Orbital Disposal of Launch Vehicle Upper Stages

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Launch vehicle upper stages contribute to space debris when they do not have enough impulse capability to de-orbit themselves after placing their payload into orbit. Typical launch vehicle missions expend the vast majority of their lift capability to deliver spacecraft to orbit, leaving very little propulsive capability to dispose and safe the launch vehicle upper stages.

The issue of space junk becomes more critical every year as the international launch rates increases. When two large satellites collide (like the 2009 collision of Iridium 33 and Kosmos-2251), they create a cloud of orbital debris, possibly impacting launch opportunities until the debris field becomes minimized. Although upper stage vehicles today are tracked and satellite vehicles are maneuvered to preclude possible collisions, if more clouds of orbital debris are created through collisions, the criticality of the issue can increase exponentially.

United Launch Alliance (ULA) is pursuing technologies to enable enhanced disposal capabilities. This paper will describe the development of these technologies and the planned future state of ULA's upper stages. Developments are revealing that with readily achievable technological enhancements, cost can be reduced to acceptable levels. Through the use of technologies to provide thrust and power using gaseous hydrogen and oxygen gaseous from upper stage main propellant tanks, the capabilities can be implemented with a net weight savings. These technologies include hydrogen/oxygen thrusters and fuel cells. Extensive hot-fire testing has been conducted on the thruster, with a flight experiment planned in 2016. These components are building blocks for the Integrated Vehicle Fluids system that can replace the hydrazine attitude control system and heavy batteries on current launch vehicles.

The paper will describe the operational aspects of space policy requirements for launch vehicle upper stage disposal. It includes rationale for prioritizing upper stage controlled re-entry disposals and reducing/precluding long duration decaying disposal orbits that would eventually de-orbit in an uncontrolled manner. A summary of possible solution sets for the disposal of launch vehicle upper stages across the typical mission orbits will be discussed.

By utilizing comprehensive operational concepts, the capabilities can be implemented with minor performance costs. With this systematic approach we can even provide expanded secondary mission capabilities while providing full compliance to disposal requirements. Orbital disposal compliance can be achieved cost effectively and can be conducted while minimizing impact to the launch vehicle performance capability and in some cases, enhancing performance. As increasing launch rates place even more upper stage vehicles in non-compliant orbits, the probability of collision increases and un-controlled re-entries will continue to grow, making damaging terrestrial and orbital impacts more probable. Orbital disposal technology is becoming a critically important area of concern. Solutions are being developed and space policy must be enforced to ensure future operations do not head along the path where space congestion grows to deny us access to space.

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Nomenclature

ACES	=	Advanced Cryogenic Upper Stage
AIAA	=	American Institute of Aeronautics and Astronautics
CCAM	=	Contamination Collision Avoidance Maneuver
DCSS	=	Delta Cryogenic Second Stage
dv	=	delta velocity, or change in velocity
g0	=	gravitational constant
GFSSP	=	Generalized Fluid System Simulation Program
H2-O2	=	Hydrogen/Oxygen in a free state
HYPRS	=	Hydrogen Tank Pressure Simulation
IES	=	Innovative Engineering Solutions
Isp	=	Rocket Engine Specific Impulse
me	=	empty mass
mf	=	full mass
mp	=	propellant mass
ODMSP	=	Orbital Debris Mitigation Standard Practices
ULA	=	United Launch Alliance
USAF	=	United States Air Force

I. Introduction

With the ever expanding role of space based assets (see Figure 1), the issue of space congestion has moved to the forefront. Between increased reliance on space based technology and near misses and collisions of satellites, there has been significant interest in and investigation of the issues around space congestion. There have been numerous studies, intitiatives and papers[1] on the the topic.

