Vulcan Reuse

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This is an exciting time in the space launch market. We have providers developing various reuse concepts to help drive continued cost reductions in access to space. At the same time visions of a future marketplace in space are emerging that have energized the community to move toward economically viable space-based ventures. This paper explores the intersection of these two developments. Specifically, we focus on the underlying technologies developed for ULA's Sensible, Modular, Autonomous Return Technology (SMART) approach to reuse and the intersection with needs in the cislunar marketplace.

ULA has been working with NASA Langley Research Center on maturing their Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology into the Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) technology demonstration mission scheduled to fly with the JPSS-2 Launch in 2022, and have honed in on a 6m diameter HIAD for that application. These efforts, under the NASA Space Act Agreements (SAA), have helped identify elements requiring further development for SMART Reuse, which could also benefit other potential mission infusion opportunities. This has proved to be a very fruitful collaboration as these aspects have evolved. The paper further delves into applications across commercial space and NASA's Space Exploration mandate, in addition to the reusable launch vehicle applications.

Nomenclature

AFB = Air Force Base
AIAA = American Institute of Aeronautics and Astronautics
CCAM = Contamination Collision Avoidance Maneuver
EDL = Entry Descent and Landing
FTPS = Flexible Thermal Protection System
HIAD = Hypersonic Inflatable Aerodynamic Decelerator
IRVE = Inflatable Reentry Vehicle Experiment
IS = Inflatable Structure
LEO = Low Earth Orbit
LOFTID = Low-earth Orbit Flight Test of an Inflatable Decelerator
RTLS = Return to Launch Site
RV = Reentry Vehicle
SAA = Space Act Agreements
SMART = Sensible, Modular, Autonomous Return Technology
ULA = United Launch Alliance

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I. Background

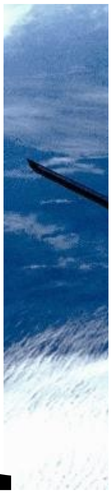


Figure 1: X-33 Credit: NASA

Reuse has been engrained in the vision of access to space since the early days of science fiction. While the development of the Space Shuttle matured the technologies necessary to enable deployment and operation of a reusable launch system, attempts to build on that heritage (Figure 1) to provide economic reuse remained an elusive goal. With recent successes in the recovery, testing and relaunch of boost vehicles, debate on the merits of various approaches to space access continues. The challenge of closing the business case around a reusable architecture remains key to fielding a long-term viable reusable launch system. ULA continues to refine its SMART Reuse concept as one approach to close the business case[1].

The last decade has seen both expanded evidence of the maturity and efficacy of retro-thrust technology for booster recover. However, it has also seen limitations in application as small launch continues to pursue other technologies for the benefits without adopting the risks associated with thrust based solutions. Obviously one aspect of this is the performance penalty from reserving 40% of the boost capacity to halt the descent and mitigate the heating of the booster falling to Earth.

On the other side of the debate companies like Masten, Blue Origin and SpaceX have demonstrated the capability afforded with booster hop and landing technologies. Masten has had over 600 flights of their Entry, Descent and Landing testbed vehicles. Blue Origin has been perfecting their booster reuse approach with 5 and 6 successful launches and landings of its two most recent boosters. This reuse record was just tied by SpaceX in August of 2020 with the 6th successful landing of B1049. Of course, SpaceX has had far more successful used vehicle landings with about 60 successful landings and an 80% success rate over the last decade. Recent improvements have reduced the landing failure rate but with an average usage of 3 flights per booster, the effective number of uses per stage is still ill-defined.

II. Business Case

LV Reuse

While the debate on the merits of the two approaches to reuse continues, it is worth revisiting the key points around the two techniques. They begin with very different assumptions, applications, and adjacent market perspectives. It is interesting to note that the Starlink missions, which launch 60 SmallSats at a time, leave enough excess performance for booster recovery but no room for additional payloads. The Atlas V fairing sizes allows significantly more volume enabling lower $/kg solutions. The retro-thrust solution has application for rocket reuse, assuming fueling systems pre-exist, for Mars flight, while the HIAD-based system has application for large mass, one-way delivery to Mars. While the retro-thrust approach is a dedicated solution for booster reuse, the HIAD technology has an adjacent market for return of cislunar products to Earth. Thus it is apparent that the development of retro-thrust aligns with an internal focus on Mars transportation while the HIAD based SMART system is focused on leveraging an emerging supply chain to improve the $/kg for delivery.

