HEART FLIGHT TEST OVERVIEW

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ABSTRACT

The High-Energy Atmospheric Reentry Test (HEART) demonstrates the utility of hypersonic inflatable aerodynamic decelerator (HIAD) technology via a low ballistic coefficient entry system that can return more than 5000 kg from low-Earth orbit (LEO). Planned for launch in late 2016, the stowed HEART entry system and host spacecraft berth with the International Space Station (ISS) for cargo exchange operations, and then return to Earth, with the HIAD inflated, on a trajectory that develops reentry environments relevant to future planetary missions. HEART matures key HIAD technologies, including inflatable aeroshell structures and flexible thermal protection systems (TPS) that withstand conditions consistent with Earth entry and planetary entry environments.

1 INTRODUCTION

1.1 Entry System Needs

Current planetary entry systems use rigid aeroshells to develop aerodynamic drag to decelerate the vehicle and lift to control its flight path through the atmosphere. A disadvantage of a rigid aeroshell is that its size is constrained by the geometry of the launch vehicle fairing (Fig. 1). Constraining the aeroshell diameter limits its aerodynamic drag area (A), which with the entry mass (m) and drag coefficient (C_D) establish the vehicle's ballistic coefficient (β) as shown in Eq. 1.

$$\beta = \frac{m}{C_D A} \tag{1}$$

The ballistic coefficient governs the deceleration profile as a vehicle descends through the atmosphere. Vehicles with higher ballistic coefficients do not decelerate significantly until lower altitudes where the increase in atmospheric density allows sufficient drag to be developed. Vehicles with lower ballistic coefficients, however, begin decelerating higher in the atmosphere, providing more time between atmospheric interface and landing to deploy parachutes, sense ground hazards, and fire thrusters for safer, more precise landings at higher elevations.

Precisely landing large payloads at high elevations on Mars is challenging because of the planet's thin atmosphere, which is only 1/80th the density of Earth's atmosphere at the surface. To date, all U.S. Mars missions have delivered landed masses of less than one metric ton to elevations below -1 km Mars Orbiter Laser Altimeter (MOLA). Future Mars science and exploration missions, however, call for landed payloads approaching 5 to 10 metric tons for robotic precursor exploration missions, and 50-60 metric tons for human-scale missions, all to be delivered to elevations equal to, or higher than zero km MOLA.

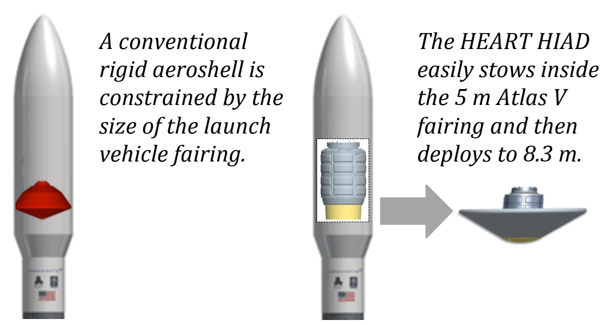

Fig. 1: HIADs are less constrained by the geometry of the mission's launch vehicle fairing.

HIAD technology fulfils these needs with the capability to dramatically increase the entry vehicle drag area while lowering its ballistic coefficient. Fig. 1 depicts the accommodation of a conventional rigid aeroshell and the HEART HIAD in the 5 m diameter Atlas V fairing. The rigid aeroshell diameter is limited to about 4.5 m (16 m^2 drag area), while the HEART HIAD stows within a 2.5 m diameter and then deploys to 8.3 m (54 m^2 drag area) prior to atmospheric entry.

1.2 Comparison to Planetary Missions

Illustrating relevance to future potential planetary missions drives the selection of the HEART entry environment. Systems performance studies have been completed to illustrate the size and relevant environment for entry missions to Mars, Titan, and Earth. Key mission elements include entry mass, entry speed, and HIAD size. Previous studies [1] have shown relevant scaling from robotic feed forward type missions to human-scale entry missions at Mars, leading to the conclusion that the HEART scale (size and environments) is consistent with robotic planetary entry missions (see Table 1) compatible with the existing fleet of expendable launch vehicles.

Table 1: HEART flight test environments are consistent with other planetary missions

Dest.	Dia. (m)	Entry Mass (kg)	Peak Heat Rate (W/cm^2)	Peak Dyn. Press. (kPa)	Entry Speed (km/s)
HEART	8.3	4500	30	4.5	7.6
Mars[1]	8.5	4600	40	4.6	6.0
Mars[2]	8	5600	49	2.8	5.8
Titan	5	1500	42	5.9	6.0

1. Within limits of existing Expendable Launch Vehicles
2. Near-term human precursor robotic mission-Direct, to 0 km MOLA

2 HEART MISSION ARCHITECTURE

HEART leverages existing flight opportunities to realize a reduced cost for demonstrating these critical technologies. HEART will be hosted as a secondary payload on an existing Cargo Resupply spacecraft for the International Space Station. The Orbital Sciences Cygnus vehicle is used as the baseline for the purposes of this study. HEART will be integrated between the Cygnus Service Module (SM) and the Pressurized Cargo Module (PCM) as shown on Fig. 2.

2.1 Mission Phases

The HEART mission consists of five primary operational phases: (1) Launch, (2) Chase/approach to ISS zone, (3) berthing to ISS, at ISS, and deberthing, (4) departure to deorbit, and (5) entry, descent, and landing. During Phases 1 through 3, HEART is dormant with only survival heaters energized. The HEART avionics subsystem is powered on during Phase 2 to perform a post launch checkout, and then the avionics is powered down. Phase 3 consists of the initial approach towards the ISS, the berthing process at ISS, at ISS (including cargo transfer), and departure from ISS. Phase 3 can be as short as five days and as long as 60 days. HEART is energized near the end of Phase 4 prior to the final deorbit maneuver. A state handoff from the Cygnus vehicle to the HEART navigation subsystem is performed. Phase 4 includes the final deorbit maneuver by Cygnus. Phase 5 consists of attaining the specified orientation, separation of the Cygnus SM from the PCM (thus exposing the HEART inflatable structure and TPS), inflation of the inflatable structure, followed by the entry, descent, and landing.

