Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) Mission Overview and Science Return

J. M. DiNonno[1] and F. M. Cheatwood[2]
NASA Langley Research Center, Hampton, VA 23681, U.S.A.

The Low-Earth Orbit (LEO) Flight Test of an Inflatable Decelerator (LOFTID) mission was the culmination of two decades of research and development led by NASA Langley Research Center for Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology. A HIAD aeroshell can be hard packed into a small volume for launch and then deployed prior to atmospheric entry for stable aerodynamic deceleration through the atmosphere. Much larger than traditional fixed diameter aeroshells that are constrained by the size of launch vehicle shrouds, inflatable decelerators create more drag and start the deceleration process in the upper reaches of the atmosphere with greater efficiency and stability. Large deployable heatshields enable spacecraft to carry bigger, heavier payloads, including scientific instruments and human support systems for planetary landing and exploration. The success of the LOFTID mission could enable new NASA missions to Mars (including access to higher altitudes than currently possible), Venus, and most solar system destinations with atmospheres, as well as cost-effective payload returns to Earth. With its unique 6m diameter inflatable heatshield, LOFTID was the first-of-a-kind orbital reentry flight, and the largest blunt body atmospheric entry of any kind. On November 10, 2022, the LOFTID aeroshell endured the harsh environments of atmospheric reentry while exhibiting stable aerodynamics through the entire spectrum of hypersonic, supersonic, transonic, and subsonic flight. The demonstration confirmed the HIAD technology structural and thermal performance as the aeroshell protected the 1100 kg Reentry Vehicle (RV) entering Earth's atmosphere at 8 km/s, reaching Mach 30, and experiencing 9.5 g deceleration before deploying parachutes and gently splashing down in the Pacific Ocean, where it was recovered in excellent condition. The LOFTID aeroshell was exposed to an aeroheating environment representative of many Mars and LEO HIAD applications, and successfully demonstrated the ability of the heat-affected inflatable structure to withstand aerodynamic forces that exceeded those expected at Mars. This mission further demonstrated the viability of HIAD technology to deliver large payloads safely and accurately through an atmosphere via a controlled entry, descent, and landing. Whereas LOFTID was indeed a first-of-a-kind flight for an inflatable heatshield, its remarkable performance assured that it will not be the last of its kind.

---

[1] LOFTID Chief Engineer, AST, Aerospace Flight Systems, D208

[2] LOFTID Principal Investigator, NASA Senior Technologist for Planetary EDL, D205, AIAA Senior Member

I. Introduction

The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) mission was the culmination of two decades of research and development led by NASA Langley Research Center (LaRC) for Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology. Though led and managed by LaRC, the LOFTID project involved contributions from other NASA centers, including Ames Research Center, Marshall Space Flight Center, Armstrong Flight Research Center, and Kennedy Space Center. LOFTID flew as a secondary payload rideshare with the National Oceanic and Atmospheric Administration's (NOAA) Joint Polar Satellite System 2 (JPSS-2) mission on a United Launch Alliance (ULA) Atlas V launch vehicle. The project involved a key partnership with ULA through a non-reimbursable Space Act Agreement (SAA). Obtaining a dedicated launch vehicle that can deliver substantial mass to orbit is generally cost-prohibitive for technology demonstrations. By partnering with ULA, NOAA, and NASA's Launch Services Program (LSP), LOFTID was able to achieve an orbital velocity reentry flight demonstration of a scaled-up HIAD as a system in its intended environment. Among its many benefits for a broad range of space missions, HIAD's unique inflatable heatshield, is an enabling technology for ULA's approach to return the Vulcan booster engine module for reuse [1], and ULA contributed significantly to the flight demonstration effort. The success of the LOFTID mission and its HIAD technology demonstration can ultimately enable bolder NASA missions to Mars, Venus, and most solar-system destinations with atmospheres, as well as cost-effective payload returns to Earth, including in-space manufactured materials, objects from Earth orbit, and launch vehicle asset recovery.

This was a flight like no other and required overcoming considerable challenges through ingenuity and a strong collaborative effort. The rideshare involved the JPSS-2 satellite as the primary payload, which is a national asset with highly sensitive optical instruments. LOFTID had to ensure it could do no harm to the primary mission and avoid any contamination of the primary payload. Toward these ends, LOFTID Reentry Vehicle (RV) was designed to be powered off until well after the primary payload was delivered to its orbit. Further, the LOFTID RV was enclosed within the primary payload adapter stack to ensure it could not contaminate the primary payload during launch vehicle integration operations as well as during launch and ascent to orbit. This payload adapter architecture required LOFTID to design and qualify a long-stroke actuation system, called the Payload Adapter Separation System (PASS), to ensure the payload adapter canister enclosing the RV would separate and clear the length of the stowed vehicle [2].

The flight objectives included collecting a large amount of flight data from the RV. The project could not ensure that the RV would remain afloat after enduring a reentry pulse and splashing down in the ocean, and as a secondary payload, the project could not hold the launch to ensure favorable ocean conditions for splashdown and recovery. The amount of data to be captured exceeded capabilities for streaming in real time through a satellite network, so to ensure the flight data was obtained, the RV included an Ejectable Data Recorder (EDR) system. The system would eject a data module prior to splashdown that would float and provide a location signal for at least a month, which required its own mechanism design and qualification testing. Furthermore, the flight objectives involved successfully demonstrating the HIAD in a relevant environment while also exercising the physics of the system and gathering data from it at elevated temperatures to correlate analytical models. This meant the project needed to thread the needle between sufficient margin to ensure a successful mission while not having so much margin that the flight did not sufficiently exercise the system by yielding in-depth elevated temperatures for the heatshield and structure. Given all the uncertainties and dispersions among the analytical predictions of a novel flight configuration, especially early in the project development to establish the design, striking the right balance required an innovative technical approach. The LOFTID project overcame these inherent challenges, along with other contingencies, proving the HIAD technology performance in this first-of-a-kind mission.

II. HIAD Technology

With the ability to pack into a small volume for launch and cruise, and then deploy and inflate to a much larger diameter prior to atmospheric entry, HIAD is an enabling heatshield technology for decelerating heavy payloads at destinations with atmospheres. It is not just the up-mass capability of a launch vehicle, but the size (diameter) of the payload's aeroshell, that currently limits the deliverable payload. Traditional rigid aeroshells are limited by the payload compartment diameters of their launch vehicles. This limits the aerodynamic drag during entry, which ultimately constrains the mass of the payload for sufficient deceleration. In addition, for a given reentry mass, a larger aeroshell decelerates earlier in the less dense upper reaches of the atmosphere, reducing the heating environment and reaching descent and landing speeds at higher altitude, allowing access to higher elevations at the surface.

The mass efficient HIAD deployable aeroshell consists of two main elements; a heat resistant Inflatable Structure (IS) sufficiently rigid to maintain shape against aerodynamic forces, and a Flexible Thermal Protection System (FTPS), or heatshield, that shields the IS and payload from the extreme aeroheating and shear environments of atmospheric entry. The IS consists of a concentric stack of increasing diameter tori that establish a conic shape. Each torus is constructed with a fiber over-braid, and the structural loads are distributed and carried by a configuration of woven webbing straps among the stack of tori. The IS integrates with an FTPS, which consists of a ceramic fabric outer layer and underlying insulator material that is backed by an impermeable gas barrier layer (see Figure 1).

