposed to cryogenic temperatures, the spacesuit boot materials may become more rigid. The effect of contact force on spacesuit boot thermal conductance was evaluated in this testing campaign by varying the applied load from the spacesuit boot onto the stomp pad (0 N, 178 N, and 445 N) and determining the spacesuit boot heat leak and appropriate spacesuit boot thermal conductance values.

6) *Cold Soak Duration:* To promote efficient data collection, a thermal steady-state condition of less than 1°C temperature change per hour on all of the thermocouples was defined for this test protocol. The cold soak duration had to be long enough to both allow the spacesuit boot temperatures to reach this defied thermal steady-state condition as well as provide enough cold soak duration for the chamber to reach the appropriate thermal environment test conditions prior to inserting the spacesuit boot into the chamber.

IV. Test System Configuration

To enable accurate representation of lunar South Pole thermal environment conditions and spacesuit boot EVA conditions, significant test support equipment was developed.

A. xEMU Spacesuit Boot Test Article

This thermal vacuum test series used a government reference design xEMU lunar spacesuit boot[2, 4]. This boot was also used in the xEMU Chamber B Thermal Vacuum Test on "Suit 2". Based on the results of that previous xEMU thermal vacuum testing, an improved Environmental Protection Garment (EPG) design was incorporated for the CITADEL TVAC testing. The multi-layer insulation (MLI) material was updated to add more loft. Previous EPG designs potentially could have compressed the MLI layers during fabrication, leading to decreased effectiveness of the MLI thermal insulation. An additional design change for the CITADEL TVAC testing was to extend the EPG to cover the top cap of the spacesuit boot. The final design change

Figure 3: xEMU Spacesuit Boot

was to add a felt insulation layer between the frame and outsole to address performance gaps discovered in the previous xEMU Chamber B TVAC testing.

The spacesuit boot test article used quantity 56 externally mounted Type-T thermocouples that were mapped to the CITADEL interface panel/connectors. Quantity 16 Type-T thermocouples were internally mounted on the inside of the spacesuit boot test article. There were quantity 6 EPG coupons instrumented with a thermocouple on both sides of the coupon, and the coupons were installed around the spacesuit boot in the TVAC chamber to measure the radiation environment experienced by the spacesuit boot. The thermocouples were "stacked" in the same location across the multiple layers of boot materials. For example, a thermocouple "stack" would consist of a thermocouple placed on the bladder, restraint, frame, thermal insert, and outsole. All of the spacesuit boot materials are thermally insulative and do not transfer heat "in-plane" across a material layer well. Since thermocouples measure the temperature at the specific location the thermocouple is placed, "stacking" the thermocouples across the spacesuit boot layers provides insight to the heat transfer and temperatures through the spacesuit boot.

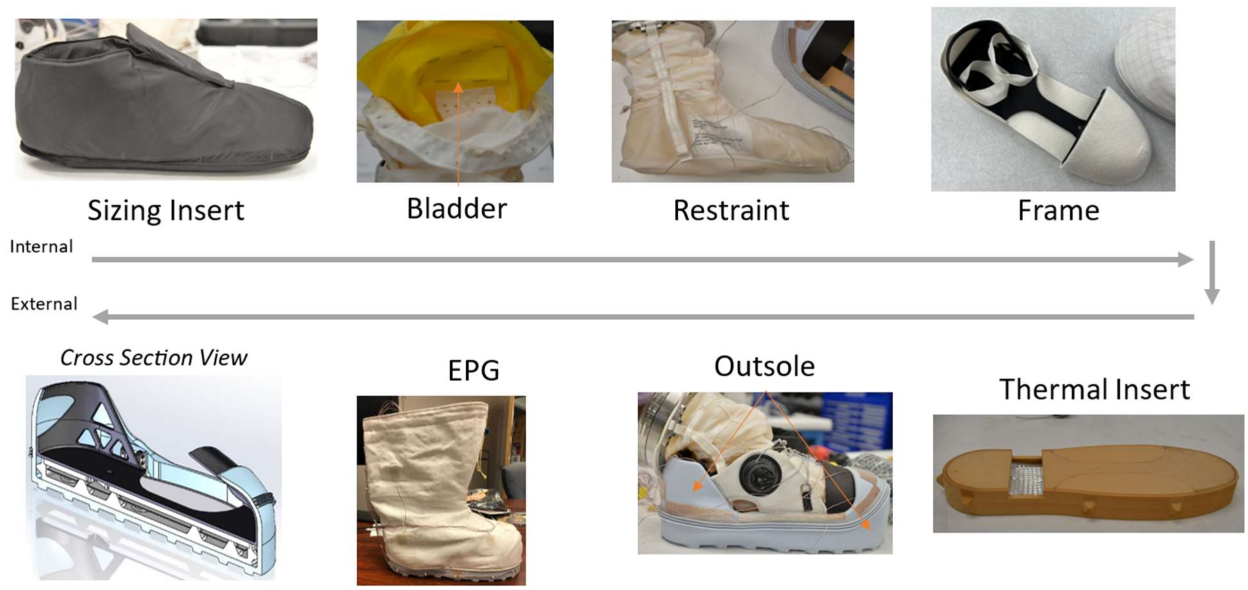

Figure 4: xEMU Spacesuit Boot Material Layup.

