

EELV Partially Reusable Booster

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The development of reusable launch vehicles is a continued priority in an effort to reduce cost, increase responsiveness, and avoid expending expensive rocket hardware. Reusing an EELV booster engine combines reusability, proven launch vehicles, and EELV-sized payload capacity. In addition to cost reductions, it allows for flexibility in engine production rate. This paper outlines how the reusable launch vehicle community can utilize partial reusability options on Evolved Expendable Launch Vehicles (EELVs) as a springboard for long-term developments and proposes that in addition to the pursuit of responsive, reusable boosters for small payloads, partial reusability be developed for EELV-sized payloads.

Many approaches to booster recovery have been considered in the past. Flyback boosters suffer from huge non-recurring cost and large performance impact. Parachute recovery of an engine module to the ocean suffers from high-impact G loading and exposure to harsh ocean environments which require a complex system to fully seal off the engine. However, the use of an inflatable hypersonic decelerator and helicopter mid-air recovery to retrieve a booster engine module as it descends under a parafoil is a low-development-cost approach which brings back the booster engine with exposure to only benign environments.

Nomenclature

AIAA	American Institute of Aeronautics and Astronautics	MAR	Mid-Air Recovery
BRM	Booster Recovery Module	PAI-DAE	Program to Advance Inflatable-Decelerators for Atmospheric Entry
DARPA	Defense Advanced Research Projects Agency	SRB	Solid Rocket Booster
GSE	Ground Support Equipment	TRL	Technology Readiness Level
IAD	Inflatable Aerodynamic Decelerator	ULA	United Launch Alliance
IRVE	Inflatable Re-Entry Vehicle Experiment	XPC	External Payload Carrier

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I. Introduction

United Launch Alliance (ULA) is currently pursuing a variety of launch vehicle cost-reduction initiatives while maintaining reliability and performance—one of those initiatives being the reuse of the Atlas V booster's RD-180 engine. Assessments show that there is really only one object worth recovering from an operational rocket: the booster engine. It represents the highest value element on any booster and dominates the reliability and performance calculations for the booster. The labor costs for its installation and checkout are also dominant. In comparison to nearly every other part of the rocket, booster engines are a scarce commodity with a strict limitation on the total number that can be produced yearly. The production of a high-performance reliable booster engine historically has demanded a protracted manufacturing process with intensive engineering support and oversight with costly testing. This testing is often bound to critical facilities with limited throughput. The cost to amplify yearly production even slightly ranges from the hundreds of millions to billions of dollars simply to upgrade facilities. The schedule effects of damage to these facilities can be long lasting. In short, the payback potential for reusing the booster engine is large.

The booster engine on the Atlas V, the RD-180, has several other features that enable practical reuse. It is a compact object fabricated with robust structures, as seen in Figure 1, yet it is not excessively heavy. Most importantly, it is an evolved version of the RD-170 engine designed for 10 operational uses. This last fact provides the foundation for economical reuse.

Partial Booster Reuse enables a launch capacity of double or even triple current engine production capabilities, resulting in a decrease in launch cost at higher launch rates. Additionally, a recovered engine can be subject to a full teardown for engineering purposes instead of being reused.

II. Partial Booster Reuse Sequence

With the RD-180 as a viable target for recovery and reuse, the critical element of recovery is to ensure that the engine is not subjected to environments for which it was not qualified. The RD-180 must be operated, shutdown, and secured much as would be done during an acceptance hot-fire test. This process is straightforward and consists of traditional purges, the use of external vacuum to remove residual propellants, and closures to prevent internal contamination during the subsequent recovery process.

The partial booster reuse sequence commences when the Booster Recovery Module (BRM) is jettisoned from the booster after the upper stage launch vehicle has separated. An Inflatable Aerodynamic Decelerator (IAD) unfurls at maximum nominal release altitude (around 750,000 feet). The IAD provides a moderate deceleration profile to minimize potential damage to the engine, and it is jettisoned in the lower atmosphere. At subsonic speed, a parafoil with a trailing drogue line and internal GPS system inflates above the BRM and steers toward a target area for helicopter intercept. The system is illustrated in Figure 2 and discussed in detail in a technical paper presented at the American Institute of Aeronautics and Astronautics (AIAA) Space 2008 conference.¹

