Ongoing Launch Vehicle Innovation at United Launch Alliance

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Abstract—General Dynamics and McDonnell Douglas revolutionized global space access with the introduction of their respective commercial Atlas I and Delta II rockets. [1][2]Developed with support from the Air Force as an anchor tenant, the commercial Atlas and Delta rockets evolved from their legacy ancestors. Through continuous innovation, these early commercial vehicles evolved to the current Atlas V and Delta IV launch vehicles that provide the backbone of America's national security and science space access. Through numerous acquisitions and mergers, both of these world class rocket families are now part of United Launch Alliance (ULA).

The long history of innovation that resulted in these vehicles continues today at ULA, ensuring that the Atlas and Delta families will continue to provide reliable, cost-effective space transportation for decades to come. Ongoing development of common manufacturing and processing, an improved RS-68A, and GPS metric tracking will provide enhanced customer support in the next few years. Currently in preliminary development, the Advanced Common Evolved Stage (ACES) and human rating will substantially enhance ULA's ability to support its customer needs. With conceptual development of partial booster reuse, orbital refueling, long-duration stages, and long-duration cryogenic propulsion stages, ULA is setting the stage to provide revolutionary space transportation in the years ahead.

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ACRONYMS

ACES	Advanced Common Evolved Stage
CBC	Common Booster Core
CCAFS	Cape Canaveral Air Force Station
CFM	Cryogenic Fluid Management
CRYOTE	Cryogenic Orbital Testbed
DCSS	Delta Cryogenic Second Stage
DMSP	Defense Meteorological Satellite Program
EDS	Emergency Detection System
EELV	Evolved Expendable Launch Vehicle
ESPA	EELV Secondary Payload Adapter
FTINU	Fault Tolerant Inertial Navigation Unit
GH2	Gaseous Hydrogen
GO2	Gaseous Oxygen
GRC	Glenn Research Center
GSO	Geosynchronous Orbit
GTO	Geostationary Transfer Orbit
HLV	Heavy Lift Vehicle
ILS	Initial Launch Capability
IOC	Initial Operational Capability
Isp	Specific Impulse
IVF	Integrated Vehicle Fluids
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LO2	Liquid Oxygen
MEO	Medium Earth Orbit
MLI	Multi Layer Insulation
MLP	Mobile Launch Platform
MRS	Minimum Residual Shutdown
NRO	National Reconnaissance Office
OSP	Orbital Space Plane
PLF	Payload Fairing
PRA	Probablistic Risk Assesment
RCS	Reaction control system
SRM	Solid Rocket Motor
ULA	United Launch Alliance
VAFB	Vandenberg Air Force Base
VIF	Vertical Integration Facility

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1. INTRODUCTION

United Launch Alliance (ULA) was formed to streamline America's space access, reducing costs while encouraging innovation through combining the talent of the people supporting Atlas and Delta. ULA by charter is a launch services company, providing equal space access to all users. ULA's rockets encompass the Delta II, Atlas V, and Delta IV families spanning the medium to heavy lift payload requirements. The continuous evolution (Figure 1) of Atlas and Delta has resulted in very reliable launchers.

The Atlas V and Delta IV versions were developed with participation from the U.S. Department of Defense in the form of $500M of funding. Lockheed Martin and Boeing funded the majority of the development, seeking to service both the national security needs and the anticipated robust commercial communication customer market. With the dot-com bust of the late 1990s, the commercial communication market never materialized. ULA was formed to enable the continuation of assured access to space even under the fiscal reality of a severely reduced launch market.

In the first three years of existence, ULA has consolidated management and engineering in Denver, CO (Figure 2). Through co-location of the engineering disciplines, ULA encourages cross pollination of methodologies and the use of common tools and process. With the recent implementation of a combined Atlas V and Delta IV sustainment contract, the Air Force and National Reconnaissance Office (NRO) are realizing further savings by eliminating multiple contracts and rules. Launch support consolidation is well underway with common crews supporting Atlas and Delta operations at Cape Canaveral Air Force Station (CCAFS) and Vandenberg Air Force Base (VAFB). ULA's consolidation continues with the transition of Atlas Booster and Centaur final assembly from Denver to

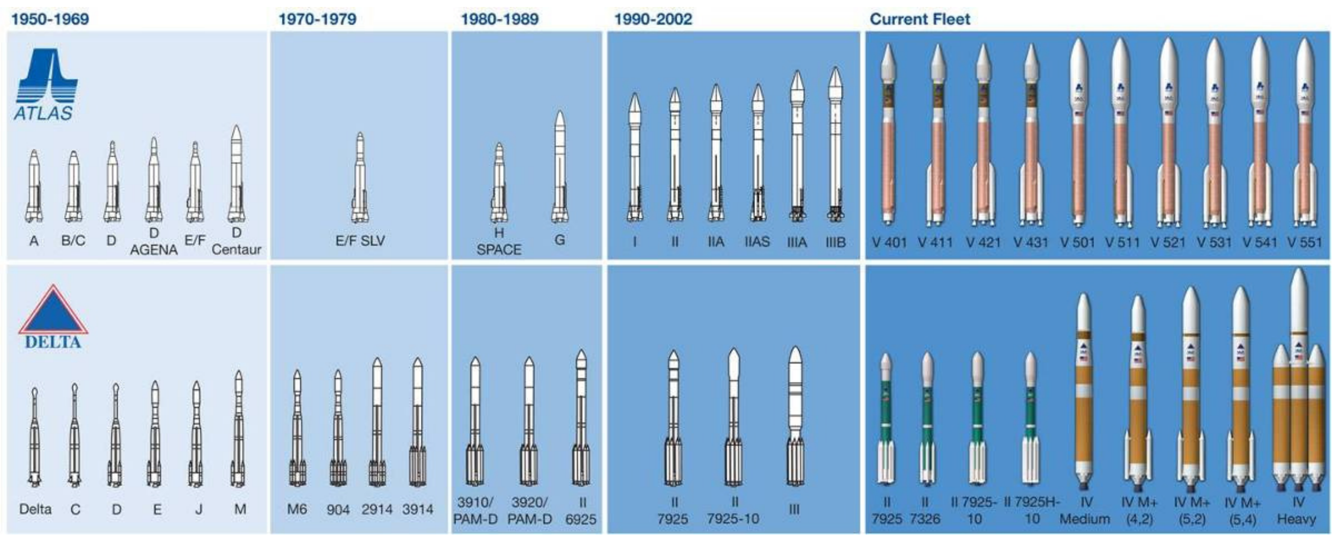

Figure 1 – Atlas and Delta have a long and successful history of evolving to meet customer requirements

