ACES Stage Concept: Higher Performance, New Capabilities, at a Lower Recurring Cost

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The Advanced Common Evolved Stage (ACES) concept combines the best features of Atlas and Delta upper stages. We will discuss how ACES leverages and improves upon the stainless steel common bulkhead structure of Centaur which already results in a world-best mass fraction for an H2/O2 stage. ACES incorporates the Integrated Vehicle Fluids (IVF) H2/02 system to eliminate main vehicle batteries, all hydrazine, and most helium bottles, which can all limit mission duration and number of starts. Coupling additional low boiloff technologies with IVF, ACES becomes extensible for week long missions beyond LEO. We will discuss the ability add kits for rendezvous and docking, propellant transfer, and even to convert the stage into an efficient lunar lander. Though the promise of higher performance upper stages and greater extensibility is not new, we now see the potential of realizing these capabilities in a stage that cost no more than the smaller Centaur stage it replaces, which becomes a game changer.

Nomenclature

ACES = Advanced Cryogenic Evolved Stage
DCSS = Delta Cryogenic Second Stage
EML1/L2 = Earth/Moon Lagrange Points #1 or 2
GEO = Geosynchronous Orbit
GH2 = Gaseous Hydrogen
GO2 = Gaseous Oxygen
H2 = Hydrogen
IC = Internal Combustion
ICBM = Intercontinental Ballistic Missile
IVF = Integrated Vehicle Fluids
LEO = Low Earth Orbit
ISS = International Space Station
MLI = Multi-Layer Insulation
O2 = Oxygen
OML = Outside Mold Line
RCS = Reaction Control System
SRB = Solid Rocket Booster
ULA = United Launch Alliance
3-DOF = Three Degree of Freedom

I. Introduction

United Launch Alliance carries the legacy of over a century of combined Atlas and Delta operation. Specifically for cryogenic upper stages the Centaur began flying in 1962 (see figure 1), with over 226 Centaur's flown to date on Atlas and Titan launchers. The Delta Cryogenic Second Stage (DCSS) family began flying in 1998 on Delta III with 30 flown primarily on the Delta IV booster. As successful and reliable as these stages have been, it has long been apparent that these upper stages are undersized relative to their Atlas V and Delta IV boosters, particularly when they are enhanced with SRBs. Some individual missions may gain from more propellant (e.g., Heavy GEO) or more thrust (e.g., Atlas LEO, as evidenced by the restart of the Dual Engine Centaur for ISS crew missions), but to

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realize gains across the market spectrum we need an upper stage that combines more thrust and more propellant. This will increase max lift capability to enable the transition of all Delta IV Heavy missions to the new Vulcan booster, and provide lower cost on typical missions through SRB elimination.

A larger upper stage, the Advanced Cryogenic Evolved Stage (ACES) has been under evaluation and refinements since even before ULA was formed in 2006. Recently, ULA made the decision to start development of the Vulcan booster, with either the primary BE-4, or backup AR-1 engine options. This new booster has not fundamentally altered the design concept of the ACES stage, but it does create an opportunity for integrating ACES on only a single booster with this ACES as part of a block upgrade after the initial fielding of the Vulcan booster. The DCSS and Centaur now have decades of lessons learned ready to apply to a new stage, coupled with innovative new concepts such as Integrated Vehicle Fluids (IVF), we expect ACES to set a new standard for state-of-the-art in Hydrogen Oxygen upper stages. Though ACES has had a long gestation period, its ability to enable all Delta IV Heavy missions to transition to the Vulcan booster gives it a new impetus to move forward.