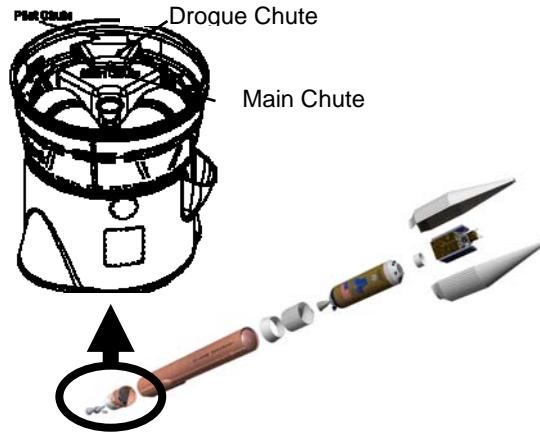


Figure 1: The Booster Recovery Module (BRM) can be severed from the booster for recovery

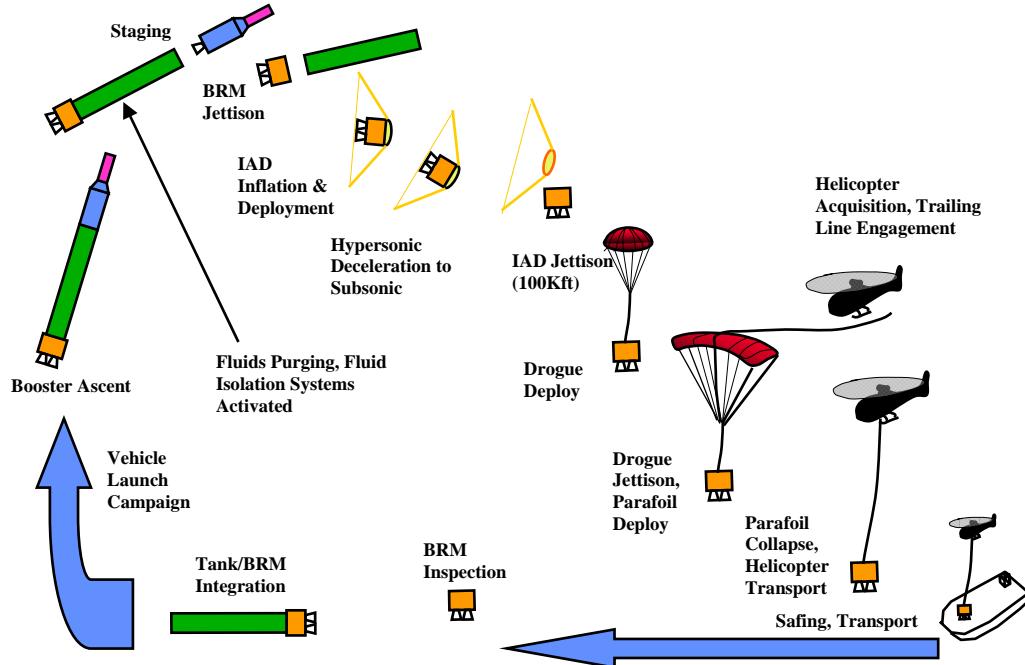


Figure 2: Maintaining Benign Environments is Key in making Partial Booster Reuse Cost-Effective

The velocity and altitude state of the booster at burnout are highly dependent on the Solid Rocket Boosters (SRBs) on the booster. The majority of current Atlas V launches do not use SRBs and hence the booster is typically left in the lowest energy state. This Atlas V 401 class booster (with no SRBs) is the focus of ULA's recovery system because the 401 configuration minimizes the speed at which the hypersonic decelerator must be deployed and the distance from land where the BRM is intercepted.

A low kinetic energy state allows the next and most critical phase, hypersonic deceleration, to use hardware with the least mass and complexity. Hypersonic deceleration has the greatest potential to damage the engines by either structural overload or thermal damage. After engine shutdown and securing, the primary propellant tanks will detach from the BRM, which houses the RD-180 engines. This step is analogous to the booster jettison event that was a hallmark of Atlas flight until the advent of the Atlas III. The jettison allows a deployable decelerator to unfurl. Inflatable structures perform the deployment and hold the geometry of the decelerator under load. The hypersonic decelerator, fabricated primarily from high-temperature fabrics, allows the modulation of the deceleration forces, the control of aerodynamic heating within limits, and directional control of the descending engine package toward the surface recovery team and away from the impact zone of the remainder of the booster. Once the BRM is substantially decelerated—likely at an altitude around 100,000 feet—the hypersonic decelerator is jettisoned.

The final recovery phase centers on the use of Third Generation Mid-Air Recovery (MAR) technologies. Decelerated by small parachutes to the subsonic regime, the BRM deploys a steerable parafoil for a controlled and targeted descent towards the recovery barge. Helicopters converge to the package, establish formation flight, and use the proven trailing drogue system link to the package. Subscale flight tests demonstrated that a 750-lb pod saw less than 1.2 Gs during parafoil-to-helicopter load transferral. Once the engine package is a suspended load under the helicopter, it is transported to a support cradle on the recovery barge. This process eliminates violent impacts or the potential for salt water contamination. The recovery barge maintains safing purges and transports the engine package back to the launch site. The hypersonic decelerator and parachutes are recovered as well.