While it does not make business sense to throw away a delivery van after each trip, the business case for space transportation is not nearly that straight forward. Small launch providing a dedicated ride for $5M is not designed to minimize the $/kg, rather the business case for small launch is focused on the cost of access. The performance penalty for retro-thrust recovery lowers the insertion mass for access, rendering the benefit ineffective. Instead, the technologies envisioned for SMART Reuse hold the promise of enabling booster reuse for the small launch market. Similarly, in any scenario where one is not volume limited, the cost in performance for the benefit of recovery and reuse can quickly tilt the scales in favor of providing the expendable capability to additional payloads. As the demand for access grows, the market seeks the better $/kg benefit of large launch. The incremental cost of additional capability creates an opportunity for lower cost deployment of constellations. The math remains in favor of recovery and reuse only when the payload mass is volume limited.

If the market does blossom under the effect of reduced costs, the need for timely access may drive demand and a premium for the next available slot thereby growing capacity for a nearer term opportunity. Other factors, like time to insertion at operational orbit, while not directly impacted by the decision for recovery and reuse may be adversely impacted by the performance penalty of reuse. This effect was a key feature of Equation 1 below. The previously proposed[3] cost ratio, Equation 1, provides a non-dimensional definition of the reuse index comparing the impact of using the base capability of a launch system in a reusable configuration versus an expendable configuration. By manipulation of the various parameters one can quickly determine that the performance ratio is the most impactful term.

This performance ratio is the term that captures the fact that vehicle performance must be allocated to return the booster elements to Earth in a manner that enables reuse. For the space shuttle, in a Trans-Atlantic Abort scenario, there was very little performance impact since the vehicle was on a ballistic path across the ocean. In that case, much of the energy imparted to the shuttle was dissipated by the shuttle Thermal Protection System (TPS). Even the main engines were shielded from the reentry environments by the TPS. For vertical landing of a booster, this is not the case. Fuel must be allocated to offset the kinetic and potential energy imparted to the booster on ascent, control the descent, and minimize the impact of the reentry environments on the reusable systems.

$$I = p\left\{k\left[\frac{F}{n} + \frac{1}{n}\left(\frac{C(RHW)}{C(B)}\right) + \frac{C(RR)}{C(B)}\right] + (1-k)\right\} \qquad \text{(Eqn-1)}$$

where:

I = the reuse index

p = the ratio of the performance of the expendable system to the performance of the corresponding reusable system

k = the fraction of production cost of the hardware to be reused to the total cost of the expendable launch service

F = a factor representing the production unit cost increase when the production rate is decreased by a factor n

n = the number of uses

$C(RHW)$ = the reused portion of the cost to recover and reuse, such as the cost of recovery hardware that will be reused

$C(B)$ = the production cost of the hardware to be reused

$C(RR)$ = the expended portion of the cost to recover and reuse, such as recovery operation and refurbishment costs

One other element in the equation, frequently lost in the details, is the fact that the hardware is not the total cost of the launch service. The normal processing operations cost for integration and launch are frequently overlooked in much of the discussion of reuse. These activities can further reduce the fraction of the total cost of launch impacted by reuse (k in Equation 1). This cost of taking the produced hardware from the factory door, integrating the stages and payload, and delivering the payload to the target orbit can be more than 1/3 of the total cost of the launch service[2].

Often the cost of infrastructure to recover and refurbish the reusable system is intuitively regarded as the most important element since this is a recurring additional cost not borne by expendable systems. While minimizing this cost is clearly of benefit, the performance ratio dominates. Thus, a reusable system that reduces kg to orbit by 30 percent to enable reusability would require a 50 percent reduction in hardware cost, including additional cost for the reusability elements, to provide the same \$/kg as an expendable variant.

Clearly, targeting a larger number of uses of a system does allow significant reduction in the cost per use of that element. There is a cost to developing a system that can be used a significant number of times but moreover, the recurring cost of the element will increase when adding the protections and resilient systems capable of repeatedly operating in the harsh ascent and recovery environments. Additionally, there is a limited window for recovering those development costs. Technology and supply chains do not stand still. Parts become obsolete and vendors can find it impossible to continue to produce element for a host of reasons. Even if a rocket system continues to be produced, major upgrades to core elements will occur and with it an additional set of development costs to create and test the reusable implementation will follow. These are the costs that must be covered by each block upgrade of a reusable system. Likewise, diminishing the cost benefit, with an increased number of uses, the recovery and refurbishment costs create a floor in the recurring cost curve.