2.2 Operations Sequences

HEART is an event driven mission using simple, low-risk, sequence control. The HEART mission begins via a command from Cygnus to energize the HEART subsystems. Cygnus performs the propulsive deorbit maneuver at the specified point to allow HEART to meet its entry corridor requirements. After completing this maneuver, Cygnus reorients itself to the specified attitude so HEART will be at the desired angle of attack (nominally zero degrees) at entry interface. Cygnus then spins up to 2 RPM. During this reorientation and spin-up process, HEART initiates contact with TDRSS so that critical events data can be continuously transmitted throughout the complete entry sequence. Cygnus then commands separation of the SM from the PCM. A few seconds after the separation is complete, the HEART inflation process begins. The IAD inflation is estimated to require seven to eight minutes to complete. The change in inertia due to the IAD deployment results in the HEART spin rate reducing to the required 1 RPM for entry stability. HEART coasts for the next 10 minutes until the entry interface point is reached. HEART continues with the entry via a spinning ballistic trajectory.

After exiting from the plasma-induced communications blackout, HEART initiates the high bandwidth data return telemetry via X-band to ground stations. All of the science and engineering data will be transmitted prior to the end of mission. HEART will continue to transmit to both Tracking and Data Relay Satellite System (TDRSS) and the ground stations until loss of signal. The experiment portion of the flight test ends when HEART has decelerated to Mach 0.7. HEART continues its deceleration to the ocean where it sinks and is not recovered.

3 DRIVING REQUIREMENTS

The intent of the HEART flight test is to demonstrate the utility of the HIAD technology in a relevant environment. Key flight test requirements are:

- Demonstrate performance in a relevant environment for Earth and planetary entry (Mars & Titan) – heat rate and load, dynamic pressure, and deceleration.

- Demonstrate effects of scale – size comparable to a potential flight mission
- Minimize impacts on the Cygnus vehicle's ability to deliver mass to ISS
- Correlate ground and flight test data with predictive models

4 HEART CONFIGURATION

Throughout the HEART flight test, the Cygnus spacecraft and HIAD Module will be in different configurations as the mission progresses. Modifications to the existing Cygnus spacecraft are also needed to accommodate the HIAD module and the varying operational configurations.

The design of the HIAD consists of an 8.3 m diameter stacked torus inflatable structure with a 55-degree half-angle cone shape, along with a flexible insulating TPS to protect the vehicle and payload from the aerothermal atmospheric entry environment. Additional subsytems include a compressed gas subsystem to deploy and inflate the inflatable structure, avionics subsystems for power, telecommunications, thermal control, data signal processing and sensors, and a rigid structure to house the subsystems and provide structural support adequate to survive launch and entry loads.

4.1 Configuration Overview

There are multiple vehicle configurations to consider throughout the concept of operations. The primary configurations are the launch configuration, the cruise to and from ISS configuration, and the entry configuration (stowed and deployed).

In the launch configuration, the HIAD Module is located between the Cygnus PCM and SM (Fig. 2),

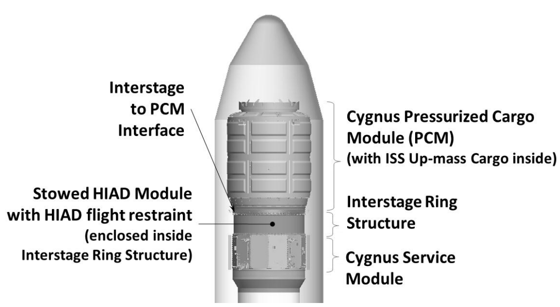

Fig. 2: HEART integrated into the Cygnus spacecraft on the Antares launch vehicle

with the HIAD module being structurally attached only to the PCM. The HIAD module is enclosed by an Interstage Structure, which serves as the load path for the PCM and HIAD during launch. At launch, the PCM contains up-mass cargo that NASA determines is necessary to be delivered to the ISS.

While the Cygnus vehicle combined with the HIAD Module is in LEO and in transit to the ISS, the configuration remains essentially the same as launch, with the exception of having the solar arrays deployed. While visiting the ISS, the crew will remove cargo from the PCM and pack down-mass cargo into the PCM.

The HEART configuration begins after the Cygnus spacecraft has deberthed from the ISS, conducted deorbit maneuvers, and the Cygnus SM and Interstage have separated from the PCM and HEART. The HEART configuration is defined as including the HIAD Module, Cygnus PCM, and the down-mass cargo packaged inside the PCM. The HEART configuration can either be in a stowed or deployed state (Fig. 3).

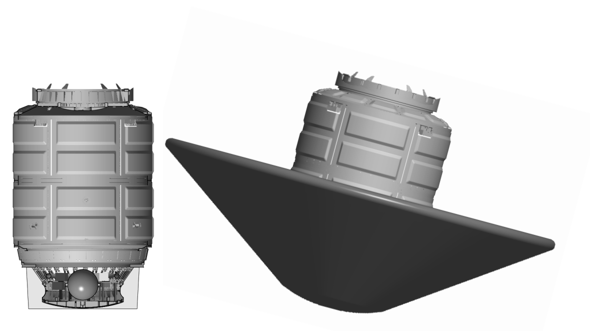

Fig. 3: (a) HEART in stowed configuration with HIAD module depicted as a Cross-Section, and (b) HEART in deployed configuration

During re-entry, the deployed HEART HIAD has a nominal entry vehicle outer mold line (OML) of a 55-degree half-angle blunted cone, with the Cygnus vehicle PCM attached. The deployed HIAD has a maximum diameter of 8.3 meters with the capability to enter masses over 5000 kg. Once the HIAD is deployed, the HEART configuration remains the same throughout the duration of the atmospheric re-entry flight test.

4.2 Accommodation within Cygnus

Accommodation of the HIAD Module within the Cygnus spacecraft necessitates a number of modifications to the Cygnus vehicle subsystems. The affected subsystems include structures, harnesses, propulsion, avionics, and flight software.

The primary structure modifications consist of the addition of an Interstage Structure and a new separation ring. The interstage serves as the primary load path during launch while also covering the HIAD Module. The top of the interstage includes the new separation mechanism that replicates the separation mechanism between the Cygnus spacecraft and the Antares launch vehicle. This separation mechanism enables detachment of the interstage and SM from the PCM during the appropriate mission phase.

Harness accommodations are needed to account for the one-meter axial translation of the PCM from the SM and the need for communications between the Cygnus avionics and the HEART avionics. There are also multiple connections (command, data, and power) between the SM and HEART, which need to be added to the Cygnus harness assembly. With the HEART flight test including a separation, the existing harnesses between the SM and the PCM and the new harnesses between the SM and HEART harnesses require the addition of a low force quick disconnect connector.