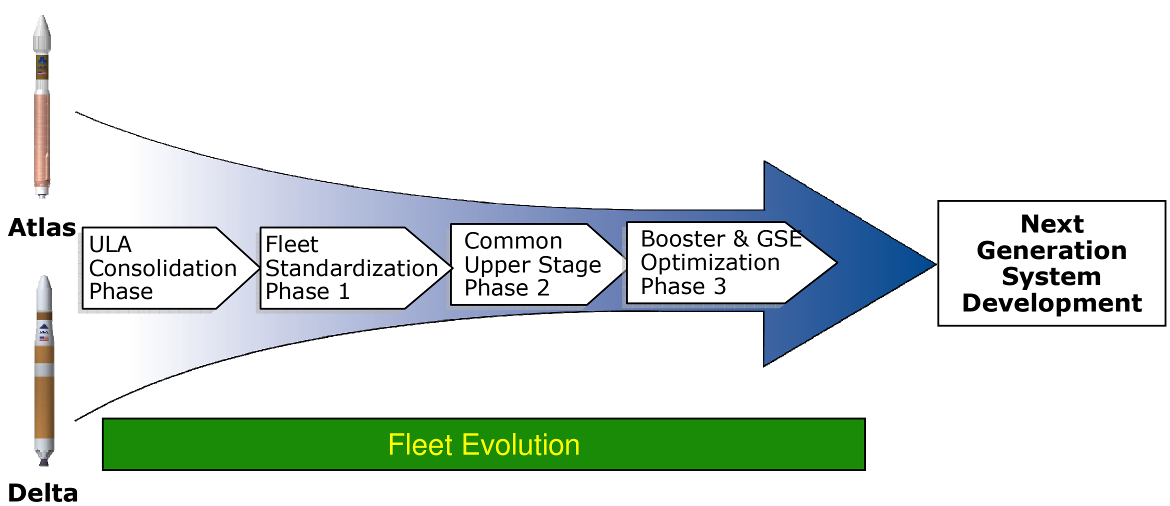

Figure 2 – ULA's consolidation of EELV contracts, management, engineering, production, launch operations and components is providing substantial savings and reliability improvements for the customer community

Decatur AL, which is expected to be complete by the end of 2009. 2010 will see the transition of Atlas booster tank production to Decatur followed in 2011 with Centaur tank production.

Going forward, ULA is investigating further opportunities for consolidation and commonality while balancing the desire for assured access to space with the customer mandate to reduce costs. Launch reliability will always be ULA's number one priority as represented in the successful flights of ULA's 37 missions as of December 2009 (Figure 3).

100% Mission Success

NROL-21 - 12/14/06 - Delta II
THEMIS - 2/17/07 - Delta II
STP-1 - 3/8/07 - Atlas V
COSMO-1 - 6/7/07 - Delta II
NROL-30 - 6/15/07 - Atlas V
Phoenix - 8/4/07 - Delta II
Worldview-1 - 9/18/07 - Delta II
Dawn - 9/27/07 - Delta II
WGS-1 - 10/10/07 - Atlas V
GPS IIR-17 - 10/17/07 - Delta II
DSP-23 - 11/10/07 - Delta IV
COSMO-2 - 12/8/07 - Delta II
NROL-24 - 12/10/07 - Atlas V
GPS IIR-18 - 12/20/07 - Delta II
NROL-28 - 3/13/08 - Atlas V
GPS IIR-19 - 3/15/08 - Delta II
ICO G1 - 4/14/08 - Atlas V
GLAST - 6/11/08 - Delta II
OSTM - 6/20/08 - Delta II
GeoEye - 9/6/08 - Delta II
COSMO-3 - 10/24/08 - Delta II
NROL-26 - 1/17/09 - Delta IV
NOAA-N' - 2/6/09 - Delta II
Kepler - 3/6/09 - Delta II
GPS IIR-20 - 3/24/09 - Delta II
WGS-2 - 4/3/09 - Atlas V
STSS-ATRR - 5/5/09 - Delta II
LRO/LCROSS - 6/18/09 - Atlas V
GOES-O - 6/27/09 - Delta IV
GPS IIR-21 - 8/17/09 - Delta II
PAN - 9/8/09 - Atlas V
STSS Demo - 9/25/09 - Delta II
Worldview-2 - 10/8/09 - Delta II
DMSP-18 - 10/18/09 - Atlas V
Intelsat-14 - 11/23/09 - Atlas V
WGS-3 - 12/5/09 - Delta IV
WISE - 12/14/2009 - Delta II

National Security - 18
NASA/Civil – 10
Commercial - 9

Figure 3 – ULA has successfully flown 37 missions since its inception in December 2006

2. RS68A Heavy Upgrade Program

The RS-68A engine enhancement was begun in 2006, driven by customers' need for increased performance. By upgrading the main injector and turbo pumps, the RS-68A adds a 108% enhanced power level while retaining the capability to still operate at 102% full power level. The minimum power level is also adjusted downward to 55% from 57%. Along with these thrust increases the RS-68A also provides increased Specific Impulse (Isp). The improved engine performance, along with other launch system enhancements, will increase the Delta Heavy Lift Vehicle (HLV) Geosynchronous Orbit (GSO) capability by more than 1,000 lbs.

The development test program for the RS-68A (Figure 4), consisting of 28 starts and 3,985 seconds of hot fire time, was completed in October 2009. The development testing has successfully demonstrated the improved engine thrust and ISP. As of November 2009, the program is transitioning to certification testing with expected completion in the second quarter of 2010. First flight of a Delta IV HLV with the RS-68A is scheduled for 2011.

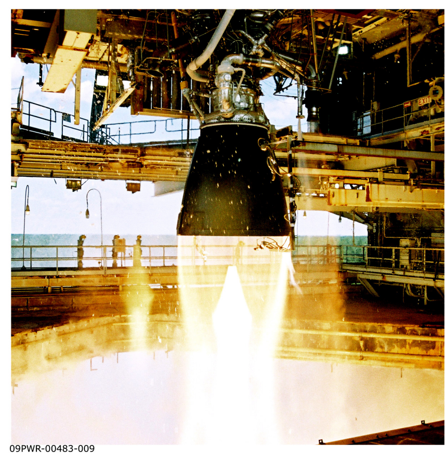

Figure 4 – RS68A undergoing hot fire testing at NASA Stennis Space Center (Credit: Pratt and Whitney Rocketdyne)

3. Common Delta Booster Core

During Delta IV development, Evolved Expendable Launch Vehicle (EELV) performance specifications drove the team to customize the common booster core (CBC) structure designs for the different vehicle configurations (Medium, Medium+, HLV). The lightest weight booster structure is used on the Medium. The Medium+ configurations, requiring more strength, incorporate a somewhat heavier structure and attachment fittings for two or four solid rocket motors (SRMs). The HLV booster core is uniquely configured to carry two strap-on liquid boosters, and the strap-on boosters themselves incorporate a unique lighter weight structural configuration. While these multiple booster configurations optimize performance, they inhibit the ability to respond to changes in the Delta manifest. Changes in customer launch schedule needs or other perturbations to a launch campaign can result in an inventory challenge. For example, a booster core developed for a M+(4,2) mission can not currently be used on a Medium mission.

With the increased performance provided by the RS-68A, ULA is pursuing transition to a truly standardized CBC (Figure 5) capable of supporting all Medium and M+ mission configurations, similar to the flexibility currently enjoyed by the Atlas. This will improve launch manifest flexibility and operational agility through allowing CBCs to be reassigned if/as necessary at the launch site. Standardized CBCs are also expected to reduce production and mission integration costs while improving reliability.

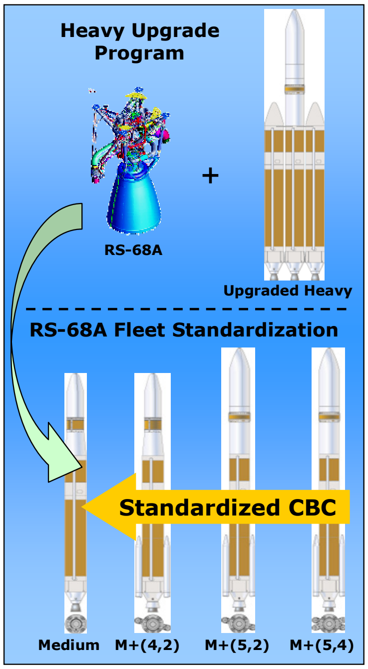

Figure 5 – Standardized common booster core

4. ATLAS V AND DELTA IV HUMAN RATING

Today's Atlas and Delta have evolved to provide reliable assured access to space for critical Air Force, NRO, NASA and commercial missions. Earlier this decade NASA embraced these designs by selecting the Atlas V and Delta IV to launch the crewed Orbital Space Plane (OSP) due to their robust, flexible designs, the reliability (calculated and demonstrated), and the confidence in these launch vehicles resulting from their evolutionary development approach that minimized the historical first flight risk. In the 5 years since NASA originally selected Atlas V and Delta IV to launch the OSP, the vehicles have incorporated additional reliability upgrades and have continued to demonstrate 100% mission success.