This assessment informed our approach to launch vehicle reuse. Minimizing the performance penalty for reuse allows recovery on a variety of missions. Co-developing solutions that provide a variety of applications reduces the likelihood of expensive, custom built solutions. Simplifying the approaches and event sequence is a sensible method to reduce the likelihood of failure in recovery which drives uncertainty in the business risk associated with the recovery, refurbishment and reuse paradigm. Modularity allows for operating in either recovery or expendable mode as well as enabling continued evolution and improvement in the core technologies utilized.

III. SMART Reuse Overview

Armed with this understanding of the cost drivers, which so often results in expendable launch systems winning out over reuse, ULA has refined its approach to provide benefit to both spacecraft operators and shareholders. Our SMART reuse concept minimizes the performance penalty while maximizing the dollar value of the elements returned. While maximizing the reuse index in Equation 1, the concept leverages favorable booster partials to minimize the performance impact of the reuse hardware. This approach lowers the \$/kg to orbit while supporting the full range of payload masses and mission orbits our customers need.

The SMART concept has been improved to simplify recovery of the booster engines. The Vulcan development builds on the flight-proven engine separation heritage from the Atlas 2AS systems. Rather than use vehicle performance for deceleration, HIAD technology is used. The HIAD protects the reusable Vulcan booster engines from the thermal environments of atmospheric reentry. Then, a drogue and circular parachute system is deployed to slow the descent. A crane capable ship proceeds into the landing zone targeting the initial impact point from the Vulcan booster separation state and updated with a GPS transponder. The ship then hoists the HIAD and engine section onto its deck for processing and return to port. Figure 2 provides a graphical representation of the updated approach.

ULA has expanded on our relationship with NASA Langley Research Center, maturing the HIAD concept for the LOFTID technology demonstration mission in addition to the SMART Reuse application, while we continue to refine our 12m diameter HIAD design for Vulcan reuse. These efforts, under the NASA Space Act Agreements (SAA), have helped identify elements requiring further development for SMART Reuse, which could also benefit other potential mission infusion opportunities. This continues to be a very fruitful collaboration as these aspects have evolved.

IV. LOFTID

LOFTID was proposed as the next flight experiment in HIAD technology maturation. NASA’s HIAD technology was selected for a Technology Demonstration Mission under the Space Technology Mission Directorate

Figure 2: SMART Reuse

in 2017. The flexibility afforded with stowing this deployable structure overcomes the size constraints for rigid aeroshell entry systems. It also aligns perfectly as a booster mounted deployable to enable engine recovery. ULA and the NASA team worked together to address all the issues and concerns raised with flying the LOFTID demonstration as a ride share with the JPSS-2 launch on an upcoming Atlas V mission. Partnering with the JPSS-2 mission, LOFTID will launch out of Vandenburg Air Force Base. The flight test will utilize a 6m diameter, 70-deg sphere-cone aeroshell. The concept is a roughly 1200kg reentry vehicle with a 6m diameter aeroshell on a ballistic entry into Earth atmosphere from Low Earth Orbit (LEO). The 6m scale is about as large as is achievable within mass and volume constraints on the JPSS-2 mission while targeting an appropriate heat pulse.[5] The test vehicle will be delivered to its reentry trajectory as part of the Atlas V launch vehicle disposal.[6] This partnership provided a relatively low cost and near term orbital reentry flight experiment that utilizes available ULA launch vehicle performance and demonstrates the core recovery technologies planned for ULA Vulcan engine reuse.

