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Heat-Shield for Extreme Entry Environment Technology (HEEET)

HEEET Project Final Report

Executive Summary for Design Data Book

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National Aeronautics and
Space Administration

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CONFIGURATION MANAGEMENT

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Outline of the Executive Summary for the HEEET Design Data Book

The HEEET Design Data Book (DDB) is a multi-volume publication that documents the technical products of the Heatshield for Extreme Entry Environment Technology (HEEET) project, which was conducted between 2014-2019. This Executive Summary Volume provides background and motivation for the project, and describes the general concept of three-dimensional weaving, before laying out the Requirements that the project is expected to satisfy. The Scope of the Development Effort summarizes the project content, which is shaped by the functional requirements for the technology. A brief summary of the more comprehensive content in the other technical volumes is then provided. The volume concludes with an assessment of the HEEET technical status, and recommendations for mission applications.

Motivation for HEEET Project

The HEEET project was conceived to develop a heatshield with a high performance ablative thermal protection material that can withstand the extreme entry environment produced as a result of rapid deceleration during high speed entry into Venus, Saturn, Uranus, Neptune or higher speed entry into Earth's atmosphere. Successful maturation of HEEET will support future New Frontiers and Discovery AO's, as well as Flagship and directed missions in the longer term. In addition, HEEET has the potential to evolve and to support re-entry to Earth, for missions such as Mars Sample Return. The HEEET technology fits directly into the Agency's Objective 1.7: Transform NASA missions and advance the Nation's capabilities by maturing crosscutting and innovative space technologies. In addition to science mission applications, HEEET is targeting technology transfer from NASA to industry to support future heatshield manufacturing. HEEET is pushing the limits of weaving technology, and has already spurred interest in HEEET-type weaves for application in other engineering domains. A number of government and non-government entities have expressed interest in the HEEET technology for use in DoD applications.

At the inception of the HEEET development activity, there were no flight qualified materials available to enable these missions. Fully-dense Carbon Phenolic (CP) is the only ablative TPS with relevant flight heritage, but the unavailability of precursor material (rayon) and closure of processing capabilities pose prohibitive sustainability challenges for this material. Since there is no off-the-shelf heritage CP certified for NASA missions, perceived developmental risks for thermal protection negatively impact the evaluation of competitive proposals that involve atmospheric entry.

The Heatshield for Extreme Entry Environments Technology (HEEET) project directly addresses this issue. NASA's Science Mission Directorate (SMD) indicated the need and infusion opportunity for HEEET in recent Discovery and New Frontiers AO's, by incentivizing the adoption of HEEET and making a commitment to provide it to a selected mission as Government Furnished Equipment (GFE) [1]. NASA's Space Technology Mission Directorate (STMD), through the Game-Changing Technology Program, committed to the development of HEEET under a Memorandum of Agreement with SMD for potential infusion on Discovery 2014. STMD and SMD jointly supported HEEET during the formulation stage and continued to co-fund this technology throughout its 5 year maturation phase.

The primary goal of the HEEET Project is to develop an ablative TPS heat-shield based on woven TPS technology to Technology Readiness Level (TRL) 6. Key evidence to support the TRL evaluation (identified in the MoA) includes:

- Demonstration of reproducible manufacturing of a dual layer material over a range of thicknesses and integrated on to a heatshield engineering test unit at a scale that is applicable to near term Discovery as the highest priority and future NF missions as secondary priority set of missions.
- Demonstration of predictable and stable performance of the dual layer TPS over a range of entry environments that are applicable to near term Discovery and NF missions of interest to SMD.
    - Includes completion of coupon arc jet and laser testing and development of a mid-fidelity thermal response model that correlates with test results.
- Demonstration of flight heatshield system design for a range of sizes and loads that are relevant to near term Discovery and NF missions of interest to SMD.
    - Includes completion of structural testing to validate analytic thermal/structural models and development of a material property database.
    - Includes structural testing of a ~1m Engineering Test Unit under relevant entry loads.

Key Performance Parameters for the HEEET project are shown in Table 1, drawn from the Project Plan. They are consistent with the primary goal and the associated need to generate evidence for TRL assessment. There is one additional performance metric, which is the areal mass of the HEEET system. While this metric is strongly dependent on the entry conditions for specific missions, the general goal is to reduce mass by 40% relative to a Carbon Phenolic solution for an equivalent mission. Representative TPS sizing results are included in the Design Guidance Volume of the DDB. A mass advantage relative to Carbon Phenolic has been realized in all studies completed during the HEEET project, including multiple proposals for New Frontiers 4.

KPP Category	KPP Sub-Category	State of Art	Threshold	Goal
Manufacturing	Manufacturing	1" thick, 6" wide, 20"long flat panels	Successful manufacturing and integration of 1-meter ETU with 1" thick material	Successful manufacturing and integration of 1-meter ETU with 2" thick material using design and manufacturing processes that are scalable to a 3.5 meter vehicle
	Areal Mass (Unmargined)	Tape-Wrapped Carbon Phenolic (TWCP)	0.8 x TWCP	0.6 x TWCP
	Acreage Thermal Performance	Tape-Wrapped Carbon Phenolic	Stable and predictable thermal performance at nominal heat fluxes and pressures (~2000 W/cm2 and 2 atm)	Stable and predictable thermal performance at maximum tested heat fluxes and pressures (~5000 W/cm2 and 5 atm)
Performance	Seam Thermal Performance	TWCP to CMCP with phenolic adhesive	Delta recession: 0-50% > acreage. Delta bondline Temp < 1.2 x Acreage	Delta recession: 0-20% > acreage. Delta bondline Temp < 1.1 x Acreage
	Structural Performance	TWCP/CMCP	Successful 1 meter ETU performance during testing under most challenging load cases (static load and multiple thermal cycles)	Successful 1 meter ETU performance during testing under additional load cases (vibration and pyroshock) to envelop anticipated mission load set

Table 1. Key Performance Parameters for HEEET Development Project, from the Project Plan (GCDP-02-PEA-13125)

The HEEET project tasks largely align with these development and demonstration goals. Details of final manufacturing processes are provided in the System Manufacturing volume, #2. Discussion of demonstrated aerothermal performance is provided in the Aerothermal Test volume, #3. Similarly, structural and thermostructural performance is discussed in Volume 4. Volume 5 documents the development activities that culminated in the final system architecture. A summary of evidence supporting HEEET TRL assessment is included in this Executive Summary volume of the HEEET DDB, but more comprehensive development information is included in the Design Development Volume. Volume 6 provides Design Guidance for future missions, by distilling best practices from the lessons learned during execution of the HEEET Development Project.

