HIAD on ULA (HULA) Orbital Reentry Flight Experiment Concept

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Abstract: This paper describes a proposed orbital velocity reentry flight test of a Hypersonic Inflatable Aerodynamic Decelerator (HIAD). The flight test builds upon ground development activities that continue to advance the materials, design, and manufacturing techniques for the inflatable structure and flexible thermal protection system (F-TPS) that comprise the inflatable heat shield. While certain aspects of material and system performance can be assessed using a variety of ground testing capabilities, only orbital velocity energy on a trajectory through the gradient density of the atmosphere can impart the combined aerodynamic and aeroheating design environments in real time. To achieve this at limited cost, the HIAD would be delivered to a spin-stabilized entry trajectory as a secondary payload on the Centaur stage of a United Launch Alliance (ULA) Atlas V launch vehicle. Initial trajectory studies indicate that the combination of launch vehicle capability and achievable reentry vehicle ballistic numbers make this a strategic opportunity for technology development. This 4 to 6 meter diameter scale aeroshell flight, referred to as HIAD on ULA (HULA), would also contribute to ULA asset recovery development. ULA has proposed that a HIAD be utilized as part of the Sensible, Modular, Autonomous Return Technology (SMART) initiative to enable recovery of the Vulcan launch vehicle booster main engines [1], including a Mid-Air Recovery (MAR) to gently return these assets for reuse. Whereas HULA will attain valuable aerothermal and structural response data toward advancing HIAD technology, it may also provide a largest-to-date scaled flight test of the MAR operation, which in turn would allow the examination of a nearly pristine post-entry aeroshell. By utilizing infra-red camera imaging, HULA will also attain aft-side thermal response data, enhancing understanding of the aft side aerothermal environment, an area of high uncertainty. The aeroshell inflation will utilize a heritage design compressed gas system to minimize development costs. The data will be captured to both an onboard recorder and a recorder that is jettisoned and recovered separately from the reentry vehicle to mitigate risk. This paper provides an overview, including the architecture and flight concept of operations, for the proposed HULA flight experiment.

Introduction: Utilizing aerodynamic drag is a mass-efficient method to decelerate a spacecraft for landing on a planetary body with an atmosphere. Conventional rigid heat shields are limited by the maximum size of the launch vehicle shroud, thus limiting their aerodynamic drag performance. Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology enables a heat shield that can be stowed inside a launch vehicle shroud for transit, and then deployed to a larger diameter prior to atmospheric entry.

Figure 1 shows the relative scale at comparable entry masses for the Mars Science Lab (MSL) rigid aeroshell that was maximized within the diameter of the launch vehicle shroud and a HIAD deployable aeroshell from the High Energy Atmospheric Reentry Test (HEART) concept that would reenter with a cargo module from the International Space Station (ISS). Future Humans to Mars missions will be much more massive than the MSL mission, and even the potential subscale precursor robotic mission, Mars Entry, Descent, and Landing (EDL) Pathfinder, will require deceleration of about an order of magnitude greater mass [2].

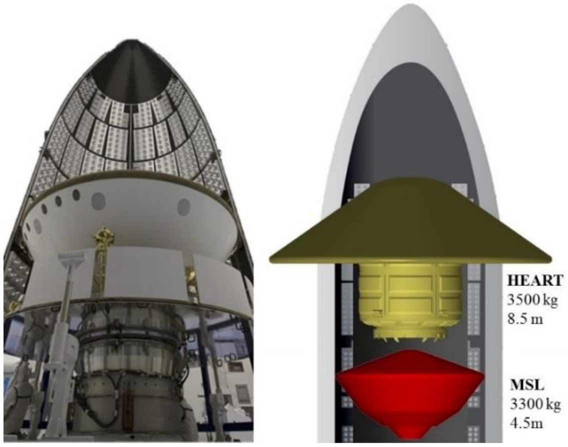

Figure 1: MSL within the shroud (left), HEART to MSL relative scale (right)

After inflation, a HIAD behaves much like a rigid aerodynamic device of the same geometry. Its increased drag area (lower ballistic number) provides high-altitude deceleration that makes it suitable for aerocapture or entry. That deceleration in the upper reaches of the atmosphere provides reduced aeroheating, access to higher elevations for landing, and increased landed mass capability for destinations with a sensible atmosphere - which is particularly enabling for larger scale missions to Mars.

