# Artemis I Space Launch System Base Heat Shield Thermal Protection System Performance

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**The Space Launch System (SLS) Core Stage base heat shield experienced the highest external heating environments on the entire launch vehicle during Artemis I ascent flight. This result was consistent with design predictions. The base heat shield experiences P50 cork combustion dynamics at low altitudes, plume-induced recirculation at moderate altitudes and then in-space base flow physics out to Main Engine Cut-Off (MECO). The base heat shield thermal protection system (TPS) is composed of a P50 cork ablator which is bonded to a substrate. The heat shield protects the gimbal actuation system, RS-25 turbomachinery systems and other aft section sensitive components during ascent. This paper estimates the base heat shield TPS performance from Artemis I using flight data from the NASA Langley Research Center's Scientifically Calibrated In-Flight Imagery (SCIFLI) Airborne Multispectral Imager (SAMI), development flight instrumentation (DFI) and other TPS recession flight measurements. Predictions from computational and ground test-derived engineering ablation models and observations are also applied. Since no base heat shield substrate thermocouple data were obtained for Artemis I, an estimate of the TPS performance data is derived here. This data assesses thermal margin of the SLS Core Stage base heat shield and best informs the Artemis II Crewed mission to the moon.**

## Nomenclature

| | | |
|---|---|---|
| *Al* | = | Aluminum |
| *BHS* | = | base heat shield |
| *BFS* | = | BTU/ft$^2$-sec |
| *BET* | = | best estimated trajectory |
| *CFD* | = | computational fluid dynamics |
| *CS* | = | SLS core-stage |
| *CT* | = | computed tomography |
| *DFI* | = | Development Flight Instrumentation |
| *FIAT* | = | Fully Implicit Ablation and Thermal Code |
| *GTP* | = | gas temperature probe |
| *HGF* | = | Hot Gas Facility |
| *HF* | = | Green Run Hot-Fire Test |
| *MECO* | = | Main Engine Cut-Off |
| *P* | = | pressure |

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|---|---|---|
| *P50* | = | Phenolic resin cork with 50 *u*m granules |
| *R* | = | gas constant |
| *RAD* | = | radiation measurement from an IR radiometer |
| *qdot*r | = | radiative heat flux |
| *SLS* | = | Space Launch System |
| *SRB* | = | Solid Rocket Booster |
| *T+* | = | SLS lift-off time or test start time |
| *T* | = | temperature |
| *t* | = | time |
| *TC* | = | thermocouple |
| *TD* | = | Thermal Desktop |
| *TOT* | = | total heat flux from calorimeter measurement (BFS) |
| *TPS* | = | thermal protection system |

## I. Introduction

Artemis I was the first human-rated lunar system test flight since Apollo 5 in 1968 where the Saturn V launch vehicle carried the Service, Lunar and Command Modules around the moon[1-3]. Artemis I was the first integrated test flight encompassing the Space Launch System (SLS) launch vehicle and the Orion spacecraft. Artemis I successfully launched from Pad39B from the Kennedy Space Center, Florida on November 16, 2022, as shown in Figure 1. The SLS was propelled with four liquid hydrogen ($LH_2$) and liquid oxygen ($LO_2$) rocket engines and two five-segment solid rocket boosters (SRB)[1-3].

There were various base components for the SLS vehicle that were instrumental for mission success. The base heat shield (BHS) which is the largest aft-end acreage structure, protects the base of the vehicle and its internal components and avionics cabling from excessive rocket plume-induced heating. Boeing, the prime contractor of the SLS Core Stage, used P50 cork coated with Hypalon paint for the base heat shield. Thermal blankets were used for the engine-mounted heat shield (EMHS) which protects the RS25 turbopump machinery and gimbal actuators while allowing the gimbal actuators to move. Thermal protection systems on the aft end of the vehicle are needed due to the high thermal environments experienced on ascent due to multi-engine launch vehicle operations.