The DDB was originally included as a KPP, to emphasize the importance of documentation to achieve technology transfer beyond the project team. Since it is a project performance metric rather than a technology performance metric, it was re-designated as a key Project Deliverable. The DDB is actually a collection of documents that are organized in a file tree structure. It is distributed as a single zip file that can be unpacked to access individual files. The top 2 levels of the structure are presented in Table 2.

Table 2. Hierarchical structure of 6 volume Design Data Book.

- 1 ExecutiveSummary
  - HEEET-0003-SystemRequirements_Draft_v4.xlsx
  - HEEET-1004_DDBExecutiveSummary_Draft_v2.docx
  - Project Documents

- 2_SystemMfgGuide
  - HEEET-2017 - ETU Manufacturing and Integration Lessons Learned Rev.NC.pdf
  - HEEET-4034-Rev.A - HEEET Manufacturing Requirements.pdf
  - HEEET-XM-6013 - Rev-5 - ETU All Integration Procedures.docx
  - Process Specifications

- 3_DesignDevelopment
  - 3.01_Introduction_DesignDevelopment.docx
  - 3.02_FailureModesAndMargins
  - 3.03_ArchitectureSelection
  - 3.04_Forming
  - 3.05_InfusionDevelopment
  - 3.06_Cutting_Machining
  - 3.07_Attachment_Adhesives
  - 3.08_IntegrationTrade
  - 3.09_ExpandingSoftenedHEEET
  - 3.10_CloseoutPlugs
  - 3.11_IntegrationDevelopment
  - 3.12_NonDestructiveInspection
  - 3.13_Repair
  - 3.14_StructuralModel
  - 3.15_ThermalResponseModel
  - 3.16_MaterialProperties
  - 3.17_Appendix_IRB_Presentations

- 4_ThermalResponseCharacterization
  - HEEET-3001-Rev A-HEEET Arcjet and Thermal Testing Plan-signed.pdf
  - TestReports
  - IndividualTestPlans

- 5_StructuralCharacterization
  - HEEET-3012-Rev B-HEEET Structural Testing Plan-signed.pdf
  - TestReports
  - IndividualTestPlans
  - Pre-test Analysis

- 6_GuidanceForFutureDesign
  - HEEET-0013-RevNC-HEEET Sustainablitity Assessment2.docx
  - HEEET-2011 - ESH DesignGuide-signed.pdf
  - HEEET-2012-Thermal Margin Policy and Sizing Guide_v2.docx
  - Interfaces

The Need for TPS for Extreme Environments

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 [2]. Due to their extreme entry environments, thermal protection system (TPS) options for these missions were previously limited to a single heritage material: Carbon Phenolic (CP). The HEEET project has developed a woven TPS technology that provides an efficient and readily-manufacturable heat shield material for entries with heating rates between 1500 W/cm^2 and 6,000 W/cm^2 and stagnation pressure between 1 atm and 6 atm, although it is not fully verified at the high end of these environments. If mission designers have the flexibility to keep environments towards the lower end of this range, the quality of performance verification that can be achieved in existing ground test facilities is significantly enhanced (which also applies to qualification of a new CP material). Bringing this new TPS capability to TRL 5/6 enables proposed atmospheric entry missions to be selectable in competed NASA opportunities.

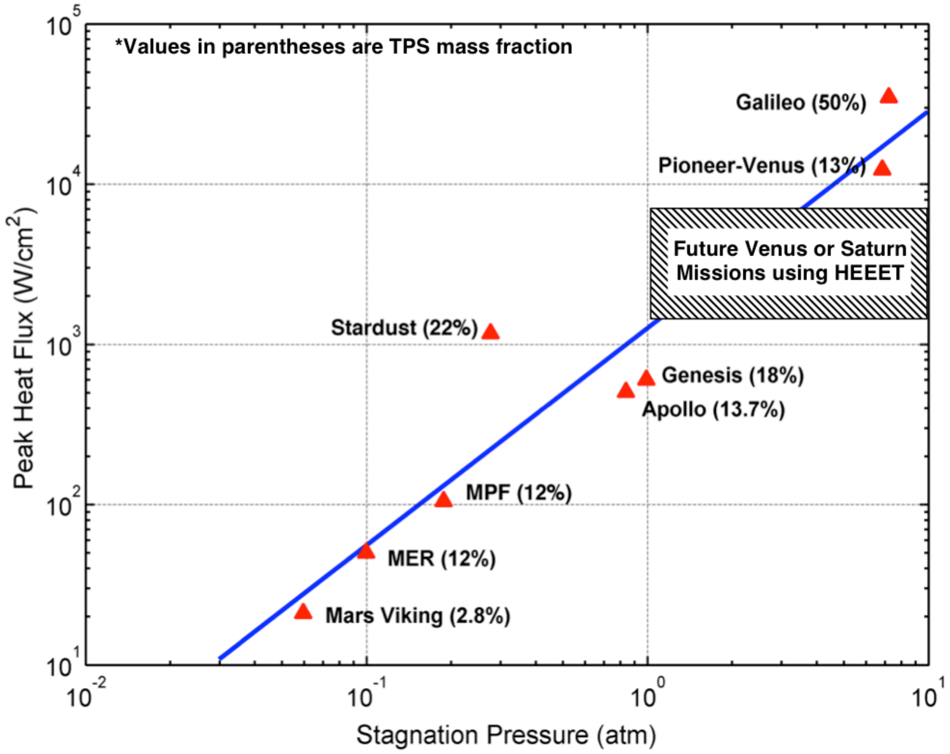

Figure 1. The HEEET project will develop efficient and robust thermal protection material for extreme entry environments