Propellant system modifications are limited to extending the existing PCM mounted thruster propellant lines to account for the inclusion of the HIAD Module and adding four tubing cutters to be used immediately prior to separation. The Cygnus propulsion subsystem has the needed isolation capability within its existing latching valve arrangement. The Cygnus avionics system will be modified to provide the commands for isolating and severing the propellant lines prior to SM separation.

Additional modifications to the PCM include accommodating HEART antennas for TDRSS and GPS communications, hosting the four video cameras, hosting the flight test sensors (pressure sensors and accelerometers), and the associated cabling for this HEART hardware. One additional flight control module will be required so that Cygnus can perform the spin-up and separation maneuvers. This limited software modification coupled with the rest of the HEART sequencing software changes will undergo extensive testing.

Finally, there are data interfaces between the Cygnus vehicle and HEART to provide health and status monitoring of HEART while berthed with ISS, along with power for survival heaters.

4.3 HIAD Module Subsystems

The HIAD Module consists of the subsystems necessary to deploy the inflatable decelerator and conduct the HEART flight test experiment. A summary of the HIAD Module mass is shown in Table 2.

Table 2: Summary of HIAD Module Mass

Element	**CBE Mass (kg)**	**Max. Expected Mass (kg)**
Structure	450	504
Avionics, Data, & Thermal	380	530
Inflation	72	83
Inflatable Structure	169	196
TPS	241	279
HIAD Module Total	**1312**	**1592**

4.3.1 Inflatable Structure

The inflatable structure (Fig. 4) serves as the aeroshell to generate drag and support the TPS. The inflatable structure is an 8.3 m maximum diameter stacked torus sphere cone with a nominal 55 degree half-angle cone and relies heavily on feed-forward elements of the IRVE-3 [2] flight test IAD and the HIAD program 6 m ground test IAD undergoing wind tunnel testing at the National Full-Scale Aerodynamic Complex at NASA Ames Research Center.

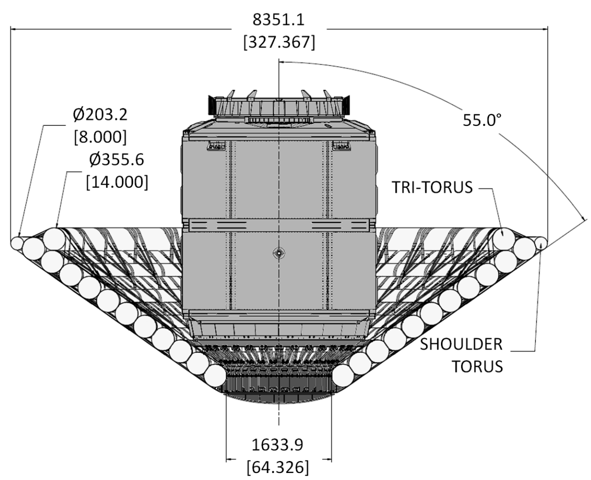

Fig. 4: Inflatable structure configuration for HEART - mm (in)

In addition to eleven structural tori that make up the inflatable structure stack, a smaller diameter shoulder torus and an additional "tri-torus" structural torus are included. The smaller diameter shoulder torus is intended to reduce oscillations due to vortex shedding. The "tri-torus" is mounted leeward of the inflatable stack between the outermost two structural tori and improves stiffness, providing resistance against aft axial deflection and buckling, and allows for lower inflation pressures in the remainder of the stack.

To maximize mass efficiency, the tori must be constructed of a light-weight high strength material capable of withstanding inflation loads and re-entry aerodynamic loading. To maximize volumetric efficiency, it will be necessary to pack the deployable structure to a relatively high packing density. The inflatable structure must withstand packing and the associated creasing stresses and abrasion caused by chafing during handling, packing, storage, and deployment. Additionally, the inflatable structure must experience minimal degradation resulting from exposure to thermal cycling or ultraviolet radiation while on-orbit. Lastly, the inflatable structure must exhibit reliable manufacturability.

Each of the tori are made from an inflatable silicone bladder wrapped in a bias braided Kevlar sheath and coated with a silicone based RTV. The tori are attached via a structural restraint Kevlar webbing. The structural restraint consists of a series of pairing loops and "crows-foot" straps. The pairing loops join adjacent tori while the "crows-foot" strap sets relieve the loading on the inner tori by bypassing the aerodynamic load of the outer tori directly to the center-body. The inflatable is attached to the center-body using a loop strap that interfaces at both ends to a pin and clevis type mount attached directly to the center-body (Fig. 5).

When deployed, the tori are pressurized with nitrogen. Tori T-1 and T-2, the two innermost, are pressurized to 103 kPa to resist bearing stress associated with the high loading of the structural restraint straps. Torus T-10.5, the "tri-torus", is also pressurized to 103 kPa to resist aft deflection and out-of-plane deformation. The remainder of the stack is pressurized to 69 kPa.

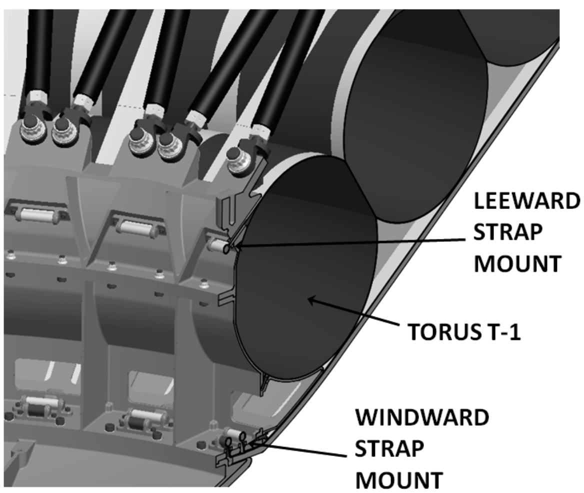

Fig. 5: Cross-section illustrating attachment interface of inflatable to rigid structure

4.3.2 Thermal Protection System

The HEART TPS must meet unique requirements that rigid aeroshells have not had to address. In addition to being able to withstand the traditional aerothermal entry environments of heat flux, pressure, shear force, and heat load, the TPS must also be flexible to accommodate storage in a relatively small volume prior to inflation and entry. The TPS may remain in this tightly-compressed, stored configuration while subjected to vacuum and low temperature environments for months while docked at ISS. TPS selection must not only take into account the usual aerothermal environments but must also consider the material flexibility for the storage and inflation needs.