This technology can also be applied at Earth. With the retirement of the Space Shuttle, the U.S. lost its capability to return large payloads from the ISS. Commercial cargo resupply providers could employ a HIAD to restore that capability. Another potential commercial application is the recovery of spent launch vehicle assets for future reuse, thereby lowering overall launch costs. Correspondingly, the ULA Sensible, Modular, Autonomous Return Technology (SMART) baseline utilizes HIAD technology to enable recovery of the Vulcan launch vehicle booster main engines.

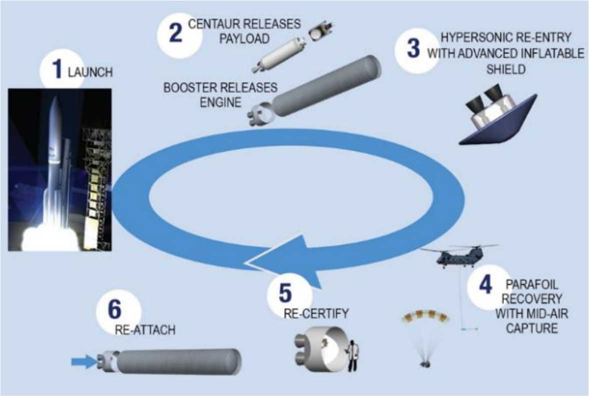

Figure 2: ULA SMART reuse concept (credit: ULA)

Background: NASA has collaborated with multiple organizations to design, fabricate, integrate, and test HIAD reentry vehicles on sounding rocket flight missions. The Inflatable Reentry Vehicle Experiment (IRVE) series provided flight demonstrations and data for the development of HIAD technology. Most recently in 2012, the IRVE-3 flight test demonstrated the effectiveness of the inflatable heat shield using first generation materials on a 3m diameter vehicle with a 60 degree cone angle, entering the Earth’s atmosphere on a steep flight path angle and incurring 20g’s deceleration. This trajectory maximized the peak heat rate available from the three stage sounding rocket, achieving a heat rate of 15 W/cm^2 at the stagnation point [3].

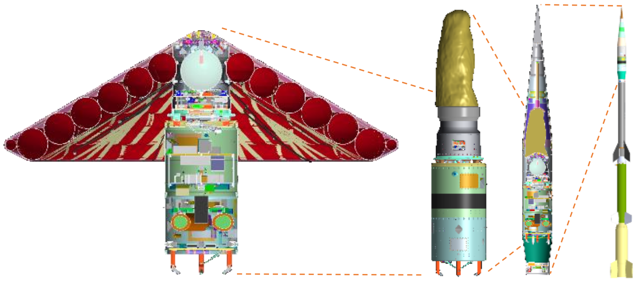

Figure 3: IRVE-3 configuration

Figure 4: IRVE-3 in flight

After the success of IRVE-3, ground development activities continue to advance the materials, design, and manufacturing techniques for the inflatable structure and flexible thermal protection system (F-TPS) that comprise the inflatable aeroshell. This progress is addressing the challenges of large scale human-rated missions to Mars, while enhancing the cross-cutting capabilities of HIAD technology for a variety of mission applications.

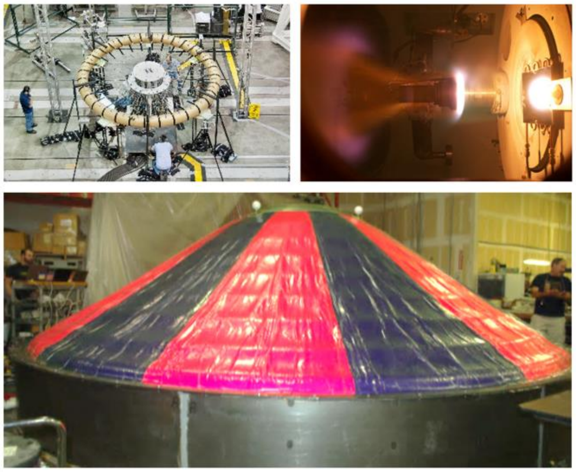

Figure 5: HIAD ground testing examples - torus compression (upper left), arc jet stagnation (upper right), 6m static load (bottom)

