HEATSHIELD FOR EXTREME ENTRY ENVIRONMENT TECHNOLOGY (HEEET) THERMAL PROTECTION SYSTEM (TPS)

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Abstract

Starting in 2013 and completing in 2019, the Heatshield for Extreme Entry Environment Technology (HEEET) project has been working to mature a 3-D Woven Thermal Protection System (TPS) to Technical Readiness Level (TRL) 6 to support future NASA missions to destinations with extreme entry environments such as Venus, Saturn, Uranus, Neptune and high-speed sample return missions to Earth. A key aspect of the project has been the building and testing of a 1-meter base diameter Engineering Test Unit (ETU) representative of what could be used for a Saturn probe. This paper provides a high-level overview of the HEEET project including 1) manufacturing and testing of the ETU for structural model verification, 2) establish system capability and 3) verify manufacturing workmanship.

Introduction

Venus probes and landers, Saturn and Uranus probes, and some high-speed sample return missions have been highly ranked for their scientific value by the National Research Council (NRC) Planetary Science Decadal Survey (PSDS) committee [1]. Due to their extreme entry environments, thermal protection system (TPS) options for these missions were typically limited to heritage fully dense Carbon Phenolic which is heavy and in order to be utilized in a mass efficient manner often results in steep entry flight paths that result in very high g-loads which can limit the kinds of instrument payloads that can be flown.

The HEEET project has developed and matured a 3D woven TPS technology that provides a mass efficient and readily-manufacturable heat shield system for entries with heating rates between 1500 W/cm^2 and 3,600 W/cm^2 and stagnation pressure between 1 atm and 5 atm. HEEET enables missions to fly a broader range of entry flight paths, particularly shallower flight paths with lower g-loads during entry opening up the possibility of incorporation of more sensitive instrumentation.

A key objective of the HEEET project was to demonstrate the manufacturing of full-scale parts, integration of those parts onto a carrier structure and demonstrate the heatshield functionality at relevant scale by manufacturing and testing an Engineering Test Unit (ETU) in relevant thermal and structural environments. Testing of the ETU was used to validate analytical models that are essential for design of future entry vehicle systems. Bringing this new TPS capability to TRL 6 enables proposed atmospheric entry missions requiring extreme entry environments to be selectable in competed NASA opportunities.

HEEET Architecture and Engineering Test Unit (ETU) Manufacturing

HEEET has been developed to be broadly applicable to a range of missions and scales, examples include 1-meter Saturn probes to 3.5-meter Venus landers. The HEEET architecture, shown in Figure 1, consists of a high density all carbon top layer which is exposed to the entry environment and the thickness designed based on amount of recession expected during entry. Below the top layer is a lower density layer composed of a blended Carbon/Phenolic yarn that is more insulating and the thickness is designed to achieve a low enough temperature at the interface between the TPS and the structure beneath the TPS to allow it to be adhesively bonded to it. This woven architecture is then infused with phenolic resin, which is uniform throughout the thickness of the material.

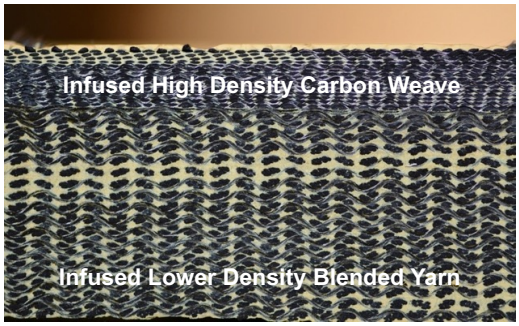

Figure 1. HEEET 3D weave in cross-section showing dual layer architecture.

A layer-to-layer weave is utilized in HEEET that mechanically interlocks the different layers together in the thru-the-thickness direction. This mechanical interlocking is not just between layers within either the high-density carbon layer or the lower density blended yarn layer, but also mechanically interlocks these two compositionally distinct layers to each other across the interface between them.

The HEEET project has concentrated on single compositions for each of these distinct layers, but the thicknesses of these layers can be tailored for a specific mission to optimize (minimize) the overall TPS mass.