The HEEET material system is structured with a high density layer of carbon fibers at the surface, designed to provide robust recession performance (Recession Layer, or RL), backed by a thicker layer of lower density blended yarns (Insulation Layer, or IL) that provides insulation to the bondline between the RL and the carrier structure. One of the primary objectives of HEEET is to enable a broader range of science missions to be performed by allowing greater trajectory flexibility in the entry phase. HEEET is more insulating than heritage CP and hence more mass efficient. While CP is an excellent ablator that can withstand extreme heating rates, its high conductivity makes it inefficient for shallow entries that have high integrated heat loads. Use of CP results in steeper entry flight path angles due to its performance inefficiency. The steeper entry flight path angle produces extreme entry conditions of heat flux, pressure, shear, and high g-loads. Due to higher insulative efficiency, HEEET enables missions to fly at shallow entry flight path angles with higher heat loads but lower peak heat-flux, pressure and g-loads. HEEET opens up the potential to use more delicate science instruments and also the ability to reach a wider range of target destinations. Furthermore, the lower entry conditions are more testable, which enables easier flight certification and increased robustness.

Although CP has mission heritage from Pioneer Venus and Galileo, the heritage rayon-based carbon fiber is no longer available and manufacturing processes require recertification. Exact reproduction of previously-flown CP is not possible, which increases uncertainty about the performance and reliability of a new CP product. In contrast, the HEEET material system employs readily-available carbon fibers that are produced for a range of other applications. Sustainable production is an explicit goal for the HEEET project.

In order to make a blunt heat-shield, for NASA applications, two different manufacturing techniques are needed for carbon phenolic in the nose and flank regions. The tape-wrapped version that is suitable for the flank is used extensively for Department of Defense rocket nozzle applications. The chop-molded form of CP, which has been used on the nose of NASA vehicles and is NASA unique for entry applications, has displayed a spallation failure mode in some ground tests. The three-dimensional weave employed in HEEET materials improves robustness, so that recession is more controlled in similar aerothermal environments. Figure 2 compares the surfaces of test articles after arc-jet testing at severe conditions. The roughened surface of chop-molded CP indicates mechanical loss of material after testing in the worst orientation (chop-preferred orientation parallel to flow), while the intact weave of the HEEET material indicates that any mechanical loss has been limited to local damage of individual yarns.

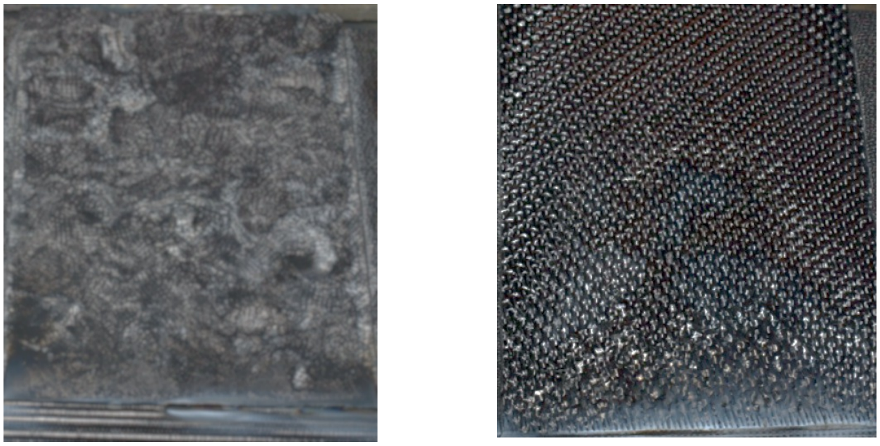

Figure 2. The woven TPS at right shows no indication of mechanical loss of material, in contrast with the chop-molded CP at left.

Three-dimensional Woven TPS Concept

The weaving industry has made dramatic progress on automated techniques in recent years. They control accurate placement of fibers of different composition to manipulate material composition, density and fiber orientation, so a TPS material with distinct functional layers is now achievable. Figure 3 shows a schematic of a generic 3D layer to layer weave that shows the ability to vary density and composition. It has a higher density top layer, a lower density middle section and a higher density bottom section.

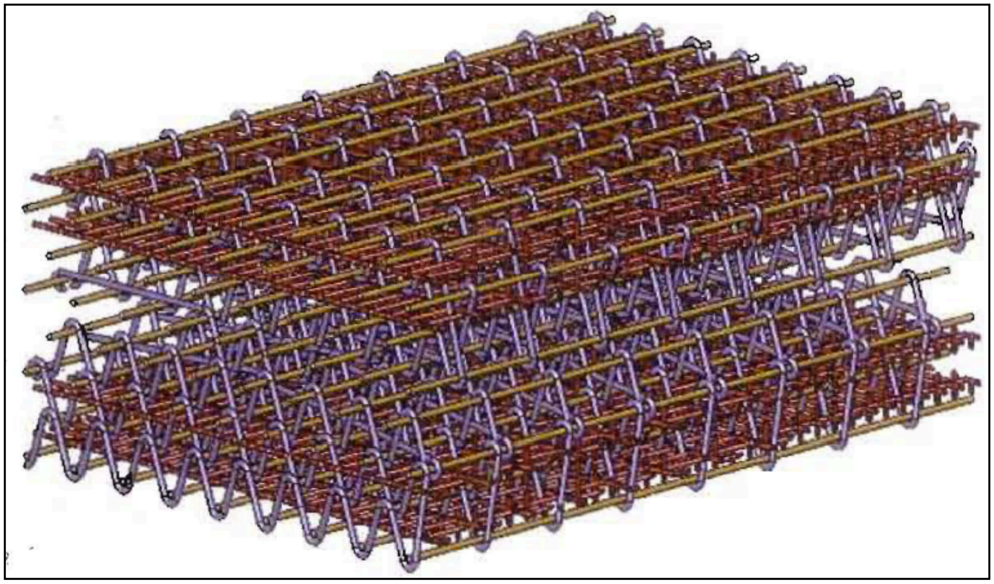

Figure 3. Three dimensional weave avoids simultaneous loss of multiple layers, and permits through-the-thickness tailoring of density.