Figure 6: HIAD 6m wind tunnel testing

However, analytical model and thermal response assessments of these advancements as a system require significantly higher heat rates and integrated heat loads than those achievable in sub-orbital flight, with more flight-like environments than are available in ground testing. While certain aspects of material and system performance can be assessed using a variety of testing methods, only orbital velocity energy on a trajectory through the density gradient of the atmosphere can impart the combined aerodynamic and aeroheating environments on the HIAD system in real time. The HULA mission would demonstrate the effectiveness of the HIAD at these conditions and provide critical flight data relevant to future Mars missions and the ULA SMART initiative.

Objective: The primary objective of the HULA secondary payload experiment would be to demonstrate a high energy flight test of a scaled-up HIAD. The Earth orbital reentry introduces the HIAD technology to a design-reference atmospheric entry environment. It builds upon IRVE-3's success with a suborbital trajectory by more than doubling the expected peak heat rate (from 15 to 40-60 W/cm^2), and increasing the expected integrated heat load by more than an order of magnitude (from 0.2 to 3-5 kJ/cm^2). This thermal environment is similar to that expected for an MSL-class HIAD entry at Mars, and provides a direct opportunity to test the technology for Earth reentry applications.

The minimum success criteria for HULA would be to survive orbital reentry and do no harm to the ULA primary mission. The comprehensive success criteria would involve achieving the desired reentry state for the experiment as defined by the reentry flight path angle, orientation, and velocity at atmospheric interface; demonstrating aerodynamic stability; characterizing aerodynamic performance; capturing the comprehensive experimental data to evaluate and correlate with modeling and simulation tools; and recovering the HULA aeroshell for post-flight physical examination.

Mission Scale: To challenge the F-TPS toward its designed capability, it is desirable to fly a relatively high ballistic coefficient to approach aeroheating allowables, along with a relatively large aeroshell to test a representative running length against aerodynamic shear forces and turbulent heating augmentation. The ballistic coefficient involves a ratio of mass to drag area, so for a given ballistic coefficient, the mass of the reentry vehicle would need to increase as the square of the aeroshell diameter increases. As a secondary payload, the available mass from the launch vehicle limits the ballistic number achievable at a particular aeroshell size, which is itself limited by the available volume for the stowed reentry vehicle with its packed HIAD. Within these constraints, the HULA secondary payload experiment provides a logical scale increase from the 3m diameter IRVE series. A 6m diameter HULA aeroshell is approximately half scale for the ULA SMART initiative and the potential Mars EDL Pathfinder mission, and it would provide flight data relevant to both. NASA has demonstrated manufacturing, handling, structural performance, and initial hard-packing trials at this scale with a 6m ground test article. HULA would provide significant incremental strides for both HIAD and Mid-Air Retrieval (MAR) in that it would be the largest blunt body heat shield ever flown, the largest MAR operation ever demonstrated, and the first inflatable aeroshell recovered for post-flight inspection.

Figure 7: IRVE-3 (3m) to HULA (6m) scale comparison

Trajectory Analysis: Trajectory simulations were used to assess the parameters of the HULA mission. A spin-stabilized ballistic reentry simplifies the test vehicle and utilizes the reliability of the Centaur second stage to establish the flight experiment entry conditions. This approach eliminates the need for the test vehicle to include a reaction control system, and takes advantage of readily available capabilities of the Centaur. A reference primary mission provided the initial HULA trajectory state from the end of mission for the ULA Centaur second stage. Trajectory simulations were performed for a fixed HIAD diameter of 6m at an incremental range of potential ballistic coefficients (30-50 kg/m2) for this Low Earth Orbit (LEO) end of mission shallow entry condition. The shallow entry condition tends toward a desirable combination of relevant total integrated heat load, reduced peak deceleration load, and a bounding debris dispersion case. The footprint of the Centaur reentry break-up debris was evaluated for determining the associated recontact and recovery risks in a feasibility assessment, and the probabilities were found to be conservatively low.