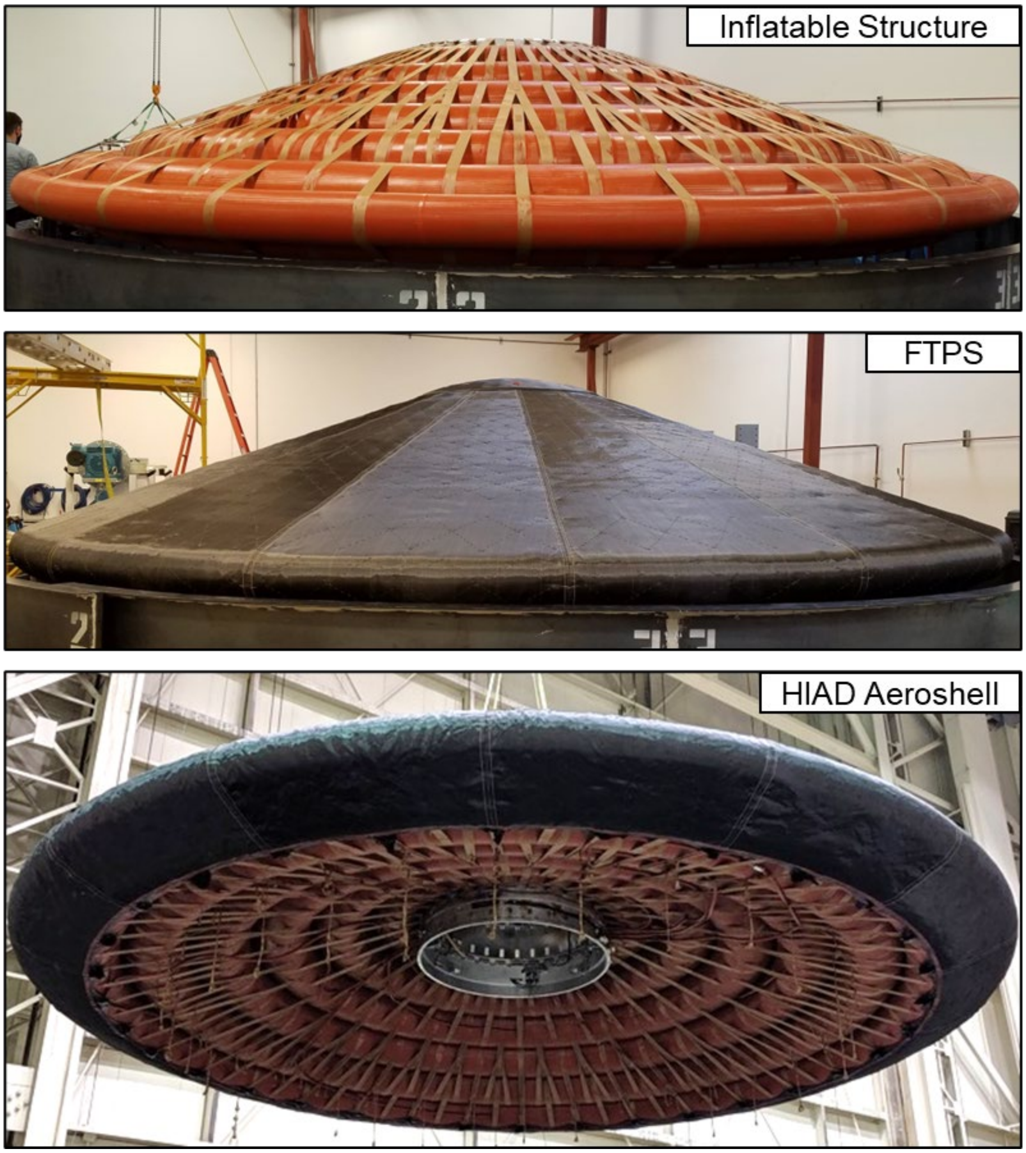

Figure 1: Anatomy of a HIAD, using the LOFTID Aeroshell as an Example

A HIAD does not deploy rapidly like an automobile airbag, but rather inflates over a several minute period in microgravity and vacuum prior to atmospheric entry. With well-distributed load sharing, the structure is very strong and stiff when inflated to operating pressure, so that the HIAD behaves like a rigid aeroshell in flight. It can be designed to specific diameters and cone angles per mission requirements. The flexible term in FTPS refers to it being foldable, packable, deployable, and tailorable. Its tailoring features, such as seams, allow it to be customized and

Figure 2: HIAD in Stowed Configuration for Launch, using LOFTID as an Example, with Internal Rigid Structures and Allowable Volume Superimposed and Semitransparent

accommodate large geometries. The aeroshell can be folded, packed under pressure, and tightly restrained into shapes and volumes available in the architecture (see Figure 2). Despite the abuse of packing, it still performs in extreme drag, shear, and aeroheating loads after deploying to shape. The FTPS can employ different insulator materials and thicknesses depending on the profile of the entry environment. By providing a menu of options for packed geometry, deployed geometry, load capacity, and thermal mitigation, HIAD technology can be optimized for a multitude of mission applications.

III. Early Mission Development

To address the constraints of flying as a secondary payload, the LOFTID team conducted multiple trade studies and made decisions early in the project to establish the mission design for an effective demonstration enabled by the versatility of the HIAD technology. One of the early trades involved the HIAD diameter. Given the substantial mass margin remaining from the primary mission, in collaboration with ULA, NOAA, and LSP, the Launch Vehicle (LV) architecture incorporated an extended payload fairing to accommodate a taller payload adapter, increasing the volume in which LOFTID would reside for launch. The 6-meter diameter aeroshell design was the result of balancing the largest scale achievable within volume and mass constraints while targeting a suitable ballistic coefficient, which is a function of mass divided by drag area. Orbital reentry at this scale would provide similar aeroheating to many Mars and Low Earth Orbit (LEO) HIAD entry missions, while providing the opportunity to exercise the heat-affected aeroshell with aerodynamic forces that exceed those expected in Mars mission applications [3]. This scale also provides a sufficient running length along the flank of the aeroshell to develop shear in the FTPS and to ensure turbulent heating augmentation. These characteristics add uncertainties when determining margins, and are particularly difficult to test on the ground, so it was desirable to fly at a scale that achieves these conditions. This mission design would be a significant step up for HIAD technology, building on the successes of the Inflatable Reentry Vehicle Experiment (IRVE II and IRVE-3) missions that were conducted on 3-meter diameter aeroshells deployed from suborbital sounding rockets [4, 5]. Launched in 2012, IRVE-3 was the most energetic HIAD demonstration to date, but LOFTID, at 4 times the drag area, would enter with nearly 3 times the velocity, more than twice the peak heating, more than 6 times the heat pulse duration, and more than 10 times the total heat load (see Figure 3). Additionally, at 6-meter diameter, this would be an opportunity to fly the largest ever blunt body entry vehicle, which would be a significant achievement on its own.

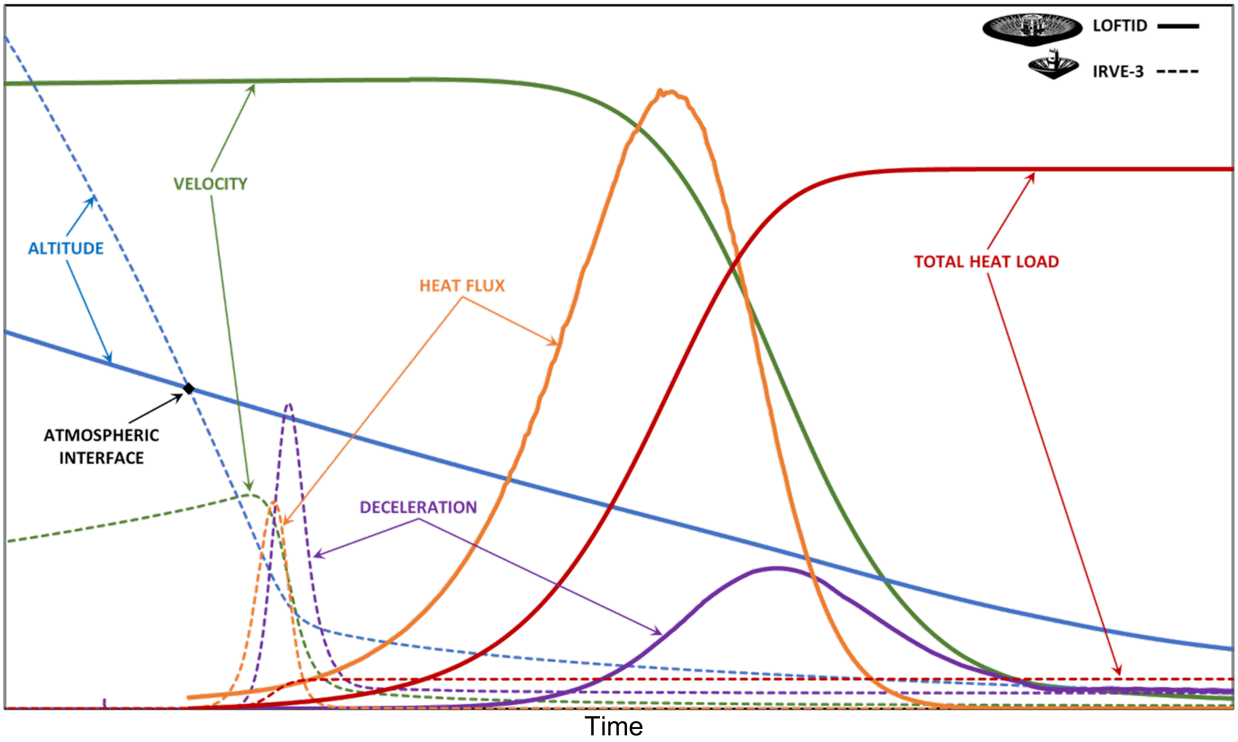

Figure 3: Entry Pulse Comparison between IRVE-3 and LOFTID

Another early trade involved the balance between sufficient and excessive thermal margin. The quandary was in determining how to margin against uncertainties to ensure mission success while truly exercising the aeroshell. To anchor the physics-based thermal models, it was important to gather data at elevated in-depth insulator temperatures. Traditional heatshield margining practice involves using separate uncertainty tolerance methods on trajectory flight mechanics analysis, aeroheating Computational Fluid Dynamics (CFD) analysis, and thermal response analysis, each with their own resulting dispersions. These stacked uncertainties then get incorporated into the heatshield thickness margin. Whereas this is a good way to ensure mission success, it is also likely to ensure the mission will not stimulate elevated temperature physics through the depth of the heatshield. With the heatshield performance being the item of interest for this mission, the LOFTID project decided to attack this quandary in two ways.