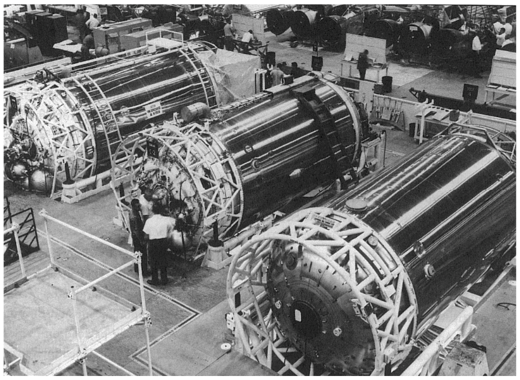

Figure 1. Centaur Stages in 1960's

II. ACES Stage Design

The ACES stage is being designed for 150 klb of propellant, just over 3 times larger than the Centaur. Its engines will put out between 100 klb and 150 klb of thrust per shipset, so at least 4 times more thrust than the Centaur. Though a much larger stage than Centaur, by increasing its diameter from 120" to 212", the same as both the Ruag 5.4m fairing and the Vulcan booster, ACES is able to provide an efficient load path, incorporate this large propellant capacity in the same stage length as Centaur, (seen in figure 2), and satisfy the same launch pad facility constraints. From an aerodynamic standpoint Vulcan/ACES will look nearly identical to the initial Vulcan/Centaur configuration using the 5m payload fairing. Like Centaur the design will accommodate a common bulkhead, but in this case concave upwards with a central LH2 sump.

The broad range in thrust listed above reflect the fact that there are several engine candidates being considered, with the basic design of ACES to be optimized around each engine candidate. ACES can accommodate one 100-150klb, two 50-75klb, or four 25-35 klb engines, obviously with differences in thrust structures and feedlines resulting. At the National Space Symposium 2015 Tory Bruno, ULAs CEO, identified the Aerojet Rocketdyne RL-10, a Blue Origin BE-3 derivative, and an XCOR engine as three of the ACES engine candidates. At the time of engine downselect ACES will be tailored to the selected engine.

Figure 2. ACES size vs Centaur (Example Shown with BE-3 Envelope)

Vehicle performance varies with mission and the number of SRBs, but in general ACES provides a similar benefit to at least 3 SRBs, so an Atlas 551 mission could generally be satisfied with a Vulcan 52XA, with "X" representing the number of liquid engines, which will depend on the downselected engine (e.g., 4 small or 1 large engine), and the "A" designator indicating ACES. Figure 3 shows the step function in Vulcan performance once ACES is introducted in 2023. Elimininating the boattail section which shrouds the centaur of the 5m fairing and reducing the number of SRBs will both lower launch cost in addition to direct ACES stage savings.

With very low incremental $/kg associated with added SRBs, and with larger increments of performance for Vulcan/ACES with added SRBs, Vulcan/ACES becomes an even greater $/kg bargain at with increasing payload class. All candidate engine alternatives are expected to offer generally similar performance, but performance discriminators, in addition to cost discriminators, will emerge that will influence our engine downselect decision.