The HEEET material developed in the current project is a dual layer, without a dense layer at its base. Near the surface, where recession is expected, carbon fibers are woven layer to layer, so that the loss of fibers that bind layers together does not cause simultaneous loss of multiple layers. This architecture mitigates ply lift and delamination failure modes inherent in 2-D carbon phenolic. Away from the surface, in the insulating layer, a blended yarn that combines carbon and phenolic fibers is used, to reduce fiber conductivity. In this layer the fiber density is lower, to further reduce conductivity and the overall density of the material in that layer. The two layers are integrally woven together, with fibers in the Thru the Thickness direction (z-direction) mechanically tying the layers together even as they transition between the dense outer carbon layer and the lower density insulation layer.

The HEEET project has concentrated on a specific weave architecture suitable for harsh environments, but it is possible to tailor the weave to achieve densities between that of Carbon Phenolic and PICA, without changing the manufacturing technique. Three-dimensional weaving is already being developed for Orion compression pad [3] and for deployable heatshields [4]. A family of robust mass efficient materials can be developed in the future to support atmospheric entry at multiple destinations.

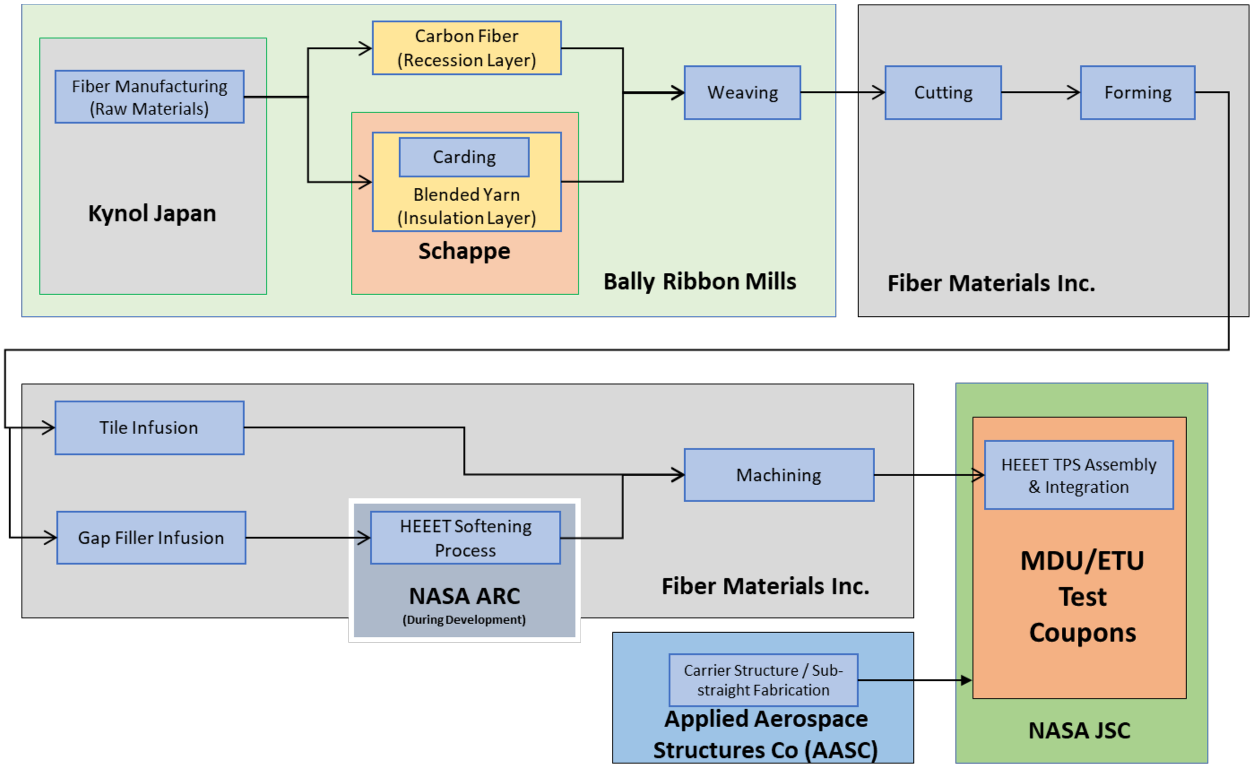

Figure 4. Process for building integrated heatshield

The woven material has limited width, constrained by the width of the loom hardware. A heatshield with a diameter larger than the loom width must therefore be constructed from several panels, which are cut to shape and joined to each other. The material is formed to the heatshield shape while it is dry, and then infused with phenolic. Individual pieces are then machined to final shape, and attached to the substrate. Finally the gaps between tiles are filled. Figure 4 provides a schematic of all the steps that have been developed in the course of the HEEET project, and finally demonstrated at fully relevant scale in an Engineering Test Unit that is representative of a planetary probe with 1 m diameter.

Requirements for HEEET Project

The HEEET project developed a set of generic Level I and Level II requirements that are intended to be applicable to any TPS system. The top requirements and rationale are shown in Table 2. Verification statements and documents containing supporting evidence are listed in Table 3, in the Status of HEEET Technology Development section of this report. All levels of requirements are fully captured, with HEEET task associations, in HEEET-0003 System Requirements and Verification Plan, which includes Level 3 child requirements that link to specific tests and analyses conducted by the HEEET project.

The mission phases, and the type of loads applied to the TPS, are similar for any mission (ground, launch, on-orbit (transit) and entry) but the magnitude of each load imposed upon the TPS depends on mission-specific details. The project decided to use two mission destinations, Venus and Saturn, to define the level of performance to be targeted in the development project. Saturn demands a thick TPS on a relatively small (1 m diameter) probe, whereas Venus missions may involve heatshields up to 3.5 m in diameter, with typically thinner TPS. Hence Venus is a stronger driver for large-scale manufacturing demonstration. If the project demonstrates that the HEEET system can be tailored to support both of these mission opportunities, then there is high confidence that the system can be used for missions to all destinations except, perhaps, Jupiter.