The largest scale and highest energy HIAD flight to date was the successful Inflatable Reentry Vehicle Experiment 3 (IRVE-3). The steep flight path angle trajectory for IRVE-3 was designed to maximize the peak heat flux available from the three-stage sounding rocket. Flight performance data for the FTPS and IS was collected throughout the atmospheric entry on this relatively low-cost experiment. The 280kg IRVE-3 reentry vehicle inflated the HIAD from less than 0.5m diameter (when stowed) to 3m diameter (when deployed), and demonstrated aerodynamic stability (both static and dynamic) through hypersonic, supersonic, transonic, and subsonic flight regimes. IRVE-3 endured a deceleration of up to 20g, and experienced ~15W/cm^2 peak heat flux.[7] The ULA booster module recovery, along with other potential HIAD mission infusion concepts, will be much more energetic and will require a larger aeroshell. To this end, the HIAD team (NASA and its industry partners) is working on scaling up and ground testing the Inflatable Structure (IS) and FTPS technology for manufacturing, handling, packing, and performance. An increased scale, high-energy flight test is the next logical step in HIAD development.[5]

Significant FTPS design margins are required for mission applications due to uncertainties in modeling of the aeroheating environment and the uncertainties in the FTPS aerothermal response to that environment, along with the inability to replicate all flight parameters on the ground simultaneously. HIAD technology development includes physics-based model development for the FTPS and IS. With increased confidence in these predictive models, and with the modular material approach to HIAD, customization of FTPS layups and IS configurations can be more accurately sized and more accurately modeled for various mission applications. The LOFTID flight experiment will provide thermal and structural response data at these mission-relevant conditions, which will provide increased confidence in our predictive capabilities for aerodynamics, aeroheating environments, thermal response, and structural modeling. The flight data will also help to assess the relevance of ground testing constrained by facility physics, which can then further improve the analytical models. At larger diameters (large surface area), small changes in system specifications, such as FTPS insulator thickness, may yield appreciable changes in areal weight and stowed volume, so reductions in uncertainties will impact design and packaging requirements on larger-scale missions.

V. LOFTID Integration

Figure 3: Scale comparison among IRVE-3, LOFTID, and Vulcan Engine Recovery

The LOFTID Reentry Vehicle (RV) is designed to fit within the available volume of the payload adapter stack (see Error: Reference source not found). The HIAD aeroshell is packed and stowed forward of the RV nose. The Centaur payload adapter, from the aft end moving forward, consists of a C-13 Launch Vehicle Adapter, Aft D1666S Payload Separation Ring, RV Payload Adapter Interface Ring (RVPAIR), 1666 Forward Separation Ring, Forward D1666S Payload Separation Ring, three consecutive C-XX Launch Vehicle Adapters, and the B1194 Payload Separation Ring for the Primary Payload. LOFTID provides a long stroke actuation mechanism, called the Payload Adapter Separation System, that assists the separation of the Payload Adapter Canister over the length of the stowed RV. The RVPAIR and the 1666 Forward Separation Ring remain with the RV after separation from the Centaur.

One of ULA's key tenets for secondary payloads, as well as ride share, is strict adherence to its "Do No Harm" paradigm. The LOFTID payload is designed to launch unpowered. After the primary payload separation and the associated Contamination and Collision Avoidance Maneuvers (CCAM) have been completed, the Centaur performs a transfer burn and then a deorbit burn to put LOFTID on its targeted reentry trajectory. After the deorbit burn main engine cut-off, the Centaur commands the LOFTID RV to power on, while it maneuvers for Payload Adapter

Canister jettison. The Forward D1666S Separation System releases and initiates the separation of the Payload Adapter Canister, and the LOFTID Payload Adapter Separation System provides continued actuation over the length of the stowed LOFTID RV. After the Payload Adapter Canister is clear, the RV deploys the HIAD aeroshell and gradually inflates it to its regulated internal pressure. The Centaur will then spin up the inflated LOFTID RV, perform a final attitude trim, and release the RV using the Aft D1666S Separation System. As the Centaur performs a divert maneuver for disposal, the LOFTID RV will continue on its spin-stabilized ballistic reentry trajectory for the demonstration mission. Upon completion of the reentry environments and deceleration to subsonic conditions, the LOFTID RV will eject a back-up data recorder and then deploy a circular chute to slow the RV descent to the ocean surface. The HIAD remains attached to the RV structure, providing floatation, after water impact. Upon recovery, the HIAD aeroshell will be available for post-entry inspection.