Figure 1 shows the Artemis I flight Core Stage and SRB base region with all first-stage engines and solid rocket motors firing nominally. The complex flow field can be seen with six rocket exhaust plumes and atmospheric air interacting in the SLS Core Stage and SRB base regions at T + 15 seconds. The T + 0 second point for Artemis I flight data analysis was defined at SRB ignition which occurred on November 16th, 2022, at 1:47:44 AM EST. All flight times in this paper are respect to this reference time. The SRB aluminum-oxide laden plumes were bright (near saturated pixels) while the RS-25 plumes were observed to be relatively transparent, being dominated by water vapor. Along with the complex plume flow field, there were two-phase TPS – gas phenomena occurring on the surface of the heat shield during ascent which will be described in detail within this paper. This infrared (IR) imagery data (Figure 1) was captured by the MARS Scientific ground-based imager system which was part of the NASA Langley Research Center's Scientifically Calibrated In-Flight Imagery (SCIFLI) Team[4].

Figure 2 shows the various components on the SLS Core Stage. Hypalon-coated P50 cork was used extensively on the base heat shield, boat tail and acreage of the engine section. It was also used on certain regions of the Intertank which experienced high aerodynamic heating. It was also used recently on the Artemis II vehicle and is planned for Artemis III – V. Cork is also used as an ablator TPS on other elements of the SLS and Orion vehicles such as the solid rocket boosters and the launch abort system (LAS).