B. Thermal Foot System (TFS)

The thermal foot system is a custom, heated, and instrumented manikin foot that was designed for this testing campaign by a commercial vendor, Thermetrics[5]. The thermal foot system consists of a foot manikin, control box, chiller cart, and data acquisition system user interface. The manikin shell is an additively manufactured nylon shell segmented into two physical pieces (foot and ankle) and three thermal zones (lower foot, upper foot, and ankle). An ankle extension feature serves as the interface between the ankle segment and foot segment, facilitating donning and doffing of the boot. Thermal regulation is maintained by internal water flow to the three thermal zones, with each zone

Figure 5: Thermal Foot System.

having separate fluid lines and connections. Local “skin level” temperatures and heat-flux sensors are strategically placed on the surface of the thermal zones. There are quantity 13 heat flux sensors on the foot and quantity 3 heat flux sensors on the ankle. The temperature of the water is conditioned by heating elements in both the control box and the chiller. The data acquisition system (ThermDAC) displays inlet/outlet water loop temperatures, flow rates, and temperature/heat flux readings at the sensor locations. The thermal manikin foot is also structurally attached to the chamber interface block such that load could be transferred from the chamber interface block, to the thermal manikin foot, and ultimately onto the spacesuit boot/stomp pad.

C. CITADEL Thermal Vacuum Chamber

This testing campaign utilized NASA JPL’s CITADEL thermal vacuum chamber to create the necessary environmental conditions, to provide fluid, mechanical, and electrical penetrations, and to collect data with the facility data acquisition system. NASA JPL’s CITADEL thermal vacuum chamber was chosen for this test series because of unique capabilities in reaching lunar PSR temperatures and being equipped with an airlock to simulate the IVA to EVA transition. The CITADEL thermal vacuum chamber operates with helium compressors routed to cold heads attached to the thermal vacuum chamber to achieve temperatures in the lunar PSR range.

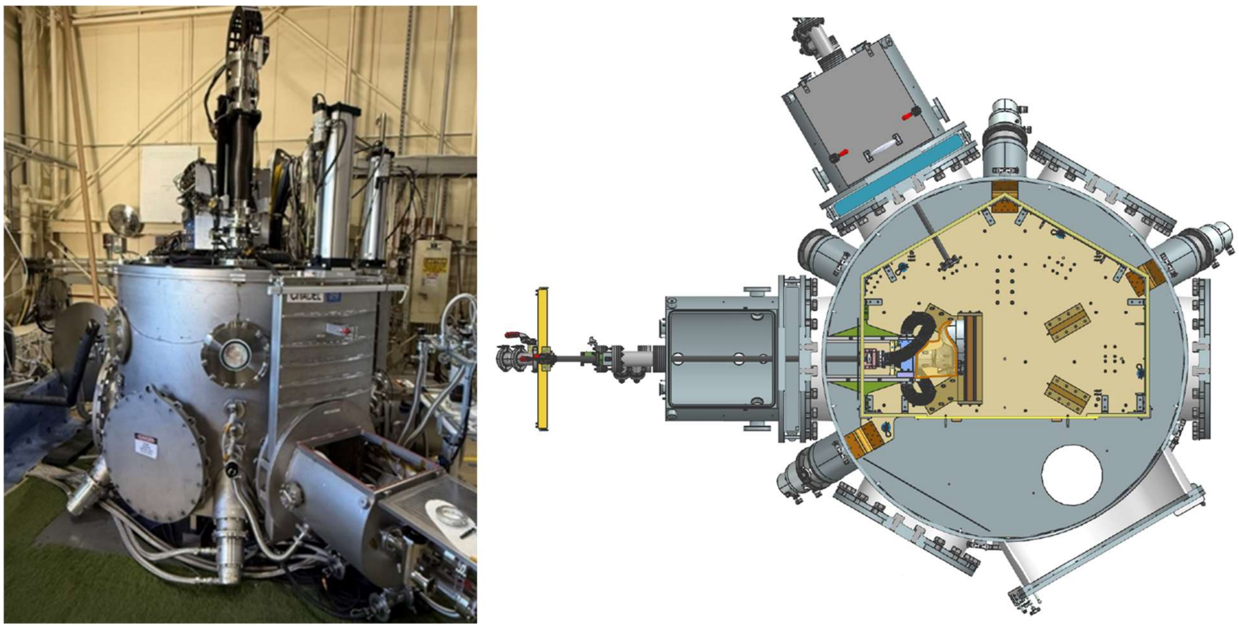

Figure 6: JPL CITADEL Thermal Vacuum Chamber.

D. Loadlock Capability

The IVA to EVA transition capability is critical for performing spacesuit thermal vacuum testing. Unlike traditional spacecraft (such as vehicles, satellites, and stations) that are continuously exposed to space thermal environments, spacesuits are only exposed to space thermal environments for at most 8-hours at a time. Consider the James Webb Space Telescope (JWST) for a comparative example. The JWST employs a sunshield to maintain instrument temperatures ideally under 50K (-370°F). Behind the sunshield, JWST instruments are allowed to cold soak for the duration of the mission, eventually reaching a thermal steady-state condition with the space environment. Unlike JWST, spacesuits begin an EVA at ambient temperature inside of a vehicle airlock. The spacesuit then embarks on an up-to-8-hour EVA, where the spacesuit will begin to cool down as the spacesuit is exposed to lunar South Pole thermal environments. After the EVA is complete, the spacesuit will return to the vehicle airlock and warm back up to ambient temperate. An EVA duration of up-to-8 hours is not long enough for the spacesuit to reach a thermal steady-state condition with the environment. It is therefore crucial to perform thermal vacuum testing of spacesuits with the appropriate cold soak duration in the thermal vacuum chamber.