The first approach was to employ an end-to-end Monte Carlo probabilistic method for the FTPS thermal response uncertainty analysis [6]. This incorporates the uncertainties comprehensively among the various analyses of atmospheric entry conditions in a Monte Carlo manner, where the resulting probabilities pertain directly to the thermal response as opposed to adding margin on top of margin at each analytical step. Then LOFTID could impose dueling requirements, within acceptable mission success probability and confidence, for the gas barrier to stay below an allowable temperature while simultaneously exceeding a minimum temperature. Using this approach, the project could trade and iterate key trajectory design parameters (entry flight path angle, velocity, and RV mass) until both temperature requirements were satisfied, and then fine-tune the target trajectory toward the high end of acceptable temperatures, all within the constraints of the launch vehicle trajectory capability after the primary mission, along with the range safety and recovery operations. In what is a rare case for most aerospace engineers, the RV centerbody had to be designed to be heavy as opposed to mass-efficient, and this included designing for adjustable ballast to achieve the ballistic coefficient for the intended environmental conditions. Through this diligent process, iterated throughout the development of the project, the RV reentry mass settled at 1100 kg, and LOFTID, ULA, and LSP honed the “sweet spot” trajectory targeting for the mission.

The second approach to the thermal margining quandary was to conduct an experiment within the experiment. The deployable aeroshell interfaces a rigid cylindrical centerbody, and transitions to a rigid nose. Whereas the rigid aluminum nose structure was not part of the inflatable aeroshell demonstration, its FTPS would demonstrate a key element of the HIAD technology in flight. The nose FTPS insulator design could approach, or even exceed, the gas barrier temperature limits at low mission risk because the consequences could be mitigated at this location. The underlying nose structure was a large conductive thermal mass that could dissipate significant heat load, and the nose structure could be further isolated from the FTPS with additional insulators behind the gas barrier (see Figure 4). This allowed the nose FTPS to be aggressively designed to ensure it would exceed the in-depth allowables and capture elevated temperatures from the gas barrier outward. This through-thickness "experiment within an experiment" at the nose provided data to correlate thermal modeling with physical flight data at high temperatures without compromising the likelihood of mission success.

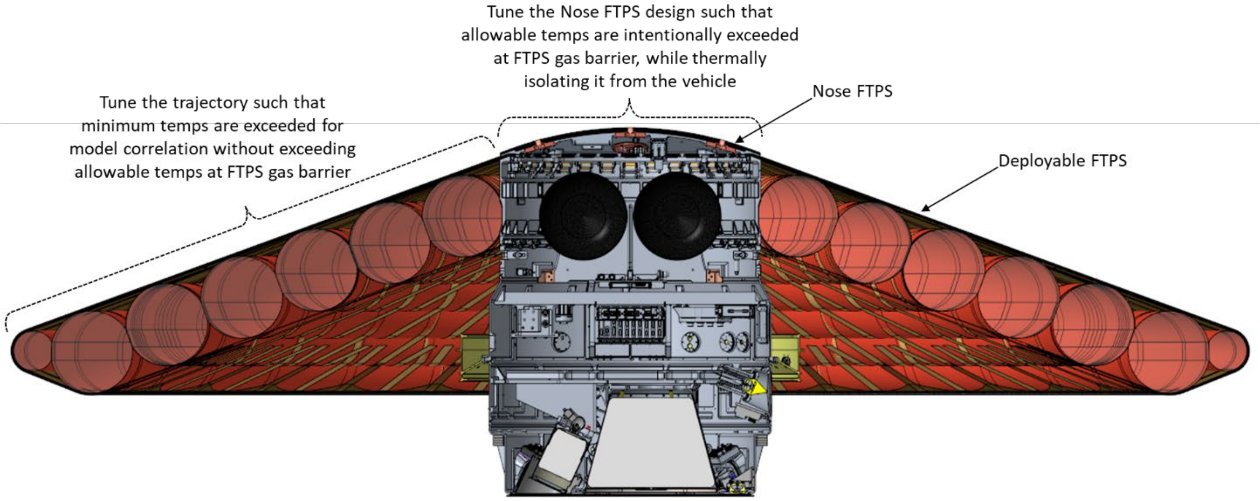

Figure 4: LOFTID Approach to Exercise HIAD Technology while Assuring Mission Success

IV. Mission Concept of Operations and Architecture

Along with the ability to get to orbit, LOFTID, of course, needed a way to get out of orbit and reenter the atmosphere on a prescribed trajectory. The ULA Centaur upper stage of the Atlas V is very capable, and it was to LOFTID's advantage to utilize this capability. After delivering the JPPS-2 primary payload to its polar orbit and performing a Contamination and Collision Avoidance Maneuver (CCAM) for mission safety, the Centaur could conduct a second engine burn to bring the RV to a prescribed orbital state and then conduct a third engine burn to deorbit on a prescribed reentry trajectory from that state. After separating the portion of the payload adapter enclosing the LOFTID stowed RV, the HIAD aeroshell could deploy and inflate while the RV was still attached to the Centaur. Then, after the aeroshell reached maneuverable stiffness, the Centaur could precisely orient, spin-up, and separate the RV to perform a spin-stabilized ballistic reentry while the Centaur performed a divert and disposal maneuver before burning up in the atmosphere. This concept of operations meant that the RV did not need its own deorbit capability, nor did it need attitude control capability, which greatly reduced the potential complexity and cost of the RV and allowed more of the available mass and volume to be dedicated to the technology demonstration aspects. To inflate the aeroshell, LOFTID leveraged the heritage design and some of the spare flight hardware from the IRVE-3 mission for its blow-down inflation system, and ULA provided flight qualified tanks for the supply gas [7].

With the long-stroke PASS mechanism, aeroshell restraint release, and inflation of the aeroshell being first flight items on this architecture, there was appreciable risk that the RV might not be set up correctly for its reentry flight. If it failed in flight, the LOFTID project would need to distinguish whether the initial setup at entry contributed to the failure. This led to the requirement for receiving in-flight data from the RV before entry. Due to the entry flight path, entry velocity, and onboard geometrical constraints preventing high bandwidth telemetry, the project incorporated a "Real Time Beacon" (RTB) that would transmit limited data packets from the RV to the ground via the Iridium satellite network using a patch antenna. With the understanding that, as a secondary payload, LOFTID could not prescribe the timing of the launch to coincide with ideal satellite constellation positioning, the requirement for this system was to communicate at least one data packet prior to entry and one data packet after entry, though it was designed to make the attempt about every 20 seconds. Given this unique opportunity to gather science on a HIAD in flight, LOFTID was ambitious with its instrumentation, including 19 onboard cameras along with the numerous thermocouples, heat flux gages, pressure transducers, load cells, etc. [8]. This required substantial data acquisition accommodations from the avionics system, along with the inherent LV electronic interface, sequencing control, pyrotechnics control, telecommunication, and power needs. The RTB would not be sufficient to recover the comprehensive data, and the project could not assure favorable ocean conditions, nor the duration that the RV would float after splashdown, so LOFTID incorporated an EDR system with the RV. The extensively tested EDR ejection mechanism was designed to eject the pear sized Ejectable Data Module (EDM) clear of the RV after it was subsonic and before it deployed its parachutes. The likewise extensively tested EDM was designed to survive ejection and splashdown, float for at least 30 days, and send a locator signal for at least that duration. During formulation of the LOFTID project, as a pathfinder step for the SMART reuse approach, ULA initially intended to demonstrate a Mid-Air Recovery to retrieve the LOFTID RV prior to splashdown [9]. The approach has since evolved to a splashdown recovery, and toward a best effort to recover the RV, ULA contributed the RV parachute system, consisting of a mortar-fired pilot chute that drags out the main chute, along with the ocean recovery vessel. The LOFTID mission concept of operations and resulting architecture are illustrated and annotated below in Figure 5 and Figure 6 respectively.