The trajectory analysis inserted a simulated second stage burn to produce a change in velocity (delta-V) at apogee. This simulated increase in velocity would actually be employed as a reduction of the original retrograde deorbit delta-V for the end of mission shallow entry condition, as shown in Figure 8, reducing the entry flight path angle and targeting specific deceleration loads (8, 10, and 12g) for estimating the resulting heat rates and total integrated heat loads.

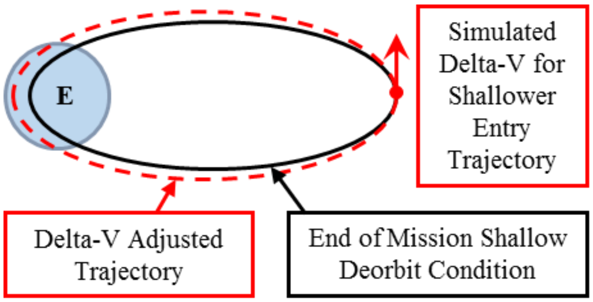

Figure 8: Schematic of delta-V applied for targeted deceleration

The resulting entry velocities and flight path angles were compared to the skip-out conditions. The delta-V required for 10g peak atmospheric deceleration provided a suitable combination of test conditions for aeroheating and aerodynamic loading, while comfortably avoiding skip-out conditions. A nominal atmosphere profile was used to determine the delta-V required. As a feasibility check, dispersed atmospheric profiles of +/-3 standard deviations for density, pressure, and temperature were used to determine the sensitivity of the required delta-V values to atmospheric variability. Only ~2.5 m/s change in delta-V was observed when accounting for the effect of atmospheric variability on the applied delta-V required. The ballistic trajectory simulations provided feasibility assessments and predicted conditions to inform the conceptual design.

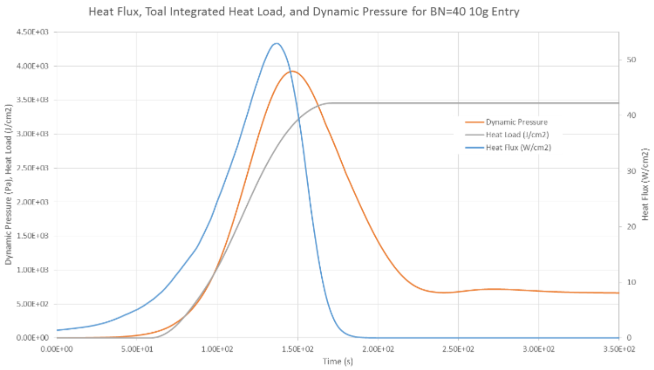

Figure 9: Plotting heat rate, total integrated heat load, and dynamic pressure for a particular case from the trajectory analysis

Conceptual Design: The test vehicle concept utilizes a 6m diameter, 70 degree HIAD aeroshell. The F-TPS insulator was sized to accommodate the expected aeroheating, a mass for the inflatable aeroshell was calculated from empirically derived estimators, and then the aeroshell stowed volume was established within a demonstrated packed density. To achieve a ballistic coefficient approaching 40 kg/m^2, the mass of the entry vehicle needs to be about 1,700 kg. While this is within the mass available from candidate primary missions, this is an unusual design case compared to typical flight vehicles that usually attempt to minimize the mass. The vehicle must be sufficiently massive within the volume constraints to achieve the desired aeroheating test conditions. The available volume is driven by the allowable axial location for the primary payload and the standard payload adapters and separation mechanisms utilized by the launch vehicle second stage. A section of the test vehicle centerbody skin structure is an integral component of the payload adapter mating the primary payload to the Centaur. Due to the need for sufficient mass on the test vehicle, this skin structure thickness will be sized beyond that required for structural purposes.