A flexible TPS development program [3], which includes aerothermal ground testing [4], analytical modeling, and material property characterization, is developing a flexible TPS suitable for meeting the HEART requirements. Initial development efforts have resulted in a baseline TPS configuration that consists of two structurally robust outer cloth layers for protection against mechanical forces followed by layers of insulating materials for thermal management and finally a nonporous layer of material that serves as a structural underlying support and gas barrier to prevent hot gas penetration to the underlying inflatable structure. The entire TPS material layup is stitched together using a high-temperature thread so the structural gas barrier carries the applied structural load.

The outer cloth layers are two layers of a fabric woven from alumina-boria-silica fibers (3M™ Nextel™ 440 BF20) which has demonstrated its capability to withstand the maximum expected flight temperatures and the packing and inflation. These outer layers protect the underlying insulation from aerodynamic shear forces during entry and the abrasion from handling, packing, and inflation. While one layer of this material is sufficient, a second redundant layer is used to insure structural integrity during entry.

The insulating layers are fabricated using a silica aerogel combined with reinforcing fibers resulting in a flexible blanket (Aspen Aerogels® Pyrogel® 2250). Ground testing and analysis have shown that five-layers are sufficient to thermally manage the margined peak heat flux and heat load.

The final component in the TPS layup is the structural gas barrier which is fabricated from a Kapton®-Kevlar® laminate. The Kapton® provides a gas barrier to keep hot gas from penetrating the porous mechanical and insulating layers above and reaching the underlying inflatable structure. The Kevlar® in the laminate provides a structural support that the above layers are mechanically attached through a stitching pattern.

The flexible TPS baselined for HEART is similar to the TPS installed on the IRVE-3 vehicle [2]. The difference is the IRVE-3 TPS has fewer layers and a slightly different version of the Pyrogel® insulating material due to the IRVE-3 peak heating and total heat load being less than HEART.

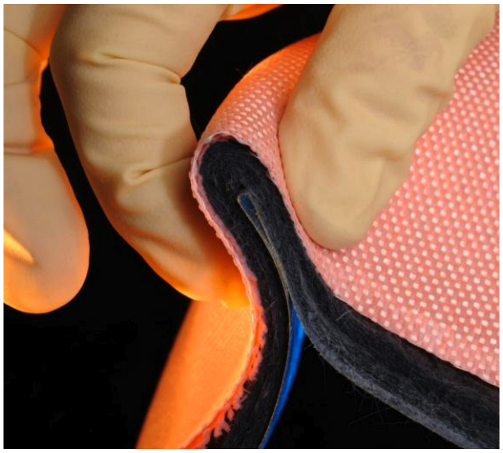

Fig. 6: IRVE-3 flexible TPS being folded - similar to the HEART TPS

4.3.3 Rigid Structure

The HEART rigid structure (Fig. 7) provides the mounting interface for the inflatable aeroshell, serves as the load path and structural attachment to the Cygnus PCM, and houses the avionics and instrumentation package as well as the inflation subsystem. The rigid structure is composed of three sub-elements: a nose cone assembly, a center-body, and PCM interface struts.

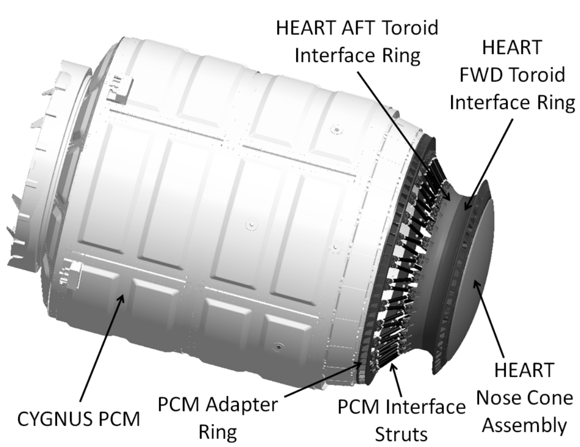

Fig. 7: HEART centerbody structure shown with Cygnus PCM (inflatable removed for clarity)

The nose cone assembly is an aluminum nose that accommodates a the same TPS of the type used on the inflatable aeroshell. The nose cone serves as the primary mounting interface for the two-deck equipment assembly, which holds the avionics and instrumentation subsystems and the inflation subsystem. The nose cone assembly bolts directly to the center-body.

The center-body is comprised of two aluminium rings with a bolted joint: a forward toroid interface ring and an aft toroid interface ring. The forward interface ring hosts the windward IAD strap mounts and the TPS strap mounts. Flight test instrumentation wire leads are routed from the IAD through the forward interface ring. The aft ring interface ring hosts the leeward IAD strap mounts. The IAD is then packed as an annulus around the center-body.

A set of sixty interface struts serve as the load path and structural interface between HEART and the Cygnus PCM. Each strut is adjustable and utilizes clevis type ends. The struts attach to the aft toroid interface ring and the Cygnus PCM adapter ring.

4.3.4 Avionics

The HEART avionics subsystem shown in Fig. 8 consists of the controller, power, sensors & data acquisition, and RF communications with both satellite assets and receiving ground stations. Given that HEART is classified as a Class D mission, per NPR8705.4 [6], most of the Avionics will be single string. The Controller processes inputs from the Cygnus SM, on-board data system, GPS and inertial navigation unit, and separation indicators along with providing the sequencing of power, inflation, heater control, pyro, video, data collection and transmission.

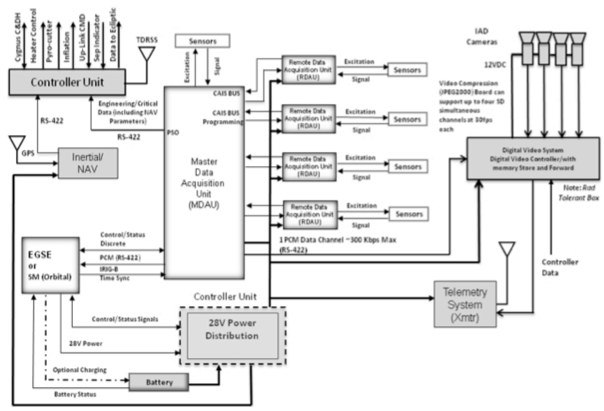

Fig. 8: Functional block diagram with Cygnus interfaces for HEART avionics

The controller is a Field Programmable Gate Array (FPGA) based event sequencer. HEART requires minimal computation such that milestone events and timing can be used to control and fly the mission. The controller resides on an essential bus such that when the HEART power system is enabled, the controller is initialized. Once initialized, the HEART controller receives the state information from Cygnus allowing the HEART navigation element to be correlated.