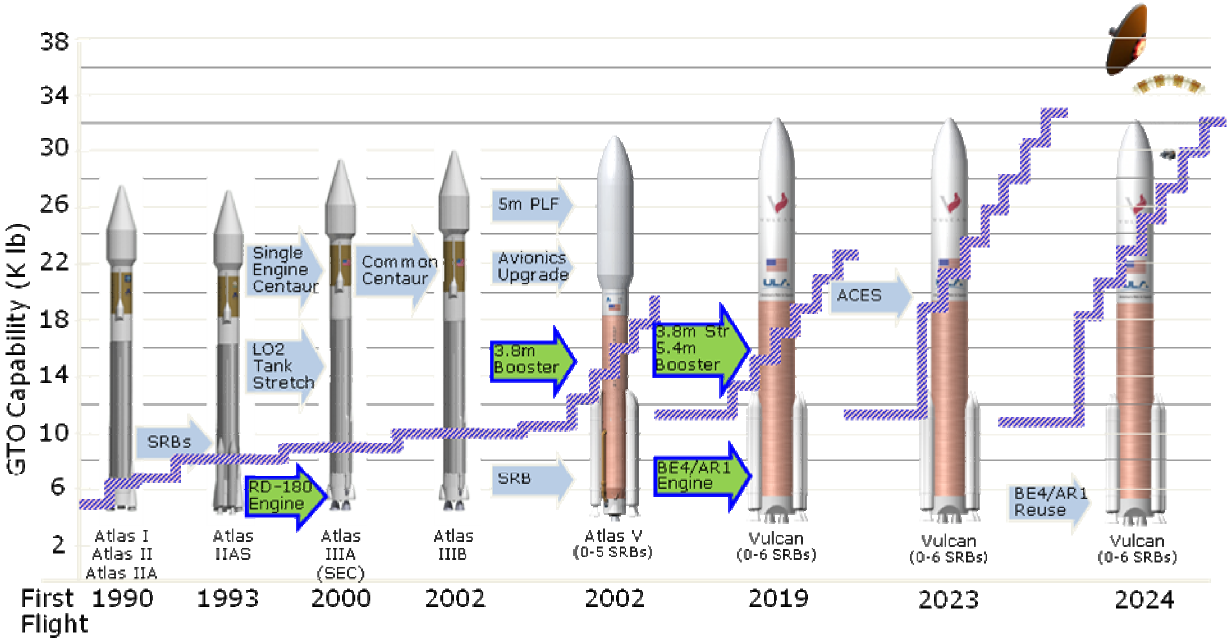

Figure 3. ULA Vehicle Evolution Roadmap

For scenarios with four small 25-35Klb class engines, an obvious option is to creates a smaller propellant capacity two-engine variant to more cost effectively address the low end of the market, since eliminating SRBs is not an option for these missions. A small ACES variant is currently assumed to compliment the larger ACES baseline.

One feature from Delta that we are including is aft avionics as seen in figure 4. That should allow payloads to be encapsulated for easier handling, and free the ACES from being fabricated in a cleanroom since any particulate contamination on the ACES will not share a common volume with the payload.

ACES is planned to use Centaur's structural concept of monocoque steel tanks with common bulkhead, which remain the highest mass fraction tanks more than 50 years after it was introduced on the Atlas ICBM. ULA has an excellent point of comparison for the mass fraction benefits of the monocoque, stainless steel construction from Centaur. ULA's 4m DCSS with conventional separate bulkhead, isogrid aluminum construction, and current Centaur were each designed for identical payloads and with nearly identical propellant loads. The Centaur's structural weight is ~50% of that of the Delta 4m DCSS due to its construction. Despite having higher parts count due to the individual dome gores, and cylinder segments, Centaur tank construction is comparable in cost to aluminum with one-piece spun domes.

We expect to achieve an overall > 0.92 Mass Fraction on the ACES stage, which directly results from scaling Centaur, taking advantage of scale benefits of the larger stage since some weight elements such as avionics do not scale with propellant load. IVF, which is discussed later, also provides measurable mass fraction benefits both in dry weight savings, and in lowered net residuals.

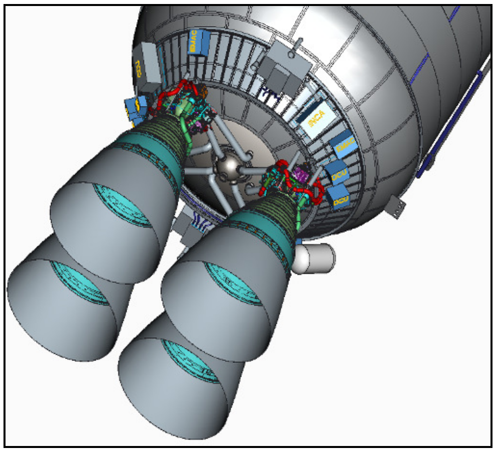

Figure 4. Central LH2 Sump with Radial Feedlines and Aft Avionics (RL10 Engine Example)

III. ACES as a Low Cost Stage

The notion that the much larger ACES stage will outperform existing DCSS and Centaur upper stages is obvious, but the notion that the much larger ACES can be built for the same or less recurring cost than Centaur is not intuitive. ACES as a low cost stage is a new emphasis in our strategy. Cost savings depends on being able to build the (1) structure, (2) propulsion subsystems, (3) avionics, and (4) engines for the same or less cost.