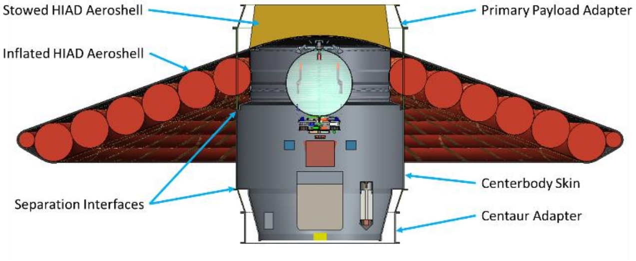

Figure 10: HULA concept design

The HULA test vehicle will provide one half of a standard ULA payload separation interface on both the forward and aft sides of the skin section within the payload adapter stack. The forward separation interface will utilize a long-stroke separation system to release and eject the primary payload adapter, within which the HULA test vehicle is stowed between the primary payload and the Centaur. The aft separation interface releases the HULA test vehicle from the Centaur. The HIAD will be packed and stowed forward of the HULA test vehicle centerbody.

The centerbody is the modular primary structure stack of the HULA test vehicle. The centerbody contains the aeroshell structural interface, the compressed gas inflation system with its spherical tank, the avionics system, data recorder ejection system, and the MAR system.

The inflation system utilizes flight heritage design and components from the successful IRVE-3 reentry vehicle, which helps to minimize development costs. It regulates the pressure of the supply gas (Nitrogen) and inflates the aeroshell using a mass flow control valve. The control valve maintains the inflatable structure internal pressure within a prescribed tolerance band using a feedback controller that monitors individual torus pressures.

The avionics system includes the post-separation power and control functions, experiment instrumentation, operational instrumentation, and data acquisition system. The major components were sized and modeled in three dimensions using Creo (Pro-Engineer) computer-aided design (CAD) software. For a quick feasibility assessment, the components were packaged in a simple, non-optimized way, and the conceptual CAD model shows that ample volume exists within the centerbody to accommodate the vehicle subsystems.

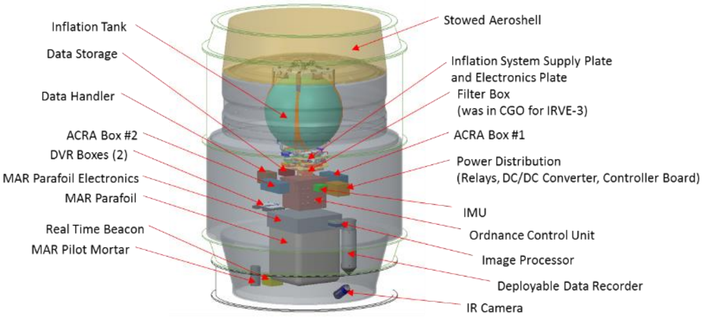

Figure 11: HULA internal packaging feasibility check

Flight Concept of Operations: As part of the assurance to do no harm to the primary mission, the HULA test vehicle launches unpowered and ULA provides a command to power up the HULA test vehicle after the primary payload has been separated from the payload adapter. Additionally, ULA initiates all pyrotechnic events while HULA is attached to the Centaur, which include the release of the launch restraint for the long stroke separation system, the upper payload adapter separation, the HULA aeroshell retention release, HULA inflation, and the lower payload adapter release of HULA from the Centaur.

After separation of the primary payload, the Centaur performs a burn to put the test vehicle on the desired entry trajectory. If there are any additional secondary payloads that desire to re-enter, they can be ejected at this point. The portion of the payload adapter forward of HULA is then separated allowing the HIAD to be deployed and inflated while the test vehicle is still attached to the Centaur. After the aeroshell is inflated to maneuverable stiffness, the Centaur spins up to the rate required for the HIAD test vehicle to maintain pointing from separation through atmospheric interface. Once the desired spin rate is achieved, the test vehicle separates from the Centaur, removing the inhibits on the MAR drogue chute and data recorder jettison. The Centaur then performs a divert maneuver and vents its remaining propellants prior to entry disposal, while the HIAD test vehicle proceeds on the spin-stabilized ballistic entry trajectory for the experiment.