HEART includes navigation with the avionics subsystem to aid in flight path reconstruction. HEART navigation baselines the use of a Space Integrated GPS INS (SIGI) to provide inertial and absolute position, attitude, and state determination. HEART navigation also includes an altitude switch (barocell) as part of the end of flight experiment determination.

The data system configuration includes a collection of sensors wired to the four distributed Remote Data Acquisition Units (RDAU) or to the Master Data Acquisition Unit, which also controls the RDAUs. There are more than 800 measurements allocated for the flight test. The bulk of the measurements (nearly 500) are thermocouples located within the layers of the IAD TPS. Other measurement types include heat flux, load cells, accelerometers, inertial, GPS, and pressures to characterize system performance. The thirteen IAD Nose pressures are configured to create a Flush Air Data System to derive entry attitudes and capture peak dynamic pressures. Four video cameras are mounted near the top of the PCM. Video will capture the entire IAD deployment and inflation process along with the peak dynamic pressure period to help determine shape, perimeter asymmetry, and/or local tori deformation. Variable frame rates will be defined and selectable depending on the predicted dynamic events associated with various points along the entry trajectory.

Electrical power is derived from a set of primary batteries. Power conditioning and regulation along with grounding are also included with the electrical power subsystem. Prior to separation from Cygnus, electrical power for the survival heaters is provided directly from the Cygnus power system. In addition, Cygnus provides the power to initially energize HEART and any necessary preheating prior to enabling the HEART primary batteries.

Telecom for HEART consists of two different communication elements; an S-band system for critical events communications with TDRSS, and an X-band system for transmission of all science and engineering data to ground stations. The S-band telecom system transmits essential health, status, and science data using PCM mounted antennas to TDRSS. This low bandwidth system begins communication prior to the separation event and continues until loss of signal near the end of mission. All of the data, including the critical events data, will be transmitted to a ground station through a high-rate X-Band telemetry link. Time-history mission science data along with the critical events, housekeeping, and video data will be collected and buffered in the store and forward flight recorder and ultimately transmitted to the ground station after the expected RF blackout region. The X-band antenna(s) are mounted on the rigid nose structure behind the TPS. The TPS has been tested to demonstrate RF transparency at X-band frequencies. Also, the wires for the sensors mounted in the nose TPS are routed around the antenna keep-out zones to minimize any potential interference effects. The total data volume for both the video and sensor data throughout the 20-minute mission duration is approximately 12.1 Gb, of which 10.9 Gb is Video.

Having a robust and effective Avionics suite will be crucial in the success of the HEART mission. Ensuring that timely sequencing is performed and monitoring of the critical sensors will be imperative for proper deployment of the IAD. Furthermore, having performed analysis on the reentry ionization blackout period and the South Atlantic Anomaly radiation doses along with link margins on the RF transmission will provide confidence that data collection will be successful in capturing real-flight environment Mission Science Data needed for improving model correlation and determining vehicle performance.

4.3.5 Inflation

The HEART inflation subsystem is a pressurized gaseous nitrogen (GN_2) blow down system, modelled after the pressurant systems of traditional spacecraft propulsion subsystems. The system is configured to reduce the total quantity of components and control requirements. A schematic of the inflation system is shown in Fig. 9**.**

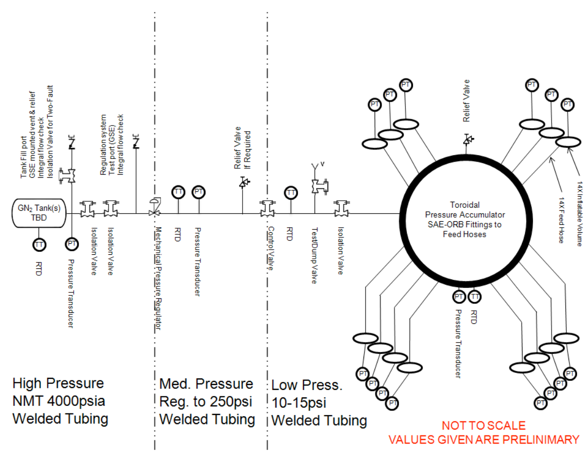

Fig. 9: Inflation subsystem schematic for HEART

A composite overwrapped pressure vessel (COPV) is the key storage element for the HEART inflation subsystem. This COPV is sourced from the retired Space Transportation System orbiter Atmospheric Revitalization Pressure Control System. For ISS visiting vehicle and proximity requirements, the high-pressure isolation and storage system is two-fault tolerant by design. These isolation valves are mounted in series to provide a restriction to prevent slam-start of the mechanical pressure regulator.

Pressure control is provided through a mechanical pressure regulator for initial pressure reduction, followed by a solenoid valve with a deadband control scheme. The mechanical pressure regulator is a high flow component capable of reducing the pressure from a maximum of 20.7 MPa to 1.7 MPa, with a minimum inlet pressure of about 3.45 MPa from storage. A solenoid valve capable of maintaining continuous duty operation during the re-entry experiment serves as the final control of the inflation pressure in the HIAD's inflatable structure. This valve maintains specified pressure conditions with the valve current driver being controlled through the sequence controller. The inflation pressure is to be maintained in two zones with a dead band-width of 6.9 kPa.

The HEART inflation system features a large volume accumulator. This accumulator serves as a damping component against the high flow solenoid valve's abrupt start/stop operation, as well as a pressure distribution manifold to ensure that the inlet pressure to each feed hose is similar. This component reduces the amount of high-pressure tubing as well as the fabrication complexity of the inflation system.

There is a resistive temperature device located in the COPV, on the accumulator, and inline after the mechanical pressure regulator. Pressure transducers monitor the operation of the system before the isolation valve, after the mechanical pressure regulator, in the accumulator, and from a sensing hose leading to each inflatable volume. Flowrate is inferred using the system pressure and temperature measurements, which are calibrated in the ground characterization testing prior to flight.