Though lacking in the drama of hypersonic decelerators or mid-air helicopter recovery, the reinsertion of the BRM back into the production flow is the most critical step for economic viability. Here, ULA reaps the benefits of a controlled and documented recovery process. Extensive teardown, rebuild, and retest are not required because the engine has not been abused, which is proven via data taken throughout the

recovery process. Simple functional tests and inspections verify engine integrity and permit the re-mating of the BRM to a waiting booster tank. ULA intends to initially use the RD-180 engine for three flights. This allows ULA to stay comfortably within known operational times. As experience is gained, the number of reflights can be extended; however, a balance must be struck to ensure that the production rate of new engines is not compromised.

The BRM recovery and reuse process requires hardware including: (1) an Atlas V booster that has been upgraded with BRM components, (2) a hypersonic decelerator, (3) a transonic decelerator (if necessary), (4) a subsonic parafoil with a stable drogue line, (5) a helicopter, (6) a steerable aerodynamic remote-controlled grapple, and (7) Ground Support Equipment (GSE) for the recovery/refurbishment process.

III. Hypersonic Decelerator

A large portion of this paper will focus on a test opportunity for the long-lead hypersonic decelerator technology called the IAD, shown in Figure 3. This is the element of partial booster recovery with the greatest technological challenge.

The anticipated mass of the BRM is 25,000 lbs and is packaged in a shape that did not anticipate recovery. While the overall energy is tractable, the entry angle has the potential to be far steeper than a traditional re-entry from orbit. The modulation of this entry angle from the initial parabolic trajectory is a key requirement. The deployment, entry, and jettison events are equally critical. Without an innovative test approach, the qualification of this device will be extraordinarily expensive.

To advance IAD technology, hypersonic modeling and entry analysis will be conducted by NASA with the geometry being a collaboration of many parties. NASA has been on the forefront of IAD technology since its inception in the 1960s. NASA has continued IAD research and development through a number of programs initiated in this decade. ILC Dover has partnered with NASA on many of these programs, and is the IAD manufacturer for NASA's Inflatable Re-Entry Vehicle Experiment (IRVE)-I and IRVE-II flight tests. During the IRVE-II flight in 2009, the aeroshell inflated as designed and maintained stability not only through hypersonic reentry but also through the supersonic, transonic and subsonic flight regimes.

Beyond IRVE, other NASA programs such as Program to Advance Inflatable-Decelerators for Atmospheric Entry (PAI-DAE) are examining IAD thermal protection system materials, IAD structural designs, and IAD aerodynamics in the hypersonic, supersonic, and subsonic speed regimes. Further, NASA has made investments in computational tools for analyzing the interaction of the IAD flexible structure with the surrounding airflow. ILC Dover, in its partnership with NASA, is characterizing high temperature properties of candidate IAD materials for the hypersonic environment as well as building subscale models for supersonic tests that provide data to correlate NASA's models. ILC Dover also currently supports inflatable decelerator development for the Defense Advanced Research Projects Agency (DARPA) Rapid Eye program and has worked numerous other projects with various IAD configurations, including stacked toroids, radial spars, double-walled, skinned tube trusses, tension cones, and isotensoids. The IAD will take advantage of this experience base to bring high Technology Readiness Level (TRL) configurations and materials to its development. In addition to its hypersonic modeling and analysis capabilities, NASA's facilities and experience in supersonic and hypersonic testing will be key to the IAD development.

While the development of the decelerator will proceed initially as a design, analysis and ground test task, it is clear from the outset that real-world data must be gathered as early as possible to reduce risk and suppress development time and cost. The simulation of the hypersonic environment on the ground is difficult and is restricted to sub-scale models. While this can be used to support the basic geometry and qualify the materials, it must be followed up by larger scale flight testing that addresses the end to end function of the IAD.



Figure 3: An Inflatable Aerodynamic Decelerator (IAD) Can Be Used at Hypersonic Speeds

Initial testing is anticipated on sounding rockets as a follow-on to the ongoing IRVE project. Depending on the IAD design concept, the basic IRVE systems may be modified to demonstrate the new decelerator using a sounding rocket. This would provide a quick look at the IAD performance at subscale under high supersonic conditions.

