***Additive Manufacturing of Thermal Protection Systems (AMTPS)***

Flight Test Requirements

Rev. E (5/18/2021)

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Version History:

Rev C (2/19/2021): Initial Word format release

Rev D (3/23/2021): Added goal for post-flight reconstruction; added detail on telemetry; updated baseline diameter and mass budget; add cover page

Rev E (5/18/2021): Add OML figure, stagnation point pressure; change number of TPS formulations; add req’ts related to ejection mechanism cradle

# Flight Test Goals

1. Design, fabricate, fly, and recover a small capsule with an additively manufactured (AM) thermal protection system (TPS) on a suborbital sounding rocket flight.
2. The capsule shall be launched onboard a suborbital rocket and be separated/deployed from the rocket exoatmospherically. The capsule shall then descend through the atmosphere, exposing the AMTPS to aerothermodynamic heating.
3. The capsule shall land such that the AMTPS is sufficiently intact to enable meaningful post-flight inspection.
4. Post-flight reconstruction of the trajectory shall be sufficient to establish the environmental conditions experienced by TPS to within *TBD* uncertainty.

# Requirements

## Geometry

* 1. The capsule shall use a 45 degree sphere-cone geometry based on the Mars Microprobe outer mold line (OML) shown in Figure 1. The OML consists of a blunted 45 degree cone with a hemispherical backshell.

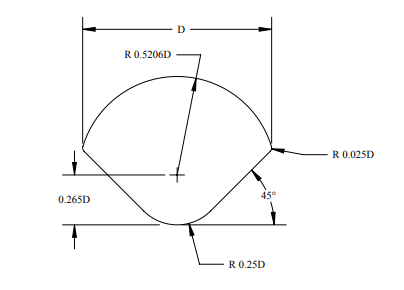


Figure 1. Nominal outer mold line (OML) geometry

* 1. The maximum diameter of the capsule, D, shall be no more than 16 inches with a target diameter of 14 inches.
     1. The nose radius of the capsule shall be no more than 25% of the maximum diameter. Smaller nose radii are acceptable to increase stagnation point heating. However, aerodynamic stability must be maintained (*Section 8)*.

## Masses

* 1. The hypersonic ballistic coefficient of the capsule (defined as the mass over the drag area) shall target 300 kg/m2 (and no less than 285 kg/m2) to ensure that target entry heat fluxes can be met (*Requirement 4.c.*)
  2. The total capsule mass is not to exceed 40 kg with a target mass of 30 kg. Targets by subsystem are as follows:
     1. TPS: 3.5 kg
     2. Structures (minus ballast): 6 kg
     3. Ballast: Allowed to vary to meet target mass
     4. Avionics: 0.5 kg
     5. Recovery (parachute and deployment mechanism): 2.5 kg

## Budget

* 1. Total cost for the flight test hardware, materials, and testing shall not exceed $60,000, with a target of $45,000. Tentative targets by subsystem are listed below. (Note: these targets may be exceeded by up to 33% and larger exceptions may be possible.)
     1. TPS: $10,000
     2. Structures: $25,000
     3. Avionics: $3,000
     4. Recovery: $3,000
     5. Testing (Mechanical and Vibration): $2,000
     6. Testing (NDE): $2,000

## Mission Profile

* 1. The launch vehicle shall deliver the capsule to a minimum speed of Mach 6 (and desired speed of Mach 10) at entry interface. Entry interface shall be considered to occur at an altitude of 125km above mean sea level.
  2. A separation mechanism shall deploy the capsule exoatmospherically prior to entry interface. The capsule must separate from the rocket without re-contact of the two bodies.
  3. Targeted entry environment parameters are outlined below:
     1. Forebody
        1. Peak heat flux at the capsule stagnation point
           1. Minimum: 20 W/cm2
           2. Target: 100 W/cm2
        2. Peak heat flux along flank of forebody
           1. Minimum: 10 W/cm2
           2. Target: 50 W/cm2
        3. Peak stagnation point pressure
           1. Minimum: 30 kPa
           2. Target: 150 kPa
     2. Backshell
        1. Peak heat flux along capsule backshell
           1. Maximum: *TBD*

## Instrumentation and Telemetry

* 1. The following instrumentation/sensors shall be included in the capsule design:
     1. Forebody:
        1. Thermocouples: 2 locations / 2 TCs each minimum (3 locations / 4 TCs each desired)
        2. Pressure: *TBD* minimum (*TBD* desired)
        3. Heat flux: None required (1 desired)
     2. Backshell
        1. Thermocouples: 1 location / 2 TCs minimum (2 locations / 4 TCs each desired)
        2. Pressure: None required (1 desired)
        3. Heat flux: None
     3. Internal
        1. IMU: 1 minimum (2 desired)
        2. Barometric pressure: 1 minimum (1 desired)
        3. Position/altitude (e.g., GPS): 1 minimum (1 desired)
  2. Telemetry shall be collected at the following rates during the entry (if sensor is present). These are peak rates, which may be reduced during non-critical segments of the flight. “Non-critical” shall be determined by the development team.
     1. Forebody:
        1. Thermocouples: 10Hz minimum
        2. Pressure: 10Hz minimum (24Hz desired)
        3. Heat flux: 10Hz minimum
     2. Backshell:
        1. Thermocouples: 10Hz minimum
        2. Pressure: 10Hz minimum (24Hz desired)
     3. Internal:
        1. IMU: *TBD*
        2. Barometric pressure: *TBD*
        3. Position/altitude: *TBD*
  3. All data from all sensors shall be stored onboard a physical storage device with sufficient capacity. The storage device must survive intact for post-flight data recovery and analysis.
  4. In-Flight Telemetry:
     1. Telemetry shall be transmitted through at least one vehicle-to-ground system to aid with post-flight recovery and in the event onboard data is not recovered.
     2. In-flight telemetry rates may be reduced to allow real-time transmission (*rates TBD*).
     3. In-flight telemetry shall include the vehicle position, at minimum, to aid with locating the capsule after landing. It is desired that vehicle velocity also be telemetered in-flight.
  5. Post-Flight Telemetry:
     1. The capsule position should continue to be transmitted post-landing to aid in recovery operations.
     2. Post-flight position telemetry shall be transmitted at a minimum rate of 1 packet every 5 minutes (with a target of 1 packet every minute).
     3. Post-flight position telemetry shall be accurate to within +/- 100meters (with a target of +/- 20 meters).

