An Integrated Vehicle Propulsion and Power System for Long Duration Cryogenic Spaceflight

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Abstract

Proposed crewed exploration activities demand that high-performance, cryogenically fueled, in-space stages perform high delta-V missions that range from days to months in duration. Although vehicles such as the Apollo Service Module performed similar missions decades ago they were fundamentally low delta-V and non-cryogenic in nature with only small storage liquid oxygen and hydrogen systems for power generation. Long duration flight of large vehicles containing many tons of liquid hydrogen and oxygen has not yet been demonstrated and many technologies must work together to make this a practical reality. The storage of cryogens for extended periods has been the subject of intensive work with many promising approaches being brought forward. How these propellants are efficiently used in vehicle systems is equally important and equally challenging. For several years United launch Alliance has been developing an integrated system that can extend the present mission durations of existing upper stages from the present twelve hours to the regime of days and weeks. This Integrated Vehicle Fluid system uses some novel methods, some originally conceived in the early 1960's, to combine power production, attitude control and propellant thermal management to accomplish this goal. It can achieve this while providing a drastic reduction in vehicle dry and total mass and can wholly eliminate toxic propellants and high pressure gases from the vehicle systems. All vehicle functions can be performed using only the hydrogen and oxygen propellants stored in the main propellant tanks. Importantly these technologies can be applied incrementally to first perform post mission experiments, phase in as replacement systems for existing upper stages and ultimately be applied to advanced upper stages such as an Earth Departure Stage. Integrated Vehicle Fluids thus forms a foundational technology for next generation space transport.

Nomenclature

ACS	=	Attitude Control System
GH2	=	Gasous Hydrogen
GHe	=	Gasous Helium
GO2	=	Gaseous Oxygen
ICE	=	Internal Combustion Engine
ISG	=	Integrated Starter Generator
IVF	=	Integrated Vehicle Fluids
Isp	=	Specific Impulse
LH2	=	Liquid Hydrogen
LO2	=	Liquid Oxygen
MR	=	Oxygen to Hydrogen Mixture Ratio
ULA	=	United Launch Alliance

I. Introduction

The design of space vehicles is entering a new phase which steps beyond traditional methods to obtain a new level of performance, reliability and affordability. To understand what this new design phase implies and what its motivations are we must briefly review the design of a representative in-space stage. Figure 1 shows a schematic of the existing Centaur upper stage which is typical of most in-space vehicles. The electrical power system, attitude

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control system (ACS), main propulsion system, tank vent and pressurization systems are almost wholly segregated. Each system contains its own hardware redundancy to boost functional reliability and separate fluid mass margins are loaded to assure that the worst case usage conditions are covered, but there is no ability to move available resources around to address a failure or improve performance. A substantial leak in the helium storage system, required to pressurize the main vehicle propellant tanks, will render that system inoperative and cause a mission