Today these systems offer the key to significantly reducing the gap in US human spaceflight capability by providing flight-proven launch systems that offer the benefits of early Initial Launch Capability (ILC), lowest nonrecurring and recurring costs, and demonstrated reliability that meets or exceeds NASA Loss of Mission requirements. With the addition of a robust launch abort system, both Atlas and Delta can exceed stringent NASA Loss of Crew requirements. Both launch vehicles offer unique advantages for a commercial crew program or for the launch of the Orion Crew Exploration Vehicle [1]. The EELVs are ready to support crew lift with flight proven vehicles that will have an even longer legacy of flights by the crewed Initial Operational Capability (IOC) date with superior demonstrated reliability compared to any new system.

The Atlas V, with the relatively minor addition of an Emergency Detection System and a dedicated NASA Vertical Integration Facility (VIF) and Mobile Launch Platform (MLP), is ready for commercial human spaceflight and complies with NASA human rating standards. The 3 ½-year integration span is likely shorter than the development of any new commercial capsule that might fly on it.

The Delta IV has ample performance to support the existing Orion vehicle, without Black Zones. The Delta IV can support a mid-2014 Crewed IOC, which is superior to Orion launch alternatives. The proposed 37A pad is a look-alike counterpart to the existing 37B pad with low development risk. Human rating the Delta is a relatively modest activity, requiring the addition of an Emergency Detection System, and an array of relatively small redundancy and safety upgrades (both in the vehicle and the engines) that are almost trivial compared to the original development of the Delta IV.

Figure 6 illustrates the demonstrated reliability benefits of a common fleet of launch vehicles supporting both crew and other launch needs. By 2015 Delta IV will have flown over 50 Common Booster Cores, including eight Delta IV-Heavy vehicles. Atlas V will have flown nearly 65 times.

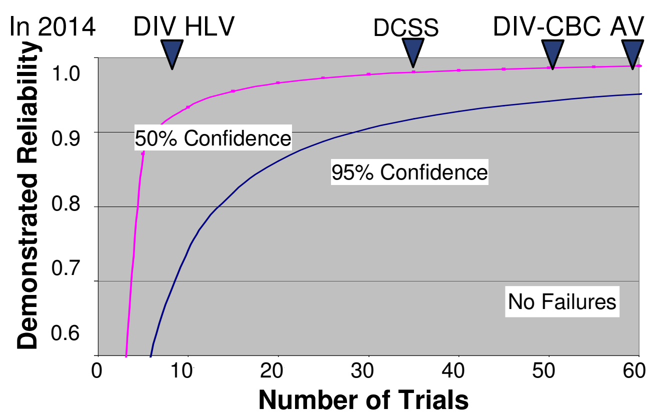

Figure 6 – A common family of launch vehicles providing crew launch demonstrates reliability sooner than a unique vehicle

ULA believes that human rating should be comprised of three primary factors: (1) launch vehicle reliability, (2) addition of an Emergency Detection System (EDS), and (3) intact abort capability (Figure 7). The combination of these three elements provides a common-sense, system-level approach to accomplish the goal of safe, reliable transportation to Low Earth Orbit (LEO).

Launch Vehicle Reliability

Probably the single most important factor for human spaceflight is demonstrated reliability. Atlas and Delta have used an evolutionary approach to enhance the capabilities of the systems, which is evident in their long history of launching successfully. This record has not been achieved by accident. Rather, it is the reliance on experienced people;

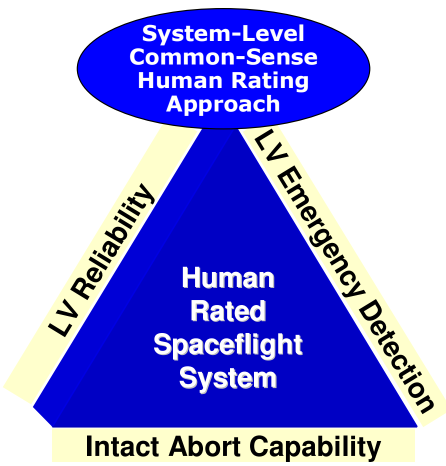

Figure 7 – Human rating triangle of truth

robust, repeatable processes; single-fault tolerant systems where reliability is enhanced; robust vehicle designs and vehicle characterization; and rigorous, closed loop "test-as-you-fly" processes. These advantages come as direct results from ongoing launch operations. The Atlas V and Delta IV design reliability is based on a detailed, probabilistic risk assessment involving Aerospace Corporation, the Air Force and NASA. The results are shown in Table 1, along with the associated LOC numbers, assume the probability of a failed abort is 1/10.

Table 1 – EELV Loss of Mission and Loss of Crew calculations based on PRA developed mission reliability

Vehicle	Loss of Mission		Loss of Crew	
Delta IV Heavy	0.9875	1/80	0.9987	1/800
Atlas V Heavy	0.9900	1/100	0.9990	1/1000
Atlas V 401	0.9960	1/250	0.9996	1/2500
Atlas V 402	0.9942	1/170	0.9994	1/1700
Note: All values represent 50% confidence level				

Addition of an Emergency Detection System (EDS)

Historically, launch systems have incorporated some level of EDS that would monitor critical systems and issue status, warning and abort commands. For Atlas and Delta, the EDS would be common and scalable, and utilize existing sensors within an architecture that uses an independent, fault tolerant failure sensing system. Operational systems such as Atlas and Delta offer the advantage of flying the EDS on all missions, in addition to having flight environments that are well known and well characterized.

Intact Abort Capability

Liquid propulsion systems offer the key advantages of minimal catastrophic failures (compared to solid systems) and thrust termination prior to any abort. The resulting benign environment will maximize the ability of the crewed vehicle to successfully abort and return the crew safely. Finally, in conjunction with the crew vehicle design, Atlas and Delta can meet NASA Human rating requirements specified in NASA-STD-3000 for Crew Loads Limits without any abort Black Zones or significant reduction in performance.

5. Common Centaur

ULA currently boasts a plethora of unique flight elements including three cryogenic upper stages, two similar but different RL10 engines, six different payload fairing (PLF) families, two independent flight avionic systems, and a number of different payload adapters. To accommodate all of the unique elements we have a host of overlapping facilities including software integration labs, avionic labs, and adapter and fairing vendors. At ULA's forecasted flight rate of eight to twelve EELV missions per year, many of these labs and vendors only support one or two missions per year. While the existing situation supports a narrow definition of assured access to space, it is not affordable and results in a fractured, ailing supplier base.

A common upper stage provides a focus and opportunity to consolidate the hardware and infrastructure while improving overall reliability by enabling healthy launch rates for all systems. ULA has performed trade studies to determine how best to consolidate around a common upper stage (Figure 8).

Use of the Delta IV 4m or 5m upper stages as a Centaur replacement on Atlas resulted in the need to add an SRM to nearly every mission due to the heavier dry masses.

Centaur's use on Delta IV improved mission performance for nearly every mission thanks to the 1,500 to 3,000 lb dry mass reduction. The ability to add a second engine further improves Delta IV LEO performance. However, Centaur degrades Delta's high energy mission performance such as GSO due to the lower propellant load (46 klb compared to Delta's 5m stage 61 klb) and the reduced RL10A-4-2 Isp of 451 sec compared to the RL10B-2 465 sec.