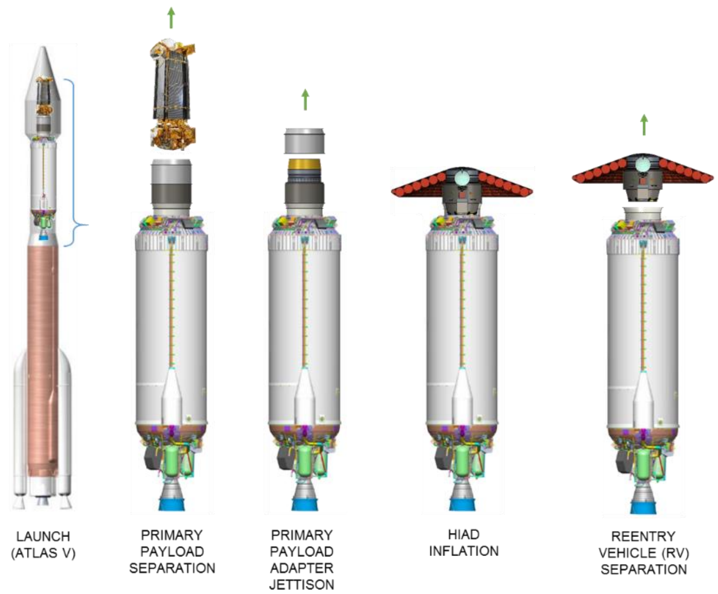

Figure 12: HULA configurations from launch to separation (credit: ULA for launch vehicle images)

After entry and prior to surface impact the test vehicle will be recovered via the MAR operation, allowing for data recovery and inspection of the aeroshell. This will also provide a largest-to-date demonstration of the MAR operations with parafoil deployment and helicopter capture, which feeds forward to the ULA SMART reuse initiative. As a risk mitigation to ensure data recovery, a second data recorder will be ejected from the vehicle prior to MAR parachute deployment in a container suitable for water impact and sustained surface loiter with systems to aid in location and recovery of the data module.

Experiment Data: Measurements necessary to reconstruct the trajectory of the test vehicle, determine the entry environment experienced by the test vehicle, and evaluate the HIAD response to the entry environment will be stored on-board on a flight data recorder. The nose and aeroshell of the HULA vehicle will be instrumented with thermocouples, pressure transducers, and potentially other structural and thermal response developmental instrumentation. The avionics system will include an inertial measurement unit (IMU) and global positioning system (GPS) unit to provide location, orientation, velocities, and accelerations. The centerbody will mount visible and infrared video cameras with fields of view toward the aft side of the aeroshell. The visible video will help assess the structural response of the HIAD, along with overall visual and possible diagnostic examinations in flight. The infrared video will provide thermal response flight data to help characterize the aerothermal environment at the aft side of the aeroshell, which is an area of high uncertainty in computational fluid dynamics (CFD) analysis and hypersonic