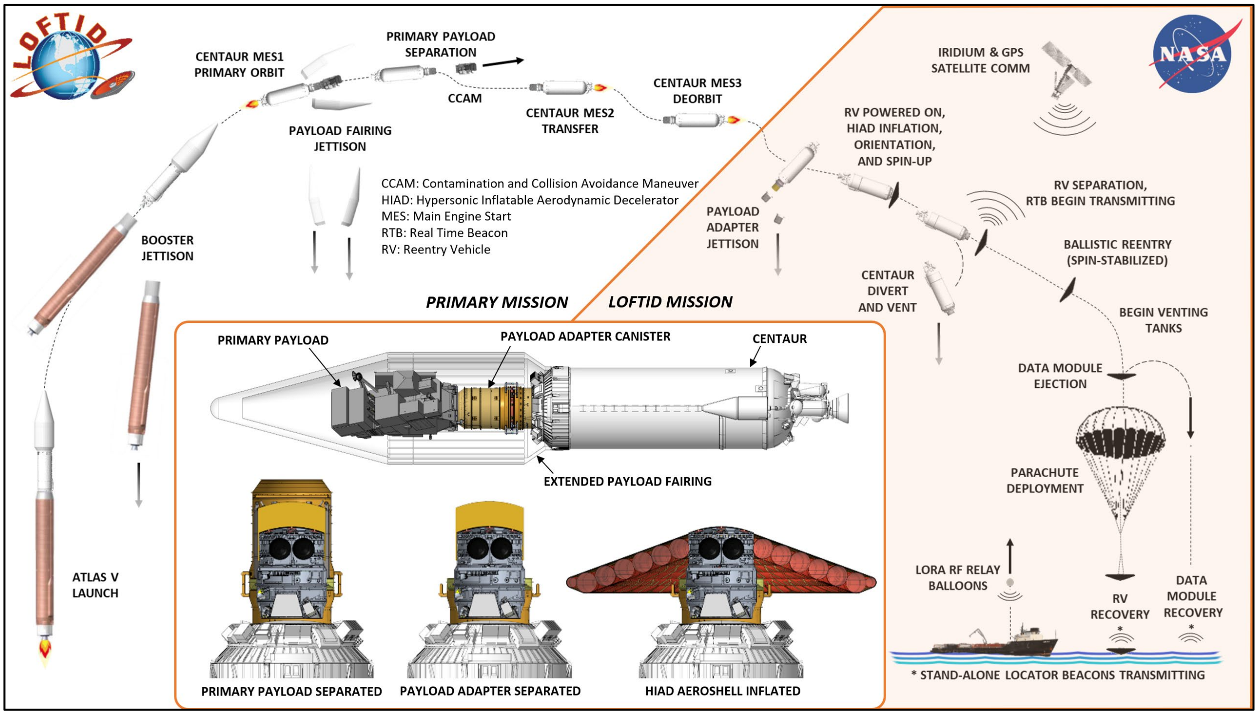

Figure 5: LOFTID Mission Concept of Operations

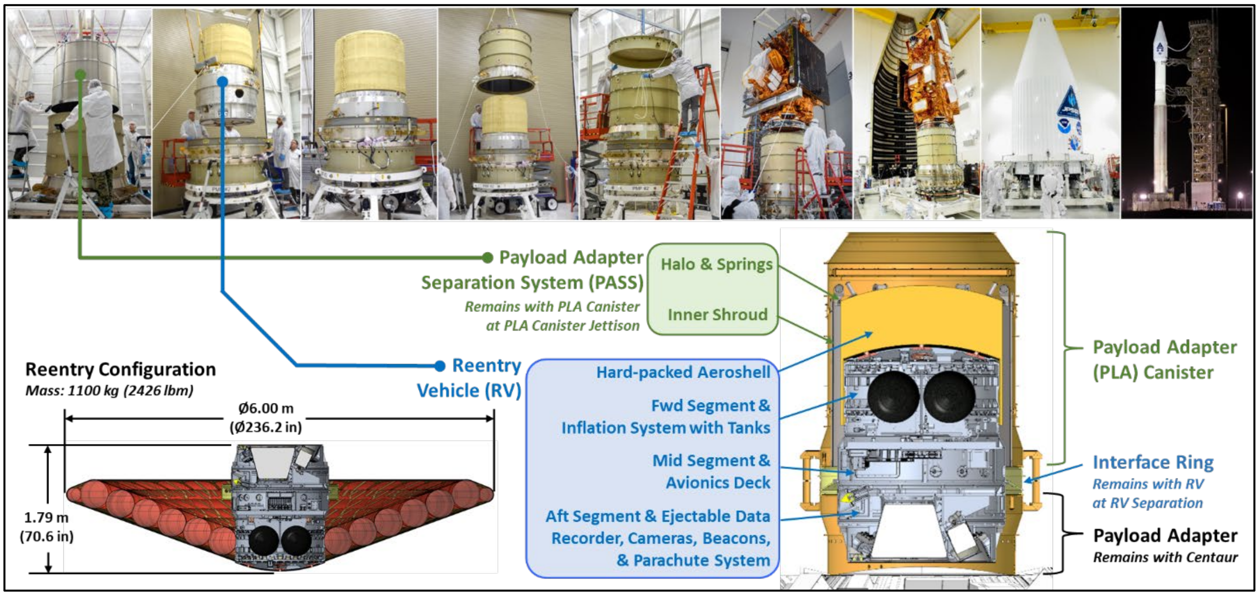

Figure 6: LOFTID Mission Architecture

V. LOFTID Flight

On November 10, 2022, LOFTID launched on an Atlas V rocket from Vandenberg Space Force Base (VSFB) in California as a hosted payload aboard the JPSS-2 primary mission. Approximately 28 minutes into the flight, the JPSS-2 satellite separated from the Centaur as it was successfully delivered to its polar orbit. After the CCAM maneuver, the Centaur performed its second main engine burn about 45 minutes into the mission. Then, after 65 minutes into the flight, the Centaur performed its third and relatively short burn to deorbit. While coasting on a trajectory to enter the Earth's atmosphere, the Centaur issued the power on command to the stowed LOFTID RV, which began booting up its electronics and started its timer-based command sequence. Then the Centaur oriented its primary axis away from the flight path and initiated the separation ring to release the Payload Adapter Canister. Assisted by the LOFTID long-stroke PASS mechanism, the Payload Adapter Canister smoothly jettisoned away from the vehicle without contact (see Figure 7) and continued to free fall on its reentry path to burn up in the atmosphere.

Figure 7: Payload Adapter Canister Jettison

With the packed aeroshell now exposed, the RV fired the pyrotechnic cutters that released the packing restraint, and the HIAD aeroshell immediately unfurled in the microgravity and vacuum environment (see Figure 8) while the packing restraint, propelled away from the RV by the strain energy of the release, continued its free fall to meet the same fate as the Payload Adapter Canister.

Figure 8: Packing Restraint Release to Deploy the Aeroshell

The RV then issued the command to start inflation, and the inflation system controller began commanding the electromechanical mass flow control valve to release compressed Nitrogen gas into the HIAD inflatable structure. After the initial soft start duration, the valve was opened more fully and the aeroshell immediately took shape. Upon a margined duration to ensure the aeroshell was pressurized sufficiently for vehicle maneuvers, the Centaur oriented the RV to its prescribed attitude, and then spun up about the primary axis to 3 rotations per minute (rpm). The LOFTID flight mechanics analysis had established that this spin rate was plenty sufficient to maintain stable attitude orientation for entry.

Just over 75 minutes after the launch, roughly above the Sinai Peninsula, the Centaur released the LOFTID RV on its spin-stabilized ballistic reentry trajectory. The separation was announced as nominal in the control room, and the Centaur began its maneuvers to reorient and divert toward its atmospheric entry breakup and burnup disposal. By design, the RV would not begin transmitting until after it separated from the Centaur, and the LOFTID team was eagerly awaiting a signal from the RV, but it did not come prior to atmospheric entry as expected. However, after some time to download, the low fidelity video transmission from the Centaur was displayed in the control room. Much to the team's relief, the images showed the RV separated and spinning with its HIAD aeroshell fully inflated (see Figure 9).