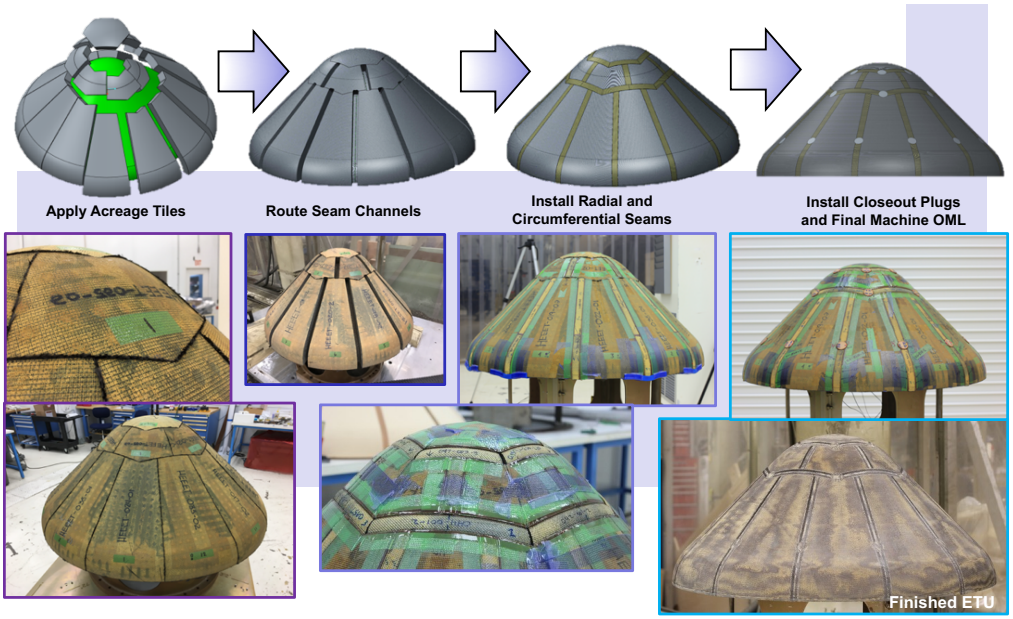

Figure 2. HEEET integration steps.

The woven material has limited width, constrained by the width of the loom hardware, therefore a heatshield will typically be constructed from several panels or tiles. The woven material is formed to the heatshield shape, infused with phenolic resin and machined to final shape. Then the tiles are bonded to the substrate, seams between the tiles are routed out and gaps between the tiles are filled with a gap filler. Figure 2 provides a schematic of the integration steps that have been developed in the course of the HEEET project, that were demonstrated at a relevant scale on the Engineering Test Unit.

Thermal/Arcjet Testing

Development and verification of tools to predict the required TPS thickness to survive entry and establishment of material and system (seams) capability during entry utilizes testing in arcjet facilities which produce the best ground based simulation of the entry environment. Due to limitations in ground testing capability, qualification of HEEET (or for that manner virtually any TPS) is achieved by piecing together evidence from multiple ground tests, none of which fully bound the flight conditions and vehicle configuration. Desired heat flux, pressure and shear conditions cannot typically be achieved simultaneously in ground facilities; therefore, testing at each facility focuses on achieving bounding conditions for only one or two parameters of interest. For the extreme entry environments that HEEET is targeting the ground facilities are pushed to their limits and small test coupons have to be employed to achieve the desired heating conditions. The results are challenges with testing seam designs under relevant conditions and increased uncertainty in test conditions and data interpretation. Many of these challenges are not exclusive to HEEET but rather apply to any TPS for use in extreme environments. Table 1 lists all the arcjet tests completed by the HEEET project. Test conditions (hot-wall), coupon geometry/size and number of coupons are provided for each test series. Evaluation of the HEEET material's robustness against failure and assessment of its recession predictability was pursued through stagnation point testing of small coupons at NASA Ames in the Interaction Heating Facility (IHF) using the 7.6-cm (3-inch) and 15-cm (6-inch) nozzles. Wedge testing was performed at the Arnold Engineering Development Center (AEDC) using the H3 facility to achieve flight-relevant shear conditions albeit at lower heat flux and pressure.

Table 1. HEEET arcjet testing campaign.