## Thermal / TPS

* 1. The TPS shall withstand loads encountered while installed in the launch vehicle payload bay without damage. That includes loads encountered during installation and launch. *(Cross-reference Requirement 12.b.ii.)*
  2. The TPS shall withstand loads encountered during ejection/deployment.
  3. The TPS shall be designed to withstand the expected entry environment without failure either within the material or at the bondline (*see Section 3: Target Environmental Conditions)*.
  4. The TPS shall ablate and decompose in a controlled and predictable manner with no spallation.
  5. The interior of the capsule and avionics system shall be maintained within an acceptable temperature range during the entirety of the flight: launch, exoatmospheric flight, entry, landing, and recovery. *See Requirement 9.a.*

## Manufacturing

* 1. The TPS shall be manufacturable in the AMTPS robotic cell under development at Oak Ridge National Lab (ORNL).
     1. Size and geometric complexity shall be limited to that achievable within the AMTPS cell.
     2. The selected TPS material must be compatible with all processing equipment within the AMTPS cell.
     3. The selected resin and filler components must meet all necessary safety and health requirements for approved usage in all facilities handling the materials, including NASA JSC, NASA ARC, ORNL, and any third-party vendors (e.g., toll compounder).
  2. The TPS shall consist of a graded architecture of at least 2 material formulations (3 formulations desired) spanning the thickness of the heat shield: an insulating material at the inner mold line (IML), possibly one or more transitional formulations, and a robust, charring material at the outer mold line (OML).
  3. Defect size shall be limited such that the mechanical integrity of the TPS is not compromised during any segment of the flight. *Size is TBD.*
  4. The heat shield shall be inspectable using one or more NDE techniques (ultrasonic, terahertz, CT, etc.). The technique(s) used shall be capable of detecting defects on the size of that required in *Requirement 8.c*.

## Aerodynamics and Stability

* 1. The capsule shall be self-righting to a nose forward direction (into the wind) prior to significant incident aerothermal heating. This point shall be determined such that any aeroheating on the backshell TPS is below that of *Requirement 3.b*.
  2. The capsule shall be statically stable during all flight regimes (hypersonic, transonic, and subsonic).
  3. The capsule shall be dynamically stable during all flight regimes (hypersonic, transonic, and subsonic).

## Recovery

* 1. The capsule shall deploy a parachute prior to landing to reduce touchdown velocity. The recovery system shall be sized such that the touchdown velocity is no more than 20 feet / sec with a targeted maximum of 15 feet / sec.
  2. Deployment shall occur at a point in the trajectory that allows successful inflation of the parachute and sufficient deceleration to meet *Requirement 9.a*.
  3. The recovery subsystem (including the parachute, parachute cords, fasteners, and all load-supporting components) shall be designed to support the loads encountered during deployment, opening, and descent.

## Avionics and Power

* 1. All electronics boards and components shall be designed to operate without interruption between -20 deg C and 80 deg C
  2. The avionics subsystem must be powered through the duration of the flight and recovery (*see Requirement 4.b*). If possible, hardware and/or sensors should be operated in a low power state (or turned off) when not needed. However, these devices must successfully power up when needed during the flight and/or recovery.
  3. Activation and flight sequencing:
     1. The avionics shall be designed for pre-launch activation on the ground. The avionics may be operated in a low power state prior to exoatmospheric deployment.
     2. The avionics must detect and/or sense when deployment has occurred. This requirement may be met through interfacing with the launch vehicle (see *Requirement 12.b*).
     3. The avionics shall trigger parachute deployment at a time dictated by *Requirement 9.b.*

## Structures/Loads

* 1. The capsule structure and all components attached to it shall withstand the peak axial and radial loads expected during flight. *(Loads are TBD)*
     1. Launch
     2. 2nd Stage Burn (if used)
     3. Deployment from Rocket
     4. Entry
     5. Parachute Deployment
     6. Landing
  2. The capsule structure and all components attached to it shall withstand the vibration environments expected during flight. *(Vibration environments are TBD)*
     1. Launch
     2. 2nd Stage Burn (if used)

## Launch Vehicle Integration

* 1. The capsule shall be designed to fit within the payload section of the UpAerospace Spyder rocket with an internal diameter of 16.75”.
  2. The capsule must integrate with the custom ejection mechanism to be designed by the launch provider.
     1. The capsule shall provide a mechanical interface/linkage to prevent roll within the ejection mechanism prior to deployment.
     2. The TPS shall be designed to withstand all forces exerted on it by the ejection mechanism cradle. No crushing of the TPS may occur.
  3. The rocket must provide a minimal communications interface accessible to the capsule. This interface shall provide a signal indicating when deployment/ejection occurs.