The United States Air Force continues to recognize the issue and risks of space congestion. As recently as last summer's AIAA Infotech@Aerospace Conference Plenary speech on the Global Horizons effort within the USAF, congestion was highlighted as a key challenge for the future. That said, the cost of any significant debris removal effort has been a major stumbling block in reducing the existing clutter. Historically, disposal requirements set forth in the US Government Orbital Debris Mitigation Standard Practices have been scoped with mission requirement and cost effectiveness caveats. Because the impulse required to dispose degrades the launch vehicle capability, disposal is in direct competition with delivering the most capable satellite system as possible to orbit. There has long been an acknowledgement of these competing interests in access to space.

While a launch vehicle has limited opportunity to be disposed of, plans for safe disposal of satellites have long been a requirement for space based systems. Those systems inherently understand the risk retired assets pose to the continued use of their operational belts. There is conceivably a built in desire to retire spacecraft, bring a new generation of capabilities to bear on customer needs, and move the retired satellite to a safe location. Thus, while end of life maneuvers for satellites may reduce the operational life, this frequently occurs after a replacement vehicle is on station which minimizes the cost impact of disposal.

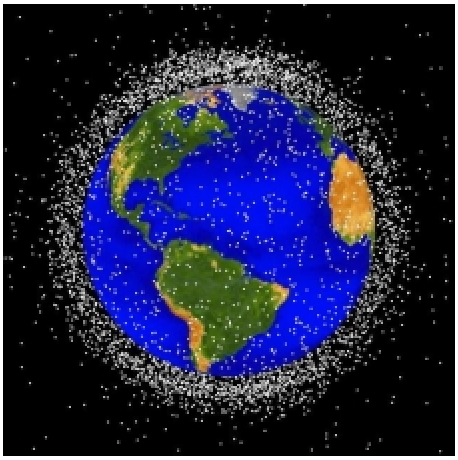

Figure 1: Space debris is tracked as it orbits Earth. Credit: NASA

This paper approaches the challenge of debris mitigation from the launch vehicle side of the debris equation. Much attention has been given to the satellite side of debris creation, but ½ of the source material for debris is the launch vehicle upper stage. Historically the upper stage would give every ounce of energy to get satellites into their desired orbit. While today's upper stages are more capable systems, the lift desired by the satellite community can still exceed the capability, leaving us with the historic disposal quandary. Fortunately, for as much as ½ of our current launches we are able to utilize excess performance and design trajectory solutions which allow for compliant disposal of our upper stages. We will focus this paper on new technologies being explored at ULA to increase upper stage orbital disposal capability while mitigating launch vehicle performance impact.

II. Upper Stage Disposal

A. The Challenge for Upper Stage Disposal

The principal element that impacts disposal is the energy cost of lifting the payload mass to the energy state of the target orbit. This cost function can be though of in two parts. First the payload needs to be raised to the altitude of some point on the desired orbit. For the second part the payload needs to be accelerated to the orbital speed at that point on the orbit. In the simplest example one could approach this as an initial thrust to lob the spacecraft all the way to the geostationary orbit altitude (35786 km), and then fire a motor to accelerate the spacecraft to a velocity of 3075 meters/sec.

The challenge in the situation becomes clear if we examine the ideal rocket equation

$$dv = I_{sp} * g_0 * \ln\left(\frac{m_f}{m_e}\right)$$

By reformulating it and solving for the propellant cost where the propellant load m_p is the difference between the full weight m_f and the empty weight m_e it can be seen that:

$$m_p = m_e * \left(e^{\left(\frac{dv}{g_0 * I_{sp}}\right)} - 1\right)$$

With examination of this fundamental equation of rocket science, we can see that the propellant mass required grows exponentially with the change in velocity required. But it is equally critical to recall that to boost the payload will also require boosting the dry weight of the upper stage and any propellant required for follow on activity, like disposal. Obviously the system is also sensitive to the performance of the engine and propellants used which drive the Isp value.