Consolidation around a Common Centaur will allow ULA to consolidate around the Fault Tolerant Inertial Navigation Unit (FTINU), common avionic and software labs, a single

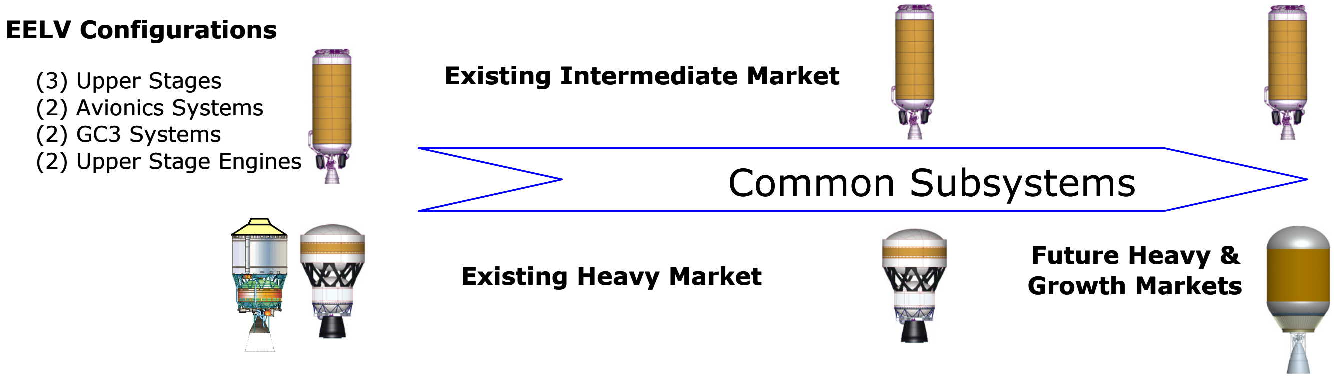

Figure 8 – As part of ULA's overall consolidation strategy we are pursuing consolidating to a common upper stage that supports both Atlas and Delta boosters

set of 4m and 5m PLF families, a reduced number of payload adapters, and a common RL10.

Propulsion Evolution

With a large inventory of RL10B-2 engines, ULA plans to re-manufacture some of these engines to support Atlas/Centaur missions starting in 2013. This period of remanufacturing RL10s will provide Pratt and Whitney Rocketdyne with a window of opportunity to perform its own consolidation prior to building a next generation RL10 that combines features of the RL10A-4-2 and RL10B-2.

ULA continues to investigate alternative engine options that provide the required performance and reliability while being simpler and less costly to develop.

6. Enhanced Launch Service Capabilities

To satisfy evolving customer requirements ULA is continuously looking to improve our on-orbit flexibility to accommodate more burns, longer mission durations and improved operational flexibility. To this end ULA is pursuing a number of technology innovations.

Flight Demonstrations

Six distinct demonstrations were performed on Atlas V AV-017 DMSP-18 (Figures 9 and 10) specifically designed to improve our understanding of propellant settling and slosh, pressure control, RL10 chilldown and RL10 two-phase shutdown. Demonstrations such as these and the many that have previously flown are designed to guide further upgrades to ULA's current Atlas and Delta cryogenic upper stages improving performance and allowing longer, more demanding missions. These results also directly benefit current operation of the Air Force Evolved Expendable Launch Vehicle (EELV) fleet, development of ULA's planned Advanced Common Evolved Stage (ACES), and other cryogenic systems such as long-duration cryogenic propulsion stages and orbital refueling.

Special research and development instrumentation was added to Centaur, the Atlas cryogenic upper stage, to

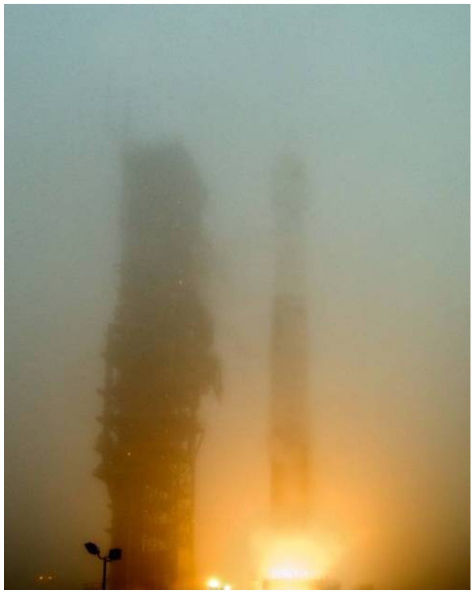

Figure 9 – Lift-off of AV-017 carrying the DMSP satellite for the Air Force

Figure 10 – Centaur's sidewall was painted white and numerous dedicated instruments were added to support the on-orbit CFM demonstrations

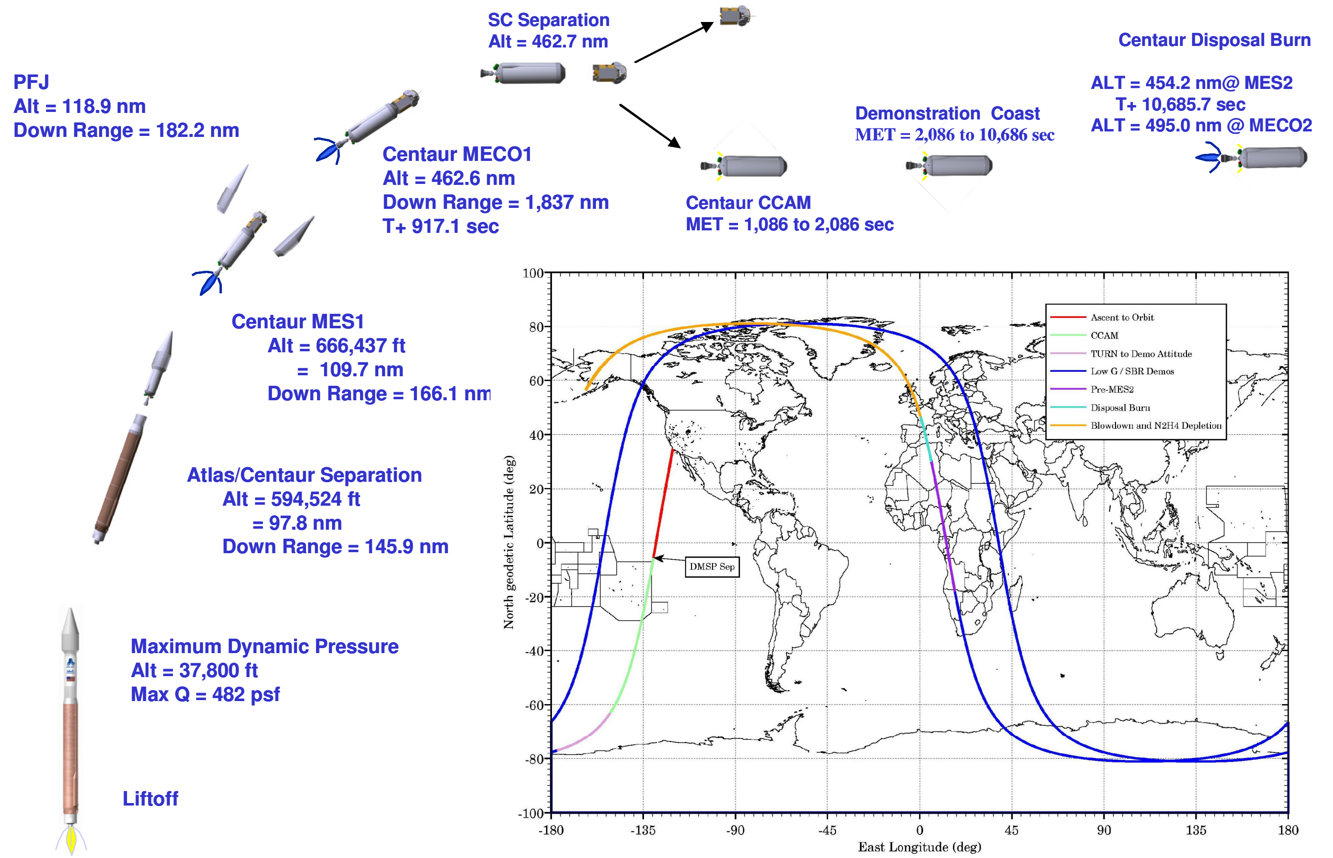

Figure 11 – A 2.4-hour post spacecraft mission extension was added to the DMSP-18 launch to allow for a number of on-orbit demonstrations

