

Enabling Long Duration Spaceflight via an Integrated Vehicle Fluid System

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Abstract

This paper offers a summary of capabilities for the Integrated Vehicle Fluids (IVF) system that United Launch Alliance (ULA) is developing in order to reduce cost, reduce upper stage mass and reduce the number of independent upper stage systems. In addition, IVF increases the upper stage capability to enable long duration spaceflight. IVF is a single system that replaces three independent upper stage subsystems, the helium pressurization system, the reaction control system and the electrical power storage subsystem. IVF is critical to this long duration capability and is essential for the Advanced Cryogenic Upper Stage (ACES) that will replace Centaur and increase performance for the Vulcan booster. This capability is revolutionary and is a departure from the incremental evolution of the existing Evolved Expendable Launch Vehicle cryogenic upper stages. This paper will explore the basic concept of operations and results of development and proof of concept testing recently accomplished. The results show that there is a high technical readiness and a valid risk reduction approach to using the otherwise unusable gases from the liquid oxygen and hydrogen tanks to fuel an internal combustion engine that powers the pressurization, attitude control and electrical needs of the upper stage. It will also explore the possibility of in-space refueling from lunar or other resources already in space.

I. Introduction

For over 109 flights, United Launch Alliance has successfully launched Atlas V, Delta II and Delta IV to deliver the world's most critical space capabilities for the Department of Defense, National Reconnaissance Office, NASA and commercial users. Atlas and Delta launch vehicles have supported the United States' premier position in space for more than 50 years, with 100% mission success. ULA is poised to continue delivering mission success by developing the capability to launch the next generation launch vehicle that provides not only an affordable launch system but also increases payload to orbit performance. In addition, the revolutionary path we are on will extend the reaches of launch transportation to a significantly greater level. This is in terms of both spaceflight duration and capabilities of the vehicle while in space, which extends well beyond the current fleet of launch vehicles. ULA's 20 year development roadmap includes 4 Steps that are focused on increasing performance, decreasing cost and continuing 100% Mission Success. The first two steps are outlined below.



Figure 1 Vulcan Booster First Flight planned for 2019 significantly reduces cost and increases performance

Step One of ULA's roadmap includes designing a Vulcan Booster that will fly with the existing Centaur, driven by the need to transition to a domestically produced first stage engine. Currently the BE4 LNG/LO2 engine produced by Blue Origin is the primary path, with an alternate design being considered using the AR1 Aerojet Rocketdyne LO2/RP engine. The Vulcan Booster design is a straightforward development drawing upon key principles gleaned from heritage Atlas and Delta mature vehicle designs, while incorporating new, more efficient system and subsystem designs, and promotes use of new technologies in the design and manufacturing area. With the ability to fly 6 solids, the performance capability will exceed even the largest of the Atlas V (AV) configurations, the AV 552 (5 meter payload fairing, 5 solids and 2 upper stage RL10s). In addition to the 5 Meter Payload Fairing (5M PLF) configuration, the Vulcan will incorporate an expansion of the 4M PLF to 4.4M to accommodate greater payload. Figure 1 contains an illustration shows both Vulcan booster flight configurations.

Step Two of the ULA roadmap involves development of the Advanced Cryogenic Evolved Stage (ACES) that will dramatically reduce the cost of space access and significantly increase the performance capability of the single stick configuration beyond our most powerful launch vehicle, the Delta IV Heavy, for about 1/3 the cost. The ACES upper stage (Figure 2) will carry 3x the propellant capacity of Centaur, be able to fly up to 4 RL10's (or equivalent alternative engines), and be produced for the same cost of today's Centaur. But a



Figure 2 ACES Upper Stage

key enabling technology for this performance gain is the Integrated Vehicle Fluids System (IVF) that replaces the Helium pressurization system, the Hydrazine Reaction Control System (RCS), and the main vehicle battery power system. This patented system, described in the rest of this paper, not only enables significant cost and weight reduction (from 100's to 1000's of lbs depending on configuration), but extends mission duration and capability of the upper stage to well beyond the mission durations associated with typical USG, communications and science satellites. The idea is, if we bring new launch and in orbit transportation capabilities to bear, what other capabilities might the rest of the aerospace community dream up to take advantage of this opportunity? The new capabilities allow us to extend the reaches of mankind in space, and the security of our planet and population.