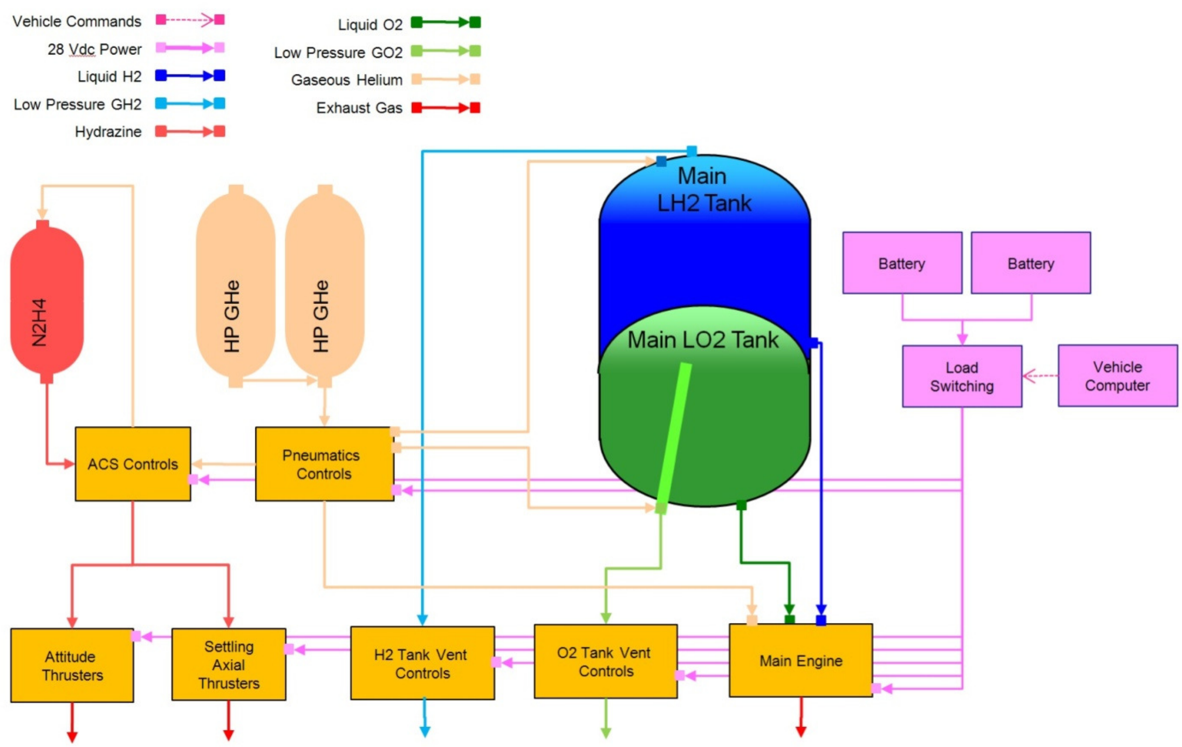


Figure 1. Simplified Centaur upper Stage Fluid Systems Schematic.

failure even though tons of hydrogen and oxygen propellants which potentially could supplement or replace that system are literally inches away. The residual propellants in the tanks at the end of the mission contain enough energy to provide all the electrical power and attitude control impulse for the mission but they cannot be accessed and are merely dumped.

Like all existing stages the systems are designed to meet a very specific and strictly bounded set of requirements. To do otherwise with present design techniques would be to incur large performance penalties. The Centaur hydrazine can deliver approximately 350 kN-seconds of total impulse. If a mission demands even 10% more the hardware must be redesigned. A requirement for 200% more would mean wholesale redesign to add more propellant storage.

The power system, based on batteries, is capable of six hours of operation in its standard configuration. Long duration missions of 12 hours are accommodated by doubling the number of batteries at considerable payload penalty. Still longer missions would incur rapidly increasing system mass until there was simply no more room for additional batteries.

The Centaur helium pressurization system is typically capable of supporting two main engine burn events. Under certain circumstances a third burn can be executed but this often mandates the redesign of the system to add additional helium storage capacity. A fourth or fifth burn which might be typical for a mission to the moon or a Lagrange point are simply not possible and would require even greater redesign.

Individual System vs Holistic Optimization

The design of the individual pneumatic, power, attitude control systems on the Centaur upper stage are each highly optimized to meet a restricted set of performance requirements and within these limits they are highly successful. In fact this optimization and refinement has been underway on the Centaur for decades. Systems design improvements at ULA are an ongoing activity and significant effort has been expended to evaluate what future improvements could be made. Next generation storage vessels, novel all-polymeric plumbing, valves with effectively unlimited life, modular design approaches have all been assessed. While these new technologies offer some promise of enabling better systems, the improvements are generally on the order of less than 10%. At present it is abundantly clear that the design and operation of these types of systems has effectively reached a plateau beyond which only diminishing returns reward investment. It appears that many designers for new vehicles such as Orion or Altair shared this conviction and in many cases hardware that had been flown in the 1960s was baselined. It was perceived that there was very little to be gained by trying to make a better hypergolic thruster or helium storage system.

The key to moving past this seeming barrier is to look past the individual systems, understand in detail the end-to-end vehicle function and conceive designs which optimize overall vehicle capability and cost instead of optimizing one system often to the detriment of others. When this approach is taken whole new avenues of design options are opened.

Integrated Vehicle Fluids Concept

For the past four years ULA has been developing a system, called Integrated Vehicle Fluids (IVF), which directly addresses the functional and reliability limits of existing systems. IVF works by using the waste gases produced by heating of the vehicle H_2 and O_2 tanks and burning them in small settling thrusters and in a very small Internal Combustion Engine (ICE). The ICE burns them at a very low oxygen to hydrogen mixture ratio (between 0.5 and 2) and produces electrical power with a generator (which doubles as the engine starter motor) charging a small rechargeable battery. The sustained peak shaft power output from a single engine is in excess of 20kW. Only 3kW are required for initial systems. Power is delivered to the rest of the vehicle in a manner directly analogous to a hybrid car; very high transient electrical loads can be addressed without excessively heavy engines, generators or batteries.