To put this relationship into perspective, we can look at the basic physics of the orbit transfer problem, neglecting atmosphere, finite burn and gravity loss effects and assuming an upperstage engine performing with an Isp of 400 sec. To deorbit a 2727 kg spent stage inserted into the GSO belt would require some 1300 kg of propellant, seemingly not an unreasonable mass. However to carry that extra propellant, injecting it to the GSO speed of 3075 mps along with the stage and a 2727 kg satellite, would require an extra 1550 kg of fuel for the GSO burn. So now we have an extra 2850 kg of fuel that we have to boost from the ground to the GSO alititude. To boost that extra 2,850 kg of fuel could require as much as an extra 55,000 kg of booster fuel. The booster rocket would effectively need to have 10% more capability, but more problematic, it would need to have engines capable of more than 10% increase in thrust at lift-off.

Rockets are typically designed with a specific lift capability pre-defined and the engines sized accordingly. While many initiatives have been executed to incrementally increase performance, a change of this magnitude would impact all aspects of the launch vehicles subsystems and design environment. While easier to attack from a clean sheet design, those same challenges would be faced with an incremental increase in capability for a new generation launch vehicle. Likewise cost tends to increase with performance and complexity, so there would be a financial cost penalty for a rocket designed to provide the “extra” lift capacity.

Finally, experience has repeatedly shown that, given the cost per pound to raise a satellite to orbit, the spacecraft will grow in mass to provide the most capability on orbit. Thus there is a systemic incentive for the mass of the spacecraft to max out the lift capability of the launch vehicles. This typically, leaves very little excess capapbilty for fleet wide disposal. With the experience base ULA has in launch vehicle designs, we have taken a new, innovative approach to the challenge of disposal.

B. Key Drivers

In recognition of these driving mission requirements, the US Government has a tiered approach to disposal. Obviously, from a debris perspective, the preferred approach is to de-orbit any spent stage and remove it from ever becoming an issue. If the energy of the orbit is such that a re-entry into the earths atmosphere is not an option, burning into an earth escape trajectory is considered. This places the spent stage into a heliocentric orbit with an exceptionally low probability of ever encountering another spacecraft. If these options cannot be accommodated within the mission requirements and cost constraints of the launch, the preferred path is to place the spent stage into a disposal orbit which does not intersect any operational satellite belts. This typically requires two impulsive maneuvers to adjust the orbit shape so that both sides of the orbit are moved. For some missions the delivery orbit can be selected so that while close to the operational belt, a single impulsive maneuver will move both apogee and perigee outside of the satellites operational region. These disposal options, defined by the US Government, provide a palette of compliant disposal options.

The hierarchy provided by the US Government matches the potential impact of the disposal technique. Deorbit forever removes the body from the equation. Earth escape dramatically reduces the likelihood of future interaction.

However, disposal orbit remains the most viable course of action for many high perigee transfer or circular orbits. Where Deorbit from Geostationary orbit has been shown to be exceedingly expensive, the cost of shifting to a disposal orbit could be tens of kilograms. For performance critical missions, this is clearly the preferred option.

Since some satellites want as much mass lifted as possible, one capability ULA provides is a minimum residual shutdown, basically burning the tanks to depletion. This limiting case defines the boundary condition for performing disposal. Fortunately, with the large upper stage tanks and operating pressure, we have trapped liquid and gas left in the tank after depletion. Additionally, for typical missions, we provide a guidance commanded shutdown for a precise orbit injection. When operating in this manner there are more liquid propellant reserves available for disposal. ULA has been exploring ways to convert these commodities into usable performace for post separation maneuvers that enable disposal across the launch vehicle fleet.

With these tiered requirements in mind, ULA is maturing both a Fuel Cell system to generate power and a small Hydrogen/Oxygen (H2-O2) Thruster to provide thrust. The thruster system is the critical technology converting the residual propellant into impulse to move the upper stage into a compliant disposal orbit. However, the fuel cell will allow for extended mission durations, beyond the current operational life of the upper stage batteries. This allows optimal placement of the impulse from the thrusters and negates the performance impact from the weight of the thruster system components.