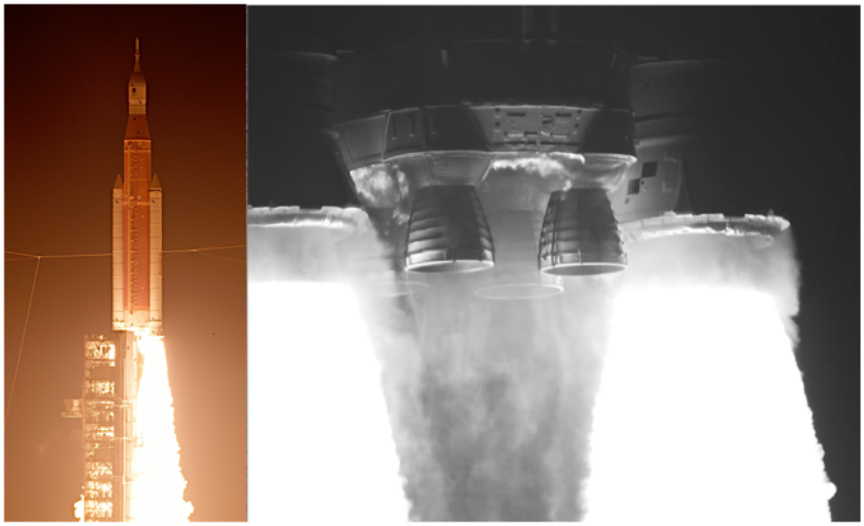

**Figure 1. Artemis I SLS launch (left) and IR image of the SLS base at T+15 seconds (right).**

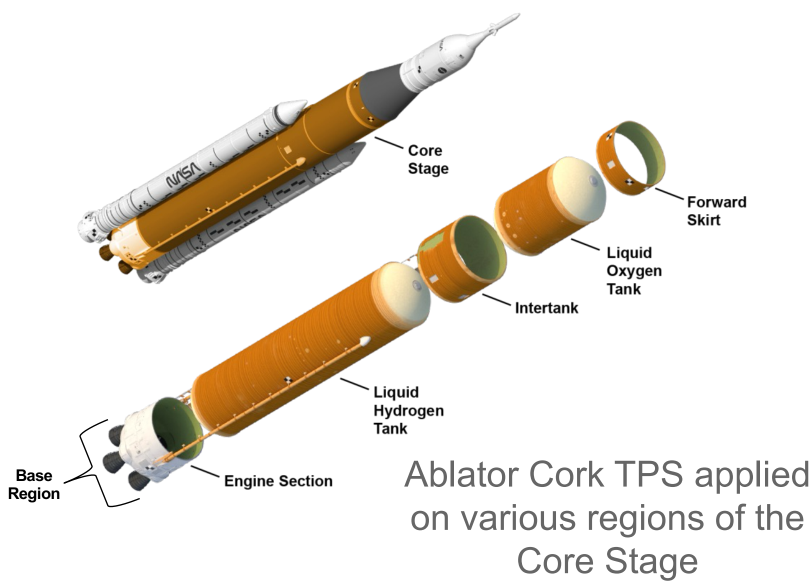


**Figure 2. SLS Core Stage layout.**

The primary objective of this paper was to estimate the SLS Core Stage base heat shield TPS performance during Artemis I using flight data, ground test data and prediction methodologies. Images of the Core Stage base heat shield are shown in Figure 3. The manhole cover central region of the base heat shield had different TPS configuration then the other regions of the heat shield. There are multiple RT455 TPS bricks observed on the surface of the base heat shield as shown in Figure 3. Multiple flight data sources are leveraged in this investigation such as the NASA Langley Research Center's Scientifically Calibrated In-Flight Imagery (SCIFLI) data, SLS base heat shield development flight instrumentation and TPS P50 cork flight recession measurements from another flight program. Ground test data from the NASA Marshall Space Flight Center's Hot-Gas Facility has also been used to characterize shear stress and thermal environments on P50 cork. Using this flight and ground test data as inputs, high fidelity computational and engineering codes were being used to provide cork recession assessments for Artemis I. There were no base heat shield substrate thermocouples on this flight test and so it is difficult to directly assess the base heat shield TPS performance. Ground truth of the TPS performance of the Orion heat shield can be accomplished since the flight hardware is returned, assessed and analyzed. This was extensively completed for the Artemis I test flight.

However, the SLS Core Stage is an expendable vehicle element and not returned to site for evaluation. There were also no TPS recession thermal plug on the base heat shield to provide ground truth in-situ measurements of the recession during flight. The purpose of this paper is to use as much of the flight data as possible along with prediction codes to provide an estimate of the TPS performance. This is an important activity due to the very high thermal environments observed and predicted on the base heat shield on SLS ascent. The Artemis II SLS Core Stage base heat shield has the same TPS design as Artemis I and this activity provided technical rationale and qualitative thermal margin for the Artemis II Crewed mission.

This paper will focus on the development of multiple data sets to estimate the SLS base heat shield TPS performance. It will briefly cover the data reduction of the various methodologies employed, the heritage of this data set where needed and the input models based on flight and ground test data that feed into multiple ablation models. The input models for the ablation models are the direct measurements of the thermal environments and the TPS surface temperatures from the Artemis I flight. Both test-based models and computational high-fidelity models will provide results of the final TPS cork recession and other ablation characteristics at MECO. From these results, thermal margin can be assessed for the Artemis I flight.

The SLS Core Stage base heat shield TPS design is Anorim P50 cork sheets which is an ablator with 50-micron granules and phenolic-resin binder. P50 cork is basically a hydrocarbon and provides thermal insulation from thermal environments. Hypalon top-coating provides moisture and fungus barrier to the cork. High moisture absorption into the cork changes the thermal properties of the TPS. P50 cork has been used as an ablator on multiple launch vehicle since the 1960s such as the Delta IV Heavy, Space Shuttle Solid Rocket Boosters, ULA Vulcan and others.