Figure 9: Reentry Vehicle Separation

After traversing over the North Pole and Alaska, approximately 105 minutes after launch and nearly 30 minutes after its separation from the Centaur, the LOFTID RV began encountering the outer reaches of Earth's atmosphere. The thermocouples and heat flux gages started showing discernible increases about 90 seconds before the RV reached the nominal 125 km altitude conventionally designated as "atmospheric interface." The RV continued accelerating, reaching a peak velocity over 8 km/s, or 18,000 mph, before it started decelerating. Soon after the instrumentation began sensing a discernible dynamic pressure increase, the drag became appreciable enough to settle the inflatable aeroshell against its tensioned straps. About a minute after the heating reached 10% of its peak, the RV reached 10% of its peak drag load. The ionized plasma glowed brightly during the reentry pulse and the forward surfaces of the heatshield reached about 1500C, or 2700 °F. The peak heating preceded the peak drag by roughly 30 seconds, and the RV experienced about 9.5 g deceleration during the peak drag, while the aeroshell maintained its shape and stiffness, deflecting as expected under peak load. Based on the predicted trajectory, the Scientifically Calibrated In-Flight Imagery (SCIFLI) team captured and tracked a targeted portion of the RV reentry on video from a pre-positioned aircraft (see left image in Figure 10). The entire entry pulse lasted for about 6 minutes, and the RV demonstrated aerodynamic stability throughout the hypersonic, supersonic, transonic, and subsonic flight conditions.

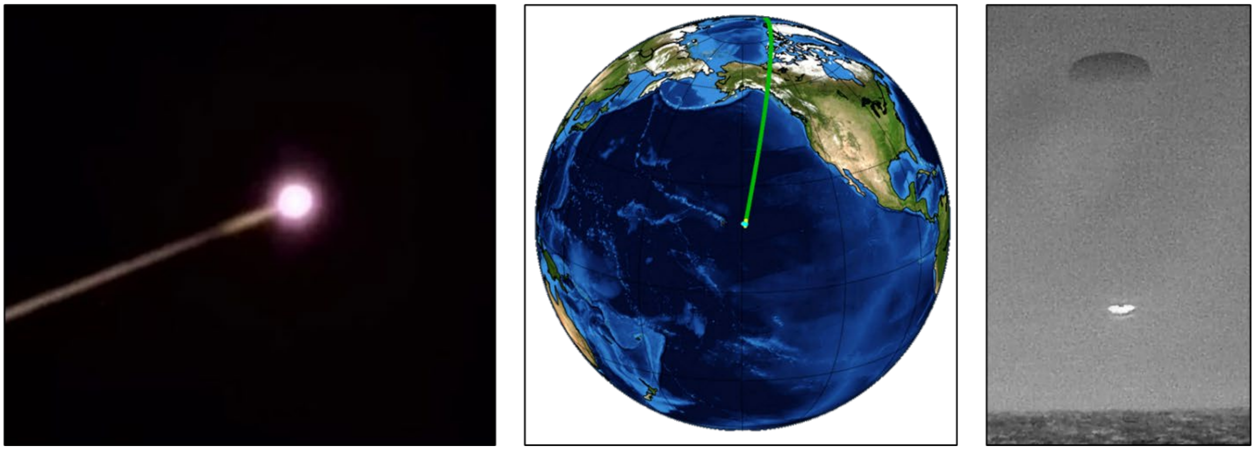

Figure 10: SCIFLI Image during Entry, Flight Path on Globe, and Infrared Image from Recovery Ship

Shortly after the entry pulse, with the RV subsonic and in a nearly vertical terminal descent, the first RTB transmission completed its handshake with the Iridium network and relayed data to the LOFTID team on the ground, verifying that the HIAD technology worked well enough for the RV to survive reentry. The inflation system opened the mass flow control valve and began venting the tanks through the manifold relief valves, and the EDR system ejected the EDM to ensure data recovery. After decelerating from over 18,000 mph to less than 80 mph, the RV initiated the pilot chute mortar, the pilot chute dragged out the main chute, and the main chute inflated to its initial shape before releasing the reefing to take its fully inflated shape. The RV descended gently under parachute and splashed down in the Pacific Ocean east of Hawaii 2 hours and 13 minutes after it launched, or about an hour since its separation from the Centaur, or roughly 30 minutes after it entered the atmosphere. It was so well on target that the team on the recovery ship recorded it under parachute via an infrared camera (see right image in Figure 10) and could see its parachute deflating on splashdown just as the RV passed beyond the horizon.

The system battery and onboard cameras continued operating after splashdown until their drives were full, while the independently powered locator beacon and flashing recovery lights aided the recovery. As the recovery ship approached the RV, the crew could see that the HIAD maintained its shape and the RV was floating high on the water, indicating the integrity of the inflatable structure. About 3 hours and 15 minutes after the launch, the recovery team made first contact with the RV from a rigid inflatable boat deployed from the ship (see Figure 11). The entire vehicle appeared like it did when its aeroshell was deployed on the ground prior to the flight, and the team prepared it for lifting from the water. While suspended out of the water below the ship’s crane, the team could see that the outer fabric of the FTPS on the rigid nose was missing, while the deployable FTPS was completely intact. After some effort in the swaying seas, the team was able to secure the RV safely into its cradle on the deck of the ship. In the light of dawn, the team easily retrieved the floating EDM from the ocean, and began heading back to Honolulu. After inspecting the aeroshell and retrieving the data recorded on the EDM, the team deflated the HIAD and processed the RV to retrieve its more comprehensive onboard data and prepare it for shipping home to NASA LaRC.

Figure 11: RV Floating in the Ocean and Aboard the Recovery Ship

VI. Science Return

Whereas LOFTID was tremendously successful with the demonstrated HIAD performance and the added benefit of recovering the RV, some of the conventional technology onboard encountered issues during the mission. Most significantly, a subset of the data was not recorded due to a network sequencing issue that was not discovered during ground testing. This unrecorded data included that from the Inertial Measurement Unit (IMU), the Global Positioning System (GPS) antenna, and most of the inflation system instrumentation. Without the IMU and GPS data, trajectory reconstruction was limited and relied heavily on the Flush Air Data System (FADS) data during entry, the initial state provided by the Centaur at RV separation, day-of-flight atmospheric conditions, and the RTB data packets received from the RV after entry. Likewise, the inflation system assessment involved discerning performance from the relief valve instrumentation, evaluating the videos, and utilizing the RTB data packets. The other major issue was already mentioned, and it involved not receiving RTB data until well after the entry. Since the RV was recovered, the original intent of the RTB requirements became moot, and this would not have mattered if all the data had been recorded onboard as designed. However, given the unrecorded data issue, the RTB data packets could have provided the missing data at the moments of its periodic transmissions in flight. Finally, one of the 19 onboard cameras did not operate correctly. As a known issue prior to flight, one of the 6 visible light cameras among the camera pods had an intermittent operation issue that was revealed during RV vibration testing, and the process required to diagnose and repair it at that point was deemed too risky, as the RV was about to ship out for launch vehicle integration operations. Figure 12 provides example frames for the individual camera views, and Figure 13 shows how they can be digitally stitched together for a synchronized composite overview. The anomalous camera, located in Camera Pod 2, was not working in ground testing prior to launch, though the recorded video confirmed it was working in flight just before the RV separated from the Centaur, and then its video stopped immediately upon the separation event. Despite these issues, both expected and unexpected, the successful LOFTID flight provided a treasure trove of data for post-flight analysis, including that from the thermocouples, pressure transducers, heat flux gages, radiometer, load cell clevis pins, visible light and infrared video imaging, and bonus data from a first flight demonstration of Fiber Optic Sensing System (FOSS) measurements.