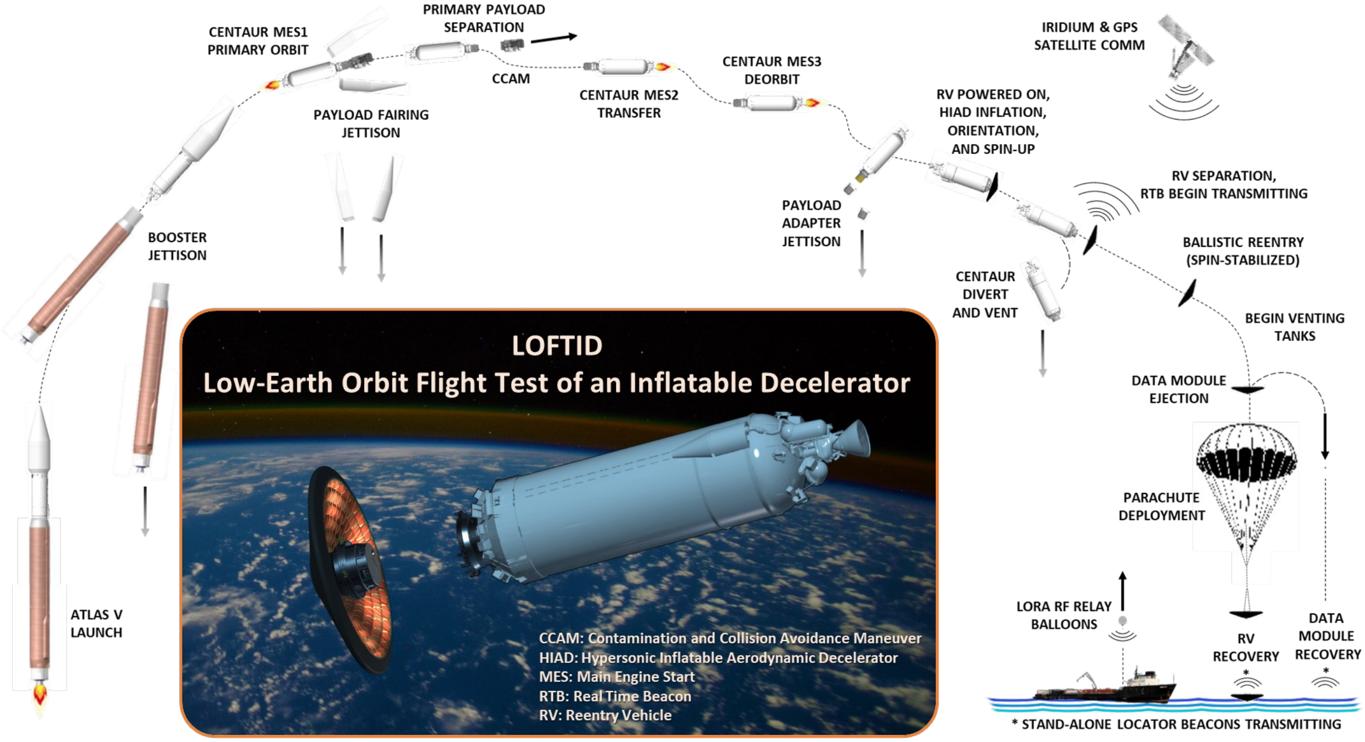


Figure 4: LOFTID Concept of operations diagram

The 6m diameter LOFTID experiment will demonstrate the largest blunt body reentry ever flown. The orbital reentry energy will exercise the FTPS through its thickness to provide surface and in-depth thermal measurements that can be used to anchor predictive models. The 6m scale provides sufficient running length to produce augmented heating due to turbulence, which can be evaluated after the flight via environmental reconstruction and thermal response measurements. Video data will provide edge deflections in flight to correlate to the structural model and ground testing. Infrared imagery will be collected on the backside of the aeroshell, providing thermal response and aeroheating environment indications in this area of high uncertainty. Ship-based recovery of the 6m diameter structure allows recovery process development on a structure ¼ the area of the Vulcan engine system. The physical condition of the materials will be examined and evaluated against the recorded data, providing additional qualitative information that flight instrumentation at discrete locations cannot capture. These groundbreaking demonstrations, and resultant data, support the development of HIAD while feeding forward to the ULA launch vehicle asset recovery.

VI. HIAD System Design

The HIAD aeroshell is composed of two separate assemblies: 1) the IS which must maintain its shape under aerodynamic loading to deliver the desired vehicle drag and stability and 2) the FTPS that protects the IS from the aerothermal environment generated by the friction of hypersonic atmospheric entry.