support the demonstration including temperature measurements on the LH2 sidewall, forward bulkhead, LH2 feedline, RL10 pump housing and aft bulkhead components. The demonstrations commenced once Centaur had maneuvered a safe distance away from DMSP-18 to ensure no risk to the spacecraft. The Centaur disposal burn was delayed by 2.4 hours to allow for the low acceleration demonstrations. The disposal burn itself provided a unique opportunity to perform demonstrations without an attached payload. The light weight of DMSP-18 allowed 12,000 lbs of remaining LO2 and LH2 propellant, 28% of Centaur's capacity, for the demonstrations.

A preliminary data review of the demonstrations showed very favorable results. The majority of instrumentation worked properly, providing a wealth of data.

Low-G Settling Demonstration— Centaur and other cryogenic space propulsion systems, such as the Delta IV second stage and Saturn V's S-4B stage, use on-orbit settling to separate liquid from gas. This separation is critical, enabling the stages to vent pure gas to control tank pressure. The required magnitude of settling acceleration directly affects the stage performance and maximum coast duration. For this demonstration, Centaur was settled by pulsing its four hydrazine thrusters at a reduced duty cycle to provide half of the acceleration that is typically used to support Centaur's longer coast missions. Lower duty cycle settling reduces the hydrazine consumption rate, allowing longer mission durations.

Results from the sidewall and bulkhead temperature measurements show that LH2 remained settled for the majority of the phase. A slosh wave did briefly cool the forward bulkhead after initially achieving the lower settling level, but the LH2 remained adequately settled for the remainder of the demonstration. The short sloshing period can be accommodated on future operational missions by inhibiting venting during the start of a coast. Ultimately, this lower acceleration level is shown to adequately support future long coast missions.

Solid-Body-Rotation Settling Demonstration— For coasts longer than about 15 minutes, Centaur is rolled around its longitudinal axis to ensure uniform heating. Typically, the roll direction is regularly reversed to prevent solid body rotation of the propellant. For this demonstration, Centaur maintained a single roll direction to ensure solid body rotation. Following the low axial settling period, settling thruster firing was terminated with the objective to demonstrate that low level centrifugal acceleration could adequately retain liquid slosh. The liquid slosh must be kept sufficiently damped such that the hydrogen vent port, located on the forward door near the tank centerline, remains clear of liquid.

Initial post flight review of the attitude control thruster firings indicates that the solid body rotation did not induce nuutation affects that would adversely affect future missions. Likewise, Centaur hydrogen tank venting and bulkhead temperature measurements confirm that the centrifugal settling maintained adequate liquid control and that disturbances caused by gaseous hydrogen and oxygen venting had no negative mission impact. Initial flight review indicates that centrifugal settling is promising, but the on-going detailed data review will be required to determine if it is beneficial for future flights.

Oxygen Venting on Orbit— Centaur's oxygen vent is not balanced so oxygen venting produces a torque on the vehicle. This is not a problem during current missions since Centaur does not vent on-orbit, however, longer duration missions in the future may require on-orbit oxygen venting to control tank pressure. This demonstration was designed to determine both oxygen and hydrogen liquid propellant management characteristics and vehicle control with the asymmetric force generated during oxygen venting.

Oxygen venting was conducted during both the low acceleration and centrifugal settling demonstrations. Results show that the LH2 remained settled during the low-g settling phase. No adverse propellant motion or vehicle control issues were observed. Following the GO2 vent during the Solid-Body Rotation settling phase, LH2 sloshing was observed on the forward bulkhead as predicted. If future missions utilize solid body rotation settling we may need to inhibit hydrogen venting for a short period of time following oxygen venting.

LH2 Pulsed Chilldown— Prior to pumping LO2, the RL10 engines must be chilled. This is typically accomplished by flowing cryogenic propellants through the engine. Flight demonstrations conducted during the 1990's on Atlas and Titan Centaurs demonstrated that pulsing the LO2 flow significantly reduces the required quantity of propellant. Information gained from the 1990's demonstrations formed the basis of Centaur's current LO2 "trickle" chilldown process that substantially reduced the required LO2 consumption.

The demonstration performed on the DMSP-18 mission was designed to provide similar data for the LH2 pump chilldown. The long coast during which the settling demonstrations were performed allowed the Centaur feedlines and RL10 engine hardware to warm to relatively high temperatures. The LH2 flow was then pulsed multiple times prior to the second main engine start. Each pulse consisted of a period of liquid flow followed by a period of no flow to allow LH2 to boil and cool the pump. Flight results showed that the pulsed chilldown did a good job of removing heat from the feedline and pump housing while reducing propellant usage. This chilldown technique shows good promise for future long coast missions.

GO2 Venting during Engine Burn— There are certain situations where it is advantageous to rapidly reduce Centaur LO2 tank pressure during the burn. The influence of this pressure change on RL10 operation and Centaur environment was demonstrated on this mission. Extra instrumentation was mounted on various Centaur aft bulkhead components to determine the vibration environment and validate that the oxygen vent plume did not create an adverse environment by interacting with the engine plume. Mission results show that no adverse environment was observed and RL10 engine operation was unaffected by the pressure change, thus demonstrating that venting of the oxygen tank is feasible for future missions.

Modified Minimum Residual Shutdown (MRS)— MRS allows Centaur to continue RL10 operation until liquid pull-through. Centaur utilizes MRS to maximize performance for missions where precise orbit injection accuracy is not required. Normal MRS logic commands RL10 shutdown as soon as acceleration starts to fall off. This demonstration allowed the RL10 to continue operation until thrust fell substantially.

Good data was obtained. Engine thrust decayed once the LO2 was depleted and vehicle acceleration dropped precipitously as expected. Following pull-through, the RL10 continued to generate thrust by burning a combination of liquid and gaseous propellants before the RL10 reached final shut down at a preset time. During this period, Centaur experienced a few thrust spikes possibly caused by ingestion of trapped liquid. Potential benefits of utilizing this two-phase engine operation for future missions include increased engine performance or improved Centaur disposal options.

Useful data has already been obtained from these demonstrations and on-going detailed analysis by the Air Force and ULA will quantify the potential benefits and impacts of implementing these techniques. Just as flight demonstrations in the past have led to the high capability of today's Centaur, the results of these demonstrations will further allow ULA to improve on second stage design and operation to guide development towards more advanced space-based cryogenic systems.