The ICE is cooled regeneratively by the incoming cold hydrogen gas from the main vehicle ullage spaces. This gas would be vented as waste boiloff in a traditional system. The exhaust gases from the ICE are used to produce settling thrust. Using waste propellants to produce power and settling results in a major mass reduction. The lower energy conversion efficiency of an internal combustion engine as compared to traditional fuel cell systems is more than compensated for by the use of this waste thermal energy to settle the vehicle and store energy for tank pressurization. In effect IVF is a cogeneration system where lower energy gases are put to beneficial use. Because of this the utility of the energy released approaches 100% and ancillary cooling systems are not required.

Electrical power is used to drive small cryogenic positive displacement pumps which take low pressure liquid H_2 and O_2 from the main tanks and raise their pressure moderately, vaporize them using waste heat from the ICE and thrusters, and store these cold gases in small accumulators (roughly 10% of the capacity and at 10% of the pressure of traditional systems) that are continually replenished. Tank pressurization, purges, pneumatic power (for operating valves or spinning up a main engine for example), the ICE Oxygen supply and bipropellant H_2/O_2 attitude control thrusters are fed from these accumulators. Attitude control reactants and tank pressurants and their dedicated, storage vessels are wholly eliminated.

A. Continuous Vehicle Settling , Vehicle Thermal Management & Structural Implications

ICE exhaust is used to provide continuous milli-G level settling thrust which holds the main propellants aft, isolates them from heat sources and cuts boil off losses by 50-70% based on extensive ULA flight data. This reduction in tank heating drastically reduces propellant losses from the main tanks and, depending on mission duration, saves hundreds to thousands of pounds of propellants. With continuous ICE operation, tank pressure rise can be suppressed with a drastic reduction in required main tank operating pressure, skin gage and mass. Reductions in tank skin gage further decrease the thermal conduction along the tank which results in even lower boil off rates.

The replenishment pumps which draw liquid from the tanks can also be used as a fluid recirculation system. By recirculating the propellants and inducing mixing in the main tanks they can be more homogenous in temperature.

This prevents the formation of local areas of hot propellant which can drive high tank pressures or reduce the amount of propellant which is burnable by the main engines. IVF thus not only enables dry mass reductions in primary structure and reduces propellant losses; it preserves that propellant in a usable state thus maximizing the utility of the propellants.

B. Reduced Mass Penalty for Margins

Under classical design architectures, dispersed performance margins must be calculated for each individual system since they are completely disconnected from each other. The main engines, ACS, pressurization and power margins are wholly independent of one another and the mass penalties for these margins are simply additive. With IVF, the dispersed performance of these systems can be addressed statistically via root-sum- squares methods. Effectively the largest margin becomes dominant and there is a significant reduction in mass required to address dispersed performance. The longer, more complex, and more different a mission is from prior experience the greater this benefit becomes.

C. Mission Flexibility Without Redesign

The ability to trade main vehicle impulse (main propellants) directly against power consumption or RCS impulse or number of tank pressurization events is a capability that no existing vehicle presently has. For example an unusual mission with a long duration must add hundreds of pounds of “mission peculiar kit” hardware because of the rigid performance boundaries of traditional architectures. For the first time ever IVF dissolves this barrier. The benefits due to hardware commonality, reduced one-off engineering efforts, and tremendous expansion in mission design flexibility are expected to be substantial.

D. Simplicity of Manufacture, Assembly, and Low Recurring Cost

IVF is constructed of hardware which is neither complex nor difficult to manufacture. It leverages over a century of ICE design and manufacture as well as the newer hybrid car technologies such as small low-cost rechargeable batteries and rare-earth permanent magnet motors and generators. There are no long-lead, single-supplier, high-speed turbo machines, super alloy castings, costly catalysts or severely life-limited combustion chambers. Transient high mixture ratio combustion events which would destroy turbomachinery is tolerated by intermittent combustion devices and mitigated by the low design mixture ratios.