Figure 7: Spacesuit Boot Installed in Loadlock.

If the spacesuit boot was located inside of the thermal vacuum chamber while the thermal vacuum chamber was cooling down, the spacesuit boot temperatures would begin to cool down with the chamber. This is unrealistic as during a lunar EVA, the spacesuit boot will start at ambient temperatures, and then immediately be exposed to cold lunar South Pole temperatures. The CITADEL chamber is equipped with an airlock (hereby referred to as "loadlock") that is thermally neutral and can be depressurized/pressurized independent of the main thermally conditioned vacuum chamber. This loadlock allows for the vacuum chamber to cool down to the desired test temperature while the spacesuit boot remains at ambient temperature. Once the chamber reaches the desired test temperature, a door between the loadlock and main chamber is opened, and the spacesuit boot can traverse into the cold thermal environment in the main chamber.

E. Push Rod System

The push rod system is another enabling test system in developing this test protocol that allowed the spacesuit boot to traverse into and out of the loadlock and main thermally conditioned vacuum chamber. The quantity 2 push rods are a hollow, pressure sealed volume that provided space to route the water lines for the thermal foot system, a gas line for the spacesuit boot pressure system, and quantity 56 thermocouple wires running from the inside of the spacesuit boot to a chamber penetration outside of the loadlock. The push rod system is mounted on wheels and required manual actuation to push the spacesuit boot in and out of the main chamber. One interesting finding during dry-run testing of the push rod system was that the push rod system had a tendency to shift towards the retracted position. This likely had to do with difference in pressures between the vacuum chamber, the inside of the push rods, and the ambient atmosphere. Maintaining a constant contact force between outsole and stomp pad was a critical test point and should the push rod system float towards the retracted position (towards the loadlock), this would reduce the contact force between the outsole and stomp pad. Therefore, a locking system was implemented on the push rods that provided mechanical interference preventing the push rods from moving after the appropriate contact force was applied.

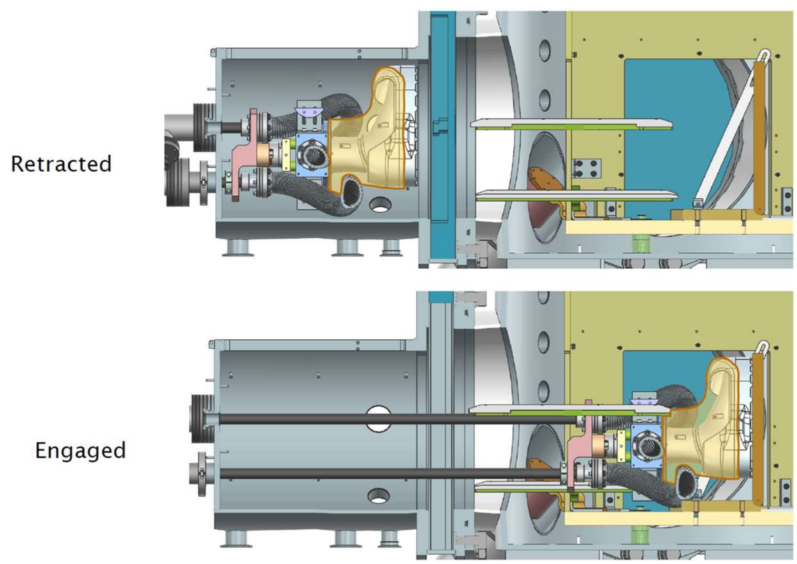

Figure 8: Push Rod System.