Integrated Vehicle Fluids (IVF)

Today's Centaur and Delta Cryogenic Second Stage (DCSS) missions are limited to three burns over the course of an eight hour mission due to the limited supply of hydrazine, helium and power. Even to satisfy our existing range of missions from LEO to Medium Earth Orbit (MEO), Geostationary Transfer Orbit (GTO), and GSO, a variety of mission kits are required. To improve mission flexibility, ULA is developing the IVF system to allow the use of hydrogen and oxygen from the upper stage primary tanks to satisfy the settling, attitude control, pressurization, and power requirements (Figure 12). The IVF will allow the elimination of hydrazine and helium from the vehicle while

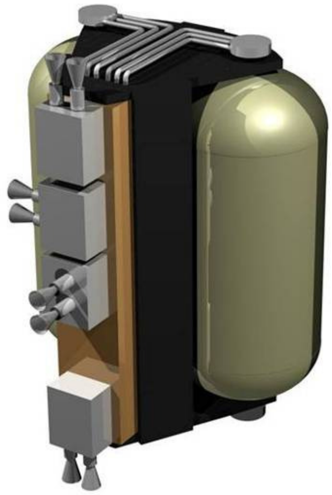

Figure 12 – Integrated vehicle fluids module is designed to support RCS, pneumatic and power requirements

Figure 13 – Testing has demonstrated the functionality of this low cost hydrogen/oxygen thruster (Credit: Innovative Engineering Solutions)

replacing the existing large capacity batteries with small rechargeable batteries.

Development of the hydrogen/oxygen thruster is progressing well with concept testing under way (Figure 13). Cryogenic composite pressure bottle testing is also progressing well. Development of the small pumps that will enable system operation is in the early stages.

Common Bulkhead Insulation

Heat leak from the LO2 to LH2 tanks through the common bulkhead is one of the factors limiting Centaur's ability to support long-duration missions. Over the past three years, ULA has performed extensive insulation material studies seeking a replacement for Centaur's existing matt using a unique cryogenic test dewar developed specifically to mimic the common bulkhead (Figure 14). The pressure loading requirements resulted in many promising candidate materials, such as glass bubbles and aerogel, not performing particularly well. The testing did point to a particular solution that is robust, minimally compressive, inexpensive, and meets all of our thermal and mass requirements. This material can be retrofitted into the existing Centaur's bulkhead as well as support future stages.

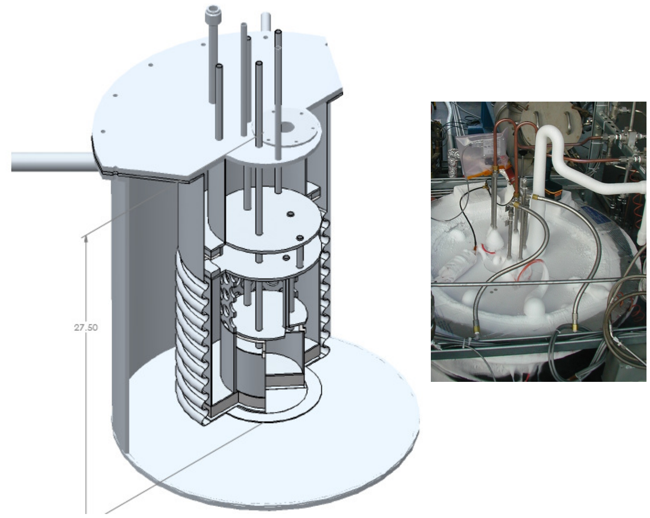

Figure 14 – A cryogenic dewar that can simulate the thermal and compressive environment of Centaur's common bulkhead was developed to test candidate insulation materials (Credit: Innovative Engineering Solutions)

Sun Shield

When using the Atlas 5m PLF, the Centaur is fully encapsulated. This allows Centaur to be shrouded in a multi-layer insulation (MLI) blanket to reduce cryogenic propellant boil-off and efficiently support eight-hour GSO missions. For the Atlas 4m PLF or Delta IV missions, the upper stage side wall is fully exposed to the atmosphere during ascent preventing use of fragile MLI. Without MLI, these vehicles experience very high on-orbit boil-off rates. This significantly reduces GSO performance for the Delta HLV. The Atlas 4m PLF configuration is not offered for GSO missions due to the high boil-off rates.

In order to address these issues, ULA has partnered with ILC-Dover to develop a deployable sun shield. Once on-orbit, the conic sun shield is deployed to shade the upper stage from direct solar or Earth radiation (Figure 15). To allow for an extremely compact design, the sun shield is pneumatically deployed using a culminator (Figure 16). Even with efficient shading, the upper stages will evolve substantial quantities of Gaseous Hydrogen (GH2), making use of inflatable structures ideal. To date, the sun shield has evolved through learning from multiple proof of concept shield developments including thermal vacuum testing at NASA Glenn Research Center (GRC).

Vapor Cooling and Para-Ortho Conversion

Vapor cooling offers an attractive method to intercept external stage heating to reduce heating, increase performance and allow for longer mission durations desired by some customers. GH2 para-ortho conversion improves the vapor cooling effectiveness by ~10% by taking advantage of unique hydrogen properties. ULA is investigating the use of hydrogen vapor cooling and para-ortho conversion on Centaur and the DCSS to eliminate LO2 boil-off and reduce hydrogen boil-off (Figure 17).

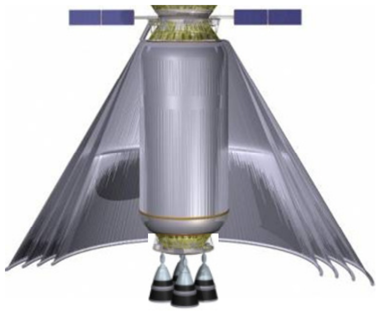

Figure 15 – Conic sun shield shades the cryogenic upper stage to minimize boil-off

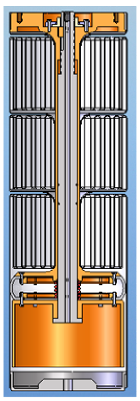

Figure 16 – The sun shield is pneumatically deployed through use of a culminator (Credit: ILC Dover)

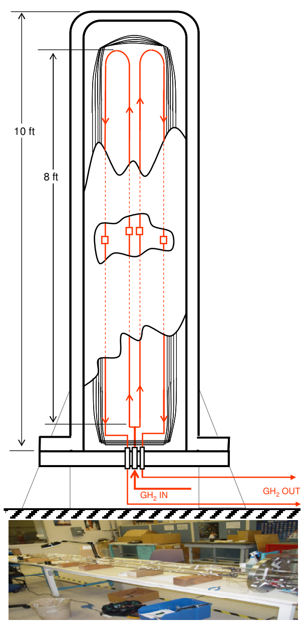

Figure 17 – Testing has demonstrated the vapor cooling improvement using hydrogen para-ortho conversion (Credit: Boeing)

CRYOTE

While we have learned much from utilizing the existing upper stages to demonstrate cryogenic fluid management (CFM), the need to guarantee no risk to the primary payload and the short duration limits the types of learning that can be accomplished. We can further the ability to upgrade our stages and satisfy growing customer requirements by utilizing an on-orbit CFM laboratory that enables the testing of hardware and procedures that would be impractical on our current stages.

In partnership with NASA and industry, ULA is developing an affordable CRYogenic Orbital TEstbed (CRYOTE) [2] to demonstrate a broad array of critical CFM technologies in space. These technologies include system chilldown, transfer, handling, health management, mixing, pressure control, active cooling and long-term storage. Testing and validation in the micro-gravity environment is essential for developing improved mission capabilities using cryogenics.