To fully understand the IAD performance, ULA proposes to use the Atlas booster itself as a testbed. Recent work has shown that a sizeable experiment package can be flown within a pod called an External Payload Carrier (XPC), which attaches to the existing solid rocket motor mounts. This experiment can be deployed or ejected at any time during booster flight. On many missions the performance excess is so large that an experiment package weighing several tons could be accommodated. The capability to cost effectively deploy IAD prototypes into a hypersonic/rarefied environment which accurately simulates the entry conditions enables a test-driven development program that retires risk more rapidly and with greater certainty of results. It is our intent to mature the IAD to the greatest possible extent using the XPC as the test venue. This capability is almost unprecedented and represents a powerful tool for not only IAD development but any hypersonic vehicle design effort.

IV. External Payload Carrier (XPC)

A near-term opportunity for testing the hypersonic deceleration of partial booster recovery is the XPC that Special Aerospace Services, LLC is developing, through internal investment and partnering with United Launch Alliance. It utilizes the existing attaching hardware for the current Solid Rocket Boosters on the Atlas V rocket (Figure 4).

The XPC leverages existing hardware attach points on the Atlas V booster for the Aerojet produced solid rocket boosters. The XPC system is a hollow, unpressurized canister that provides the necessary electrical, power, and control systems to jettison suborbital payloads for the particular research need. The XPC canister can either be attached or jettisoned depending on the experiment being performed, with minimal or no impacts to the existing booster design, and no impacts to the primary payload.

- **Market Potential Identified for “Suborbital Heavy Lift”**
- **Flies in place of SRB**
 - Anytime excess launch vehicle performance is available
 - Mimics “empty” SRB
 - Unpressurized
- **Remains attached or can be jettisoned**
 - Multiple trajectory jettison points
 - Entire length of Stage 1 trajectory
 - Disposable or reusable
- **Large payload volume and mass**
 - 1200 ft³
 - 60 inch diameter, 50 feet length
 - 6000 pounds
 - Exceeds NASA’s sounding rockets and suborbital commercial providers

Figure 4: Location of the XPC Suborbital Heavy Lift Vehicle attached to an Atlas V Booster

XPC can be utilized as a testbed for suborbital, re-entry and hypersonic research. Each XPC configuration concept can be leveraged from successful flights from the previous concepts, and innovations of a mature TRL can be applied in a manner that does not make large system development leaps. The XPC Team has conducted trade studies for integrating various technologies including inflatable hypersonic decelerators and considers the testbed a near term capability.

The XPC concept leverages both NASA and ULA expertise in utilizing excess performance on the Atlas family of launch vehicles. XPC can carry in excess of 5,500 lbs of payloads in suborbital trajectory that mimics the altitude parameters of the existing NASA suborbital research vehicles.

XPC Suborbital Flight Regime

The XPC allows very large payloads to achieve a flight regime that is similar to the Black Brant suborbital rocket and other systems. The benefit is in the volume and size available to a payload, which lends itself to large fullscale or subscale hypersonic vehicles such as X-51, X-43, Hypersonic Test Vehicle (HTV) or subscale lifting bodies and capsules. Mach regimes are in excess of Mach 14 for hypersonic reentry vehicle demonstrators.

XPC Concept of Operations

The XPC vehicle mimics the existing handling operations currently in place for the Aerojet SRBs. The IAD would be integrated into XPC in a separate processing facility prior to launch. The XPC system would be self contained with minimal interfaces with the Atlas V Booster and launch vehicle. Figure 5 shows the evaluation of the existing handling fixtures and infrastructure utilized for potential processing of XPC.

- **Mimics Atlas V SRB**
 - Ground Operations
 - Processing
 - Attachment (uses identical SRB hardware)
 - Flight Operations
 - Aerodynamically equal to inoperative SRB
 - No impact to launch vehicle or primary payload
 - Multiple jettison points
(transatmospheric/exoatmospheric/ocean impact)



Figure 5: XPC will leverage existing concept of operations based on SRB processing

V. Conclusion

Partial booster recovery of existing Evolved Expendable Launch Vehicles (EELVs) is still a viable solution to solve challenges that are created with a launch rate greater than 15 launches per year. Engine throughput is maintained at a reasonable rate. Launch vehicle costs are reduced because the most expensive components on the rocket are being reused. Engine reliability is increased when engines are reused that have already been launched, thereby being “flight-proven”.

A future that contains ready accessibility to space is one that reuses key expensive components. The ability to advance the technology where this can be possible is feasible and is waiting to be fully developed. A key technology that requires significant development is the inflatable aerodynamic decelerator. Using the EELV External Payload Carrier to test this hypersonic decelerator at high-altitude, hypersonic conditions, significantly advances TRL without the full cost of a sounding rocket or launch vehicle.

References

¹ “Partial Rocket Reuse Using Mid-Air Recovery”, M. Gravlee et al. AIAA Space 2008 Conference, San Diego, CA (AIAA 2008-7874)