With automation in our dome weld process, use of wider steel coil stock, and elimination of expensive tank bracketry on the aft LOX dome we believe the structural cost goal is in reach despite the larger tanks, and greater material usage.

The IVF subsystem is expected to be lower cost that the hydrazine RCS, He pneumatics, and main vehicle batteries found on Centaur, and vastly less expensive than those traditional systems if they had been scaled for the larger ACES tanks.

Avionics remains fairly insensitive to stage size. Adding more cost saving upgrades, plus the ability to pull growth requirements into the IVF controller means that we can contain avionics cost. For example, providing TVC control for four RL-10 class engines instead of one or two engines could otherwise drive up cost in batteries, power conditioning, and EMA controllers. But IVF, with more efficient 300v power and a capable controller, can satisfy growth requirements at lower recurring cost. Although ULA is currently in the process of fielding our new Common Avionics system, opportunities still exist for additional cost savings, and ACES is seen as an opportunity to implement those added savings.

Finally, and most importantly, we believe that we can achieve aggressive cost targets on the engines, despite having 100klb-150klb of total thrust per shipset. We are encouraged by discussions with multiple engine providers that our aggressive engine cost targets are achievable. Our challenge may be that we have too many good engine options rather than too few.

With costs comparable to Centaur, ACES could be used for all missions. If using four 25Klb class engines this means high engine production rates with rate benefits that creates a virtuous cycle supporting the starting low engine cost assumption. Conversely, with the older vision of ACES which had the stage used for a relatively few high-end missions, lower build rates and higher engine costs result.

IV. Integrated Vehicle Fluids

IVF is a novel technology and a cornerstone to the ACES stage concept. It revolutionized our propulsion subsystems, creating cost savings, performance benefits, mission flexibility, and extensibility benefits. This innovative system has been the subject of its own paper[2]. We will try to briefly summarize this innovative system and its benefits here (See Table 1). Fundamentally IVF is a Hydrogen/Oxygen auxiliary power unit, that uses free boiloff hydrogen and oxygen to generate electricity (eliminating main vehicle batteries), provide autogenous tank pressurization (eliminating most or all Helium bottles), and feed GH2/GO2 reaction control system thrusters (eliminating all stored hydrazine). Power, He supply, and hydrazine supply are all current constraints on mission duration. With this change, coupled with straightforward low-boiloff enhancements on the upper stage, mission durations on the order of days vs. hours become practical. For example, ACES with IVF could perform a lunar orbit insertion burn for a commercial lunar mission without requiring another dedicated stage. Similarly, IVF can perform targeted disposal burns using waste boiloff, from essentially any orbit, due to its ability to operate longer, and perform propulsive RCS burns with durations limited only by having propellant remaining in the main tanks.

Table 1. IVF Benefits

- Lower recurring cost
- Increased performance (>1klb GEO)
- Unlimited burns
- Eliminates extended duration mission kits
- Eliminates Hydrazine and associated Operations – Greenest propellant
- Eliminates high pressure pneumatics
- Reduces propulsion subsystem integration time in factory
- Higher reliability through block redundancy
- Safe disposal for 100% of missions with low performance penalty
- Abundant high voltage power and controller for engine valve control
- Abundant power for payloads
- No battery limited duration constraints

At the heart of the patented IVF design is a small 6 cylinder internal combustion engine, that aspirates GH2, with O2 injection, that is joined with starter/generator, small batteries, a coolant loop, and a compressor with many similarities to a hybrid car engine. The piston engine and other automotive similarities means that IVF can piggyback on the enormous outside investments made in the automotive industrial base, with automotive suppliers such as our Roush prime contractor, able to provide hardware and test capabilities at lower cost, and at speeds much faster than our traditional aerospace supply base.