System performance prediction and validation are performed with a network flow analysis application. This tool uses empirical approximations for the resistances and thermal responses of the system to provide a system-level prediction of the torus fill time and system heating requirements of the gaseous blow-down system.

4.3.6 Thermal Control

Thermal assessments were conducted to determine the feasibility of the mission from a thermal perspective and determine if heaters would be necessary for on-board components. Initial assessments determined that the HEART on-orbit concept was viable from an on-orbit thermal perspective [7] and additional analysis was performed to determine initial heater power sizing requirements [7].

A simple HEART and Cygnus analysis model was created in Thermal Desktop and used to represent the vehicle being docked at the Node 2 nadir docking port [8]. Two distinct mission phases, non-operating and power-up, were used to determine the amount of make-up energy required by the HEART subsystems to remain above specified temperatures [8].

The analyses identified that the HIAD TPS serves as a good insulator and dampens the effects of the changing environment when cycling between extreme hot and cold thermal environments, where the environment extremes were defined by the ISS [7].

Based on the current mission parameters as inputs, the current analysis identifies that the pyrotechnic, inflation, and avionics batteries are the only components requiring heaters during the non-operating phase and totals 126 W of power [8]. All components require heaters during the power-up phases, resulting in a 401 W need due to tighter temperature constraints during this phase [8].

Thermal analysis for the HEART mission will continue to be refined throughout the project lifecycle and include forward work regarding assessing the effect of potentially varying parameters, such as the HIAD density or inflation tank parameters [8].

5 HEART PERFORMANCE

5.1 Flight Mechanics/Trajectory

Flight mechanics, or trajectory, assessments of the performance of the HEART entry vehicle are provided through a 6-degree of freedom (6-DOF) simulation using the Program for Optimized Simulation Trajectory-2. This simulation includes all estimated mass properties for HEART, estimated inflatable structure stiffness derived from ground test data, historical atmospheric models, and detailed mass and performance data from the Cygnus spacecraft. Cygnus performs a 2-burn entry after departure from ISS. The first burn places the Cygnus spacecraft (with HEART) from the ISS orbit to an elliptical phasing orbit with a 421 km apogee and TBD km perigee with a 51.6° inclination. Cygnus then performs the final entry deorbit maneuver from this elliptical phasing orbit. Trajectory simulation with dispersed vehicle and environmental properties are used to provide heating and dynamic pressure environments suitable for TPS and structural sizing. One of the key uncertainties are the mass properties of the down mass cargo contained inside the PCM. The final cargo down mass is estimated near launch, however, the arrangement of the mass within the PCM and the effect on center of gravity (CG) and inertias are not known until after the down mass cargo is loaded and post ISS separation maneuvers are performed. Estimated ranges of cargo down mass magnitude, cargo mass CG location, and cargo mass inertia have been included in the HEART 6-DOF simulation to bound the effects. This mass uncertainty leads to an offset lateral CG resulting in an unknown angle of attack. Using the range of mass uncertainties, a maximum angle of attack (99 percentile) of 10 degrees is predicted. The cargo down mass uncertainties have been included in the montecarlo performance estimates. Fig. 10 illustrates the nominal HEART altitude and velocity profile.

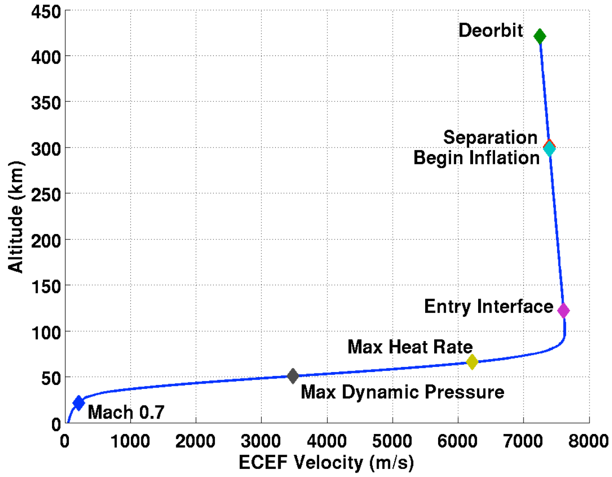

Fig. 10: HEART nominal velocity–altitude profile

The HEART vehicle is spin stabilized to provide resistance to disturbing moments prior to entry to allow for a favorable angle of attack at entry interface. During entry, the vehicle maintains a sufficiently low angle of attack to limit heating on the unprotected aft-body. The nominal environmental results are shown in Fig. 11. The nominal peak heat rate of 27 W/cm^2 is at the stagnation point on a theoretical one-meter radius nose. The detailed computational fluid dynamics (CFD) (shown in Section 5.2) provides estimated peak heat rate and heat rate distribution. The peak sensed acceleration is nominally 7 g's, with a 99-percentile acceleration of [8.5 g's] which is comparable to the maximum acceleration experienced during launch on the Antares launch vehicle.

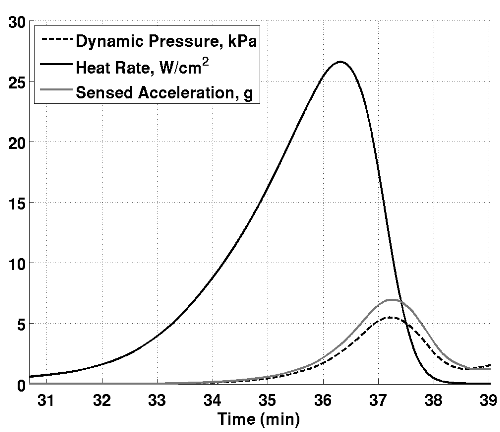

Fig. 11: HEART nominal time history

A key contributor to the HEART flight dynamics is the structural response of the aeroshell. Aerodynamic forces are expected to cause deformations of the aeroshell that act to reduce drag and to increase trim angle of attack. Future analysis and testing of HIAD structural characteristics will allow improved prediction of these effects.

5.2 Aerothermodynamic and CFD

One of the key developmental challenges for IADs is the aerothermodynamic environment and the associated TPS response during atmospheric entry. Detailed CFD assessments of the HEART baseline configuration and an alternative configuration are discussed here [9].