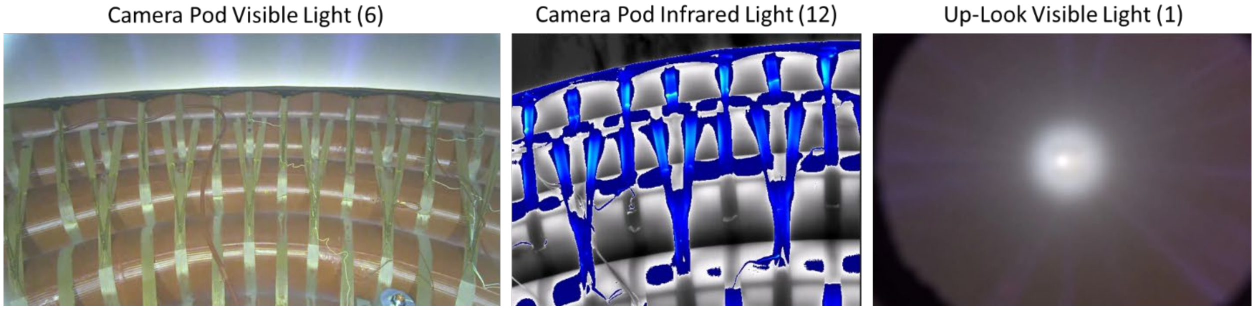

Figure 12: RV Onboard Camera Individual Views, Excerpted Near the End of the Heat Pulse

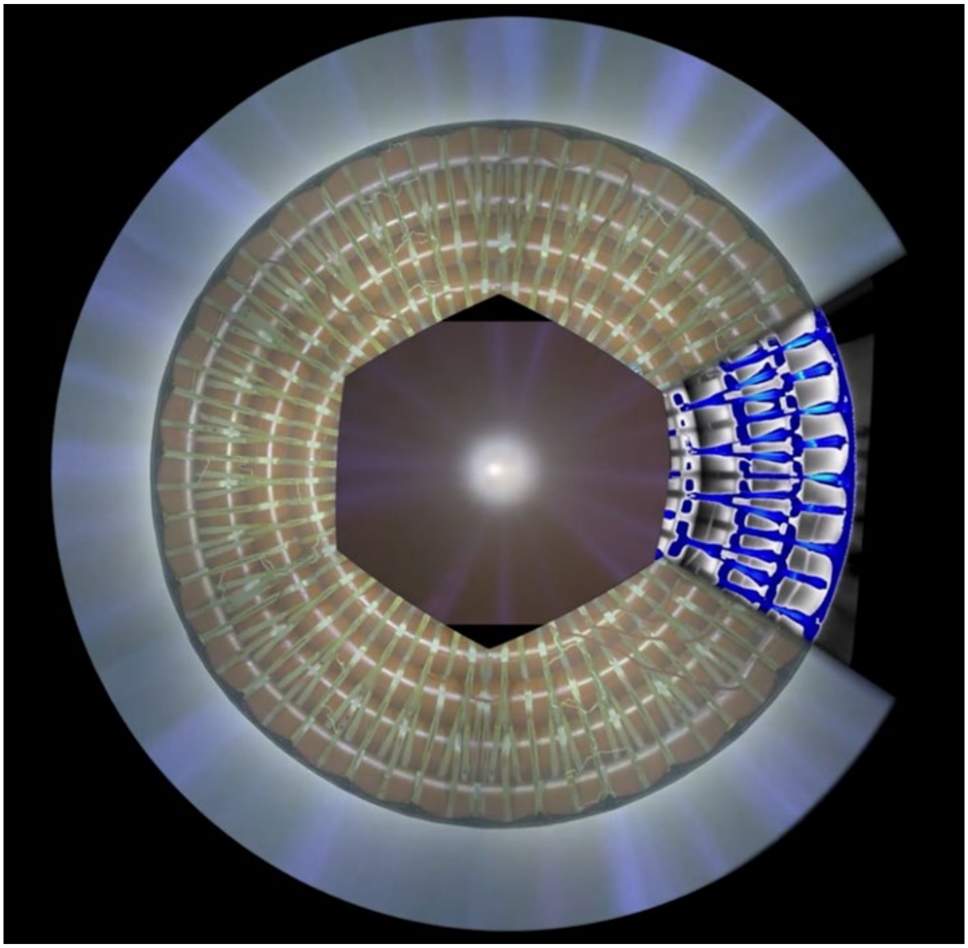

Figure 13: Stitched Composite with Infrared Replacing Visible Light at Camera Pod 2, and Up-Look in Center

The thermocouple data from the nose confirmed that the outer fabric of the FTPS was intact until splashdown. Moreover, the thermocouple flight data curves compared well with the thermal response predictions, providing confidence in the thermal models and the end-to-end Monte Carlo thermal analysis technique (see Figure 14). After assessing that the heat flux gage data was measuring less than the applied environment due to localized mounting configuration effects, an inverse surface heating analysis technique using flight thermocouple data with conservative uncertainty analysis resulted in a heat flux curve that compared well with predictions, providing confidence in the aeroheating analysis [10].

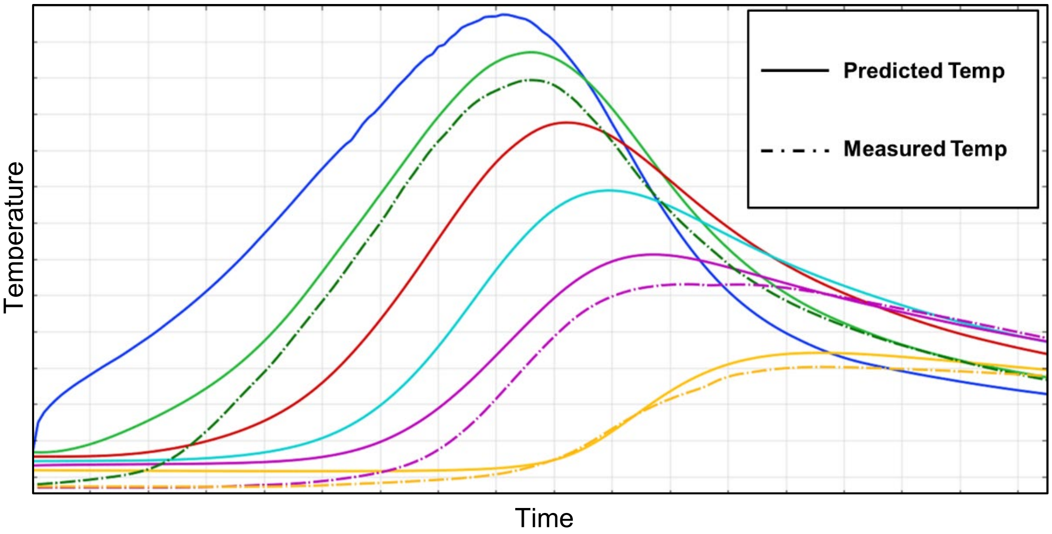

Figure 14: Example of Measured Flight Temperature Curves Compared to Predictions in the FTPS

The FADS pressure data at the nose provided the total angle of attack history, confirming the unassisted aerodynamic stability throughout the flight (see Figure 15) [11]. The dynamic pressure curve from this data compared well with the flight predictions, providing confidence in the flight mechanics and trajectory analysis. Shortly before reaching the peak dynamic pressure, the data included an interesting plateau for approximately 10 seconds before it stepped up again toward the original increasing profile. This behavior was also observed in the load cell clevis pin data for the inflatable structure, substantiating that it was a real phenomenon during the pressure pulse as opposed to an instrumentation anomaly (see Figure 16). There are several hypotheses regarding the cause for this discontinuity in the pressure pulse, and deeper analyses are planned to probe this observation over the coming years.