Figure 5. H2/O2 RCS Thruster Technology is Rapidly Maturing

GH2/GO2 thrusters, shown in figure 5, which ULA has been developing in conjunction with Innovative Engineering Solutions can either be tank ullage fed, or use the higher pressures generated by the IVF compressors for higher thrust. Use of GH2/GO2 thrusters eliminates stored hydrazine on the vehicle (excluding payloads), but also eliminates the safety driven operations constraints associated with loading and storing hydrazine. Over the last decade significant investment has be made in green propellants, but hydrogen/oxygen is the greenest propellant of all.

Less obvious is that fact that a high performance controller is needed to perform the internal combustion engine control function (just as in your car). The capabilities of the IVF controller, coupled with abundant 28v and 300v power means that IVF will be able to absorb functions being performed by other Avionics elements. From the earlier example IVF might cost effectively take over main engine EMA thrust vector control. It can provide engine EMA valve control, avoiding the cost of a dedicated engine controller. It has opportunities to efficiently expand beyond its core function to capture requirements as diverse as uplink antenna, and star tracker control.

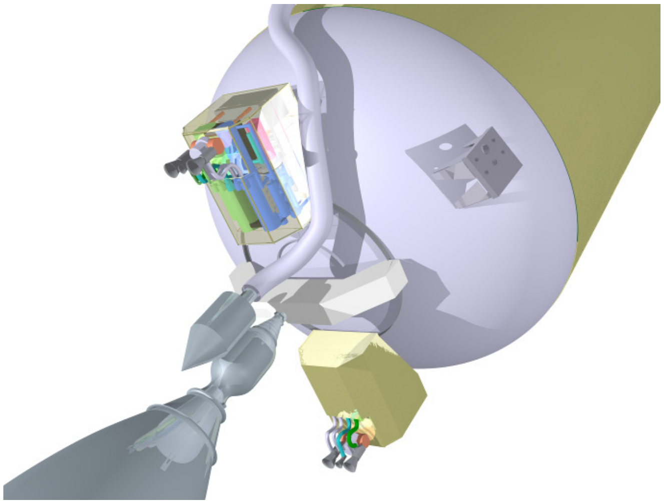

Figure 6. IVF Modules are Compact Despite Their Capability (Shown on Smaller Centaur Stage)

IVF modules, shown in figure 6, are quite small, and replace what would have otherwise have been a huge number of He and Hydrazine bottles on the back of this 150klb propellant capacity stage. The IVF system is designed for block redundancy, with either module capable of meeting power and pressurization requirements of stage, and with RCS control cross-strapped to maintain full 3-DOF control. Within each IVF module there is also complete electrical redundancy.

V. Beyond LEO Extensibility

ULA's traditional market of GEO, GTO, and some LEO missions does not currently require more than ~8 hour missions. With the emergence of commercial payloads potentially going to EML1/L2, or delivered to Lunar orbit, such as a Bigelow BA-330, ACES capabilities stand out. The IVF subsystem discussed previously shows that the mission can last as long as H2/O2 remains in the tanks. Straightforward low boiloff enhancements can provide this duration and support this class of up to one week missions.

The obvious first step is significant use of Multi-Layer-Insulation (MLI) on the stage. With ACES now designed to be an in-line stage with tanks on the Outside-Mold-Line (OML) we need a structural MLI that can hold up to launch aerodynamic forces. Fortunately we have two approaches, one internally developed, and one being developed by a supplier, which can satisfy this need. ULA has already developed a proprietary enhanced common bulkhead insulation that makes heat leak between tanks a non-issue. Vapor cooling is available, with GH2 going to the IC engine available to intercept heat on its path to the IVF module. The exhaust from the IVF modules also provides continuous settling which benefits low boiloff. ACES will be able to support week long deep space missions will relatively few additional upgrades, such as some extra radiation hardening, deep space guidance and communication enhancements. (ACES already has some measure of radiation hardening consistent with ULA's legacy GEO missions which require burns beyond LEO.)