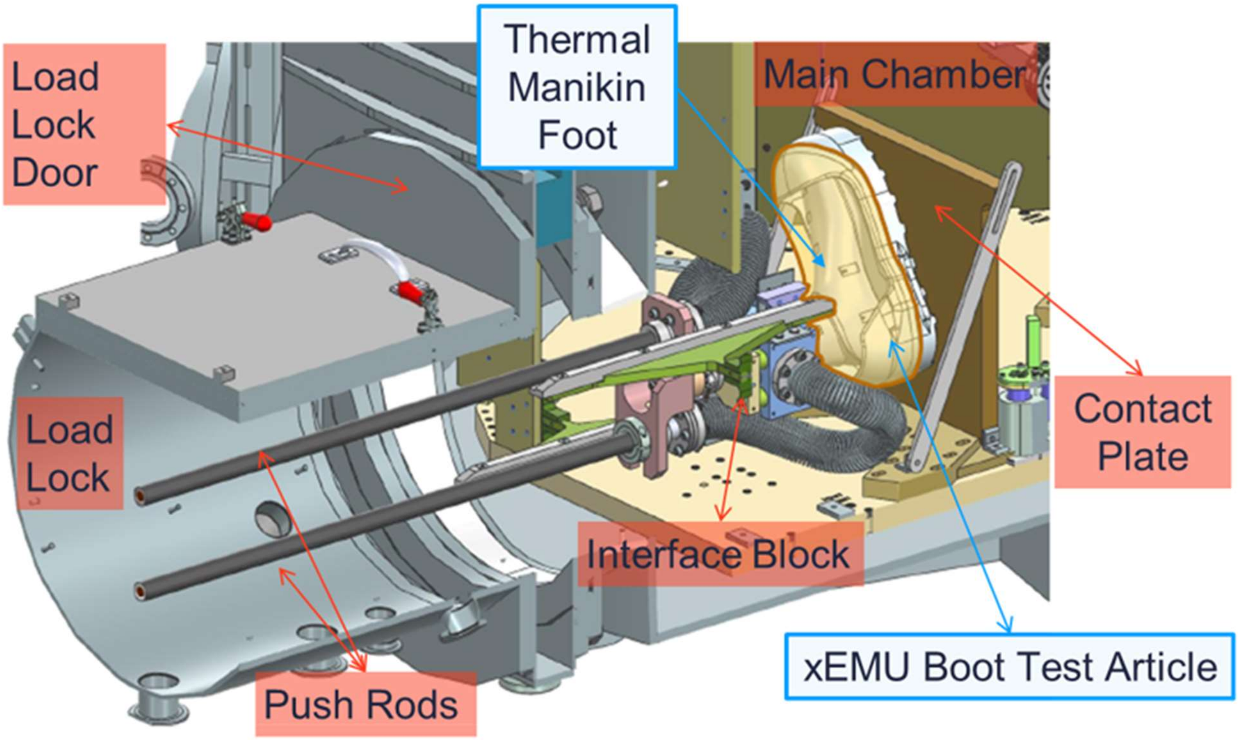

Figure 9: Spacesuit Boot Test System Diagram.

F. Boot Interface System

The spacesuit boot interface system was designed to serve several functions within the thermal vacuum test setup. First, the spacesuit boot interface system provided a bolt hole pattern interface compatible with the xEMU spacesuit boot softgoods and clamp ring. The interface system also incorporated a matching bolt hole pattern to which the thermal manikin foot can be mounted to. The interface system also served as the sealing surface for the spacesuit boot test article pressurized to 29.65 kPa (4.3 PSIA). The interface system and push rods were exposed to the pressurized volume of the spacesuit boot, and consequently, the interface system was also pressurized to 29.65 kPa (4.3 PSIA). The interface system housed the thermal foot system fluid lines, electrical harnesses, and a line to flow gas into the spacesuit boot. Finally, an in-line force transducer was located on the boot interface system to measure the applied load on the spacesuit boot/contact plate. The in-line force transducer was not rated for exposure to cold environment temperatures and therefore had to be thermally insulated from the spacesuit boot. G10, a fiberglass-reinforced epoxy laminate, was used as a standoff between the in-line force transducer and the spacesuit boot test article. The entire spacesuit boot interface system was then wrapped in MLI to prevent heat leak out of the interfaces system.

The spacesuit boot interface system also had volume constraints, in that the assembly was constrained to the inner dimensions of the door between the loadlock and the main chamber. Exceptional care was taken during the design phase to model cable and tube routing to decrease the risk of the as-built interface system encountering mechanical interference with the loadlock door wall. Ultimately, no interference issues were encountered. Another feature of the interface system was the positioning rails. With a relatively heavy spacesuit boot test article and interface system installed on the ends of the hollow, 10-foot-long push rods, significant deflection was observed when the push rods were extended into the main chamber. To address this issue, a rail position system was developed. Teflon rails were placed in the main chamber with corresponding sliders on the spacesuit boot interface system. When the push rods extended the spacesuit boot test article into the main chamber, the sliders would catch on the rail system and offload the weight of the spacesuit boot test article.

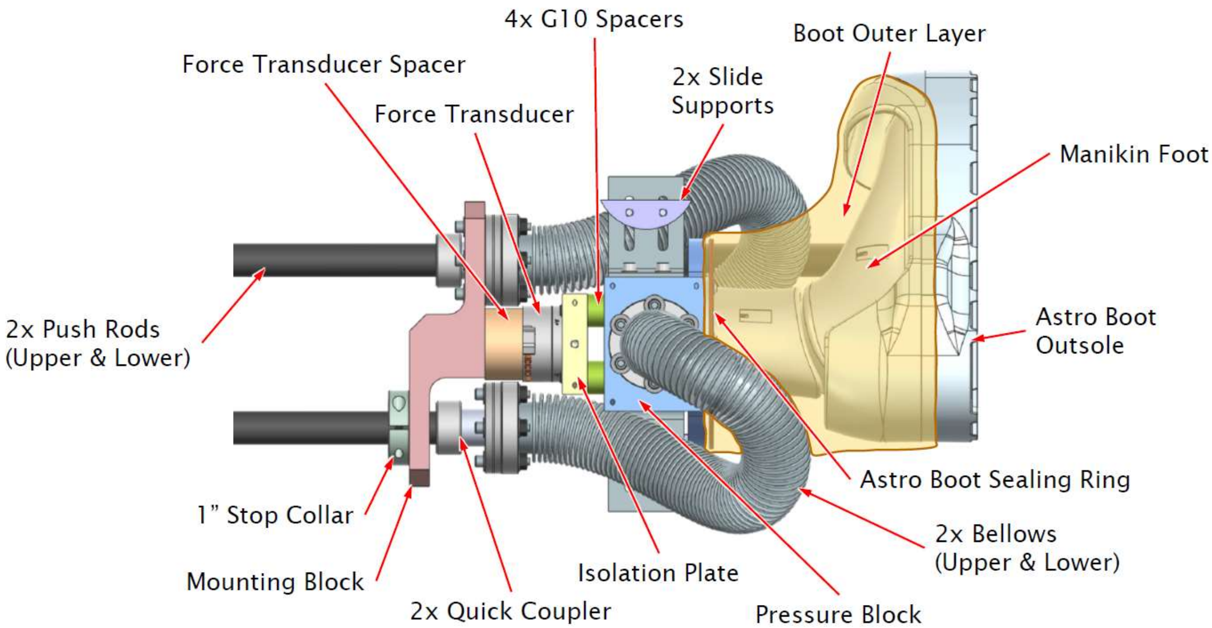

Figure 10: Spacesuit Boot Interface System.