The baseline HEART geometry was analyzed and optimized for its aeroheating environment during the Earth entry. The effects of angle of attack on the surface aeroheating are also analyzed. Ranges of TPS surface catalytic coefficients are considered including strategies to mitigate this catalytic uncertainty. For these initial assessments, the aeroshell is assumed to be rigid and the inflatable fluid interaction effect that becomes important mainly in the low supersonic part of the trajectory is left for future investigations.

The 99-percentile HEART trajectory was used for this initial assessment. A laminar 5-species air with thermal equilibrium condition was assumed. Surface temperature was computed using a radiative equilibrium boundary condition with an assumed constant emissivity of 0.85. The surface catalytic condition was assumed to be fully-catalytic (FC), in which all atoms were allowed to recombine on the surface. This condition provided the upper bound for the surface heat flux. The computations were performed using the LAURA-5 [10] code at a constant angle of attack of 10-deg. Fig. 12 provides the heat rate variability across the IAD at the maximum expected 10 degree angle of attack. Point 2163 represents a point as heating is increasing (~84 km altitude and Mach 25). Point 2255 is the maximum heat rate point in the trajectory with point 2292 being just prior to maximum dynamic pressure. Only the peak heating point, T2255, with a fully-catalytic surface and radiative equilibrium boundary condition is discussed here. Note how the heat rate peaks at the discontinuity between the elliptical nose and the conic section. This discontinuity is an artifact of minimizing the space between the Cygnus SM and PCM while providing a sufficiently large IAD. The peak heat rate of 40 W/cm^2 can be observed at this juncture with the significant roll-off of the heat rate until the shoulder where the heat rate increases to about 24 W/cm^2.

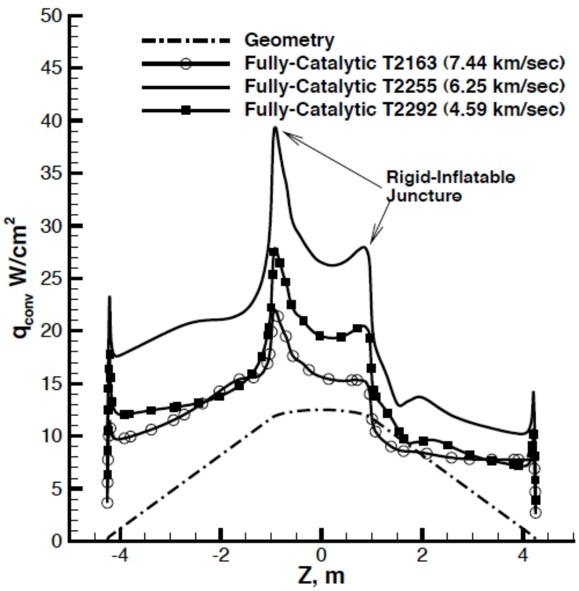

Fig. 12: Original baseline configuration – peak heat rate in trajectory

A modification to the nose geometry to reduce the discontinuity between the elliptical nose and the cone shape was made with a resulting decrease in the peak heat rate from 40 W/cm^2 to 34 W/cm^2 (Fig. 13).

The HEART trajectory is ballistic with angle of attack variations of +/- 5 degrees at peak heat rate. To account for the worst case, the optimizations were performed at an angle of attack of 10 degrees where the vehicle experiences maximum surface heating. Sensitivity of heating to the variations in the angle of attack is also considered. Using the optimized nose configuration, the results of angle of attack variability are investigated.

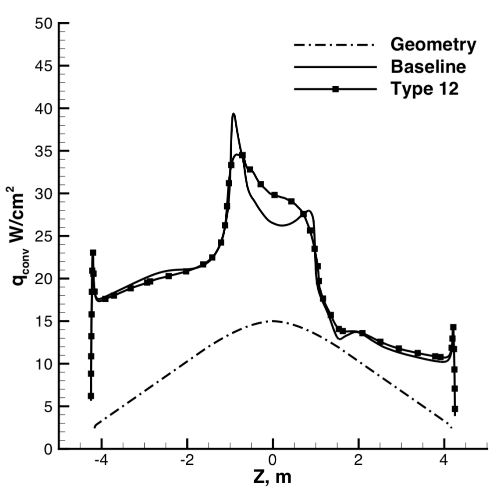

Fig. 13: Revisions to OML reduce peak heat rate

Fig. 14 shows the results of the angle of attack effect on surface heating. Open symbols indicate solutions at 10 degrees angle of attack with a fully-catalytic surface. The solid lines indicate solutions at a zero degree angle of attack. The results show a relatively minor heat flux sensitivity to the angle of attack, meaning that additional aeroheating analysis might not be needed to account for angle of attack variations during entry. Thus the optimized nose shape provides a

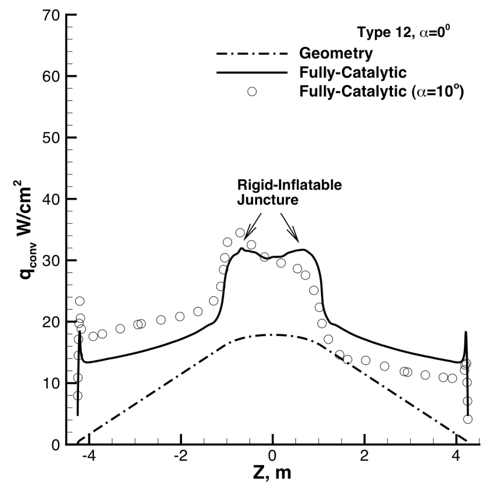

Fig. 14: Effects of angle of attack variation have been considered

relatively uniform nose curvature within +/- 10 degrees relative to the free stream velocity. Thus, the angle of attack effects on the surface heating prediction were minor. Note that the maximum surface heating of 34 W/cm^2 is reduced by about 10% with the reduced angle of attack. The IAD surface acreage also experienced slightly lower surface heat flux and temperature at zero degree angle of attack.

The effects of catalysis have been considered (Fig. 15). Additional analyses and tests are required to assess if catalysis is a realistic effect for the flexible insulating TPS. The analytical results showed that the catalytic (or diffusion) heat flux increased with increasing the surface catalysis while the conduction component remained fairly constant. The temperature gradient (conduction) influence to the total heat flux stayed a dominant factor until a surface catalysis of 5%, when the catalytic component surpassed the conduction component. However, for surface catalysis above 3%, the total heat flux reached to 100% of the corresponding fully-catalytic value. That is, the total surface heat flux stayed relatively unchanged with increasing surface catalysis efficiency. The peak heat rate of 34 W/cm^2, was derived from a 99-percentile trajectory and includes the angle of attack effects (CG location uncertainty), and the 60% uncertainty due to the catalytic effect, provides the current unmargined environmental value for the TPS design.