The IS is constructed of toroidal inflatable elements manufactured from a Zylon bias braid over an impermeable PTFE bladder. A series of inflatable elements, each subsequent element of increasing major diameter, are stacked together to produce a cone. The inflatable elements are joined together using a network of Zylon webbing elements and are attached to the entry vehicle with additional webbing elements. This structure is designed to accommodate temperatures of 400 deg C and maintain its shape at its design internal pressure.

The FTPS is constructed from an outer fabric layer that protects the system from the surface temperatures generated by aerodynamic shear (friction) along with convective and radiative heating during atmospheric entry. An insulating layer behind the outer fabric reduces the FTPS back surface temperature to the IS design limit. Behind the insulating ply is an impermeable layer (gas barrier) to dead head the FTPS assembly and prevent hot gas from flowing through and reaching the IS assembly.

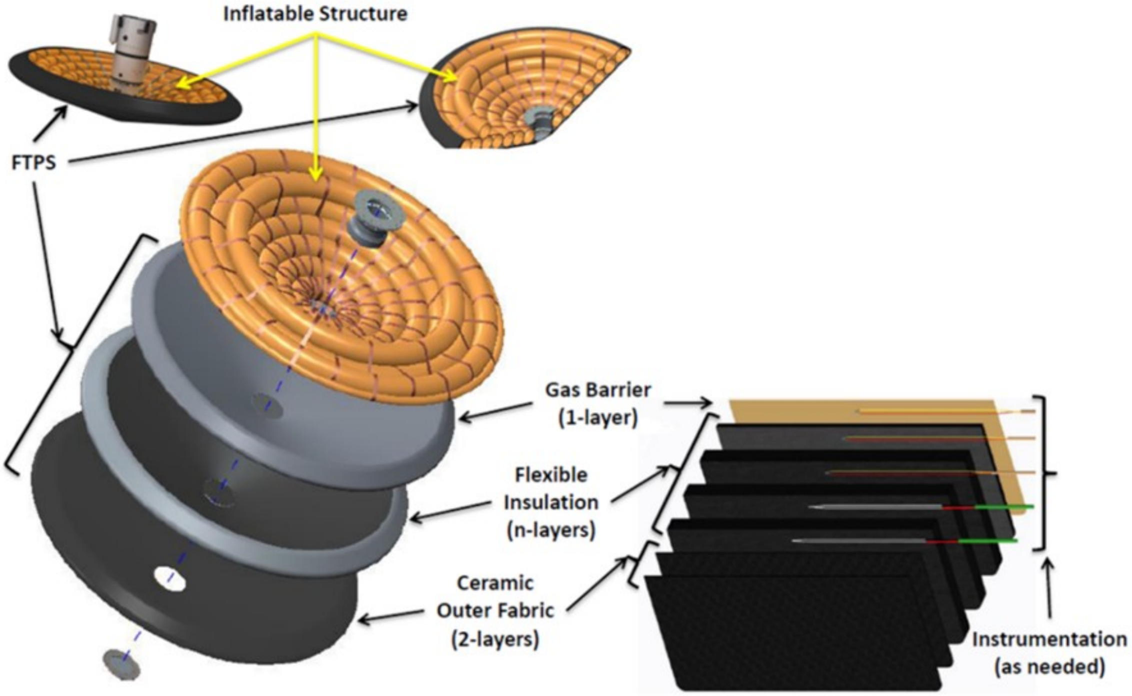


Figure 5. HIAD Flexible Thermal Protection System elements

LOFTID is targeting a peak heat flux of greater than 30 W/cm2, and a total integrated heat load of greater than 2 kJ/cm2. These targets 1) should exercise the FTS, 2) are relevant for most Mars entry applications, and 3) should far exceed requirements for ULA's SMART Reuse. Bounding this need allows accelerated commercialization by proving the system is capable of meeting currently identified commercial market needs. Risk posture will dictate the need for a full-scale test of the matured SMART Reuse system.

VII. Testing

The LOFTID project utilized a full-scale engineering design unit (EDU) consisting of both the IS and FTPS. These two components combined with the rigid nose and centerbody make up the HIAD aeroshell system. A set of three structural tests were performed on the aeroshell system.