CRYOTE is a long-duration, in-space laboratory containing a sizeable tank of LH2. The laboratory is installed on an Atlas V rocket between the Centaur upper stage and the primary payload (Figure 18). To minimize risk to the primary payload, the CRYOTE tank is launched dry, with dormant avionics. Following delivery of the primary payload, CRYOTE's avionics are activated by Centaur's flight computer. A pyro valve separating Centaur's propellant tank from the CRYOTE fluid line is fired, and a settling sequence chills the system and delivers residual LH2 from the Centaur upper stage to fill the CRYOTE tank. After CRYOTE is filled with Centaur's residual LH2, the twocraft separate, leaving CRYOTE as an independent free flyer.

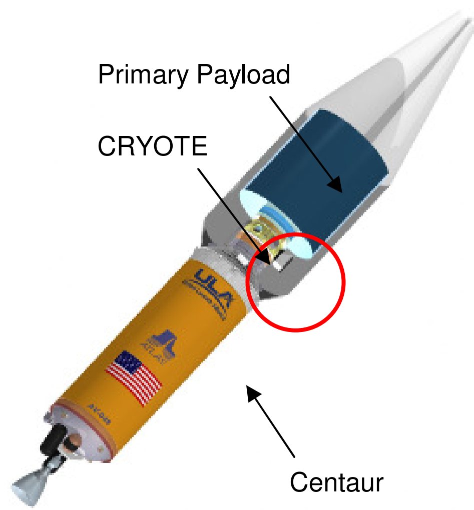

Figure 18 – CRYOTE is launched between the upper stage Centaur of an Atlas V rocket and the primary payload

There are numerous drivers that contribute to CRYOTE's design. Structural stability, vibrational modes, thermodynamics, fluid motion under various gravitational environments, interface with the Centaur LH2 tank, and fluid transfer and experiment operations must all be considered. Specifically, CRYOTE is being designed to mimic the fluid and thermal environments seen on Centaur and DCSS as well as ULA's planned ACES and other cryogenic propulsion systems.

Components integral to the CRYOTE system are an EELV Secondary Payload Adapter (ESPA) ring, a tank, a skirt (which attaches the tank to the ESPA ring), a fluid regulating system, fluid lines, a robust insulation system, and an avionics suite that includes an attitude control system (Figure 19).

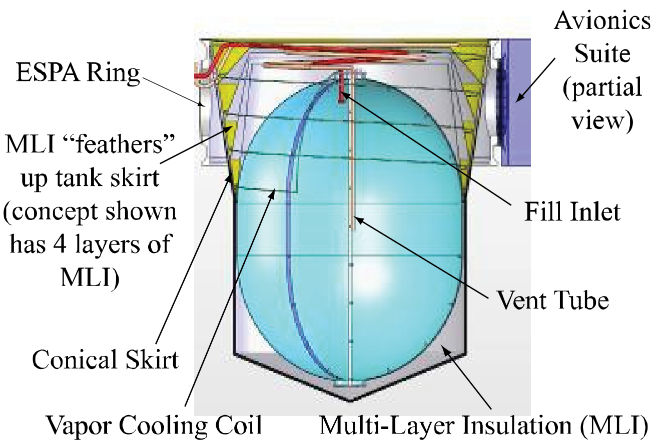

Figure 19 – CRYOTE main components (Credit: IES)

Results from CRYOTE experiments will support longer mission durations, reduced boil-off, lower chilldown consumption, improved pressure control, as well as low acceleration and micro-gravity propellant control. The improved CFM capabilities will directly benefit our existing customers while enabling us to anticipate and support future customer requirements.

7. ADVANCED COMMON EVOLVED STAGE (ACES)

ULA is in the process of defining a new upper stage that will replace Centaur and the DCSS. ACES is part of ULA's long-term strategy to improve the support we provide to our existing national security, NASA science, and commercial missions [3]. Extensibility to additional transportation needs such as increased performance, human rating, and long-duration missions is also being incorporated into the ACES design.

The baseline ACES will contain twice the Centaur or 4m DCSS propellant load and support 4 RL10 class engines providing a significant performance boost compared to our existing upper stages. The baseline 41-mT propellant load is contained in a 5m diameter, common bulkhead stage that is about the same length as ULA's existing upper stages. ACES will become the foundation for a modular system of stages to meet the launch requirements of a wide variety of users.

ACES is based on a simple modular design (Figure 20). Use of multiple barrel panels, similar to Centaur, provides a straight forward means to building multiple-length (propellant load) stages that are otherwise common. The common equipment shelf accommodates one, two, or four RL10 engines. ACES will take advantage of the existing Centaur and Delta subsystems such as avionics, pneumatic, and propulsion elements. The majority of these subsystems are directly transferable with little or no changes required.

The ACES design is optimized with long-duration cryogenic applications in mind. A number of passive-thermal management features will be incorporated into the stage at the system level. The tank geometry is designed to minimize the exposed surface area. Through the use of a thermally

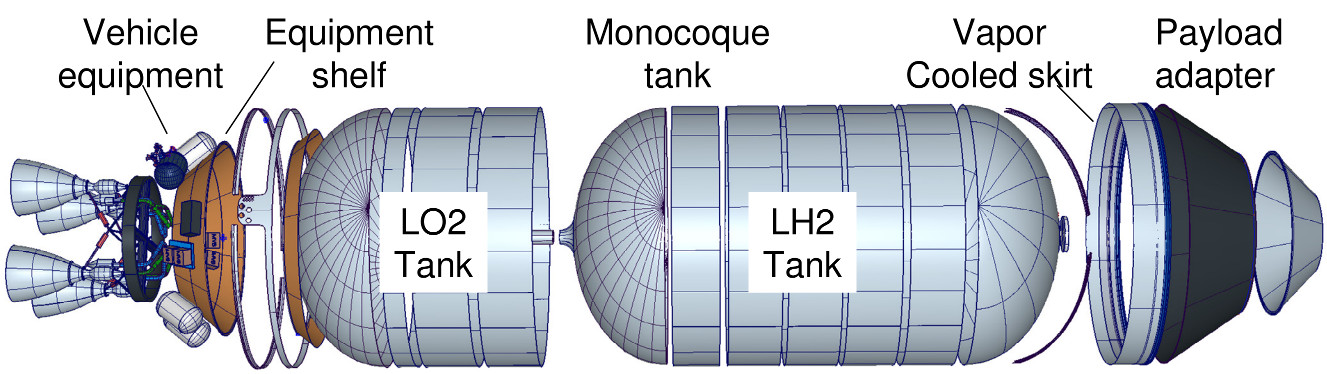

Figure 20 – ULA's planned Advanced Common Evolved Stage (ACES) will fly on both the Atlas V and Delta IV boosters, enhancing mission capability while reducing costs through commonality; ACES design encompasses intended variations supporting upper stage and in-space applications

isolated equipment shelf tank penetrations are being minimized. Vapor-cooling paths, where vented hydrogen is used to intercept the remaining high-load heat paths, are integrated into the tank structure.

Mission reliability is a key demand of our payload customers. ACES will continue to place a top priority on reliability across the entire life cycle, including design, component and process levels. ACES will incorporate single fault tolerance at least equivalent to our existing stages. Significantly, the dual and quad engine ACES variants incorporate engine out. Engine-out capability provides the single largest lever to improving system reliability (Figure 21).