The requirements are formulated as functional statements that address mission performance. Verification statements are written as project technology development goals, except for those that relate to operability and interfaces with the entry vehicle, which require mission-specific verification that is outside the scope of the technology development activity. For all the requirements identified as being within project scope, a TRL goal was established. Since the primary objective for the project was to achieve TRL 6 for the technology as a whole, it should be expected that each requirement would be verified with prototype hardware in mission-relevant environments. However, in a few places a TRL of 5 (using medium fidelity hardware) was deemed acceptable. Manufacturing of large heatshields was the most important aspect for which TRL 5 was anticipated, because the project could only afford to build at the 1-meter scale. Ultimately, with the inclusion of closeout plugs in the integration methodology, scale-up to larger area is straightforward, and higher maturity can be asserted.

The initial set of requirements was derived from TPS requirements used by Orion, Stardust and Mars Science Laboratory (MSL) missions. Several requirement statements were adjusted due to the complexity of verification that would be needed for the initial formulation, especially for differential recession (Level 3 aerothermal performance requirements) and inspectability. The Level 1 requirement for Certifiability was added to assure that inspection could detect flaws smaller than those that might compromise performance, and that relevant flaws could be inspected before and after proof testing to track any failure progression that might occur.

The project engaged with the mission development community from its inception, to assure that potential customers for the technology were satisfied with the requirements and verification strategies being implemented. Several feedback items were incorporated in requirements refinement in the first year of the project. An Independent Review Board was established, including members from mission centers (JPL, GSFC, APL, JSC, KSC), academia and managers from SMD and STMD. This Board convened about 3 times a year, to receive technical briefings and provide written feedback and recommendations. It reviewed the project’s TRL self-assessment (HEEET-0011 in DDB Vol 1), which is based on requirements verification status, and provided a written evaluation of TRL status (Appendix B of this Volume).

Detailed manufacturing requirements for the ETU were managed separately, because they evolved as the design matured. The final manufacturing requirements, which were reviewed and refined at the completion of the hardware build, could be folded into the primary hierarchy, under the Manufacturable branch. They are included in the Manufacturing Volume of this DDB.

Table 2. Top-level project requirements and rationale.

Level 1 Requirements	Requirement #	Requirement Statement	Rationale
The TPS System shall function throughout all mission phases.	1.1	The acreage TPS material shall have predictable thermal response at heat flux, pressure, shear and enthalpy combinations of the (mission specific) entry environment.	The TPS acreage needs to survive entry with no degradation in performance due to unexpected catastrophic failure modes.
	1.2	The seam TPS material shall have predictable thermal response at heat flux, pressure, shear and enthalpy combinations of the (mission specific) entry environment.	The TPS seams need to survive entry with no degradation in performance that would initiate catastrophic system failure modes.
	1.3	An assembly of acreage TPS material with seams on a relevant substructure shall survive structural loads experienced during all mission phases	The heatshield assembly needs to survive all load events with no degradation in performance throughout all mission phases
	1.4	The virgin TPS material shall have surface properties that meet thermal control requirements during cruise	During cruise phase of the mission there may be thermal control requirements imposed on the heat shield and if the heat shield material does not have the required properties then it should be compatible with a coating that does.
The TPS System shall be operable.	2.1	The TPS thermal (conductivity) and mechanical (stiffness, strength) properties shall not change by more than 10% after exposure to (mission specific) natural environments (dust, moisture,etc).	The Heat Shield System needs to survive entry with no degradation in performance after exposure to the natural environments experienced throughout all mission phases (not including Micrometeorite impact if it is accepted risk).
	2.2	The TPS shall be robust or repairable to handling damage of (mission specific) level(s).	The TPS needs to survive entry with no degradation in performance due to routine handling during processing.
	2.3	The TPS thermal (conductivity) and mechanical (stiffness, strength) properties shall not change by more than 10% after exposure to planetary protection processes and loads.	The TPS needs to survive entry with no degradation in performance due to routine processing necessary for planetary protection.
	2.4	TPS dust generation shall be characterized based on observations during structural tests.	The TPS needs to survive entry without fouling other vehicle instruments or systems.
	2.5	TPS out-gassing shall be characterized.	The TPS needs to survive entry without fouling other vehicle instruments or systems.
	2.6	The TPS thermal (conductivity) and mechanical (stiffness, strength) properties shall not change by more than 10% after exposure to purge and purge outage environment.	The TPS needs to survive entry after exposure to purge environment and after purge outages.
	2.7	The TPS shall have a service life of (mission specific) days (or years) in (mission specific) environment	The TPS needs to survive entry with no degradation in performance due to exposure to the space environment during cruise or in-space storage.
	2.8	The TPS shall have a shelf life of (mission specific) months (or years) in (mission specific) environment.	The TPS needs to survive entry with no degradation in performance due to exposure to the processing or storage environment.

Level 1 Requirements	Requirement #	Requirement Statement	Rationale
The TPS system shall be manufacturable.	3.1	The TPS material shall be manufacturable to a thickness upto 1.85" inches after infusion	Need to keep bond line temp below (mission specific) temperature.
	3.2	The TPS material shall conform to OML curvature of (mission specific) radii	The TPS material needs to conform to the OML of the structure in order to be attached.
	3.3	The TPS assembly shall cover an aeroshell of at least (mission specific) surface area	The TPS system needs to be scalable to protect the surface of the aeroshell from entry heating.
	3.4	Any contaminants from Manufacturing processes shall be included in development of system capability databases	Manufacturing processes shall not alter TPS material composition resulting in performance degradation
	3.5	The TPS shall be machinable to a profile tolerance of (mission specific) inches	Lower level requirements to support penetrations and assembly.
The TPS System shall interface with the entry vehicle.	4.1	The TPS shall accommodate Penetrations of (mission specific) size and shape.	The Mission may require structural load paths through the heatshield
	4.2	The TPS shall include closeout(s) that meet (mission specific) seal requirements.	The TPS system will need to interface with other portions of the vehicle, such as the back shell, and therefore a closeout maybe required to achieve the required seal.
	4.3	The TPS shall include closeout(s) that meet (mission specific) load transfer.	The TPS system will need to interface with other portions of the vehicle, such as the back shell, and therefore a closeout maybe required to handle load transfer.
	4.4	The TPS shall include closeouts that support (mission specific) assembly/disassembly requirements.	The heat shield system needs to allow for disassembly and reassembly.
	4.5	The TPS shall accommodate (mission specific) instrumentation.	The TPS needs to allow instrumentation for verification/conformation of material performance.