The static load testing induced a uniform pressure load across the front surface of the aeroshell simulating the expected peak aerodynamic loads of atmospheric entry. The first series of tests used the IS alone to gather data on the IS and centerbody response. The second series incorporated the FTPS for testing of the full aeroshell system. The system was instrumented to measure component loading. In addition, laser scanning was utilized to verify any localized deformation was within acceptable ranges at the simulated loads.

Subsequent to the static loading test, packing and deployment tests demonstrated the aeroshell's ability to be stowed within the allocated volume for its flight configuration. These packing and deployment tests proved out the process repeatability and demonstrated the system integrity was maintained after repeated cycles. The third

15 PSI – 28,500lbf

Laser Scan Data

15 PSI – 28,500lbf

deployment cycle is captured in the sequence shown in Figure 10. This testing program set the project up for the LOFTID flight build.

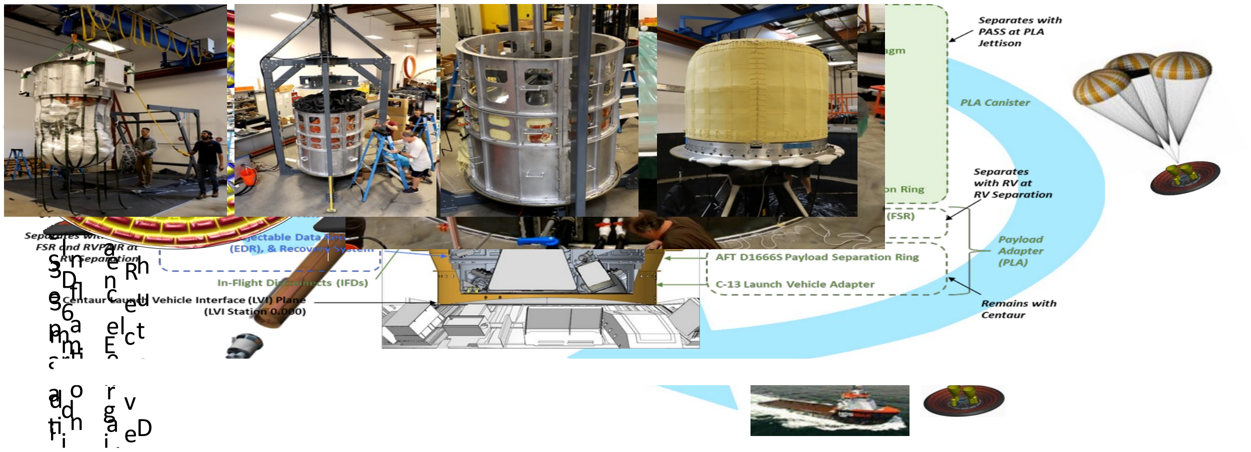


Figure 7: Packing Trials

VIII

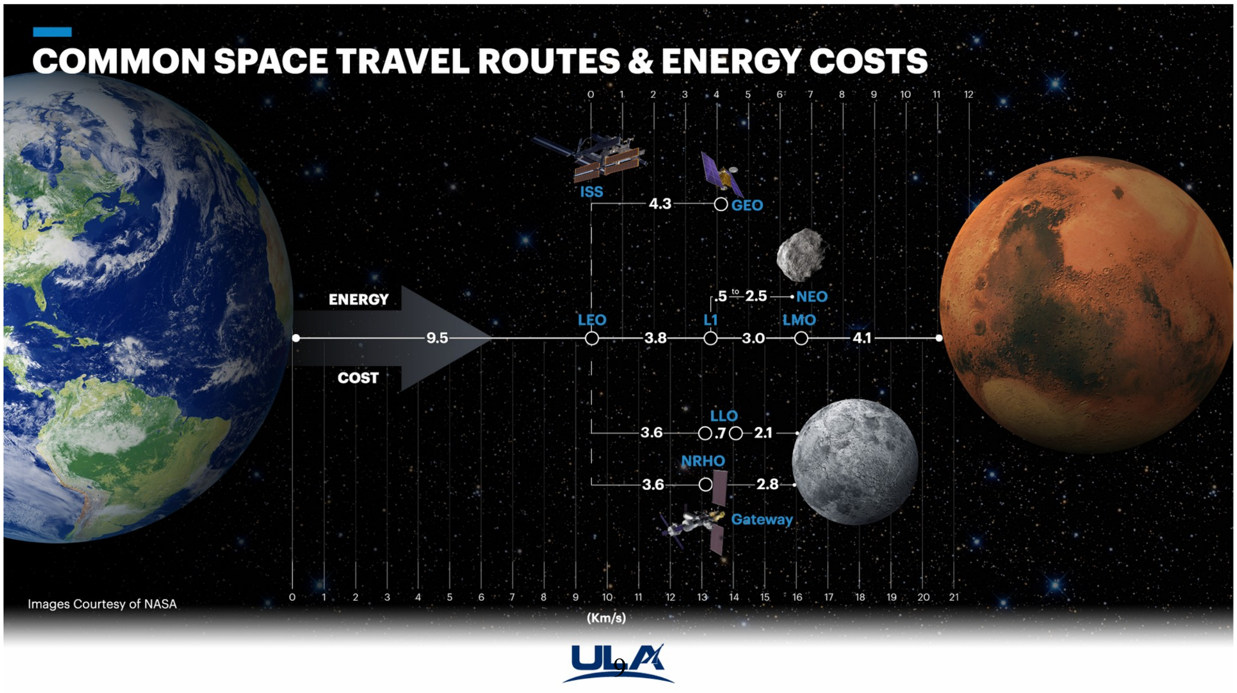
Figure 8: Third Deployment Test

Other Applications

The flight test of LOFTID and development of a SMART HIAD system provide incremental steps on the path to planetary recovery systems. The synergies between these systems allow modest incremental expansion of the current technology base demonstrated with the IRVE flights.

The system also has extensibility for inexpensive recovery of materials and products of a cislunar economy, and is scalable to provide delivery of payloads to a variety of destinations. It is gratifying to see the growth of interest with the NASA CLIPS program. One of those landers will fly on the first Vulcan Centaur flight. NASA is clearly interested in the capabilities these landers bring to market. The procurement of samples on the landers for future return to Earth holds out the hope for a customer base interest in retrieving such materials.

Similarly, interest continues to develop for in-space manufacturing in LEO and beyond. These proposed systems creating everything from high purity fiber optics to pharmaceuticals can support the arthbound market with products returned leveraging the same commercial technologies ULA will use for Vulcan booster recovery. All of these