II. IVF System Description

The elegance of the Integrated Vehicle Fluids design relies on the simple fact that the upper stage carries an abundance of propellants that can be used to power a variety of subsystems. The current upper stage carries a very complex set of power, reaction control and pressurization subsystems. Each of these subsystems is independent from each other and requires complex plumbing, control systems and power to operate. By combining the functions of these into a single IVF module, the complexity of the stage is reduced, the aft end of the upper stage is much cleaner and has the added benefit of reducing the number of heat leaks into the cryogenic tanks that cause increased boiloff and reduce upper stage life. Figure 3 shows the aft bulkhead configuration with redundant modules. Beyond the simplification of the aft end, there is a significant reduction in weight. Also, by combining these functions into a single IVF module, the system can not only save weight and provide modularity, and can be built and tested offline and integrated as a modular component onto the vehicle simplifying stage build and test operations at the factory and launch site.

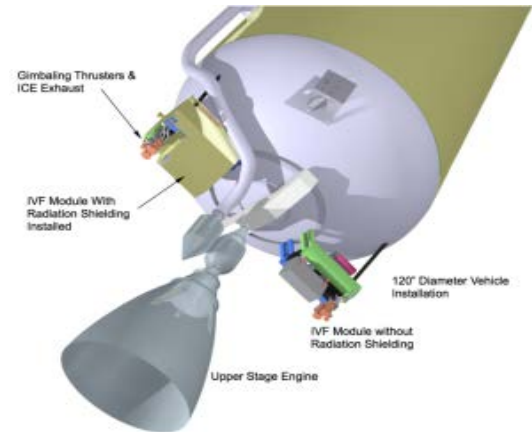


Figure 3 IVF replaces the Helium Pressurization system, the Main Battery Power System and the Hydrazine Reaction Control System resulting in a clean upper stage aft bulkhead

The IVF system has undergone several iterations of design and architecture over the past 5 years. It is now in development of the final configuration and in early component and subscale system testing. Initially the testing will consist of an early generation of the ICE with a first generation Motor Compressor Unit / Heat Exchanger (MCU/HEX) and propellant tank. Early test results using off the shelf component analogs show very promising and even better than expected results. The latest design iteration (Gen 2.0) is currently in work. Planning is underway to test a fully integrated IVF system to generate power and pressurize two large propellant tanks in a ground test in late 2017. An option exists to take this final qualified flight design flown as passively on an Atlas Centaur mission and activate it after the primary mission is complete.

The primary elements of the IVF shown in Figure 4 are as follows:

Internal Combustion Engine (ICE) – This engine is a small piston engine (750cc) manufactured by Roush Industries, that runs on waste gases from the liquid oxygen and hydrogen tank fed into the engine intake. The concept of a hydrogen engine is an existing technology in a new application. The ICE engine in development has gone thru several iterations of design to find the right balance of size and other engine characteristics (weight, vibe, etc.)

Motor Generator Unit (MGU) - The engine powers the MGU in order to generate 300V and 30V

electricity to power different elements of the vehicle. It also serves as a starter for the ICE.

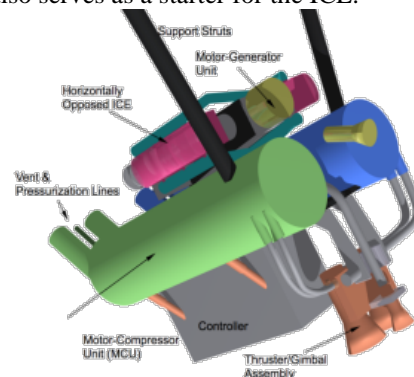


Figure 4 The IVF module is a compact single integrated module that contains all 3 systems in a single unit.

Motor Compressor Unit/Heat Exchanger (MCU/HEX) – The MCU is powered by the 300V electrical power from the MGU and is used to pressurize gas from the tanks. The HEX is combined with the MCU and exchanges the heat from the engine coolant into the pressurant gases to increase the enthalpy of the pressurant gases.

Thruster/Gimbal Assembly (TGA) – the thruster system operates off of gaseous hydrogen and oxygen (GH₂ and GO₂) from the upper stage propellant tanks and provides thrust by burning the combined gases using an internal igniter. The thrusters are mounted on a gimbal system that provides attitude control for the stage.

III. IVF System Operation

The IVF system operations concept is inherently straightforward and has three basic functions – 1) Generate Electrical Power, 2) Pressurize the tanks, and 3) Provide vehicle attitude control. As mentioned earlier this eliminates the three independent subsystems with their own complexity, weight and plumbing/wiring. The IVF module operation are synchronized by an IVF controller that monitors all the various system states and turns on and off functions as required to maintain stable stage operation. The details of the controller are not included within this paper. A top level overview of the main IVF functions and system operation are outlined below.