Nearly all IVF testing can be done under ordinary atmospheric conditions at the least cost. While often initially perceived as more complex than existing flight systems, it mimics industrial systems with decades of field experience under extreme environmental conditions and hence has a background technical foundation that is unmatched by any present space flight technology.

Because IVF completely eliminates the need for hydrazine, high-pressure helium and large storage batteries, there are no separate, complex installations of these bulky objects. IVF is built in integrated modules which can be end-to-end tested before installation. Only vehicle interfaces for each IVF module need be completed at final assembly.

E. Operational Simplicity and Robustness

Unlike solar panels, fuel cells, exotic batteries or hydrazine systems, IVF is inherently light, compact, has a very high power density, does not require ancillary cooling, deployment or gimballing systems, is tolerant of high vibration and acceleration loads, insensitive to vehicle attitude and can be turned off/on or inerted to vacuum in seconds. There are no toxic elements present and activation is functionally equivalent to starting any small engine. It can be run on the ground powering the vehicle for hours prior to launch. If desired, a complete end-to-end check of all functional elements, including thrusters, can be conducted on the vehicle without depleting vital vehicle propellant stores or creating toxic contamination.

Hardware clean levels are not especially demanding and the potential for hypergolic or corrosive chemical reactions is eliminated. IVF enables a completely different way of thinking of how to design both vehicles and missions. In effect, it brings capabilities that we take for granted on ground and air vehicles into the space vehicle regime.

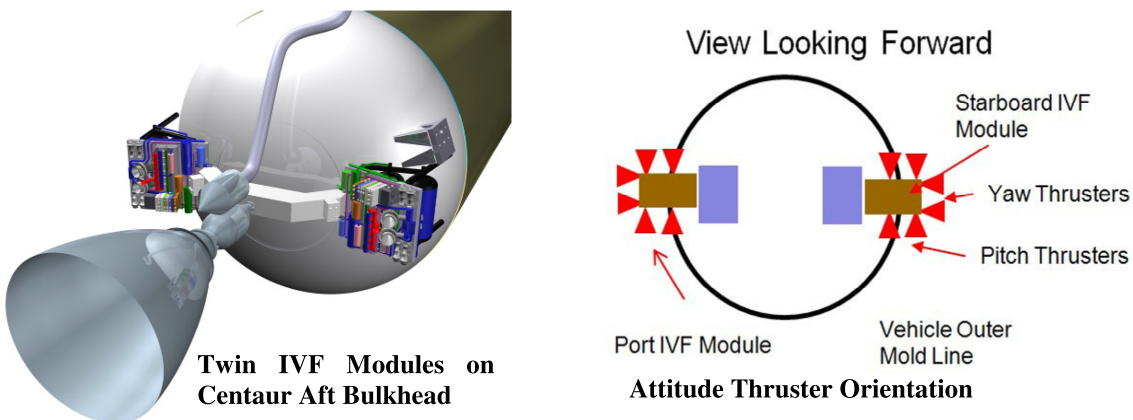
F. Cross-Cutting Benefits

IVF allows a highly flexible, long-duration stage to be built with the lowest possible hardware mass and propellant losses and at the lowest possible costs. It is so light that redundant IVF modules can be used to provide complete block redundancy for all its functions. Its ability to function using only propellant residuals allows disposal of the stage without significant mass penalty—a major benefit to commercial, Department of Defense and NASA satellite delivery missions.

IVF is directly applicable to depot-based space exploration architectures since it eliminates the need for addressing fluids other than H_2 and O_2. Its pumps, power and thermal management systems can be applied to propellant tankers, orbital depots and in-situ propellant synthesis plants in the future. Multiple engine burns, highly variable maneuver needs, variable tank sizes, multiple thruster complements or thrust levels and widely divergent mission designs can all be addressed by a standard system without unique redesigns. In short IVF technology is a foundation of future vehicle designs.

How IVF Works

Each IVF Module (Figures 2 and3) contains three functional subsystems. The End Effector Subsystem includes the lateral and axial hydrogen-oxygen thrusters and pressurization/vent controls. The Power Generation Subsystem includes the Internal Combustion Engine (ICE), generator, and controlling electronics. The Replenishment Subsystem includes the cryogenic pumps, their associated drive systems, fluid vaporizers and accumulators. There are two identical IVF modules per vehicle arranged on opposite sides of the vehicle to provide system redundancy.