G. Lunar South Pole Thermal Environment Simulation

JPL's CITADEL thermal vacuum chamber is approximately 2.22 cubic meters in volume. Cooling down this medium-sized vacuum chamber presents a challenge given the large amount of thermal mass present in the chamber. While certainly the chamber can be cooled down to target test temperatures, it would take on the order of magnitude of days to weeks to cool the full chamber to execute a single test point. To aid in executing test points more efficiently, JPL engineers developed a "mini-shroud" concept, whereby a small metallic box would be built for the spacesuit boot to fit in. This mini-shroud would be thermally sunk to the cold-heads in the chamber, cooling just the mini-shroud and stomp pad, but not the remainder of the 1.2 meter by 1.5 meter (4 foot by 5 foot) main chamber. The mini-shroud was manufactured from aluminum. The internal surfaces of the mini-shroud were painted with a high emissivity paint (Aeroglaze Z306) to increase the radiation heat efficiency of the mini-shroud. The external surfaces of the mini-shroud as well as the copper heat sink pathway were wrapped in MLI to insulate the system from the warmer main chamber. Two other features of the mini-shroud system were the addition of single-layer insulation (SLI) between the mini-shroud and load lock door opening as well as SLI "streamers" between the spacesuit boot and the warm loadlock environment. With this mini-shroud thermal environment design, the radiation environment was able to be cooled to desired test temperatures in 12 to 24 hours.

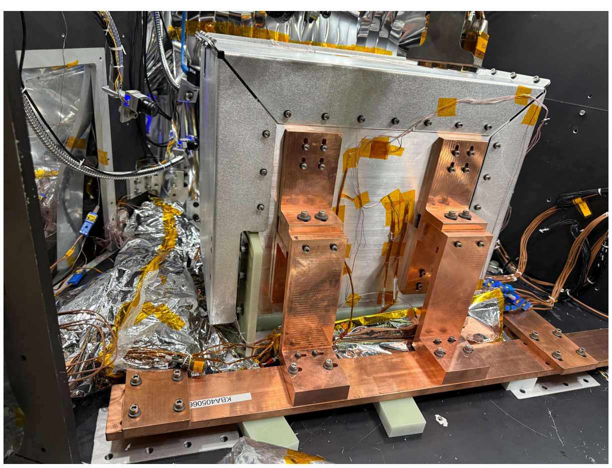

Figure 11: Stomp Pad Copper Bars.

The contact plate, also referred to as the stomp pad, was a 1-inch-thick aluminum 6061-T651 plate, mounted to a G10 hinge, and supported by two G10 side supports. The assembly rested on an aluminum 6061-T651 base plate. The mini-shroud was mounted to the stomp pad and angle adjustability (± 15°) was built into the stomp pad design as the spacesuit boot flexion angle was unknown at the time of designing the stomp pad. Ultimately, the vertical stomp pad orientation was chosen for testing. The stomp pad pivoted on a G10 circular hinge that also thermally insulated the aluminum base plate that was resting on the warm chamber floor from the cold stomp pad. On the backside of the stomp pad, copper material was used to thermally sink the aluminum stomp pad to the chamber cold heads. An initial issue that prevented the stomp pad from reaching target temperatures around 48K (-373°F) was the lack of surface area provided by four braided copper straps which connected the stomp pad to the copper bars. The copper straps were replaced with copper bars, and additional copper bars were added to the backside of the stomp pad to increase the surface area for heat transfer to occur. A final modification was made to the front side of the stomp pad where during dry-run testing; it was observed that the low emissivity surface of the aluminum was reflecting heat radiating from the spacesuit boot. A softgoods blanket was fabricated, consisting of multi-layer insulation packaged in a dark Teflon fabric. This thermal blanket had a cutout for the spacesuit boot outsole to contact the metallic surface of the stomp pad, but otherwise covered the non-contact surfaces of the stomp pad.

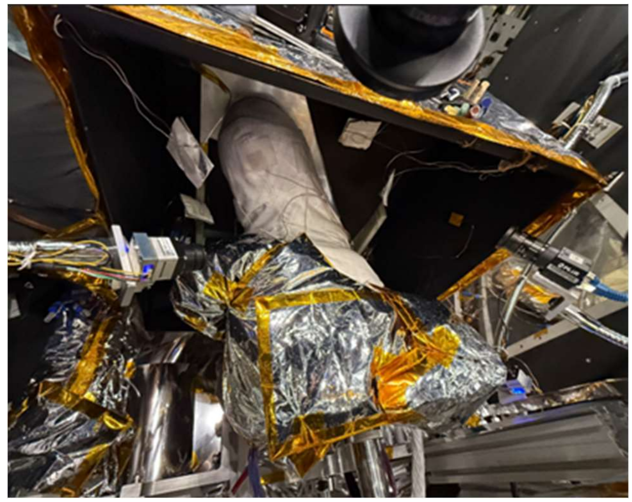

Figure 13: Spacesuit Boot Inside Mini-Shroud.