Test Date	Facility	Heat Flux (W/cm2)	Pressure (atm)	Shear (Pa)	Enthalpy (MJ/kg)	Sample Size	Sample Shape	Test Gas	TC Instrum.	Acreage Coupons	Seam Coupons
2013-Aug	IHF 7.6-cm (3-in) Nozzle	2500	5.3	0	23.4	2.5-cm	Flat Face	Air	None	4	0
2014-Oct	AEDC-H3 Wedge	1200	2.9	4000	11.6	10x12.5-cm	Wedge	Air	BackFace	2	12
2015-May	IHF 15-cm (6-in) Nozzle	1025	1.35	0	24.8	5-cm	Flat Face	Air	None	0	10
2015-Nov	IHF 7.6-cm (3-in) Nozzle	3600	5.3	0	23.4	2.5-cm	IsoQ	Air	None	8	12
2016-Aug	AEDC-H3 Wedge	1200	2.9	4000	11.6	10x12.5-cm	Wedge	Air	BackFace	2	6
2016-Aug	IHF 33-cm (13-in) Nozzle	280	0.31	0	21.2	5-cm	Flat Face	Air	TC Stack	2	2
		150	0.13	0	17.3					2	2
2018-Mar	IHF 15-cm (6-in) Nozzle	1320	1.35	0	21.3	5-cm	IsoQ	Air	None	1	0
2018-May	AEDC-H3 Wedge	1200	2.9	4000	11.6	10x12.5-cm	Wedge	Air	BackFace	2	16
2018-Jun	IHF 7.6-cm (3-in) Nozzle	1900	2.0	0	20.2	2.5-cm	IsoQ	Air	None	3	3
		3600	5.3	0	23.4					3	17
2019-Jul	AEDC-H3 Wedge	1200	2.9	4000	11.6	10x12.5-cm	Wedge	Air	BackFace	7	7
									Total	**36**	**87**

The HEEET acreage material did not fail in any of the arcjet tests conducted by the project, showing robustness against mission-relevant environments. Stagnation testing in the IHF 7.6 cm (3-inch) nozzle at 3600 W/cm^2 and 5 atm showed a very similar recession rate of the gap filler, the adhesive between the gap filler and the acreage material and the acreage material, see Figure 3.

The left side of the test article is acreage HEEET and the right side is the gap filler material, with the adhesive in the center, it is difficult to see the adhesive. There is no significant augmented recession of the adhesive. This has been consistent with multiple stagnation samples in the IHF testing of seams at other conditions, such as high shear (4000 Pa) in a wedge test article configuration at the AEDC H3 arcjet test facility, Figure 3. The ability to model HEEET material in-depth thermal response and recession was recently published in an AIAA paper by Milos, et.al [2]. Having the ability to accurately model a material's performance is essential for TPS sizing which posed some unique challenges given the dual layer nature of the HEEET system.

Figure 3. (Left) Post-test IHF stagnation model showing successful test of 0.25mm thin Nitrile Phenolic adhesive seam , (Right) post-test AEDC wedge model showing successful test of a T-Joint.

HEEET Structural and Thermo-Structural Testing

The three key elements required to properly model and characterize the HEEET design space are:

1. Determination of acreage material properties (both layers)
2. Determination of gap filler properties
3. Determination of adhesive allowables

The structural testing must cover all phases of the mission from launch through entry. The structural test campaign consisted of three basic types of testing. Element level testing, such as properties of the individual layers. Sub-component testing, such as 4pt bend testing of coupons, both acreage testing as well as seams. The sub-component testing and incorporated unique testing at the Laser Hardened Materials Evaluation Laboratory (LHMEL) test facility where 4-point bend testing was conducted while the surface of the test articles was heated by a laser. This testing was performed to establish the systems structural capability during entry as there is no practical way to perform such structural testing in the arcjet. And lastly is subsystem testing, or testing of the ETU which is in essence a Saturn probe prototype that is a relevant scale and built utilizing the materials and processes anticipated for use on a flight vehicle. The ETU testing verified the structural design tools at relevant scale and was used to determine any issues with workmanship.