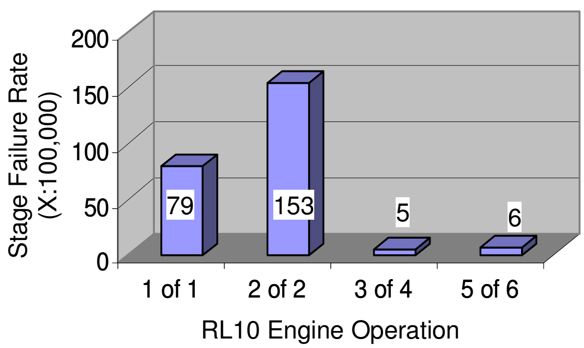

Figure 21 – By incorporating engine out accommodation ACES significantly improves mission reliability

8. Future Space Transportation

The vast majority of the world's large scale cryogenic propulsion and CFM expertise has been combined with the formation of ULA, Figure 22. ULA has utilized this vast experience to investigate transportation architectures that enable very demanding missions including heavy outer solar system payloads using multi-launch architectures [4], on orbit refueling [5], [6], and long-duration cryogenic propulsion stages [7], [8]. These space transportation architecture investigations show that affordable, near term derivatives of the existing Atlas V and Delta IV can support very heavy payloads and missions requiring extremely high energy or long durations.

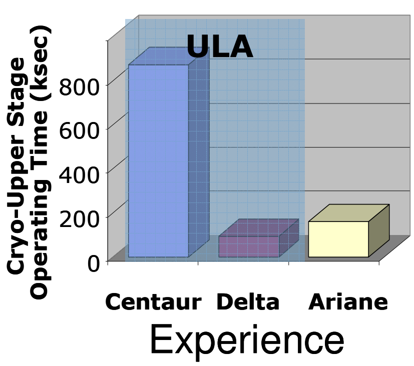

Figure 22 – Most of the worlds on-orbit propulsion CFM expertise has been combine in ULA

9. Summary

The Atlas and Delta rockets have each demonstrated 50 years of innovation and continuous product improvement culminating in the current Atlas V and Delta IV vehicles. This history of innovation has enabled the vehicles to meet growing customer requirements. This innovative legacy continues today as ULA strives to upgrade our vehicles to support increasing performance, enhanced flexibility, longer missions, more burns, crew launch and generally the ability to support a broader set of launch service needs.

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BIOGRAPHY

Bernard Kutter *is manager of advanced programs for United Launch alliance. He is responsible for developing new technology to support ULA's long term launch service needs including development of EELV evolution plans, long-duration enhancements, performance upgrades and derivative systems. In 2003 Bernard initiated and led development of Atlas evolution including in-space applications. From 1994 to 2003 Bernard managed the Atlas Centaur thermodynamics group, where he was involved in 67 successful missions. In 1988 he joined General Dynamics where he was involved in the development of cryo fluid management techniques for the new Titan IV Centaur stage, including the first successful launch. Bernard started his career at GE jet engines in 1987. He has a BSAA from the University of Washington.*

Scott Ward *is Director of Delta IV Upgrades and the Delta IV Heavy Upgrade Program for United Launch Alliance (ULA). In this position he has overall responsibility for executing projects associated with continued development and evolution of the Delta IV family of expendable launch vehicles. One of the major projects in the portfolio that Ward manages is the Heavy Upgrade (HUG) program which is enhancing the performance of the Delta IV Heavy launch vehicle in order to meet evolving customer needs. He is also managing the Delta IV Fleet Standardization Program (FSP incorporating the RS-68A into the Delta IV Medium and Medium+ vehicle configuration. Before joining ULA, Ward held the same position for The Boeing Company. Prior to this assignment Ward was Chief Systems Engineer for Delta IV Development activities, overseeing development and refinement of design concepts for evolving the current operational Delta IV fleet into higher performing variants. Ward began his career at McDonnell Douglas in 1986 as an aerodynamicist working on advanced programs at the commercial aircraft division. He later moved to the Missiles and Space Division where he held positions of increasing responsibility providing specialized Computational Fluid Dynamics analysis expertise to support various strategic defense and NASA programs. In 1996 he transitioned to the Delta IV program. Ward has a BSAE from the University of Virginia and a MSAA from Stanford University.*

Mari Gravlee *is a principal investigator in Business Development and Advanced Programs for United Launch Alliance (ULA). She supports Atlas V and Delta IV rocket technology advancement through projects that facilitate synergy between the two product lines, develop technologies for extended duration missions, and enable full use of rocket performance. Prior to joining Advanced Programs, Gravlee was an engineer in the Atlas Ground Support Equipment group for Lockheed Martin Space Systems Company where her focus was designing launch pads, transportation & handling, storage hardware, and tooling for the Atlas booster, Centaur, and solid rocket motors. Gravlee previously designed power supplies for mobile phones and laptops in Motorola's Energy Systems Group. She has a BSME from the Georgia Institute of Technology, with honors.*

Jeff Patton *is the manager for NASA and Commercial Crew and Cargo Programs for United Launch Alliance (ULA). In this role, Patton is responsible for advanced studies and programs including ongoing work to offer ULA launch vehicles for commercial human spaceflight and cargo delivery services. Jeff developed the approach for ULA launch vehicles to comply with human rating requirements and led the ULA technical teams who have completed preliminary integration of a number of potential crew and cargo transfer vehicles on ULA launch vehicles. At Lockheed Martin, he was responsible for the Systems Requirements and Integration activities for the highly successful Atlas III and Atlas V launch vehicle development Programs. At General Dynamics Space Systems Company in 1987 he was the project engineer in charge of the General Dynamics Field Office at NASA's Johnson Space Center and also worked a number of advanced technology programs including the Liquid Rocket Booster (LRB) program for the STS and the Space Exploration Initiative. He began his career with McDonnell Douglas in Houston performing Space Shuttle on-orbit flight design and crew/payload integration. Patton received a BSAE from Parks College of St. Louis University and a MSEM from the University of Colorado.*

Jon Barr *Jonathan Barr is a manager of advanced programs for United Launch Alliance. He is responsible for developing new technology to support ULA's long term launch service needs, including development of EELV IR&D plans. Jon started his career at General Dynamics, working an array of missiles, reusable space vehicles, and launches. In 1994, Jon was the Lead Vehicle Designer for the General Dynamics SSTO competitor to the DCX. In 1997, he initiated studies looking at the use of the RD-180 engine on the Atlas that led to the success Atlas III vehicle program, and he became system analysis lead for Atlas III development through CDR. After a career switch to Boeing in 1997, he supported special issues resolution for the Systems Engineering & Integration Team during Delta IV development, and he was the chief systems engineer during the early development of an Advanced Upper Stage for Delta IV. Jon has extraordinary experience with both Atlas and Delta launch vehicles that have been brought together with the formation of ULA. Jon has a BSME from the University of California at Santa Barbara.*

Frank Zegler *Frank Zegler is a senior staff engineer on the Business Development/Advanced Design team at ULA. He was a launch support tiger-team member for the Atlas on the Rocketdyne MA-5 engine, Centaur RL10 engine and hydrazine attitude control systems. He became lead designer on the Atlas booster and Centaur upper stage propulsion and fluids systems. He was directly involved in the development and qualification of hundreds of flight proven components ranging from hydrazine storage bottles, monopropellant thrusters, high-pressure composite vessels, cryogenic regulators, solenoid valves, pyrotechnic thrusters and mechanisms, large and small solid rocket motors, main engines, propellant ducting, seals, radiation shielding and insulation and spacecraft separation systems. He has an extensive background in integrated design for pneumatic, hydrazine, pyrotechnic and cryogenic engine and fluid handling systems. He presently holds eight US patents on various space-related hardware and systems. For the past seven years he has done advanced design and preliminary analysis work on the evolution of the Atlas and Centaur vehicles, cryogenic LH2 and CH4 based service modules for the Orion capsule, preliminary design for a LH2 powered horizontal landing lunar lander, orbital and lunar surface cryogenic fluid transfer and thermal management designs. Most recent activities include design of orbital depots and refinement of the ULA common upper stage design. Frank has a BSAE and BSME from Georgia Institute of Technology.*