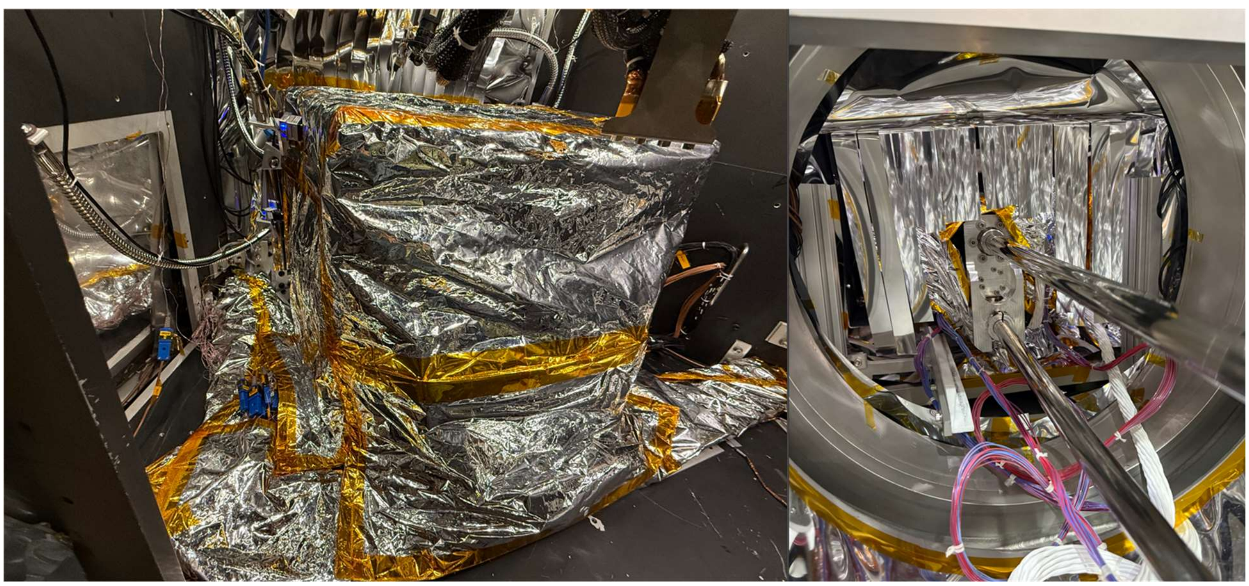

Figure 12: Spacesuit Boot Thermal Environment Design.

H. Camera System

The JPL CITADEL chamber provided both regular video cameras as well as infrared (IR) cameras to capture visible and IR images of the spacesuit boot test article during exposure to lunar South Pole temperature extremes. While these camera views were not used for direct data collection, the thermal imaging provided a useful macroscopic view of the spacesuit boot thermal gradients inside of the mini-shroud during thermal vacuum testing operations.

I. Spacesuit Boot Pressure System

A pressure system was designed and built to both pressurize the spacesuit boot to 29.65 kPa (4.3 PSIA) and to flow 12.4 SLPM (1.5 ACFM) of gaseous nitrogen (GN_2) through the spacesuit boot test article. The nominal EVA spacesuit pressure of the extravehicular mobility unit (EMU) is 29.65 kPa (4.3 PSIA) and the spacesuit pressure where most xEMU HITL testing has been performed. xEMU was designed for a nominal operating pressure of up to 56.5 kPa (8.2 PSIA) to reduce pre-breathe time for lunar EVAs. While a spacesuit pressure of 56.5 kPa (8.2 PSIA) would have an increased gas density and consequently greater convective heat transfer efficiency, this elevated spacesuit pressure was not tested. A single spacesuit test pressure of 29.65 kPa (4.3 PSIA) was chosen. Future test series and/or thermal modeling efforts could further investigate the convective heat transfer effects on spacesuit boot thermal performance at increased spacesuit pressures. The gas ventilation flow rate of 12.4 SLPM (1.5 ACFM) was chosen because the nominal gas ventilation flow rate through the xEMU spacesuit is 49.7 SLPM (6 ACFM). Each arm and leg of the Liquid Cooling Ventilation Garment (LCVG) contains a ventilation return duct where gas is pulled back from the spacesuit and into the Exploration Portable Life Support System (xPLSS). With approximately equivalent pressure drop in each ventilation return duct, it is expected that the gas ventilation flow rate at the spacesuit boot would be a quarter of the total ventilation flow rate, 12.4 SLPM (1.5 ACFM). Finally, gaseous nitrogen was chosen as the gas species due to both facility supply availability and to eliminate flammability (if oxygen was the gas species) as well as icing of water vapor (if air was the gas species) as potential hazards to the test system and test operators.

To control the gas flow to the spacesuit boot, a flow controller was placed upstream of the spacesuit boot test article. To control the pressure of the spacesuit boot, a back-pressure controller, calibrated for sub-ambient pressures, was placed downstream of the spacesuit boot. While placing two controllers in the same gas volume can sometimes lead to oscillation between the two controllers, the upstream flow controller was intentionally designed to operate in a sonic flow condition such that oscillations from the downstream back pressure controller did not cause the upstream flow controller to adjust its valve position.

To provide overpressure protection for the spacesuit boot, a relief valve (RV) system was designed. It is undesirable to mount a relief valve directly on the spacesuit boot test article for two reasons:

1) Should the RV begin to flow into the chamber, the flow could overwhelm the vacuum turbopump capability and lead to an increase in chamber pressure. When the chamber pressure increases above approximately 0.133 Pa (1×10^{-3} torr), there is enough of an atmosphere where convective heat transfer begins to be significant.