applications require deceleration from LEO return velocities (or higher) to deliver goods and components to sites on Mars, other destinations with atmospheres, or consumers on Earth. The flight regimes for these applications provide sufficient similarities to enable opportunities for common element development and production. It is interesting to note that the same energy costs that challenge launch, namely that the bulk of the energy required to travel to cislunar space applies in reverse for returning products to Earth. The bulk of the energy that must be dissipated is the energy to drop from LEO to the Earth. Thus, the LOFTID technology demonstration mission will have proven not just the ability to return goods from any LEO production facility, but really the ability to return to the surface from most anywhere in cislunar.

IX. Summary and Conclusion

In the efforts to reduce the cost of space access, the vision of a fully reusable system may not be the best way forward with current technologies. Returning a vehicle to the surface via propulsion erodes the system's effective lift capability. Given the burgeoning market for secondary payload access to space and the ever-growing number of constellations of LEO and MEO satellites, a better approach to minimize the cost/kg metric addresses the performance loss due to recovery.

ULA and NASA continue to refine the concept for SMART Reuse which enables a minimum performance impact while recovering the highest value element of the booster, its engines. Conceptual design studies have found that a 12m diameter HIAD can shield the engines for recovery and reuse with minimal or no refurbishment. The technology advancements required for SMART Reuse will have high crossover value to other applications. At this point, the SMART Reuse concept has been shown to be viable with a reduction in access cost actually achieved after a single reuse[4].

ULA and NASA are working together to develop the LOFTID technology demonstration mission flying in 2022 with the JPSS-2 launch. This demonstration will prove the maturity of the technology and the scaling of the components required to step from the 6m LOFTID mission to the 12m Vulcan SMART reuse system. This partnership allows ULA to exercise the recovery operations and approaches for reuse in support of the technology demonstration. This allows the NASA Langley LOFTID team to focus on the development, test and operation of the LOFTID reentry vehicle and the reentry technologies. This public private partnership is moving the technology forward in a manner that allows the NASA vendors to retain the rights to their IP, allowing ULA and all interested parties to procure the components commercially for their individual applications.

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