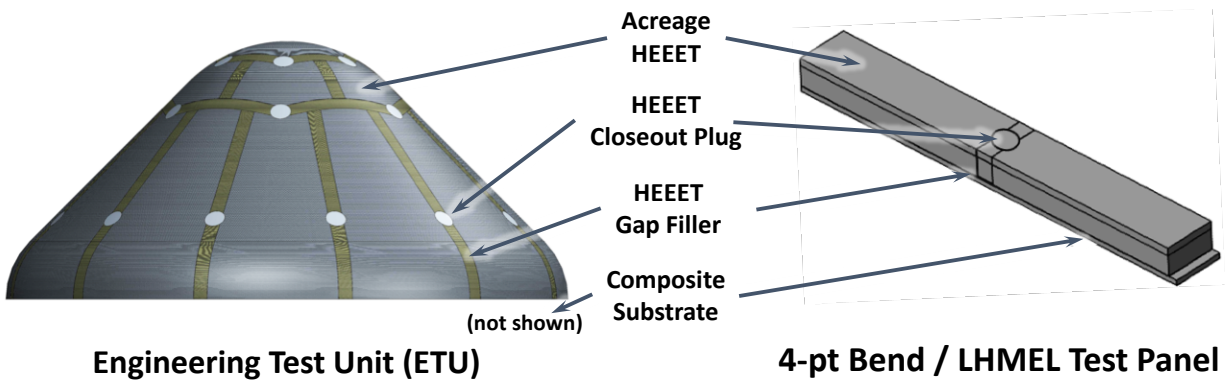

Figure 4. Structural and thermo-structural sub-component test coupon design showing relevance to ETU design features.

Figure 4 shows the types of features tested in the sub-component and subsystem testing. Given the nature of the seam and how it is fabricated, characterization of the seam at the element level is not sufficient and subcomponent testing of seams integrated in a flight like fashion is required in order to accurately understand and model the systems capabilities.

Engineering Test Unit (ETU) Testing

ETU testing covered a subset of the actual loads that a heatshield is exposed to during mission phases from launch and ascent to entry. Key load cases that were not evaluated on the ETU include vibration and acoustics (analysis showed system had substantial margins and therefore resources allocated elsewhere), shock testing (specific shock test articles utilized) and entry (no ground-based facility can test specimens at the scale of the ETU). The remaining tests of the ETU validated the material properties and finite element model utilized to design the system, established system capability (particularly in point load testing) and were used to expose and systemic issues in manufacturing workmanship.

The ETU testing consisted of 5 parts:

- Part 1 was static mechanical testing of the carrier structure alone, prior to TPS integration. The test consisted of sealing off the back of the ETU and pulling vacuum behind the structure. The test article was then tested in the autoclave and loaded in 3 different ways: elevated pressure at room temperature, elevated temperature at ambient pressure and then combined pressure and temperature. Part 1 testing was used to verify the model used to predict the carrier structures response, which was essential in order to back out the systems performance in future testing.
- Part 2 was the same static mechanical testing but in this case with the TPS integrated onto the composite carrier structure. This test was primarily a model correlation test activity showing how accurately the model, which was developed using element and sub-component testing, predicts the integrated system. The model typically predicted the measured strains to within 25% which for an ablative TPS system is considered good.

- Part 3 consisted of static point load testing where a hydraulic jack with different end effectors attached was used to apply point loads at specific regions across the ETU. For instance, some loads were in the center of tiles looking at acreage material properties, while other loaded regions were below seams, verifying the seam stiffness determined from flat 4pt bend coupons.
- Part 4 consisted of thermal vacuum testing where the ETU was heated and cooled for multiple cycles while under vacuum.
- Part 5 consisted of a repeat of a limited number of the point load tests. These were used to verify that the system hadn't changed after the thermal vacuum testing and in some instances the loads were increased substantially above the point at which the ETU was expected to fail. In no instances was there strain response during testing indicative of a failure and post-test CT scans did not reveal any evidence of a failure.