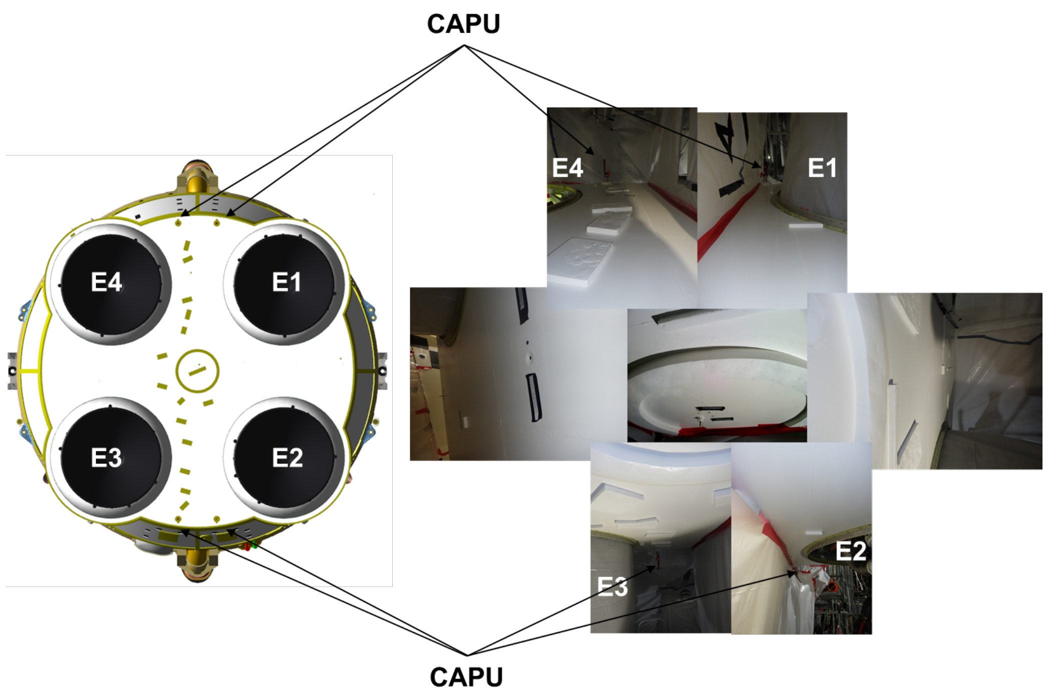


**Figure 3. Artemis I SLS Core Stage base heat shield schematic (left) and photographs (right)**

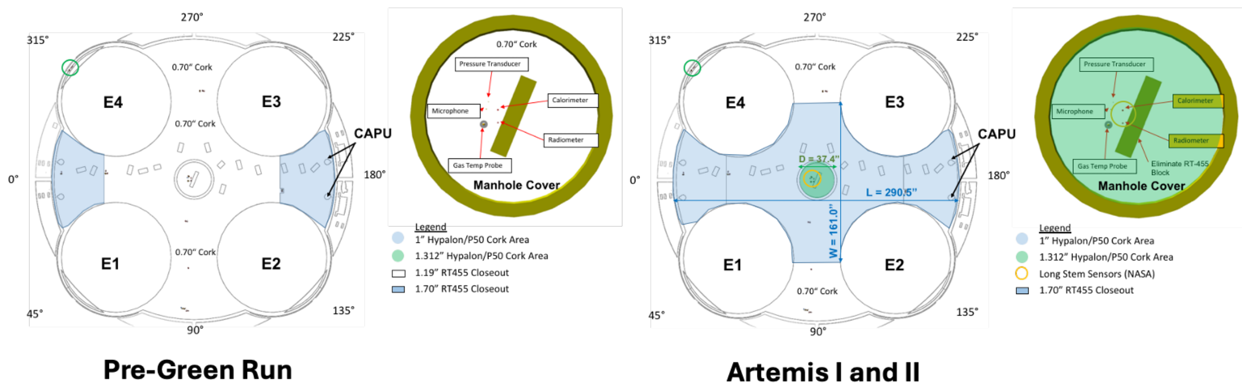


**Figure 4. SLS Core Stage base heat shield schematic configuration for Pre-Green Run (left) and Artemis I and II (right)**

Described in this paper is the detailed methodologies outlined of all the reduced flight data, ground test data, and computational analysis. This paper goes over the multiple sources of flight and ground test data to estimate thermal protection system performance of the Core Stage base heat shield during Artemis I flight. Flight environments and flight TPS surface temperatures were used to best estimate TPS performance. The paper shows time-evolving base heat shield P50 cork TPS recession distributions, integrated final recession and char-depths and final recession TPS prediction comparisons with pre- and post-Green Run design thicknesses. It shows input model results that feed into the computational and semi-empirical ablation models. We show base heat shield surface temperature distribution during Artemis I from SCIFLI imagery which is used as a boundary condition for the computational ablation models. It shows comparisons of the ground-test derived (heritage approach), commercial launch vehicle flight-test derived and computational recession predictions of the P50 cork due to base environments on Artemis I. It discloses uncertainty assessments and limitations on all analysis conducted to provide confidence levels of the TPS performance. This rich data set from multiple analysis codes and approaches provides a robust approach in establishing thermal margin on the base of the SLS vehicle and will be used to inform the Crewed Artemis II flight and beyond.

## References

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