III. Discussion of New Technologies

United Launch Alliance has embarked on an innovative path to leverage the ullage gases to enhance our ability to dispose of our upper stages. This effort is focused on ways to leverage the residuals which cannot be used by the upper stage engine to produce thrust. As a result, for normal operations these technologies have very low, if any, performance penalties. The only weight impact to the launch vehicle capability is that of the physical components themselves. A combined solution leveraging both the fuel cell and thrusters may be performance neutral since the fuel cell system is lighter than the batteries employed today. The mass for the energy storage typically required to operate these systems is already being carried as unusable or vented gas. Thus this innovative approach provides the necessary capability while sidestepping the performance issues touched on earlier.

One key element in this approach is the development of the gaseous hydrogen/oxygen thruster to convert un-usable propellants into impulse which can be applied after spacecraft separation. Leveraging this fuel source changes the performance cost equation for disposal. This form of thrust also benefits from the high Isp afforded by hydrogen combustion. This innovation will enable compliant upper stage disposal for a fraction of the traditional cost for disposal.

Both the ULA Centaur and Delta Cryogenic Second Stage (DCSS) use cryogenic hydrogen and oxygen to deliver spacecraft anywhere from low earth orbit to the far reaches of the solar system. As a consequence, the residual ullage gas in the tanks can be extremely cold. However, for the disposal application, there can be the desire for a near empty tank to coast for a significant period of time to get to the optimal point and reduce the delta-v required to dispose of the spent stage. This in turn means that there could be significant solar warming of the gases before the disposal burn occurs. Thus the new thruster needs to operate across a wide range of thermal conditions to achieve the required capability.

IV. Propulsion Systems Analysis

The propulsion analysis team was tasked with predicting inlet conditions for the ullage thrusters throughout their operation; note that two thrusters were the baseline configuration. Solutions required prediction of thruster propellant operating conditions throughout the thruster burn. Modeling must smoothly transition between initial transients at the beginning of thruster operation and continue through multi-hour burn simulations. Analyses must envelope many possible trajectories in order for the system to be useful for mission designers. Predicted propellant conditions must be at the thruster inlet, where the flow passes through external tubing to go from the ullage to the thruster inlets.

Prediction of propellant conditions was broken into two phases: initial transient flow through the H2-O2 thruster system, and quasi steady-state flow during the thruster burn. A network flow model was developed to simulate the initial several minutes of flow, from the start of thruster operation to quasi-steady-state operation of the thruster. The standard tool used to predict propellant conditions for Atlas V missions was adapted to predict the changing bulk propellant tank ullage conditions throughout the thruster burn. These two models had to be developed in tandem, since the flow rate of the H2-O2 thruster system as determined by the network flow model is an input to the ullage prediction model. In addition, the tank ullage conditions as determined by the tank thermodynamics model, is an input to the network flow model.

The tank ullage analysis was performed using the internally developed thermodynamics code Hydrogen Tank Pressure Simulation (HYPRS). This code is used to predict Centaur propellant conditions as part of standard mission integration work. Flight heritage, especially Centaur flight data from long coast missions, anchored the HYPRS code's predictions of the ullage conditions during proposed thruster burn sequences. In order to cover the large dispersions required to cover numerous mission profiles, the code was adapted to perform a thermodynamic Monte Carlo analysis. This allowed the analysis to produce conservative output without the conservatism of a stacked worst case analysis. The initial ullage conditions, the Centaur thermal environment, and knowledge of the predicted flow to the thrusters versus ullage conditions are inputs to the model, and predicted ullage conditions as a function of time during thruster operation are the main output.