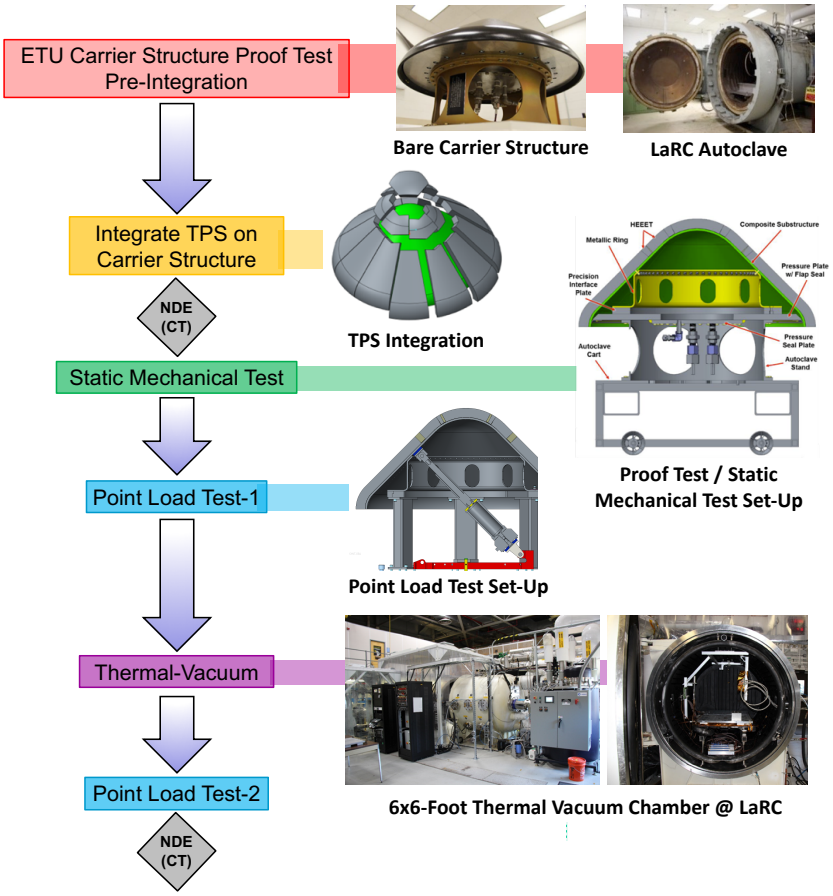

Figure 5. Summary of the HEEET ETU test campaign.

Results for a single load point, out of 23 that were tested, are shown in Figure 6. The load location, which is at a closeout plug, is circled in the figure and is point 12. The results indicate correlation within 10% for this location, which is excellent. Overall the HEEET system is estimated to have structural margins of >1 and for many >5 for relevant load cases. Although improvements in

modelling maybe feasible to better account for curved material properties (most data has been collected from flat specimens) it may not be necessary due to the large structural margins.

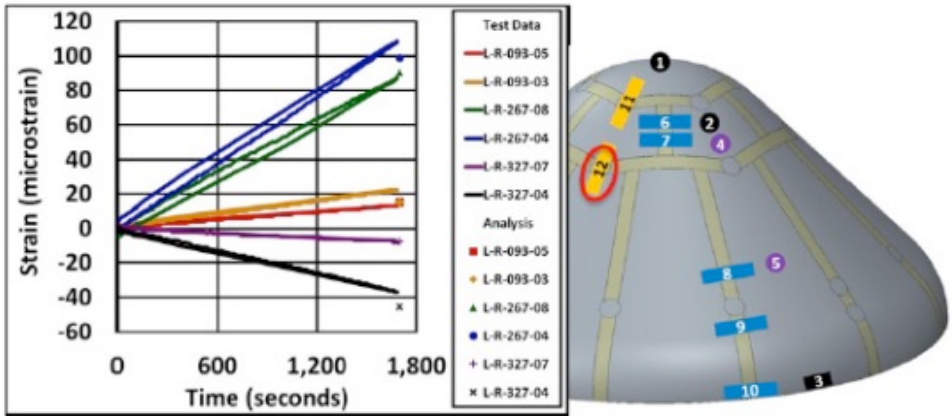

Figure 6. Example of model correlation for point loading at a closeout plug.

Summary

The HEEET project has matured the HEEET TPS to TRL 6. The project has successfully developed manufacturing and integration processes that enabled the building of a flight like prototype (ETU) and these processes were utilized in the fabrication of structural and aerothermal test articles. A comprehensive set of arcjet testing was completed to develop models to be able to predict the materials response in extreme entry environments and established the systems capabilities, including seams. A FEM model was developed as a design tool and the model was validated via testing of the ETU. The HEEET project's independent review board has concurred with the project's assessment that HEEET has achieved TRL 6 and is now ready for future mission infusion.

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