Level 1 Requirements	Requirement #	Requirement Statement	Rationale
The TPS System shall be certifiable.	5.1	The TPS acreage shall be inspectable against the acceptance criteria in the system specification.	Mission needs to know they have TPS without flaws worse than those included in performance database
	5.2	Inspection of acreage TPS to gapfiller adhesive joints shall detect void sizes specified in HEEET-4034.	
	5.3	Inspection of acreage TPS to carrier structure adhesive joints shall detect void sizes specified in HEEET-4034.	
The TPS System manufacturing and integration technology shall be transferrable to industrial partners.	6.1	Process specifications shall be developed and formally documented for each manufacturing and integration step of the TPS system	Documented process specifications ensures transferability of the TPS manufacturing and integration technology
	6.2	Acceptance criteria shall be developed and formally documented for each manufacturing and integration step of the TPS system	Development of acceptance criteria ensures transferability of the TPS manufacturing and integration technology
	6.3	All manufacturing, processing and assembly operations and specifications developed by industrial partners shall be the property of NASA.	Missions that adopt HEEET will be able to freely select vendors for manufacturing and integration of the flight heatshield
	6.4	The project shall document an assessment of raw material supply and manufacturing process sustainability based on experience with MDU and ETU.	ETU will be the culmination of manufacturing of a series of test hardware from component to system level. In this document we will provide a forward outlook of repeatability

Scope of Development Effort

The Work Breakdown Structure from the Project Plan is shown in Figure 5. Although it indicates 6 partitioned activities under the Project Management layer, the work elements were highly coupled. The Systems Engineering branch interacted with all other branches for Requirements development and verification, which guided the technical scope of all the other branches to generate the verification evidence for heatshield functional performance. Systems engineering also managed technical development risks across all branches, and advised management on resource allocation to mitigate risks as technical challenges were encountered. Later in the project, when HEEET was identified as GFE for Discovery and New Frontiers proposers, the Systems Engineering group coordinated proposal support efforts across all elements of the system design.

Aerothermal performance of the seams between blocks, or tiles, of acreage HEEET material was identified as the greatest area of concern, because it is difficult to model material response at a discontinuity, and very difficult to apply extreme aerothermal loads at representative scale. The team introduced "aerothermally monolithic" as a term to describe the desired behavior: the thermal response at seams should be indistinguishable from, or at least in family with, the acreage response. Conceptual design of an aerothermally monolithic system was an early priority, and test campaigns to demonstrate seam performance needed development. Beyond demonstration with specific hardware configurations, predictive models for seam thermostructural capability and for system thermal capability were needed to support design of systems tailored to specific mission needs. Hence, interaction between Heatshield Design Branch and Testing branches was also robust. ETU Design was updated through insights derived from Manufacturing and Integration Development, which also pushed ETU Production. After testing failed to identify a viable adhesive to fulfill all seam functions, development of Softened HEEET was pursued for seam compliance (DDB 3.08), and further evolved into Expanding Softened HEEET (ESH) to enable robust system integration (DDB 3.09). Closeout plugs were introduced as a final architectural element to mitigate tolerance stack-up issues by isolating gapfillers from each other (DDB 3.10), and thereby enable construction of heatshields with arbitrarily large area. Development activities spread across Systems Engineering, especially Trade Studies, Heatshield Design, and Manufacturing Development are collected in Volume 3 of the DDB.

From the inception of the effort, demonstration of manufacturing and structural performance with prototype hardware was viewed as the essential capstone activity. Early in the project, the plan called for building two 1 meter diameter heatshields, with a Manufacturing Demonstration Unit separate from an Engineering Test Unit. The units would not need to be identical, and lessons learned on the first unit could refine the parts and integration techniques used on the second unit. In practice, the project implemented a longer series of incremental hardware development articles because the seam architecture evolved through several iterations, as discussed in Section 3.11 of the DDB. Ultimately, a single fullscale unit fulfilled the requirements for both manufacturing demonstration and structural capability demonstration. In retrospect, it might have been better named a Prototype Test Unit, because that terminology emphasizes its role in achieving TRL 6. Engineering Test Unit typically refers to hardware that implements a mission-specific detailed design, which is not the intent for the hardware in a more generic technology demonstration activity, as noted in Section 6.6 of NASA's TRA Study Team Report [5]. However, to preserve consistency throughout the DDB, the ETU terminology is retained in this document. The final manufacturing/integration procedures distilled from development efforts and refined though ETU production are captured in Volume 2 of the DDB.