2) Most relief valves operate by a mechanical spring holding a poppet closed until the pressure plug load exceeds the compression force provided by the spring. The spring is a metallic component that, when exposed to cryogenic temperatures, will experience thermal contraction. If the relief valve is calibrated to crack at a certain pressure at ambient temperature, it is likely the RV will crack at a different pressure when the RV is exposed to cryogenic conditions.

Placing the relief valve outside of the thermal vacuum chamber in ambient temperature conditions solved the issues of exposing the relief valve to cryogenic temperatures. However, this created a new problem, as it is critical that for the relief valve to function properly, it must vent to the same environmental pressure to which the spacesuit boot was exposed. The spacesuit boot saw two different pressure scenarios:

1) *Inside of the Main Chamber:* The spacesuit boot saw high vacuum while the spacesuit boot was inside of the main chamber. To avoid venting the RV back into the main chamber, the outlet of the RV was plumbed to a separate vacuum pump that was not part of the main chamber vacuum system.

2) *Inside of the Loadlock:* The spacesuit boot saw environments ranging from vacuum to 101.35 kPa (14.7 PSIA) during load-lock pressurization operations. When the load-lock was depressurized/pressurized, the outlet of the RV was plumbed back into the loadlock volume, so the RV was referenced to the same environment pressure that the spacesuit boot was seeing.

V. Test Results Summary

A high-level summary of the test results will be presented in the paper and a more detailed discussion of the test results, analysis methods, and model correlation will be documented in a separate paper. Several different conditions were studied throughout this test series with multiple variables changing for each test point. These test points included ten contact cases and five radiation cases with varying stomp pad, thermal manikin foot, and environment temperature setpoints. Contact force was also varied for the contact cases. The gas ventilation flow rate through the spacesuit boot was also adjusted.

Table 1: Summary of the Set and Measured Parameters of Each Test Point.

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

It was found that during the December test days the spacesuit boot temperatures were not reaching a thermal steady-state conditions after an 8-to-10-hour cold soak duration. For the January and February test days, the test duration was extended to last overnight to allow additional time for the spacesuit boot to reach a thermal steady-state condition. The January and February test days were used for model correlation.

The stomp pad was able to be cooled down to around 65K (-343°F), which is close to the xEMU spacesuit boot lunar PSR temperature requirement of 48K (-373°F). However, the radiation environment was warmer than expected, on average around 180K (-135°F). There are a few potential causes for the warmer-than-desired mini-shroud temperatures. The main thermal vacuum chamber walls were not chilled down to cryogenic temperatures and consequently the mini-shroud had to rely on insulation to reduce heat leak from the mini-shroud into the main chamber. Second, the mini-shroud walls were relatively thin, resulting in larger temperature gradients along the mini-shroud surfaces. Finally, the walls of the mini-shroud were not directly strapped to the cold heads in the chamber and relied on conduction from the stop pad to the mini-shroud.