Power Generation:

HERITAGE APPROACH: The Centaur and Delta IV upper stages currently use large main vehicle batteries that are activated prior to launch, and are drained during the mission. The batteries operate at a nominal 28VDC power level, and have a limited life and are single fault tolerant. Significant mass is required because of the weight of the batteries and the lengthy wire runs between the power source and the power users.

IVF CONOPS: The module uses an ICE engine to power a generator that produces 300V DC electricity. The 300V is used to power the MCU, and is also decreased down to 30V to power the stage electrical system. This power can also be made available to payloads flying on the upper stage. A battery is used to provide power leveling during load application, but is not used to store power for long term stage or IVF system operation. The IVF controller will turn on and off various subsystems and potential payloads that use this power.

Tank Pressurization:

HERITAGE APPROACH: Large, heavy helium bottles are used to store helium at high pressures in order to provide tank pressurization on both the Centaur and Delta IV upper stages. During main engine burns, the RL10 engine provides an autogenous pressurization for the LH₂ tank that relieves the He pressurization for that short period of operation. Redundant valves are included in case of a single valve failure. Helium bottle loading typically occurs prelaunch and constrains ground crew operations around these bottles carrying high pressure.

IVF CONOPS: GH₂ and GO₂ ullage gases from each of the tanks are pumped up in pressure through their respective MCU's, which are powered by the ICE. The heat exchanger (HEX) attached to the MCU takes the energy from the heated coolant fluid from the engine, and transfers it to the propellant gases coming out of the MCU. These gases now have increased enthalpy due to the increase in pressure and temperature from the compressor and HEX functions respectively. These gases are fed back into the tanks through a diffuser which results increases tank pressure. The flow of these gases through the compressor and into the tanks is controlled by the IVF controller and takes into consideration tank conditions, upper stage main engine running or not (LH₂ tank is autogenously pressurized using the RL10 during main engine burns), gas temperature from the tanks into the compressor, and other factors. Because there are no high pressure bottles, ground operations are simplified and significant weight savings are realized.

Attitude Control:

HERITAGE APPROACH: Large, heavy bottles are used to store toxic hydrazine (N₂H₄) in order to provide reaction control system (RCS) attitude control on both the Centaur and Delta IV upper stages during non powered phases of flight. During main engine burns, the RL10 engine provides steering via the engine thrust vector control system. Fixed thrusters are used to provide fluid settling prior to engine burns in the axial direction, and stage fine pointing and roll control during various phases of flight. N₂H₄ bottle loading occurs prelaunch and has safety implications limiting ground crew operations around these bottles carrying these toxic propellants. Separate thrusters provide 3 axis roll control and settling.

IVF CONOPS: The IVF attitude control system consists primarily of 2 sets of gimballed H₂/O₂ thrusters, and significantly reduces the cost and weight of the associated large bottles and plumbing for that previous subsystem. The hydrazine system is replaced with two thruster elements mounted on a gimbal that in turn is mounted to the IVF module. By design, the thrusters utilize the H₂ and O₂ already available within the IVF module. This results in a closely coupled integration of the thrusters with the IVF module on the aft end of the stage, eliminating the need for costly and heavy plumbing running up and down and around the stage. It also eliminates complicated welding techniques and stage integration and operations. Mounting the thrusters on a gimbal platform that can slew in virtually almost any direction allows propellant settling operations, stage attitude control and thermal control maneuvers to be executed from a single set of thrusters on each module. The thruster gimbal system has been designed to allow gimbaling in a slightly forward direction, which will allow the stage to back away slowly from a separated payload, possibly eliminating the need for a complicated and expensive payload separation system that uses springs or other devices to ensure no stage recontact. LO₂/LH₂ product is water and hence a green propellant, which eliminates toxic hydrazine and the associated safety hazards simplifying ground operations.

IV. Upper Stage Enhanced Capabilities using IVF

In addition to the benefits outlined above, IVF opens the door for enhancement of upper stage and payload capabilities and operations.

Increased performance / Reduced Cost and Operational Complexity – IVF is planned to remove 3 heavy, expensive systems and replace it with a single module that can be mounted on an upper stage in a pre-integrated and pretested system. The reduction in cost and weight is on the order of a factor of 3 to 1. The reduction in operations at the factory and launch site is measured in terms of several days of reduced processing flow, also resulting in cost savings. In order to provide a lower cost flight for commercial type missions, the IVF can operate the entire upper stage with a single module in a single string fashion for all but the integrated avionics control system within the module itself, which contains a level of redundancy.