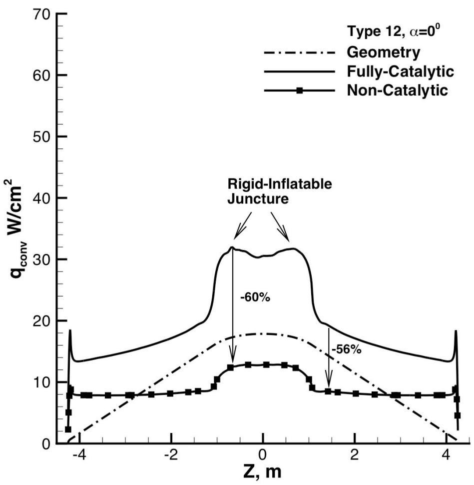

Fig. 15: Final peak heat rate at zero angle of attack

6 HEART MATURATION APPROACH

HEART is a technology demonstration flight test. The primary technologies to be demonstrated are the inflatable structure, the flexible insulating TPS, modeling of both elements, and demonstration of the HIAD accommodations on a spacecraft.

The baseline aspects of the technology development including model development, component level testing, and smaller scale flight testing are being performed through the HIAD Project within NASA's Office of Chief Technologist's Game Changing Division. Successful completion of these supporting technology development efforts, including the IRVE-3 [2] flight test, are essential for HEART to also be successful. The HEART project does not include any significant technology maturation efforts other than material property verification and updates to models to reflect the final design configuration. Noted herein is a description of the technology maturation efforts for the two primary technologies – flexible insulating TPS and the inflatable structure.

6.1 TPS Maturation Approach

As described in Section 4.3.2, a baseline TPS has been specified for the HEART vehicle, which is similar to the TPS being used on the IRVE-3 vehicle. Results of the IRVE-3 test will be important for estimating the HEART TPS performance. In addition, testing and analysis will continue on the HEART baseline TPS to fully evaluate its performance over the full range of the predicted flight envelope.

The ground testing efforts focus on the aerothermal performance and the aeroelastic performance of the TPS. Aerothermal testing, performed at the Boeing large core arc tunnel, at the predicted HEART conditions have only evaluated pristine samples in both shear and stagnation configurations. Data from the pristine sample tests are required for the development of the analytical modelling effort [2]. Future testing will focus on samples that have been through a simulated packing and folding process to determine the degradation in thermal performance, if any, resulting from handling, packing, and deployment. In addition, seams, stitching, imperfections, and damage to the TPS will be evaluated to establish performance and acceptance criteria.

Another area of ground testing and analysis is being initiated to evaluate the aeroelastic performance of the flexible material that can result from the aerodynamic forces during entry. The 8-foot high temperature tunnel (8'-HTT) at NASA Langley has been identified to perform initial evaluations of the TPS under simulated aerothermal loads at elevated temperatures. A flat plate wedge test article has been developed with a 61 cm by 61 cm cavity in the center of the flat plate where a TPS test article can be suspended and supported for evaluation. These initial tests will evaluate the test concept and provide initial data for analytical modelling efforts.

In addition to fully evaluating the baseline TPS configuration, development continues to improve the TPS in terms of mass, thermal performance, flexibility, and mechanical durability. Several materials have proven through aerothermal testing to provide improved thermal performance at the same or less areal density, which can result in the TPS being able to handle increased thermal loads or provide increased margins for design purposes. However, the mechanical durability will need to be improved before these materials can be considered a viable alternative to the baseline HEART TPS.

6.2 Inflatable Structure Maturation Approach

Maturation of the inflatable structure consists of a multi-faceted approach to address scale effects, thermal effects on material properties, assembly and integration, and material availability. Modeling of the flexible structures, including fluid-structure interactions, stresses and loads, stiffness, thermal effects are all included as part of the maturation. Design, fabrication, and testing of both a 3 m and 6 m diameter inflatable structure have been completed. Multiple material systems have been investigated with the current baseline emphasizing kevlar™ derived materials. Flight of the IRVE-3 vehicle in the summer of 2012 will demonstrate the load carrying capability and stiffness of a 3 m inflatable structure [11]. Additional technology maturation efforts include completion of the load testing of the 6 m diameter HIAD, fabrication and testing of an 8 m diameter HIAD, completion of the material property testing, and revisions to the existing analytical models to reflect test results. The planned (and funded) efforts within the HIAD Project are adequate to deliver the requisite technology maturity, knowledge, and capability to the HEART flight test.

7 CONCLUDING REMARKS

HEART is a flight test to demonstrate the overall performance and readiness of a large-scale HIAD for mission infusion. The underlying technology development efforts are in place, and progressing well. HEART is leveraging existing spacecraft and launch opportunities to reduce the overall cost while simplifying the necessary subsystems to what is essential for a successful flight test. With the successful flight of IRVE-3, HEART will be ready to proceed to the next phase of implementation.

8 ACKNOWLEDGEMENTS

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10 ABBREVIATIONS AND ACRONYMS

A	Area
C_D	Drag Coefficient
CFD	Computational Fluid Dynamics
CG	Center of Gravity
COPV	Composite Overwrapped Pressure Vessel
DOF	Degree of Freedom
FC	Fully Catalytic
FPGA	Field Programmable Gate Array
Gb	Giga bits
GN_2	Gaseous Nitrogen
GPS	Global Positioning System
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
HEART	High Energy Atmospheric Re-entry Test
IAD	Inflatable Aerodynamic Decelerator
INS	Inertial Navigation System
IRVE	Inflatable Re-entry Vehicle Experiment
ISS	International Space Station
kg	kilogram
km	kilometer
LEO	Low Earth Orbit
m	meter
MOLA	Mars Orbiter Laser Altimeter
NASA	National Aeronautics and Space Administration
OCT	Office of the Chief Technologist

OML	Outer Mold Line
PCM	Pressurized Cargo Module (Cygnus)
RDAU	Remote Data Acquisition Unit
RF	Radio Frequency
RPM	Revolutions Per Minute
SIGI	Space Integrated GPS INS
SM	Service Module (Cygnus)
TDRSS	Tracking, and Data Relay Space System
TPS	Thermal Protection System
W	Watt