ULA's XEUS lander concept[4] adds legs and a terminal descent landing system (guidance and propulsion) to an existing upper stage to allow it to become the lunar lander. A lander fashioned as a "kit" on an existing 2nd stage should be affordable for a commercial program like Golden Spike, recognizing the habitat element would still be a significant development. Unlike traditional LEM-like landers, the horizontal lander shown in figure 7 performs the mission with short legs, no longer requiring massive fairing diameters to deliver to orbit, with the crew in close proximity to the surface, with descent engines elevated to avoid throwing lunar regolith debris, and without inefficiently subdividing the propellant tanks which hurts boiloff and mass fraction. Though the XEUS concept is not specifically tied to the ACES stage, a XEUS ACES would provide excellent capability. The potential exists for IVF to power the terminal descent engines with H2/02 engines rather than storables. It could also provide abundant power in a South Pole lunar crater using residual propellants. A XEUS ACES that was fully refueled either at an EML1/L2 base, or on the lunar surface with in-situ propellants could make a round trip with ~25mT of payload including habitat or cargo module mass, and do that over and over again using the same stage hardware. Whether bringing up propellant from the earth surface, or from the Lunar surface, the 100% use of H2 and O2 with IVF frees the logistics stream from having to deliver Helium and Hydrazine.

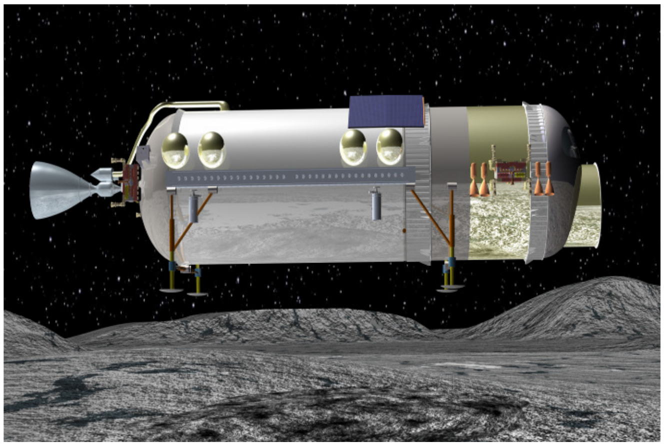

Figure 7. XEUS Modification of Upper Stage to Create a Lunar Lander (Centaur vs ACES Shown)

These ambitious scenarios lead to payload masses that quickly grow beyond the ability of the Vulcan booster to launch in a single flight. Distributed Launch, with propellant transferred from a pre-emplaced ultra-low boiloff drop tank can help enable these more ambition mission. In key 2009 & 2010 papers[4,5] Frank Zegler of ULA outlined a vision of propellant being moved up in steps out of earth's gravity well using tankers, which would transfer fuel to propellant depots. A Space 2015 paper by Bernard Kutter of ULA takes the original approach and modifies it to use disposable drop tanks rather than fuel depots to better reflect in a world with constrained flight rates for these ambitious beyond-LEO Missions.

Elements of the landing system, rendezvous and docking, and propellant transfer hardware of the distributed launch scenario that would refuel the XEUS ACES along its journey are not parts of the ACES initial design, but they are a part of the vision of where ACES might evolve.

VI. Conclusions

In conclusion, the ACES stage concept offers significant performance growth and extensibility. ACES is designed for low recurring cost, potentially as low as Centaur with important programmatic implications. ACES remains anchored in the best of both Atlas and Delta, but it is also a vehicle for introducing new innovations, such as IVF, which will radically reshape our approach for propulsion subsystems and vehicle power.

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