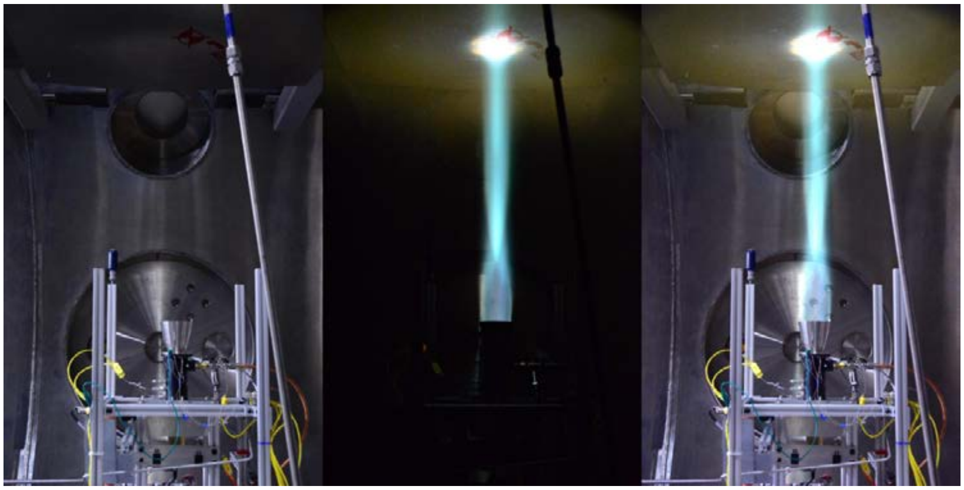

Figure 2: Thruster Testing in Vacuum Chamber

The NASA code Generalized Fluid System Simulation Program (GFSSP) was chosen to develop a model simulating the flow from the propellant tanks to the thrusters. This model simulates transient and steady-state flow, including heat transfer to and from the surroundings. The propulsion analysis group built the model with input from propulsion hardware design so that it simulates flow through the H2-O2 thruster system as accurately as possible. Both predicted tank ullage conditions and hardware configuration are inputs to the model, and predicted thruster inlet conditions (pressure, temperature, and flowrate) as a function of time are the main output.

Combining these two models in tandem has assisted in the overall development of the H2-O2 thruster system. The models were used to give input to various trade studies and weigh design options during the development of the thruster system. Among other considerations, these models assisted in the design of critical interfaces such as tank draw locations and flow choke points. The modeling effort has also given inputs to designers helping to set component requirements and test conditions.

One analysis output is predicted thruster inlet conditions outside the current capabilities demonstrated by H2-O2 thrusters. As a result, a new test program was proposed and performed with cooperation from the manufacturer, Innovative Engineering Solutions (IES). Significant effort was expended to test at these predicted conditions, including development of a test stand capable of flowing gaseous H2 and O2 into the thruster at conditions near the liquid-vapor boundary. Initial testing at the predicted propellant conditions on a best-effort basis simulating system design has demonstrated that the thruster is capable of operation near the predicted conditions. Further testing is planned to define the operational boundaries of the H2-O2 thrusters including testing with changing propellant conditions while the engine is running. In addition to ground testing, ULA is implementing a flight experiment in June 2016 to gather data to anchor analytical models.

V. System Development

Testing of the 6 pound thruster has continued over the course of the last year. We have been able to demonstrate thrust generation in ambient conditions and in vacuum (see Figure 2) as well as with varying levels of pressurant contamination. The system concept review and System Requirements Review were completed in 2013. Efforts continue in 2014, maturing the system and supporting analyses. The Preliminary Design Review was successfully conducted in February. At this point, the mission design effort for a flight test is in full swing, with the team focused on maturing the mission and component designs to a Critical Design Review level.

The H2-O2 Thruster System can be implemented across both ULA's Atlas and Delta fleets with the same basic components, shown in Figure 3. For orbital disposal, these components are thrusters, pyrovalves, and solenoid valves. Also included are ports into the main tanks, tubing, avionics harnesses, mounting provisions, and instrumentation. After spacecraft separation and the standard Contamination Collision Avoidance Maneuver (CCAM), the pyrovalves fire to enable the system. Solenoid valves control gaseous H2 and gaseous O2 propellant flow to the thrusters, and ULA is using the existing Centaur Solenoid Vent Valve to perform this task with very little additional qualification testing required. The thrusters are being developed by IES, and the pyrovalves are being developed by Systima Technologies.