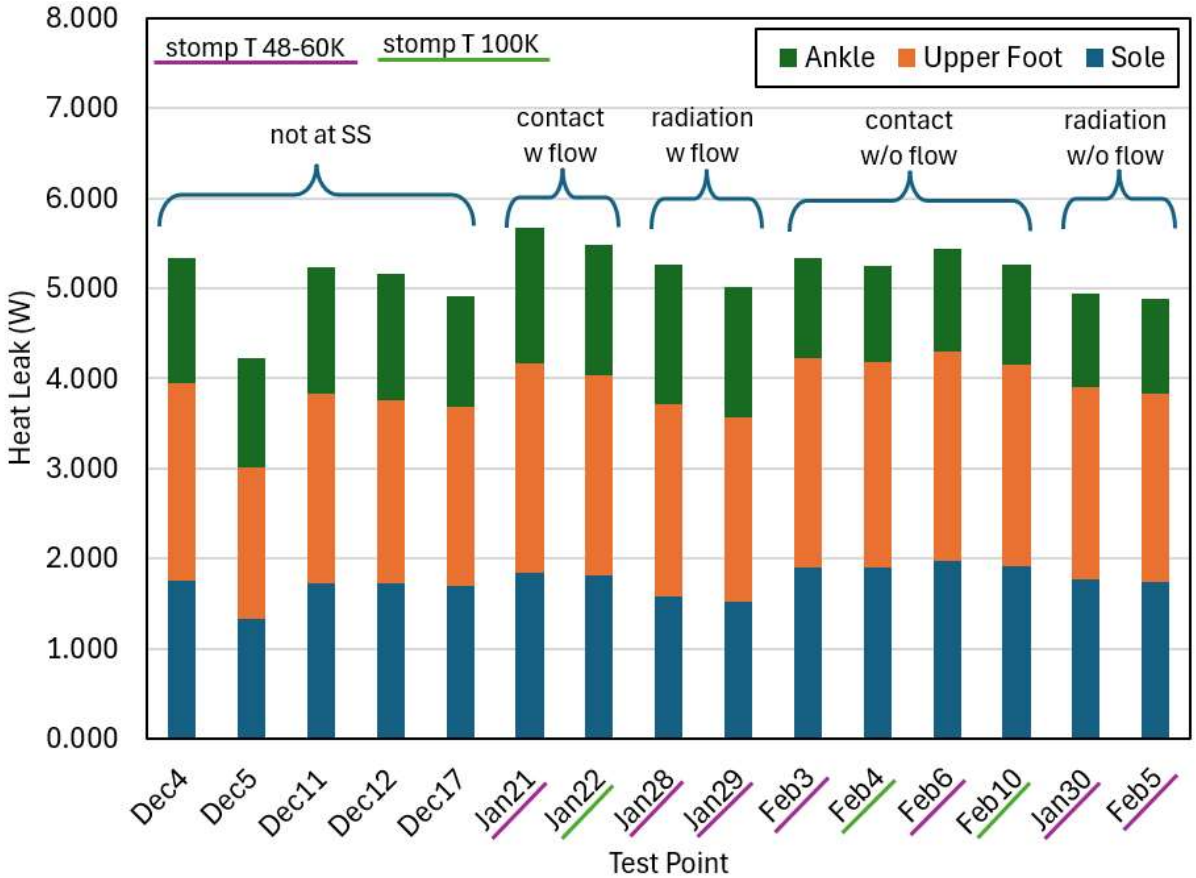

Figure 14: Experimental Spacesuit Boot Heat Leak for All Test Points.

A variety of trends can be observed in the test data. The data can be divided into categories of comparison: radiation vs. contact cases, vent flow on vs. off cases, and stomp pad temperatures colder vs. warmer cases. Comparing contact to radiation cases, it can be seen that the radiation cases consistently show smaller heat leaks than contact cases. This is expected because the conduction with the stomp pad and the pressure of compressing the layers of the boot facilitate an easier thermal path from the foot to the stomp pad. The difference in heat leak between the contact and radiation cases is lower than would be expected from prior modeling predictions which indicates a greater resistance than initially anticipated from the sole of the foot to stomp pad. This is due to the thermal insert providing better insulation than initially predicted and a smaller contact conductance from the sole to the stomp pad. The latter has slightly more uncertainty for lunar condition operation due to the difference between contacting aluminum and contacting regolith.

Between the vent flow and no vent flow cases, the no flow cases always exhibit smaller heat leaks than when vent flow is turned on. This has to do with convective heat transfer. When vent flow is turned on, the heat transfer between the sock and the bladder is slightly higher because of the forced convection.

Finally, the heat leak is higher for test points with colder stomp pad set points (this considers only contact cases, as the stomp pad was always set as cold as possible on radiation only test points). This is because the overall temperature gradient from the foot to the stomp pad is larger and there is a larger driving force for heat to leave the foot.

One other important take-away from this plot is that despite a variety of different set points, the heat leak leaving the boot is typically about 5 watts total on average, indicative of a consistent and predictable performance by the boot under a variety of scenarios.

VI. Test System Potential Improvements

It is expected that there will always be areas for improvement with developing a new test protocol, especially with a test protocol as complicated as thermal vacuum testing for lunar spacesuit boots. The following proposed test system improvements are not intended to invalidate the protocol developed in this testing effort, but to offer recommendations to improve the test system in the future.

1) *Mini-shroud:* The mini-shroud could achieve a more uniform thermal environment if the mini-shroud was changed from thin aluminum to thicker (0.5" to 1") copper. It should be noted that the high emissivity paint should still be applied to the mini-shroud walls.
2) *Test System Cold Sink:* The mini-shroud and stomp pad could be better thermally sunk to the cold head by both increasing the surface area at the connection point as well as connecting the walls of the mini-shroud to the cold heads as well.
3) *Loadlock Thermal Insulation:* The loadlock was thermally insulated from the main chamber with SLI "streamers". This could be improved by changing to MLI "streamers" to provide additional thermal insulation.
4) *Stomp Pad Emissivity Paint:* The stomp pad was covered with a MLI softgoods blanket to reduce IR camera reflections. This thermal insulation blanket resulted in the spacesuit boot seeing a warmer radiation environment than if the stomp had not been insulated. This system could be improved by removing the thermal insulation blanket and instead painting the non-contact areas of the stomp pad with the high emissivity paint.
5) *Lunar Surface Simulation:* Significant discussion was given to how best to simulate lunar regolith vs. simplifying the test system for afford better model correlation. Future tests could consider how to implement lunar regolith simulant that would fill the negative space between the spacesuit boot tread.
6) *Walking Simulation:* The CITADEL chamber has a 6 degree of freedom (DOF) mechanical arm inside of the thermal vacuum chamber. Future testing could investigate the potential to mount the spacesuit boot to the mechanical arm, then actuate the arm moving the spacesuit boot outsole onto and off of the stomp pad. This test setup could not only be used to investigate thermal transient effects of walking but also the cryogenic softgoods flexion risk.

VII. Conclusion

A repeatable test protocol was developed to evaluate planetary spacesuit boots at lunar South Pole temperatures that can be for developmental and qualification testing for upcoming Artemis missions. The secondary objectives of proving out the xEMU spacesuit boot thermal insulation design as well as validating the xEMU spacesuit boot thermal model were also achieved. However, there are still known gaps with the test protocol developed, primarily with the test thermal environmental not maintaining a PSR-relevant radiation environment, and the test system not directly evaluating the differences between lunar regolith and stomp pad contact. These areas could be improved upon with future testing. For nominal cold crater locations on the lunar South Pole, the government reference design xEMU spacesuit boot will likely provide sufficient thermal insulation. However, for PSR environments, a medium level of risk still exists for the aforementioned reasons. Continued spacesuit boot testing and analysis work could help decrease this level of risk prior to entering a PSR on an Artemis mission.

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