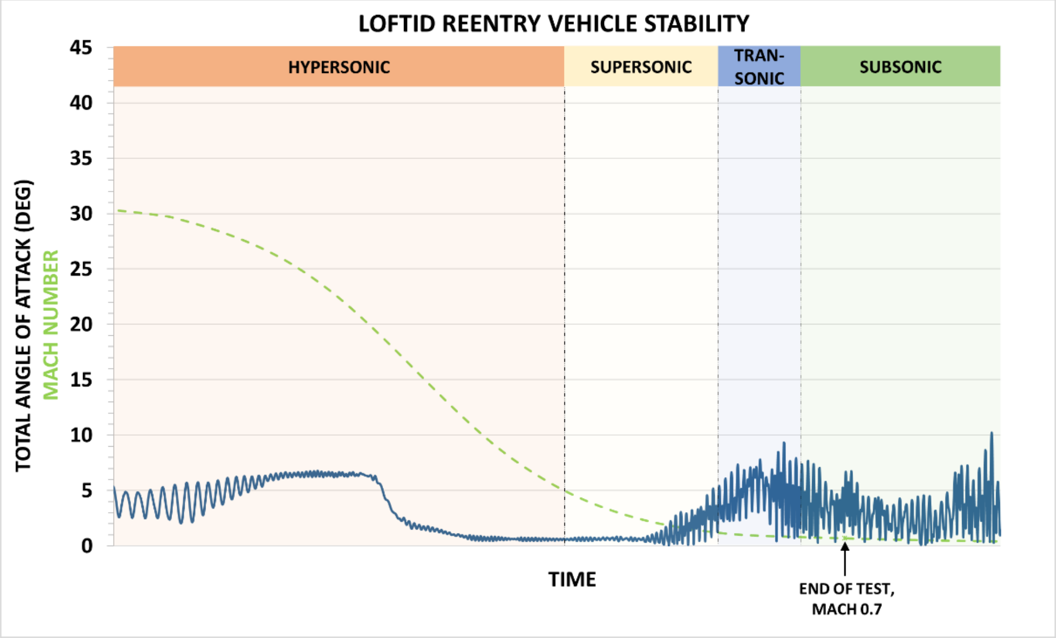

Figure 15: Total Angle of Attack History from Flight FADS Analysis

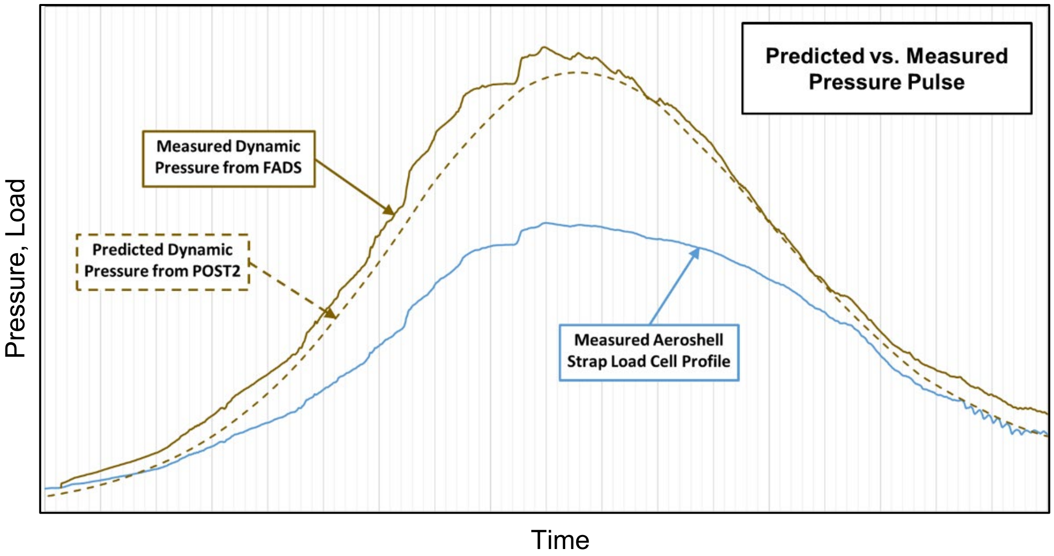

Figure 16: Dynamic Pressure Curve from Flight FADS Analysis Compared to Prediction, Along with Corroborating Strap Load Cell Flight Profile Example

The visible light video data, both from cameras looking at the aft side of the aeroshell toward its perimeter from the equally spaced camera pods and the up-look camera looking at the wake closure behind the RV, provided invaluable data throughout the mission. The outer surface of the aeroshell was heating up for about 2 minutes before the ionized plasma in the shock layer began glowing bright enough to be seen on the visible light camera footage. The camera pod visible light cameras clearly show the settling of the aeroshell against the tension of straps very early in the pressure pulse, and this was concurrent with indications from the load cell clevis pin data [12]. With the heat rate increasing, about a minute before it reached its peak and very early in the pressure pulse at less than 1 g deceleration, the visible plasma in the wake rapidly changed from an orange color to a purple color, and over the next couple

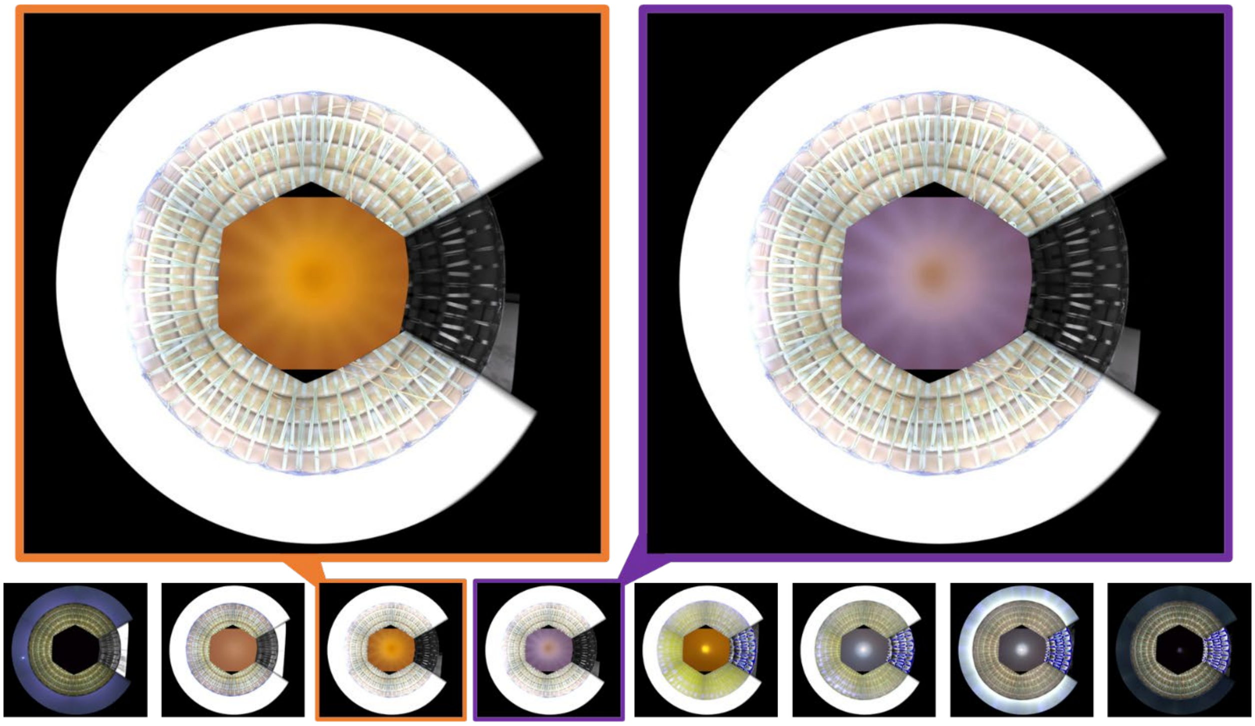

Figure 17: Composite Video Frame Excerpts during Visible Plasma from Start to Finish (left to right), Featuring the Transition from Orange to Purple occurring within the Same Second

minutes it gradually saturated back to an orange and then a nearly white color before fading out (see Figure 17). It also showed streaks that appear like spokes about the central recompression region and align with features on the aeroshell.

The 360-degree view of the plasma wake closure during reentry is a first of its kind, and the recompression region maintaining its position near the center of the view attested to the stability of the vehicle throughout the heat pulse. The camera pod video showed interesting concentrations of color, apparently plasma, glowing around straps and valleys on the aft side of the inflatable structure. The infrared videos from the camera pods indicate, as expected, that the straps on the aft side increase in temperature much faster than the tori surfaces. With wake flow analysis being an area of high uncertainty, the aft side infrared video and thermocouple data will contribute to improve modeling and wake flow understanding beyond LOFTID. Analysis of the visible light video from the camera pods confirmed that the inflatable structure deflected under load and very slightly sharpened its cone angle as predicted, behaving like a rigid structure extending from the RV centerbody [13]. Without the IMU data, video footage confirmed with sufficient accuracy that the RV did not appreciably change its nominal spin rate of 3 rpm throughout the reentry. Camera Pod 1 captured the successful ejection of the EDM well clear of the aeroshell (see Figure 18). Later, the up-look camera video captured the deployment of the parachute system, and the inflated main chute could be seen against the backdrop of the full moon as the RV descended through the night sky (see Figure 19). The camera pod videos showed the aeroshell was resilient against the dynamic loads of splashdown, and they continued recording until after the recovery team reached the aeroshell, running out of available space to record while the team was preparing the RV for its lift from the water. The video, particularly during the plasma observations, will continue to be analyzed as part of a LOFTID deep dive data analysis effort over the coming years. The observations and data assessments to date, including the recovered RV itself with its pristine centerbody and the aeroshell in remarkable condition, verify the excellent performance of the HIAD technology.

