Enabling Long Duration CisLunar Spaceflight via an Integrated Vehicle Fluid System

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Abstract

The following paper is 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 # of independent upper stage systems. In addition, IVF increases the upper stage capability to enable long duration spaceflight in support of extended 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 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. In addition, IVF can support multiple Atlas and Vulcan Centaur missions that would benefit from such capability. 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 presented will 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, both in terms of spaceflight duration and capabilities of the vehicle while in space 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

For **Step One** of ULA's roadmap, ULA is designing a Vulcan Booster that will fly with the existing Centaur, driving by the need to transition to a domestically produced first stage engine, the BE4 LNG/LO2 engine produced by Blue Origin. 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 configurations with 5 solids, the AV 552. In addition to the 5M PLF configuration, the Vulcan will incorporate an expansion of the 4M PLF to 4.4M to accommodate greater payload without having to immediately jump to a 5M configuration. Figure 1 contains an illustration shows both Vulcan booster flight configurations.

Figure 2 ACES Upper Stage

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 to much greater than that of our most powerful launch vehicle, the Delta IV Heavy, for about ¼ the cost. The ACES upper stage will carry 3x the propellant capacity of Centaur, be able to fly up to 4 RL10's (or equivalent engine thrust), and be produced for the same cost of today's Centaur. But the 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 weight and cost reduction, 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 to extend the reaches of mankind in space, and the security of our planet and peoples.

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 each. By combining the functions of these into a single IVF module, the complexity of the system is reduced, and the system and the aft end of the upper stage is much cleaner and has the added benefit of reducing the number of heat shunts 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.

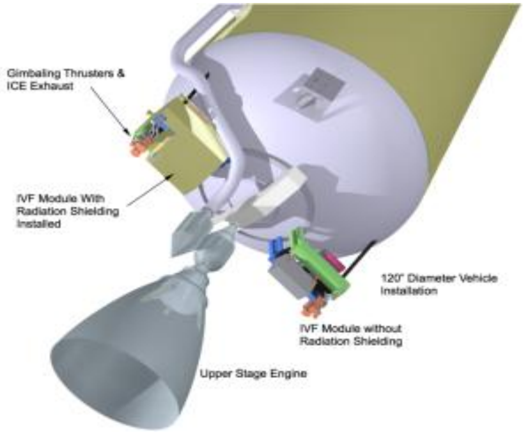

Figure 3 IVF replaces the Helium Pressurization system, the Main Battery Power System and the Hydrazine Reaction Control System resulting in a clean upper stage aft bulkhead

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 MCU/HEX and propellant tank. Early test results using off the shelf component analogs show very promising and even better than expected results. The Next Generation of design is currently ongoing and the plan is to test a full up integrated system using two large propellant tanks in a ground test end of 2017.

The IVF system is comprised of the following primary elements:

Internal Combustion Engine (ICE) – This engine is a small piston engine (~100cc) manufactured by Roush Racing, that runs on waste gases from the liquid oxygen and hydrogen tank fed into the engine intake and used to power the engine. 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 provides power to the MGU in order to generate 300V and 30V electricity to power different elements of the vehicle.

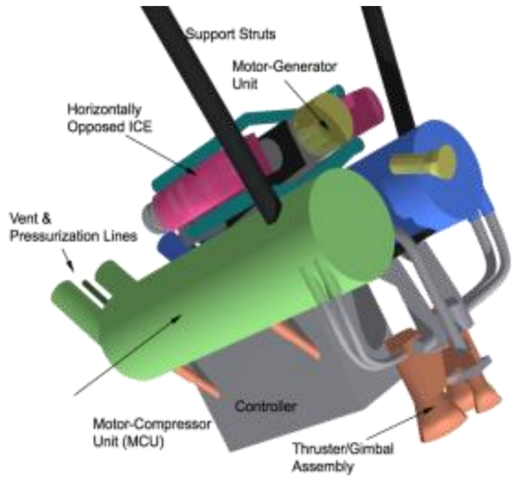

Figure 4 The IVF module is a compact single integrated module that contains all 3 systems in a single unit.

Motor Compressor Unit/Heat Exchanger (MCU/HEX) – The MCU is power 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 GH2 and GO2 from the upper stage propellant tanks and provides thrust by burning the combined gases using an internal igniter. The thruster are mounted on a gimbal system 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 Power, 2) Pressurize the tanks, and 3) Provide vehicle attitude control. As mentioned earlier this eliminates the 3 independent systems 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 limited redundancy. Because of the weight of the batteries and the wire runs due to the expanse between the power source mounting locations, and the power users. large

IVF CONOPS: The module uses an ICE engine to power a generator that produces 300V DC electricity. The 300V is used to powers the MCU, and is also bucked down to 30V to power the stage electrical system. This power can also be made available to payloads flying on the upper stage. A batter 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 potnetial 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 valve trains are used to provide failsafe system operation in case of a single valve failure. Helium bottle loading typically occurs prelaunch and has safety implications limiting 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 to increase the enthalpy, which results in an increase in pressurization for those tanks. The flow of these gases thru the compressor and thru 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 crew 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, the engine thrust vector control provides steering. 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.

IVF CONOPS: The IVF attitude cotnrol system consisting of a H2/O2 thruster eliminates the large bottles and plumbing, and associated weight for that entire subsystem. This system is replaced with two thruster elements mounted on a gimbal that in turn is mounted to the IVF module. Because the thruster burn the main stage propellant, and gases from those tanks are routed thru the IVF module, the closely coupled integration of the modules on the aft end of the stage eliminates 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 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 form 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. Elimination of the toxic propellants also relieves the associated safety hazards and simplifies ground operations.

IV. Upper Stage Enhanced Capabilities using IVF

In addition to the benefits outlined above, the use of IVF opens the door for many other possibilities in terms of upper stage and enhancement of 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 for crew or one of a kind type missions requiring that increased level of safety /redundancy. In addition, due to the elimination o 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 demonstrating 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 form earth or in orbit sources such as lunar or

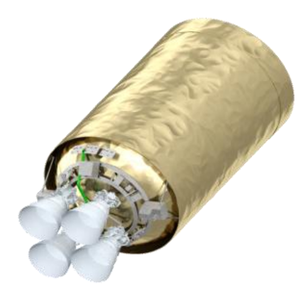

Figure 5 Long duration spaceflight is enabled with the use of IVF

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 new capabilities previously not considered. For example, habitats or on orbit factories that previously would have had to generate power thru 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 on board the payload that can now focus limited resources on other critical needs.

Figure 6

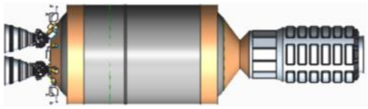

Figure 6 - Power from IVF can support payloads such as habitats

Other Capabilities Enabled With IVF – The possibilities are endless, 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 byproduct of the propellants 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 ACES with side mounted thrusters can provide transportation for a Lunar Lander capability in space with an attached crew or cargo module. With the IVF capability for on board propellant conditioning, power generation and engine restart capability on demand, the possibilities begin there.

Figure 7 Notional Lunar Lander benefits from IVF capabilities

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 non hazardous fluids and elimination of high pressure bottles 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 stages and CisLunar space transportation servicing missions, to interstellar missions and beyond are some opportunities being discussed. These possibilities and others will enable mankind to go where we have not gone before.