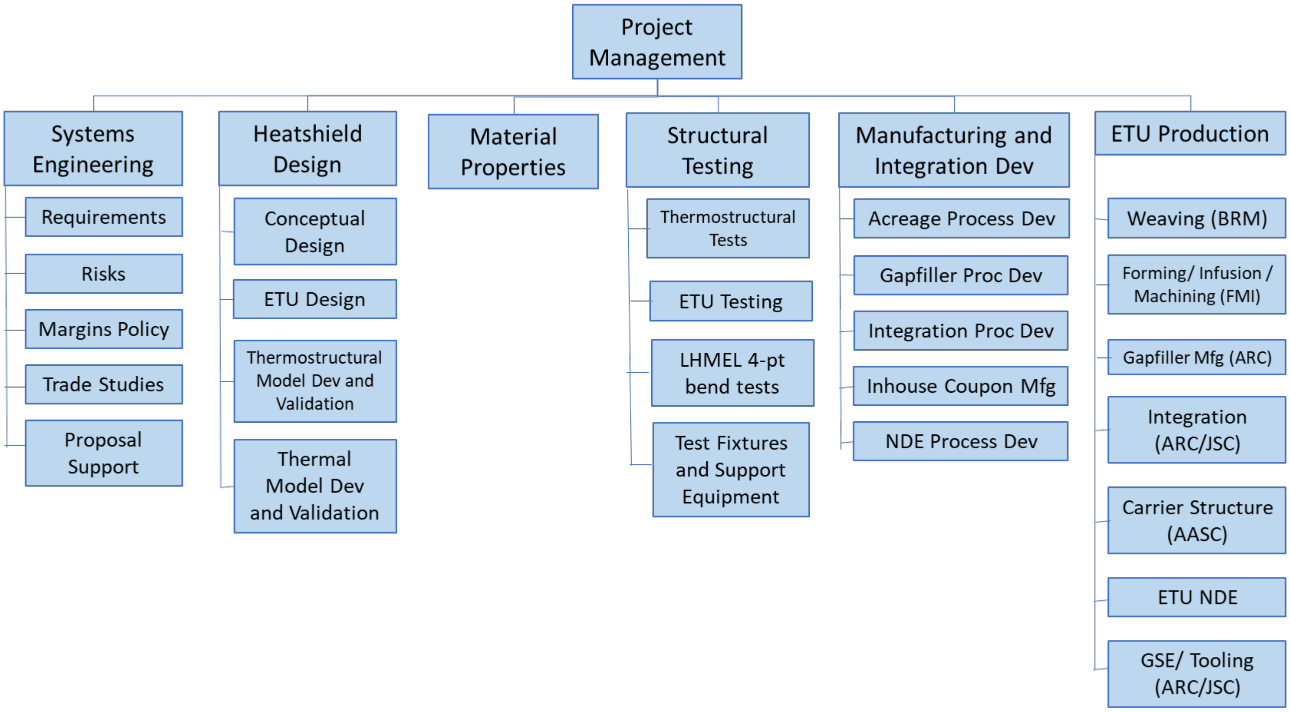

Figure 5. Work Breakdown Structure for the HEEET Project

The diagram in Figure 5 appears to omit arc-jet testing, but that activity was tracked through the Thermal Model Development and Validation work item. A fully consistent representation would have included all of the Structural Testing activity within the Thermostructural Model Development section, or added a Thermal Testing item in parallel with the Structural Testing and Material Properties activities. In hindsight, the inconsistency probably reflects the leadership's familiarity with thermal modeling and testing, which meant that some of the details were not made explicit in early project planning. The importance of thermal response characterization is more appropriately reflected in the DDB organization which devotes Volume 4 to Thermal Response Characterization, and Volume 5 to Structural Characterization. Design methodology that applies thermal and thermostructural predictive models for heatshield sizing, and is applicable for future mission design, is included as Volume 6 of the DDB.

Status of HEEET Technology Development

The project has generated evidence to support verification of all requirements that were in scope for the current activity. A summary for top-level requirements is provided in Table 3. More specific references to evidence for child requirements can be found in HEEET-0003 in DDB Volume 1. A full discussion of Technology Readiness Assessment is provided in HEEET-0012, in DDB Volume 1.

Table 3. Verification Status and Evidence for Top-Level Requirements

Level 1 Requirements	Requirement #	Requirement Statement	Verification	TRL.	Status
The TPS System shall function throughout all mission phases.	1.1	The acreage TPS material shall have predictable thermal response at heat flux, pressure, shear and enthalpy combinations of the (mission specific) entry environment.	Verification of child requirements	6	TRL 6 achieved for conditions up to 3500W/cm2 and 5 atm. Correlations between FIAT and IHF/AEDC tests for recession. DDB Vol 4 and DDB Vol 3.1 AEDC stag out of scope (not TRL 6 for those conditions).
	1.2	The seam TPS material shall have predictable thermal response at heat flux, pressure, shear and enthalpy combinations of the (mission specific) entry environment.	Verification of child requirements	6	ESH recession comparable with acreage, with density adjustment. (HEEET-5005, 5006, 5014, 5019, 5024)
	1.3	An assembly of acreage TPS material with seams on a relevant substructure shall survive structural loads experienced during all mission phases	Verification of child requirements	6	FEM correlation with LHMEL test results for adhesive opening in combined environments. FEM correlation for all ETU load cases. HEEET-2009
	1.4	The virgin TPS material shall have surface properties that meet thermal control requirements during cruise	Coupon testing of uncoated material and painted material.	6	Tests performed on painted HEEET went beyond original project scope. Post-test data reduction in progress. Similarity to PICA, which has been coated for previous missions, permits claim of TRL 5. Testing delivers TRL 6.
The TPS System shall be operable.	2.1	The TPS thermal (conductivity) and mechanical (stiffness, strength) properties shall not change by more than 10% after exposure to (mission specific) natural environments (dust, moisture,etc).	Limited to testing of effect of moisture environments	6	HEEET-5505
	2.2	The TPS shall be robust or repairable to handling damage of (mission specific) level(s).	Verification of child requirements	6	Shoulder repair demonstrated on ETU. HEEET-2017. System is robust against handling damage, particularly compared with successfully flown TPS such as PICA and LI-2200. Clamping for machining demonstrates robustness (HEEET-4027)