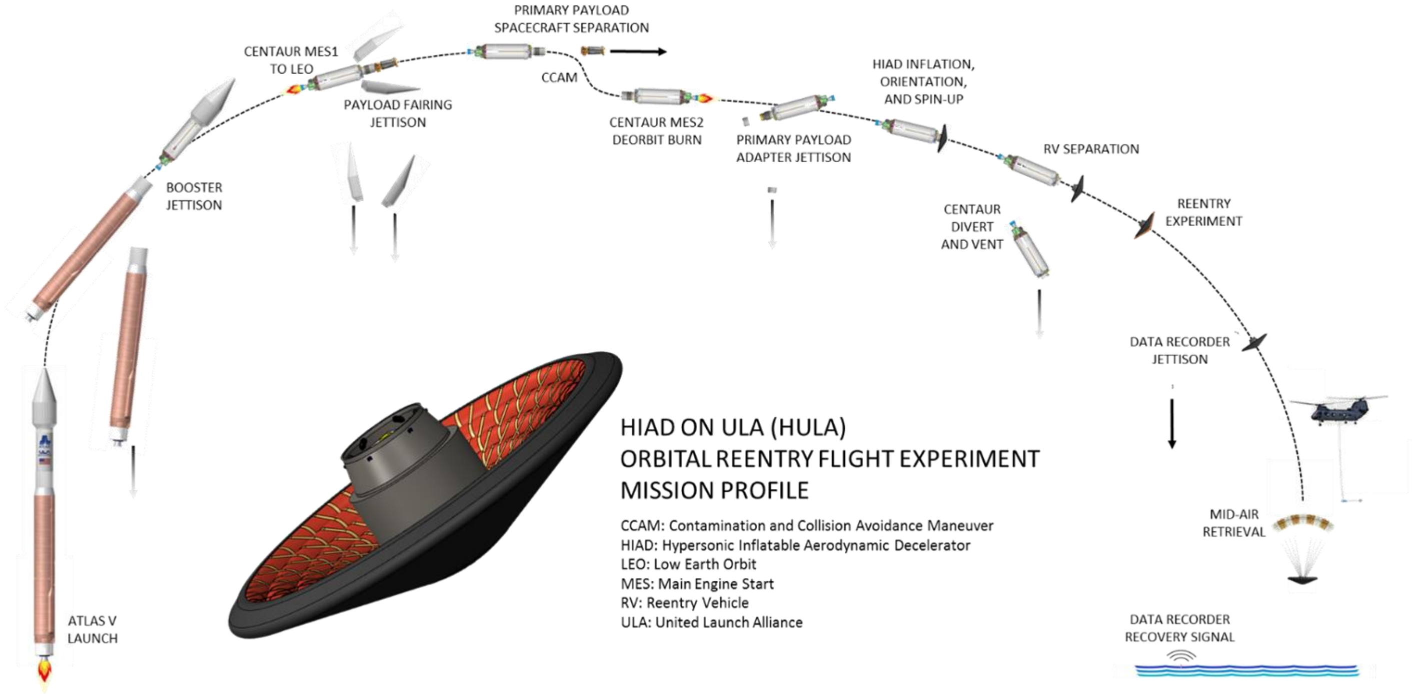

Figure 13: HULA Mission Profile
(credit: ULA for launch vehicle and MAR images)

wind tunnel testing. The inflation system includes pressure transducers for the HIAD inflatable structure internal pressures as part of its feedback loop, along with inflation system gas pressures, temperatures, control valve positions, and flow meters to characterize system performance.

The second data recorder, which is ejected, will serve as a backup in the event of a MAR failure. The test vehicle will also use the Iridium network to relay a reduced data set in near real time to verify the state of the test vehicle after separation from the Centaur, allowing verification that the vehicle was configured correctly prior to atmospheric entry and on the design entry trajectory. ULA would also provide telemetry for the interval between HULA power up and separation from the Centaur so that the HULA test vehicle state can be determined in post flight analysis and used as a state from which to propagate the post flight trajectory reconstruction.

Going Forward: Delivering a relevant scale payload to orbital reentry is often cost-prohibitive for technology development efforts, and utilizing available upmass and reducing complexity as a secondary payload on an existing orbital flight can mitigate this issue. The HULA flight test concept is adaptable to multiple primary missions using standardized ULA payload adapter and separation components. Going forward, design iterations will be performed on the HULA configuration and packaging in response to updated launch vehicle secondary payload geometry constraints resulting from examination of other candidate primary missions. When committed to a launch opportunity with a particular configuration, the more detailed design and analysis will ensue. This high energy reentry experiment would advance HIAD technology readiness for enabling human missions to Mars, robotic missions, and commercial applications.

Figure 14: Artist concept of MAR operation for HULA

Acronyms:

CAD: Computer Aided Design
CFD: Computational Fluid Dynamics
EDL: Entry, Descent, and Landing
F-TPS: Flexible Thermal Protection System
GPS: Global Positioning System
HEART: High Energy Atmospheric Reentry Test
HIAD: Hypersonic Inflatable Aerodynamic Decelerator
HULA: HIAD on ULA
IMU: Inertial Measurement Unit
IS: Inflatable Structure
ISS: International Space Station
IRVE: Inflatable Reentry Vehicle Experiment
LEO: Low Earth Orbit
MAR: Mid-Air Retrieval
MSL: Mars Science Lab
NASA: National Aeronautics and Space Administration
SMART: Sensible, Modular, Autonomous Return Technology
ULA: United Launch Alliance

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