While the development of the thruster technology and associated technologies like fuel cell increases the capability of the existing systems, the real benefit comes as these systems evolve. The use of these technologies will allow fully compliant disposal of the spent upper stage, but for many orbits like geostationary delivery, that still leaves the body in an orbit near the operational belt. However, these technologies are well suited to the application of small incremental increases in available propellant. Thus mission unique designs can minimize the future risk of collision or the impact of post de-activation collision based on the available propellant and potentially even the in flight residual levels. This approach allows for systemic approaches to improve the debris situation as future vehicles are designed and built.

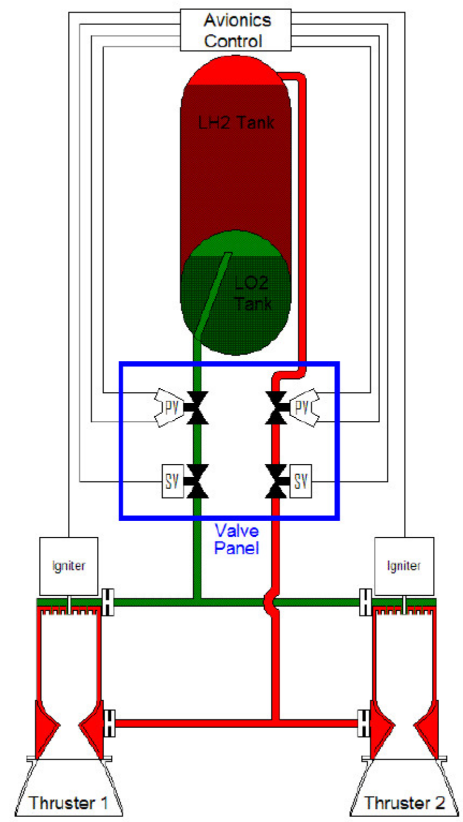

Figure 3: Thruster System Schematic

These technologies also lend themselves to future launch vehicle opportunities. Another of the innovative endeavors at ULA has been the development of a next generation upper stage called Advanced Cryogenic Evolved Stage (ACES). This rocket of the future would benefit from the flight experiences gained with this thruster development to ideally move to a clean stage concept. This would allow a single fuel source for thrust, power and attitude control and remove many of the complexities in today's upper stage designs.

The ACES design was taken through its System Concept Review in 2013. The focus of this vehicle is to maximize the lift capacity of the current booster vehicles. By making this five-meter stage a hung stage, we took the pressure stabilized tanks out of the load path. ACES uses the hydrogen and oxygen of the current upper stage families, and so is fully compatible with the current technology development efforts. It increased the propulsive capability beyond that of a DCSS 5-meter, but keeps the mass fraction in line with the highly efficient Centaur upper stage. With up to four RL10C engines, it can support the heavy lift needs of the DOD and Human Space Flight as well as the broader commercial market. The design approach supports a very long mission duration which enables a variety of disposal options. Being compatible with both Atlas V and Delta IV boosters, it offers increased mission flexibility to all customers.

VI. Conclusion

Over the course of this last year, ULA has continued to test and mature the H2-O2 thruster system, which leverages ullage gases to enhance our ability to dispose of ULA launch vehicle upper stages. The Preliminary Design Review for Centaur orbital disposal using the H2-O2 Thruster System was completed in February 2014, and development is ongoing toward a flight experiment planned for June 2016. The team remains focused on maturing the technology and analysis techniques to bring this new technology and capability into the fleet. While ULA's unwavering focus on mission success continues, we are harnessing our team's vision and energy to develop new technologies to enable better, more flexible capabilities for delivering the next generation of satellites.

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