Level 1 Requirements	Requirement #	Requirement Statement	Verification	TRL.	Status
	2.3	The TPS thermal (conductivity) and mechanical (stiffness, strength) properties shall not change by more than 10% after exposure to planetary protection processes and loads.	Coupon testing	6	Not in scope. But integration processes exceed planetary protection processes and loads, so requirement has been satisfied with ETU integration.
	2.4	TPS dust generation shall be characterized based on observations during structural tests.	Observation of shock test	6	Shock test did not indicate deleterious dust (HEEET-5503 in DDB Vol 5.2). Could cover with Nusil or paint if necessary, and analogy with PICA supports TRL of 6.
	2.5	TPS out-gassing shall be characterized.	Coupon testing.	6	Informal indication of acceptable outgassing (HEEET-1012 in DDB Vol 3.16)
	2.6	The TPS thermal (conductivity) and mechanical (stiffness, strength) properties shall not change by more than 10% after exposure to purge and purge outage environment.	Coupon testing	6	Analogy with PICA and CP
	2.7	The TPS shall have a service life of (mission specific) days (or years) in (mission specific) environment	Coupon testing after long duration exposure to space/simulated space environment	6	Analogy with PICA and CP
	2.8	The TPS shall have a shelf life of (mission specific) months (or years) in (mission specific) environment.	Coupon testing after long duration storage.	6	Analogy with PICA and CP
The TPS system shall be manufacturable.	3.1	The TPS material shall be manufacturable to a thickness upto 1.85" inches after infusion	Verification of child requirements	5/6	ETU demonstration
	3.2	The TPS material shall conform to OML curvature of (mission specific) radii	Verification of child requirements	6	ETU demonstration for nose (spherical radius 9.86", 0.6" RL thickness) and shoulder (uniaxial 5.85", 0.6" RL)
	3.3	The TPS assembly shall cover an aeroshell of at least (mission specific) surface area	Verification of child requirements	6	ETU demonstration at 1 m diameter. Closeout plugs manage tolerance stackup, so demonstrated techniques are applicable at larger scale
	3.4	Any contaminants from Manufacturing processes shall be included in development of system capability databases	Verification of HEEET-4034 Reqt 2.2.5 partially fulfills this verification. Results from ETU testing establishes system capability for articles that include all contaminants that may be encountered in baseline manufacturing process. Arc-jet test articles used the same procedures.	6	ETU demonstration. Arc jet coupons

Level 1 Requirements	Requirement #	Requirement Statement	Verification	TRL.	Status
	3.5	The TPS shall be machinable to a profile tolerance of (mission specific) inches	Verification of child requirements	6	ETU . Tiles achieved surface profile tolerance of 10 mils on all faces. Channels and ESH sides also achieved a surface profile tolerance of 10 mils.
The TPS System shall interface with the entry vehicle.	4.1	The TPS shall accommodate Penetrations of (mission specific) size and shape.	Manufacturing demonstration	5/6	Integration of closeout plugs demonstrates accommodation of conical tapered penetrations. HEEET-0009 in DDB Vol 3.10. Feasible to construct a subassembly to fit around protrusion.
	4.2	The TPS shall include closeout(s) that meet (mission specific) seal requirements.	Coupon/Component /Sub-system testing		Out of scope. More robust than PICA
	4.3	The TPS shall include closeout(s) that meet (mission specific) load transfer.	Coupon/Component /Sub-system testing		Out of scope
	4.4	The TPS shall include closeouts that support (mission specific) assembly/disassembly requirements.	Manufacturing demonstration		Out of scope
	4.5	The TPS shall accommodate (mission specific) instrumentation.	Coupon demonstration		Demonstration of instrumented plugs on wedge test article for AEDC Round 2. Similar to closeout plugs. HEEET-4041 in DDB Vol 4.2
The TPS System shall be certifiable.	5.1	The TPS acreage shall be inspectable against the acceptance criteria in the system specification.	Verification of child requirements	6	HEEET-1006, HEEET-5510 in DDB Vol 3.12
	5.2	Inspection of acreage TPS to gapfiller adhesive joints shall detect void sizes specified in HEEET-4034.	Demonstration of flaw detection	6	HEEET-1006, HEEET-5510
	5.3	Inspection of acreage TPS to carrier structure adhesive joints shall detect void sizes specified in HEEET-4034.	Demonstration of flaw detection	6	HEEET-1006, HEEET-5510

Level 1 Requirements	Requirement #	Requirement Statement	Verification	TRL.	Status
The TPS System manufacturing and integration technology shall be transferrable to industrial partners.	6.1	Process specifications shall be developed and formally documented for each manufacturing and integration step of the TPS system	Verification of child requirements	6	DDB Vol 2.5
	6.2	Acceptance criteria shall be developed and formally documented for each manufacturing and integration step of the TPS system	Verification of child requirements	6	DDB Vol 2.5
	6.3	All manufacturing, processing and assembly operations and specifications developed by industrial partners shall be the property of NASA.	Contract Language Review	6	Mostly satisfied. Large scale infusion customized by FMI. Weave architecture details are proprietary, but similar weave demonstrated by second supplier. NDE details are proprietary, but success achieved with multiple suppliers.
	6.4	The project shall document an assessment of raw material supply and manufacturing process sustainability based on experience with MDU and ETU.	Document Review	6	HEEET-0013

Recommendations for Future Mission Applications

The HEEET Thermal Protection System has generated considerable interest from mission proposers. It was included by one team in the last Discovery round, and by 4 teams in the New Frontiers 4 opportunity. It was also proposed for a European competed opportunity. None of the proposals have yet been selected for further development, but Thermal Protection System was not seen as asignificant risk in any of the evaluations. HEEET is incentivized again in the current Discovery Announcement of Opportunity.

The Mars Program is considering HEEET for the Mars Sample Return Earth Entry Vehicle. This mission has particularly demanding requirements for robustness, and HEEET's toughness against micrometeoroid damage is very attractive. The quest for an "aerothermally monolithic" system is continuing with this project, as a loom scale-up is being evaluated to enable a seamless heatshield of up to 1.3 meter diameter.

Although the project's 1 meter demonstration unit was implemented as a point design, the team strove to capture sensitivity information from the variational testing that was done during development. The Design and Development volume of this DDB is intended to capture the rationale for implementation decisions that were made, and to mention options that might be considered by future developers.

The culmination of the design effort is provided in Volume 6, which includes information on sustainability, thickness sizing for aerothermal environments, customization of the manufacturing methodologies for different thicknesses of insulating layer and recession layer, and structural analysis for margin calculations. The HEEET project team is eager for this knowledge to be applied in a host of future missions.

References

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[2] Committee on the Planetary Science Decadal Survey, "Vision and Voyages for Planetary Science in the Decade 2013-2022", National Academies Press 2011

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