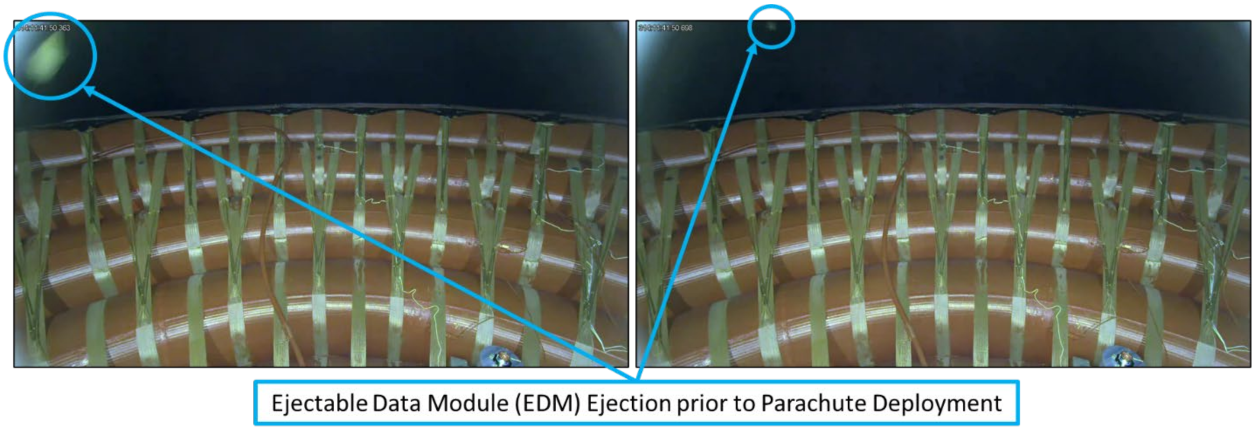

Figure 18: Camera Pod 1 Visible Light Video Frame Excerpts of the EDM Ejection

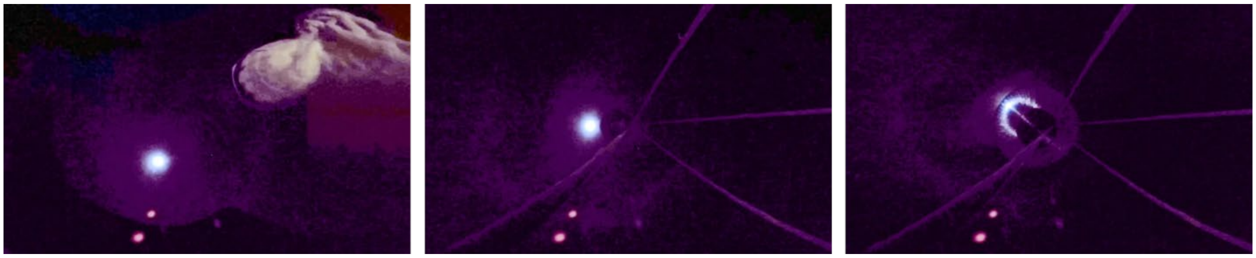

Figure 19: High Contrast Up-Look Video Frame Excerpts of the Mortar Fired Pilot Chute, Reefed Main Chute, and Fully Inflated Main Chute with Full Moon in Background

VII. Conclusion

By all accounts, LOFTID was a triumphant success. It was an ambitious endeavor to demonstrate an inflatable aeroshell, and the largest blunt body aeroshell of any kind, entering from orbit as a massive secondary payload. Through strong collaboration among multiple organizations, the concept developed systematically toward becoming reality. Its development involved ingenuity in the payload architecture and innovation for analyses anchored in ground testing. The design answered the broad variety of constraints and requirements, ensuring it could do no harm to the primary mission while safely performing its mission through launch, deployment, reentry, splashdown, and recovery. The project team overcame many inherent and contingent challenges, including the COVID-19 pandemic, to fabricate, assemble, integrate, test, and deliver the flight hardware. LOFTID's unique mechanisms for jettisoning the payload adapter canister and ejecting the recoverable data module performed flawlessly. The packing restraint released cleanly, and the closed loop inflation system pressurized the aeroshell to take shape and maintain structural integrity. The RV captured flight data to correlate physics-based analytical models and contribute to science beyond its mission. The aeroshell deployed and performed excellently in the extreme flight environments, entering from orbit and ultimately returning to NASA Langley Research Center. LOFTID was indeed a first-of-a-kind flight for an inflatable heatshield, and its remarkable performance assured that it will not be the last of its kind.

Figure 20: The LOFTID RV Back Home at NASA Langley Research Center

Acknowledgments

LOFTID received key contributions from multitalented project team members and colleagues in partner organizations. They are too numerous to note each by name, but the authors are eternally grateful to them for their diligent and tireless efforts to make the mission a success.

The LOFTID mission was sponsored by NASA's Technology Demonstration Missions (TDM) program within the Space Technology Mission Directorate (STMD), and it is dedicated in honor of Mr. Bernard Kutter, manager of Advanced Programs at ULA, who passed away in August 2020. Mr. Kutter was an advocate for lower cost access to space by using HIAD for launch vehicle asset recovery, and for the broader exploration benefits that its technology demonstration enables. He was instrumental in developing the plan to test the system on an Atlas V rocket to advance the technology. A small capsule containing some of his ashes flew on the LOFTID mission and was later returned to his family.

References

[1] Gillette, J. E., Larson, C., and Reed, J. G., “Vulcan Centaur Reuse: The Next Step to Accessible and Affordable Space,” AIAA Paper 2022-4253, October 2022.

[2] Hancock, S.M., et. al., “LOFTID (Low-Earth Orbit Flight Test of an Inflatable Decelerator) PASS (Payload Adapter Separation System) Design & Qualification,” paper submitted to AIAA SciTech 2024, Orlando.

[3] Cianciolo, A. D., Polsgrove, T. T., “Human Mars Entry, Descent and Landing Architecture Study: Phase 2 Summary,” AIAA Paper 2018-5190, September 2018.

[4] O’Keefe, S. A. and Bose, D. M., “IRVE-II Post-Flight Trajectory Reconstruction,” AIAA Paper 2010-7515, August 2010.

[5] Olds, A. D., Beck, R. E., Bose, D. M., White, J. P., Edquist, K. T., Hollis, B. R., Lindell, M. C., Cheatwood, F. M., Gsell, V. T., and Bowden, E. L., “IRVE-3 Post Flight Reconstruction,” AIAA Paper 2013-1390, March 2013.

[6] Tobin, S. A., Brune, A. J., and Bowes, A. L., “Probabilistic Risk Analysis and Thermal Margin Process for an Inflatable Aeroshell,” IPPW-2023 Poster, 20230011875, August 2023.

[7] Blakeley, H., et. al., “Heritage to Flight; The Test Program that Brought an Inflation System Back to Life,” paper submitted to AIAA SciTech 2024, Orlando.

[8] Swanson, G. T., et. al., “Overview and Performance of the LOFTID Instrumentation Suite,” paper submitted to AIAA SciTech 2024, Orlando.

[9] Reed, J. G., Ragab, M. M., Cheatwood, F. M., Hughes, S. J., DiNonno, J. M., Bodkin, R. J., Lowry, A., Brierly, G. T., and Kelly, J. W., “Performance Efficient Launch Vehicle Recovery and Reuse,” AIAA Paper 2016-5321, September 2016.

[10] Hollis, B. R., et. al., “Aerothermodynamics Analyses for the LOFTID Technology Demonstration Mission,” paper submitted to AIAA SciTech 2024, Orlando.

[11] Karlgaard, C., et. al., “Trajectory Reconstruction of the Low-Earth Orbit Flight Test of an Inflatable Decelerator,” paper submitted to AIAA SciTech 2024, Orlando.

[12] Hughes, S. J., Cheatwood, F. M., DiNonno, J. M., Swanson, G. T., “Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) Aeroshell Performance,” paper submitted to AIAA SciTech 2024, 20230016920, Orlando.

[13] Alpert, Hanna S., Kazemba, Cole D., and Swanson, Greg T., “Post-Flight Quantification of LOFTID Aeroshell Deflection Using Feature Tracking,” IPPW Poster 2023-0011256, August 2023.

[14] Swanson, G., Miller, R.A., Kazemba, C., Alpert, H., Williams, J., S., and Cheatwood, N., “Evaluation of the LOFTID Flight Thermocouple Measurements,” paper submitted to AIAA SciTech 2024, Orlando.