Increased Safety/Reliability – Increased reliability is realized on most NSS and Science high value missions by using the standard configuration of two IVF modules per flight. The two IVF modules operate in synchronicity with each other and provide a single fault tolerant capability for power generation, attitude control and tank pressurization. Each module is cross strapped to the other and provides a hot backup system in case of primary system failure of one or more functions. The second module also provide an added level of redundancy for crew or one of a kind type missions requiring that increased level of safety /redundancy. In addition, due to the elimination of high pressure bottles and toxic fluids, the IVF system brings increased safety due to elimination of hazardous operations.

Long Duration Spaceflight –Standard upper stage operations payloads to LEO, GTO GEO or Interplanetary trajectories require anywhere from less than an hour of operation up to 8 hours of operation and up to 3 main engine burns. With IVF, the possibility of opening up the window of upper stage operation expands to well beyond current capabilities. Long duration upper stage support of payload operations can be realized with the recent improvements in cryogenic propellant storage techniques

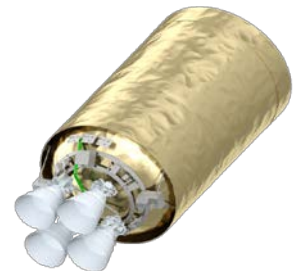


Figure 5 Long duration spaceflight is enabled with the use of IVF

such as shielding have demonstrated very low boil off. With these technologies, the stage duration can be extended to days or weeks with the possibility of months or years. Upper stage refueling using propellants delivered from earth or in orbit sources such as lunar or asteroid derived water converted to propellants can extend this life indefinitely. Using this long duration capability with a stage refueled in space can develop an order of magnitude greater C3 than any current stage enabling Interstellar missions never before possible. The ability to provide a payload with transportation beyond the traditional orbits provides the possibility of missions beyond the current thinking, and opens the doors of new possibilities and mission capabilities.

Power to the Payloads – IVF can provide long duration and high voltage power generation. 30 to 300V of power and the ability of the stage to extend operation beyond hours to significantly longer durations, brings with it the opportunity for payloads to embed capabilities previously not considered. For example, habitats or on orbit factories (Figure 6) that previously would have had to generate power on board systems, can now depend on the upper stage for power generation for life support or experiments, production or other uses. This eliminates the need for a costly and complex system such as large solar arrays, and can now focus limited resources on other critical needs.

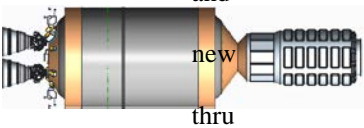


Figure 6 - Power from IVF can support payloads such as habitats

Other Capabilities Enabled With IVF – The capabilities of IVF can be extended to many other uses that can result in practical to far reaching improvements beyond our current thinking in mission operations with an upper stage. Because the product of the LO1 and LH2 is water, residuals can be used to generate additional water for habitats for human consumption, radiation shielding or thermal control. Upper stages concepts such as an ACES derived Lunar Lander (Figure 7) with side mounted thrusters can provide terminal descent propulsion capability in space with an attached crew or cargo module.



Figure 7 Notional Lunar Lander benefits from IVF capabilities

Addition of the capability to refuel the upper stage with propellants delivered from earth or in the future, propellants generated in space, the duration can be extended indefinitely. With the IVF capability for on board pressurization, power generation and engine restart capability on demand, the possibilities begin there.

IV. Summary

ULA is a leader in space transportation innovation, and IVF is the key enabling technology that provides the opportunity to expand the possibilities of today's space program. As a key component of our development roadmap, the core capabilities of IVF are to replace existing power, tank pressurization and reaction control systems with a low cost, highly reliable and lightweight module that provides these capabilities and more. The integrated module is assembled and tested offline, and can be integrated and tested at the stage level with minimal operations, greatly improving the factory and launch site flows. The use of existing commodities, Hydrogen and Oxygen, eliminates toxic propellants and high pressure bottles. This improves operational safety for both ground and flight crew.

The opportunity space that IVF enables in terms of mission capabilities are just now beginning to be envisioned – from payload power for habitats and factories, water, extended duration upper stage space transportation servicing missions, to interstellar missions and beyond are the beginning of the opportunities. These possibilities and others will enable mankind to go where we have not gone before.