Use of Additive Manufacturing for Thermal Protection Systems

Background

NASA has a need to significantly improve the manufacturing processes of Thermal Protection Systems (TPS) used on human-rated spacecraft and robotic missions with the intention of reducing cost and improving quality and system performance. The fabrication and installation of current TPS are labor intensive, cost prohibitive, and result in many seams between the segments. Future human missions to Mars will require the landing of large-mass payloads on the surface, and these large entry vehicles will require large areas of TPS to protect the structure. A sustained lunar presence will require the development of lunar-return vehicles, which will also need TPS. In order to reduce the cost and complexity of these vehicles, new TPS materials and compatible additive manufacturing (AM) techniques are needed such that both spacecraft TPS and structures can be manufactured with automated systems. Furthermore, a future capability to use AM to fabricate and repair TPS in space will be needed. Basic requirements and goals for the development of this technology are provided in this solicitation.

Objectives

The overall objective is to develop the materials and compatible AM technologies to automate the fabrication of an integrated spacecraft structure and TPS. There are two approaches to designing the spacecraft aeroshell: (1) parasitic TPS: design and fabricate the flight structure and apply the thermal protection to the structure surface and (2) integrated aeroshell: design and fabricate a high-temperature flight structure that forms the outer mold line and apply insulative thermal protection to the inner surfaces of the structure. Both of these approaches are of interest to NASA and have applications to future NASA missions.

For the first approach, the objective for this solicitation is to develop the materials and processes to deposit and adhere the thermal protection to an existing structure. It can be assumed that the structure has already been designed and fabricated. For the second approach, the objective is to develop the materials and processes to fabricate both the high-temperature structure and the integrated, internal insulation. The proposer should select one of the design approaches to address.

The intent of this solicitation is to develop the materials and technologies for automating the fabrication and integration of a thermal protection onto a spacecraft. Therefore, NASA is not interested in materials and methods to
fabricate a better block of material that would need to be manually bonded onto a structure with gaps between the blocks.

**Material Characteristics**

AM has the potential to provide capabilities to design a material to achieve the desired properties and to vary the material constituents during the fabrication process. Fibers can be added and aligned to obtain desired mechanical and thermal properties. Additives can be used to reduce density and modify other key properties and to aid the fabrication process. Although it is not a requirement for this solicitation, material systems that have a potential future development path for reusability are desirable.

The desired material properties depend on the spacecraft flight regime and the aeroshell design approach. For the purpose of this solicitation, three TPS options have been defined and the approximate desired material properties provided.

**Low-Density, Low Heat Flux (<60 W/cm²) Parasitic TPS:**

- Density ~0.3 g/cc (or lower)
- CTE <5 × 10⁻⁶ 1/°F
- Through-the-thickness thermal conductivity <0.1 W/m/K (at 1 atm and 70 °F)
- In-plane tensile strength >1.3 MPa

**High Heat Flux (100 to 600 W/cm²) Parasitic TPS:**

- Density ~0.6 g/cc (or lower)
- CTE <5 × 10⁻⁶ 1/°F
- Through-the-thickness thermal conductivity <0.2 W/m/K (at 1 atm and 70 °F)
- In-plane tensile strength >3 MPa
- Char yield >50%

**Moderate Heat Flux (>200 W/cm²) Integrated Aeroshell:**

- Density: Structure ~1.5 g/cc; Insulation 0.3 to 0.5 g/cc
- CTE <5 × 10⁻⁶ 1/°F
- Through-the-thickness thermal conductivity: Structure ~5 W/m/K; Insulation: <0.1 W/m/K (at 1 atm and 70 °F)
- In-plane tensile strength: Structure >120 MPa; Insulation: >1.3 MPa
- Char yield >50%

Since additive manufacturing techniques provide the capability to vary the material during fabrication, combinations of the materials in a single system is of interest. For example, a system may consist of an outer layer of High Heat Flux Parasitic TPS and then transition to a low-density, low heat flux material closer to the structure. The proposer can select one or a combination of the material categories to address in their proposal.

In order to achieve the desired properties and inhibit material failure in high aerodynamic shear environments, strategies that print a honeycomb or iso-grid reinforcement with filled cells may also be considered.

**Printing and Curing Approach**

The selected printing approach must be capable of fabricating the TPS using the selected materials and with limited manual intervention. The system must be scalable to fabricate TPS for flat and curved surfaces for vehicles several meters in diameter. A significant concern for all of the printed and cured materials is large porosity and voids. The proposer should describe controls to minimize these defects. Defects can be controlled by material and cure process selection and/or by print techniques. Print technique controls could include rollers/deflectors to consolidate the material and/or sensors and feedback loops during printing.
Material curing, depending on the resin system, is often achieved by a thermal cycle in an oven. For this solicitation, oven cures are acceptable as long as the thermal cycle does not exceed 180 °C for the parasitic TPS. This constraint is driven by temperature limits on the flight structure. If curing is needed, it is highly desirable to cure the material in situ using the material chemistry, local heating, laser sintering, or ultraviolet/radiofrequency energy.

The high-level goals for a scaled-up TPS additive manufacturing system are provided below.

1. System should include all of the elements for the entire workflow from material formulation to fabrication and final finishing and print quality controls.
2. System functions should be automated with minimal manual processes such that it can be operated by fewer than three technicians.
3. Post-print processing should be minimized.
4. For parasitic TPS, a 5-m-diameter dome should be completely fabricated within 1 month; 3 months for an integrated aeroshell of this size.

**Expected TRL or TRL Range at completion of the Project:** 2 to 4

**Primary Technology Taxonomy:**
- Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
- Level 2: TX 12.4 Manufacturing

**Desired Deliverables of Phase I and Phase II:**

- Research
- Prototype
- Hardware

**Desired Deliverables Description:**

During Phase I, the proposer should:

1. Develop the conceptual design of the entire manufacturing process tailored to the appropriate feed-stock proposed.
2. Demonstrate the capability to fabricate using AM the candidate materials.
3. Conduct material property tests and compare to goals.
4. Conduct aerothermal tests of the printed material.
5. Deliver to NASA small test articles for testing.

During Phase II, the proposer should:

1. Design and assemble a prototype automated system to fabricate the TPS.
2. Demonstrate the capability to fabricate the TPS for nonplanar surfaces.
3. Conduct material property tests for larger range of conditions.
4. Conduct integrated TPS/structure tests such as flexure tests.
5. Conduct aerothermal tests of the printed material.

**State of the Art and Critical Gaps:**

Current state of the art (SOA) for manufacturing and installing thermal protection on NASA space vehicles is too labor intensive and costly. Furthermore, the heat shield designs are constrained by manufacturing processes that result in segmented blocks with gap fillers that create flight performance issues. To develop an automated additive manufacturing process for spacecraft heat shields that are monolithic, the development of the materials and technologies to deposit and cure the materials on the flight structures are needed.

**Relevance / Science Traceability:**
Both Human Exploration and Operations Mission Directorate (HEOMD) and Science Mission Directorate (SMD) would benefit from this technology. All missions that include a spacecraft that enters a planetary atmosphere require TPS to protect the structure from the high heating associated with hypersonic flight. Improved performance and lower cost heat shields benefit the development and operation of these spacecraft. Human missions to the Moon and Mars would benefit from this technology. Commercial Space programs would also benefit from TPS materials and manufacturing processes developed by NASA.

References: