Launch Vehicle Recovery and Reuse

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This paper briefly reviews the history of Reusable Launch Vehicle development and recommended reuse techniques based on the lessons learned from those efforts. The paper considers a range of techniques for recovery and reuse of launch vehicles. Launch vehicle component cost and weight by major element are also discussed as a method of determining cost/benefit of reuse. Of particular interest are non-propulsive approaches as economic alternatives to propulsive approaches. These may include aerodynamic decelerators (including inflatable decelerators and parachutes) and terminal landing approaches including impact attenuators and mid-air recovery techniques. Utilizing a Hypersonic Inflatable Aerodynamic Decelerator (HIAD) for atmospheric entry should have considerable mass-fraction advantage over other technologies. Mid-air recovery (MAR) is presented as an innovative approach for precision landing of impact susceptible components such as rocket engines while minimizing contamination by avoiding salt water immersion. The economics of reuse is presented as a basis for recommendations for cost effective reuse and recovery of booster components.

Nomenclature

ARPA = Advanced Research Projects Agency
B = Hardware to be reused (such as Booster)
C = Cost
F = Production rate factor
HIAD = Hypersonic Inflatable Aerodynamic Decelerator
I = Reuse index
ICBM = Inter-Continental Ballistic Missile
IRVE = Inflatable Reentry Vehicle Experiment
ISS = International Space Station
k = Fraction of launch service cost
MAR = Mid-Air Recovery
n = Number of uses
p = Performance ratio
RHW = Recovery hardware
RR = Recover and reuse
SDIO = Strategic Defense Initiative Organization
SMART = Sensible Modular Autonomous Return Technology
SSTO = Single Stage To Orbit

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I. Introduction

SINCE the beginning of space travel, the multistage expendable launch vehicle has been the predominate approach for boosting payloads to orbit. Although this has been a reliable approach, the high cost of launch has limited civil, commercial and military endeavors in space. Engineers have attempted to design a fully reusable launch vehicle to both reduce the cost of launch and to increase the launch rates. In particular, many single stage to orbit (SSTO) concepts have been considered over the past several decades. This has proven to be an elusive goal given the state of technology of light weight materials and chemical propulsion performance. The recent proliferation of commercial launch providers, coupled with the highly competitive nature of this market, has stirred a renewed interest in identifying alternative means of recovering launch vehicle assets to reduce the cost of access to space. These companies are developing designs ranging from fully reusable SSTOs to more traditional expendable launch vehicles with reuse of high value components such as the first stage and/or its booster engines. Coupled with this development are emerging technologies for atmospheric Entry, Descent, and Landing (EDL) including the HIAD, impact attenuation airbags, and MAR. These technologies could be enablers for economical reuse of launch system elements (and resultant significant reduction in the cost of access to space).

II. Brief History of Reusable Launch Vehicles

Investigations into the reuse of launch vehicles can be traced back to the early years of the space age. For example, in 1957, Convair investigated ideas that would have allowed the reuse of the basic Atlas booster as it participated in the Air Force SR-89774 study of reusable space boosters.[1] The early Aerospace Plane Program was largely spurred by that study as well.[2] That study continued through 1965 and considered many different vehicle configurations and operational concepts.

In the 1970s, NASA designed and built the Space Shuttle, a partially reusable launch vehicle. It first flew in 1981 and was operational from 1982 through 2011. Over its 30 years lifespan, the Shuttle program flew an average of 4 or 5 missions a year. With a total program cost of $209B, the average mission cost was over $1.5B.

Serious attempts at completely reusable launch vehicles started in the 1990s. The most prominent were the McDonnell-Douglas DC-X and the Lockheed Martin X-33 VentureStar.

Figure 1. NASA picture of the DC-XA. (Credit: NASA)

The DC-X was an experimental version of the Delta Clipper, a Single-Stage-To-Orbit (SSTO) launch vehicle meant to have a nose first atmospheric entry for improved cross-range. DC-X was not designed to achieve orbital altitude or velocity. Instead, it was primarily focused on demonstrating vertical takeoff and landing of a liquid hydrogen liquid oxygen powered launch vehicle, which it did, but not without incidents. NASA took over the project from the DoD (SDIO/ARPA) in 1995 and an improved version, the DC-XA (Fig. 1) achieved 10,300 feet altitude and 142 seconds flight duration in its second to last flight.[3] The project was cancelled after its last flight failure in favor of VentureStar, a NASA funded lifting body reusable vertical takeoff horizontal landing SSTO launch vehicle.

Figure 2. X-33. (Credit: NASA)

The X-33 (Fig. 2) was a subscale VentureStar with two linear aerospike liquid hydrogen liquid oxygen rocket engines and a metallic thermal protection system. Like the DC-X, the X-33 was an experimental vehicle not intended to achieve orbital flight. It had many technological hurdles to overcome and did well on some of those. For example, its aerospike engine successfully completing 14 planned hot fire tests in the spring of 2000, accumulating more than 1,460 seconds of total operating time, as well as successfully demonstrating differential throttling. However, unlike the DC-X, the X-33 never got to first flight. After $1.33B in investments, the X-33 was cancelled after its composite liquid hydrogen tank failed during cryogenic and structural load testing.

III. Recovery and Reuse Techniques

The essential objective of reusing launch vehicles is to reduce the cost of access to space. The concept and practice of recovery of elements of a space mission is nearly as old as the early investigations of launch vehicle reuse. In 1960, the first film from a Corona reconnaissance satellite mission was de-orbited and recovered in mid-air with a C-119 aircraft. That practice continued successfully into the 1970s. (Fig. 3 and 4)

Perhaps the best example of recovery of space assets is the parachute recovery of space capsules in the 1960s and 1970s; Mercury, Gemini, and Apollo. NASA achieved a 100 per cent success rate on these missions. However, the space capsules landed in salt water and none were ever reused.

Separate stages of multi-stage launch vehicles can, and have been, returned or recovered separately for reuse. The most prominent example is the Space Shuttle. While the external tank is discarded, each solid rocket booster (SRB) is recovered and the Orbiter conducts a horizontal landing for reuse.

One can design a system that recovers a complete launch vehicle, separate stages or components. The key is to do so economically in order to reduce the cost of access to space.

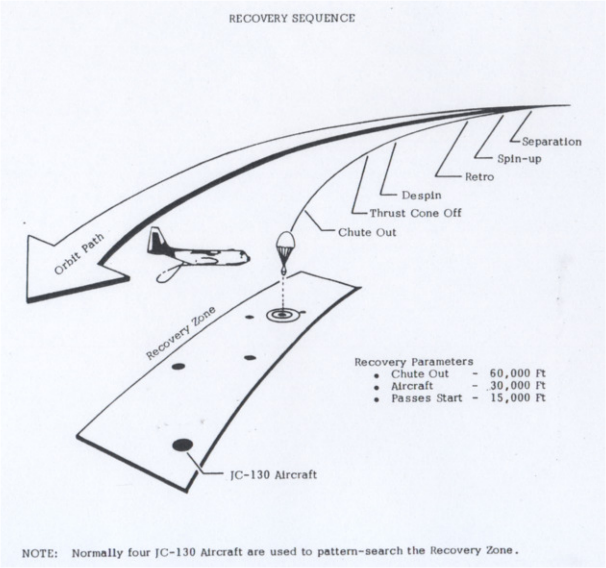

Figure 3. Corona recovery sequence (Credit: CIA Directorate of Science and Technology)

Figure 4. KeyHole satellite film mid-air recovery. (Credit: National Reconnaissance Office)

IV. Value of Launch Vehicle Elements and Cost of Recovery

A logical first step in order to decide what to recover for reuse is to understand the relative value of different launch vehicle stages or components that are candidate for recovery and reuse. Figure 5 shows a breakdown of the relative cost of the Atlas 401 launch vehicle by major element. Clearly, the most valuable component is the first stage engine.

Another important consideration is the cost of recovery. Launch operations impart substantial energy to different elements of the launch vehicle and recovery requires bringing back those vehicle elements to rest on the surface of the earth before they can be prepared for reuse. The degree of difficulty bringing back those elements depends largely on their mass and inertial velocity.

Figure 5 has the breakdown of weight by major element for the Atlas 401. It is interesting to note that the first stage engine represents the highest value per unit mass of all vehicle components.

Lower stages of launch vehicles achieve lower burnout velocities, and therefore are less expensive to recover. For instance, recovering a booster section of an Atlas ICBM - which used to be jettisoned midway through the booster stage leaving the sustainer engine firing - or a Shuttle SRB, is easier than a suborbital first stage. Typical inertial velocities for those range from 3-6 km/sec. In contrast, recovering an upper stage from low earth orbit with an orbital velocity of 7-8 km/sec requires a de-orbit maneuver and therefore is more expensive. Recovery from higher orbits, such as geosynchronous transfer orbit with 10 km/sec at perigee is even more expensive.

Cost of recovery can increase substantially if special maneuvers are required. For instance, returning to launch site from suborbital flight can be quite expensive. The Space Shuttle program avoided such expense by deploying parachutes to recover the SRBs over 100 miles downrange and towing them back to shore.

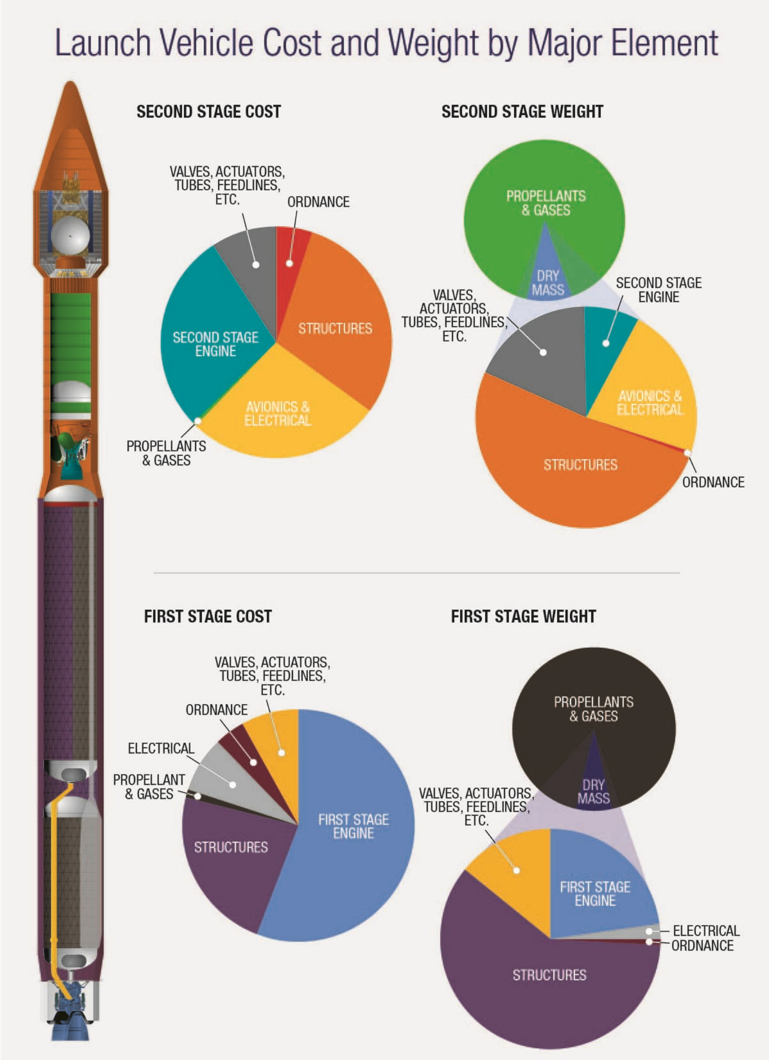

Figure 5. Atlas launch vehicle cost and weight by major element[4]

V. Technologies Required for Recovery

Recovery of hardware from space requires atmospheric reentry, deceleration, and landing. Reentry can be accomplished either by via retro-propulsion, or by utilizing the atmosphere to decelerate the object via aerodynamic drag. Atmospheric deceleration at reentry velocities requires an aeroshell featuring a thermal protection system (TPS) to protect the payload. The aeroshell has historically been limited in diameter and area by the launch vehicle shroud. The HIAD, with its inflatable structure and flexible TPS, is an emerging technology with significant promise. HIAD can be densely packed and inflated exo-atmospherically to create a heat shield with significantly more area than a traditional rigid heatshield. Two landing technologies are described: impact attenuation airbags and MAR. Recent developments in MAR have yielded in a highly reliable and practical technology which enables an object to be delivered to a precise location with virtually no impact acceleration. This becomes particularly attractive for returning rocket engines which are sensitive to impact and contamination (especially salt water).

A. Retro-Propulsion

Retro-propulsion is probably the most intuitive method of all: just reverse the launch process. It was used by Herge to land Tintin on the moon in the 1953 comic book; and by the Apollo program to land man on the moon for real in 1969, and for good reason: the moon has no atmosphere, which rather limits EDL options. It is also very expensive in the sense that the fuel required for landing must be carried to space, which erodes the useable payload capacity of the launch system.

Attempts by Space-X to land its first stage on a barge for reuse are precursors to more ambitious plans to return to the launch site. The idea is not new. It has been contemplated by the Russians[5], together with the grid fins used for stability and control during descent.[6] The data collected from the Space-X flights is a great supplement to prior wind tunnel testing.[7] The basic questions remain however: to what environment is the booster subjected? how many times can it be reused? what is the extent of refurbishment required, and at what expense (both to mission performance and in other direct and indirect costs), before it can be reused? A discussion of the economics of reuse will be presented in section VII.

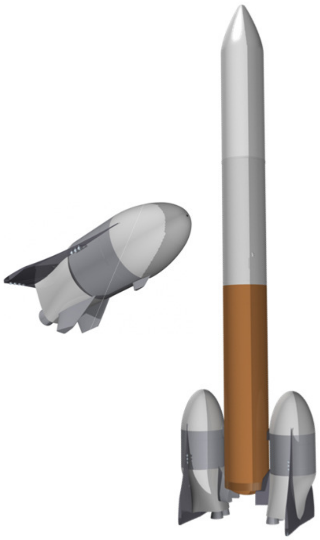

Figure 6. Vulcan with Autonomous Engine Landing and Reuse

B. Return Flight of Orbital or Suborbital Vehicles

Return flight was successfully exercised by the Space Shuttle Orbiter for decades with no incident, with the exception of the loss of Columbia which was due to damage sustained during launch. Return flight's advantage over retro-propulsion is the use of the atmosphere to bleed down energy and control the vehicle during EDL. For an orbital vehicle, one could design the mission to land at the point of departure for its next mission (weather permitting), which gives it great operational flexibility and efficiency. On the other hand, in many cases, a suborbital vehicle will have to use some propulsion, in addition to aerodynamics, to get to an appropriate landing site. Systems such as aerodynamic surfaces, controls, small propulsion, and thermal protection must be incorporated into the design with a corresponding cost and performance impact. Both United Launch Alliance (ULA) and Airbus have announced plans to incorporate partially reusable booster designs based on return flight for their Vulcan (Fig. 6) and Ariane 6 launch systems.

C. Recovery of Launch Vehicle Components

Hypersonic inflatable aerodynamic decelerator (HIAD) technology is applicable to entry and descent at planets or moons that have an atmosphere, notably Mars and our own home planet Earth. HIAD technology removes the launch vehicle shroud diameter constraint for aeroshells. A HIAD is lightweight, relatively easy to pack within the launch vehicle, and can generate lift. The latter allows controllability during atmospheric entry via a center of gravity offset like capsules or using aerodynamic control surfaces like winged flight vehicles. The HIAD is inflated while still exoatmospheric, and is capable of slowing the reentry object from hypersonic to subsonic speeds.

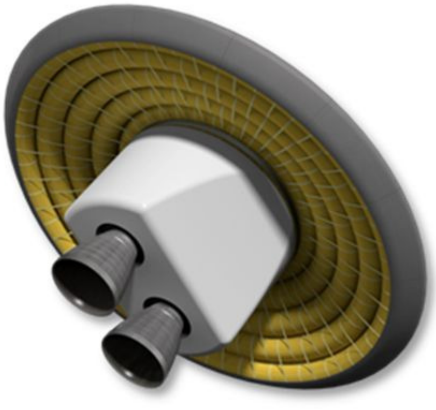

Figure 7. HIAD return concept for the Vulcan booster engine module.

An initial feasibility study has been performed to investigate utilizing a HIAD to recover the first-stage booster module for the new Vulcan launch vehicle. It appears that there is sufficient volume to accommodate a HIAD system and requisite mounting and separation hardware. The concept is shown in Fig. 7 and 8. The required 10-12m HIAD can be

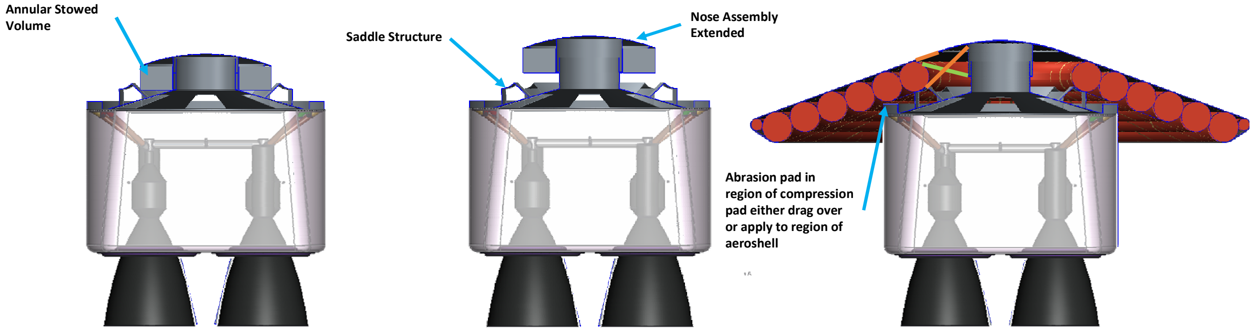

Figure 8. HIAD configurations for Vulcan booster engine module: stowed, nose extended, and HIAD deployed.

packaged into the annular volume behind the spherical nose assembly. After separation, the nose assembly extends to position the HIAD such that it will clear the separation plane when inflated. Saddle structures will react the majority of the drag load on the HIAD into the engine module structure.

Entry simulations assuming a ballistic entry predict very high peak decelerations (15g or more). The use of a lift vector to loft the trajectory is one technique that can reduce that peak deceleration. Preliminary results indicate a 10-12 meter HIAD will be required to recover the booster module.

D. Landing Impact Attenuation

Landing impact attenuation using rapidly vented airbags is an option for mitigating impact accelerations for sensitive payloads. This technology is ubiquitous in the automotive industry, and has been implemented in a range of aerospace applications including air-drop cargo delivery, space capsule landing, and helicopter crash mitigation. Typically, the airbags are densely packed until deployment. When initiated, a gas generator or compressed gas rapidly inflates them to a prescribed pressure. Upon impact, the bag is vented through a burst disk allowing gas to be expelled through an orifice and in turn dissipating kinetic energy. Currently, Boeing's CST-100 capsule employs an airbag attenuation system for their landing. Such an airbag system can limit impact accelerations to below 6-8g, is lightweight, and can be densely packed into a small volume.

E. Mid-Air Recovery

MAR was developed and used extensively in the 1960s for recovery of payloads (film canisters) from space for the Corona project. Recent developments in the technology have demonstrated a technique that is both reliable and scalable up to (and beyond) a 10 ton payload. MAR utilizes a ram-air main parachute that decelerates the payload. It also provides a stable and predictable velocity vector that enables a helicopter equipped with a flying articulated grapple to approach from the rear and capture the in-flight parachute and gently transfer the payload mass from the parachute to the helicopter. The helicopter then transports the payload to a precise location on land or sea (e.g., barge or ship) for final recovery. This approach avoids high impact accelerations and/or emersion in salt water. Figure 9 shows ULA's Sensible Modular Autonomous Return Technology (SMART) reuse concept with HIAD entry, guided parafoil descent and helicopter MAR. The large guided parafoil is a mature technology used for precision airdrop. MAR has been successfully demonstrated for 1000 lbs class objects with a benign environment less than 1.2g. That technology needs to be scaled up to the mass required for launch vehicle element recovery. However, the total mass retrieved will be limited by helicopter capability. For instance, the heavy lift CH-53K helicopter max external load capability is 36,000 lbs.

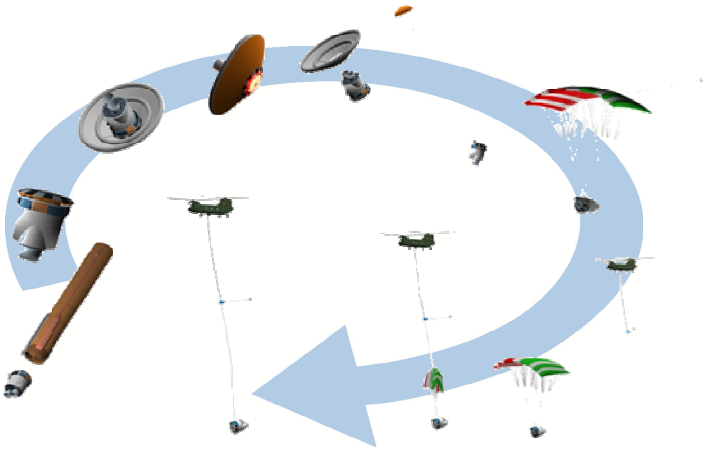

Figure 9. ULA's SMART reuse

VI. Preparing for Reuse

After recovery, the hardware to be reused needs to be checked out and prepared for the following mission. The cost of that effort can make all the difference between an economically successful program and one that is not so successful. The Space Shuttle is a prime example. While there is no breakdown between non-recurring and recurring cost for the program, the incremental cost per flight was estimated at $450 million in 2011. The Shuttle required extensive inspection and refurbishment. For example the orbiter's thermal protection tiles needed to be individually inspected (and potentially replaced), and its main engines needed to be removed to undergo extensive inspection and overhaul. The Shuttle's SRBs were contaminated with ocean salt water and had to be cleaned, disassembled, and refurbished before reuse.[8]

While it is important to design the hardware for a large number of reuses, it is equally important to stay within the design parameters of that hardware during the recovery operation. Ideally, the environment during recovery will be monitored so that minimal inspection is required before returning the hardware back to production and launch operations.

VII. Economics of Reuse

As stated before, the primary objective of reusing launch vehicle assets is to reduce the cost of access to space. While the value of recovered hardware is fairly straightforward to quantify, estimating the cost of its reuse is a little more complicated. One must be sure to include all the costs associated with the recovery and reuse operation and its impact on mission performance, production, and launch operations. All launch service costs must also be considered during that evaluation.

The parameter most often used as an objective measure of launch service cost is the cost to launch a kilogram to orbit or "$/Kg". To allow the comparison of the economics of different methods of recovery and reuse, Dr. George Sowers of ULA proposed a reuse index *I* defined as the ratio of the $/Kg value for the reusable system divided by the $/Kg value for the corresponding expendable system.[9] A lower reuse index value corresponds to more reduction of the cost of access to space.

The equation for the reuse index is provided below with its terms slightly rearranged for ease of interpretation:

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

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

Figure 10 shows the results for SMART vs. Booster Fly Back using retro-propulsion. The former becomes profitable after a couple of uses while the latter requires ten uses to become profitable. The difference is mainly because of the 30 per cent performance loss to land the booster downrange on a barge. Using the same rationale, equation, and input data, booster fly back is never profitable in a return to launch site scenario. Obviously, the results are only as accurate as the input data, which are best estimates based on available ULA and published Space-X information. However, this example should provide a good illustration of the relative importance of the different terms of the equation, as well as the need to keep the performance expended to recover the reuse hardware to a minimum.

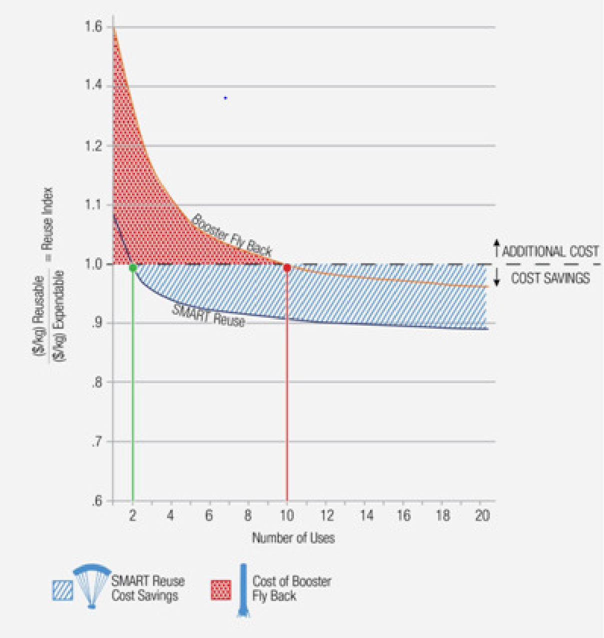

Figure 10. Reuse index vs. number of uses for SMART and Booster Fly Back[10]

VIII. Next Steps

Many launch vehicle providers are working towards recovery and reuse. Space-X has chosen the retro-propulsion approach, and plans to continue its attempts to land a booster on a barge and later return it to the launch site. Airbus is developing Adeline (ADvanced Expendable Launcher with INnovative engine Economy), its partly reusable space launcher concept that will enable the reuse of the booster's main engines and avionics. ULA, on the other hand, has chosen to recover and reuse its Vulcan booster engines in the relatively near term using HIAD, guided parafoil, and MAR. With that architecture in mind, ULA is working closely with NASA to develop a large-scale, high energy flight demonstration concept for HIAD.

The most recent HIAD flight test, Inflatable Reentry Vehicle Experiment 3 (IRVE-3)[11], flew in 2012 on a suborbital sounding rocket and was a complete success (Fig. 11). That successful flight test augmented a significant ground-based development effort to advance HIAD technology in the areas of manufacturing, packing, temperature capability, and scale. The continued success in advancing HIAD has made it a leading candidate to be part of the architecture for safely delivering humans to Mars in the 2030s. That mission might require a 15-20m HIAD.

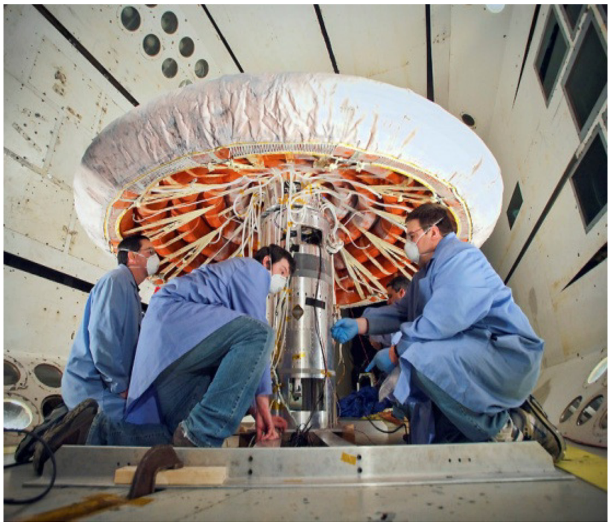
Figure 11. IRVE-3. (Credit: NASA/ Sean Smith)

NASA is working with ULA to develop a HIAD flight test concept as a secondary payload on a future Atlas V launch. As envisioned, the test article would be integrated to the primary payload adaptor. The team is targeting a total scar mass of approximately 2 tons, and an inflatable aeroshell diameter of 6m. Lower system mass opens up more secondary payload opportunities, but reduces the allowable aeroshell diameter if relevant aeroheating environments are to be realized. This experiment will be relevant (in scale and environment) for both a proposed EDL Pathfinder mission in preparation for the human Mars mission and ULA's desired Vulcan booster engine recovery. Given the latter, the flight test could include staging to a parafoil and mid air retrieval (MAR).

Figures 12 and 13, left, show the concept stowed atop the Centaur second stage integral to the primary payload adaptor. After primary payload separation, the system utilizes the restart capability and the guidance of the Centaur to deorbit the reentry vehicle. A portion of the payload adaptor is ejected exposing the stowed aeroshell. The aeroshell is deployed while still attached to the Centaur (Fig. 13, middle). Again utilizing the capabilities of the Centaur, the system is pointed to properly orient the vehicle for atmospheric entry, spun up to 4 RPM to provide inertial pointing stiffness, and released (Fig. 13, right). Utilizing the capabilities of the Centaur greatly reduces the complexity (and consequently the costs and development time) of the HIAD flight test.

Including MAR on the experiment helps ULA work out the logistics involved in using MAR to recover an atmospheric reentry vehicle. Successful retrieval also offers the opportunity to inspect the HIAD after being exposed to hypersonic atmospheric reentry conditions without experiencing ground or water impact. This opportunity to inspect the aeroshell will provide invaluable information which should reduce performance uncertainties and potentially reduce required design margins. The flight experiment will include an ejectable data recorder to assure recovery of flight experiment data in the event of a failed MAR attempt.

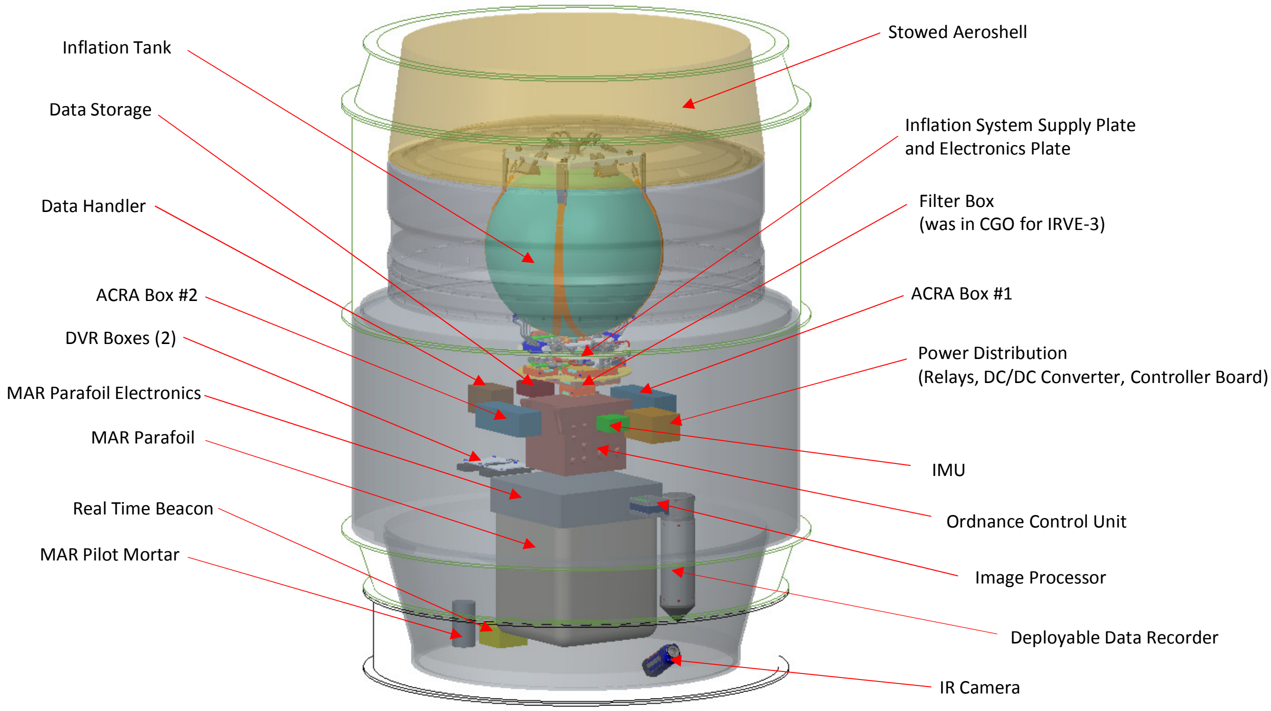

Figure 12. HIAD flight experiment concept as an Atlas V secondary payload: component layout.

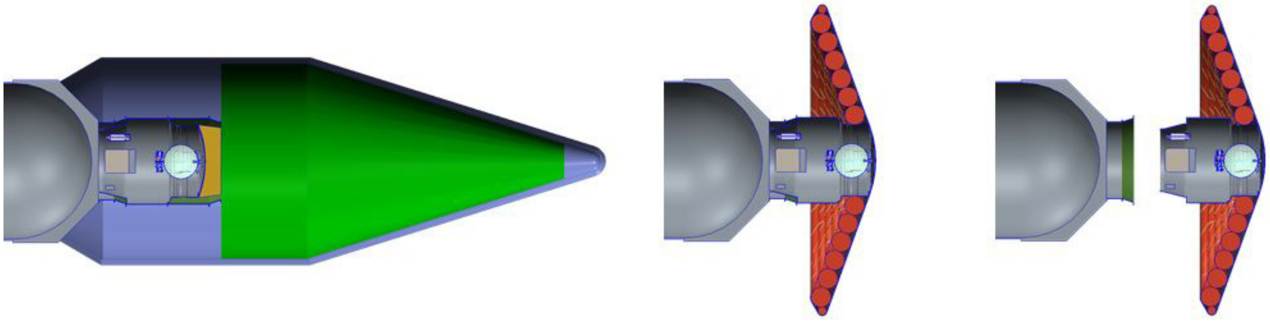

Figure 13. Atlas V HIAD secondary payload concept: (L-R) Stowed between second stage and primary payload, deployed, released.

IX. Conclusion

The idea of launch vehicle reuse (partial or total) is not new, but virtually all previous conclusions were that it was economically nonviable. Current efforts to economically recover and reuse launch vehicle elements are more promising than they have ever been. Any advancements in reduced cost access to space promises to benefit the overall launch vehicle industry. Technology and capability development efforts across government and industry provide new tools for such recovery efforts. The range of approaches favored by various launch providers allows leveraging of investments in areas such as EDL that are essential for the continued progress in space exploration. There is certainly synergy between NASA's efforts to send humans to Mars, where HIAD technology looks like a promising candidate, and ULA's desire to recover its Vulcan booster module.

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