Twin IVF Modules on Centaur Aft Bulkhead

Attitude Thruster Orientation

Figure 2 IVF Orientation View

G. End Effector Subsystem

The IVF End Effector subsystem (Figure 4) contains two types of hydrogen-oxygen burning bipropellant thrusters. The first type of thruster is the most similar to existing attitude control thrusters and is called the lateral thruster; it is principally used in a pulsed mode to produce precise pitch, yaw and roll moments on the vehicle. There are twelve lateral motors on the vehicle, six in each IVF module as shown in Figures 1 and 2. Each lateral thruster consists of a regeneratively cooled combustion chamber with a simple coaxial injector and spark ignition system. The lateral thrusters operate over a range of mixture ratios from 1.0 to 4.0 with 3.0 as the nominal MR and a nominal Isp of 400 seconds. They are supplied by the Replenishment Subsystem accumulators. Each thruster is a member of a redundant pair and they can be commanded singly or together to vary the total force. The propellants are controlled by solenoid valves which can be individually commanded. Hence if desired they can be operated in a H_2 cold-gas mode. This enables a very low impulse bit to be delivered for extremely precise maneuvering without requiring extremely short pulse widths.

The axial thrusters burn low pressure ullage gases from the main propellant tanks to produce a thrust of 27 to 54N (6 to 12 lb) each and are considerably larger than the lateral thrusters due to the low inlet pressure. These thrusters operate in a generally steady-state mode principally just before and after main engine burns to more forcefully settle the main propellants and to also vent the tanks to condition them for main engine start or reduce pressure following a main engine burn. These thrusters have a secondary cooling system which allows circulating IVF system coolant to pick up or lose heat to the thruster as desired for system operations.

H. Power Generation Subsystem

The power generation subsystem, Fig 5, contains the internal combustion engine (ICE) which is an inline six-cylinder, 600 cc displacement, reciprocating piston engine using a valve-in-block architecture. This simple, robust, low-vibration design is well suited to IVF needs. The engine is cooled with recirculating oil which rejects its heat to inducted hydrogen as well as to the LO_2 and LH_2 vaporizers in the Replenishment Subsystem. Warmed H_2 intake gas flows through the positive pressure crankcase where it sweeps away piston ring blowby gases to prevent any combustible mixture from forming in that cavity. H_2 flow to the engine and hence power is modulated by a hydrogen throttle valve. Similar to a modern automobile engine the IVF controller measures the H_2 mass inducted into the engine then commands a GO_2 injector to pulse to produce the desired mixture ratio within the combustion chamber. Gaseous O_2 is supplied from the accumulator at moderate pressure (15 to 30 Bar).
The mixture ratio of the entire engine or individual cylinders can be modulated by changing the pulse width of the GO_2 injector. The timing of the spark is also controlled by the IVF controller which can modulate the engine efficiency at a given MR by changing the start of the combustion event relative to piston position.

The ICE turns a permanent magnet based Integrated Starter-Generator (ISG) which is controlled by the ISG Control Electronics and produces up to 3kW of 300Vdc power. Many elements of the IVF use the native 300 Vdc for operation. The ISG maintains the charge on a small rechargeable battery via the battery charge control electronics. Power from this battery is used to start the ICE and supplements the ISG when combined vehicle and IVF loads exceed 3kW. This high voltage power is reduced in voltage with a buck-boost convertor to produce 28Vdc power for the vehicle.

I. Replenishment Subsystem
The replenishment subsystem (Figure 6) consists of two motor-driven positive-displacement piston pumps. One pump draws liquid oxygen (LO_2) from the main vehicle tank, the other draws liquid hydrogen (LH_2) from its main vehicle tank. The pumps are driven by variable speed brushless DC motors and can elevate the liquid pressure up to between 15 and 30 Bar. The pumps force the liquid propellants through a vaporizer heat exchanger which is heated by recirculating lube oil coolant. The discharge from the vaporizer is directly connected to either the O_2 or H_2 accumulators. As pressure declines in the accumulator due to usage the pumps are turned on to replenish them. Pump mass flow is varied to maintain an accumulator temperature of approximately 150K. Lube oil provides a considerable reservoir of heat for exchange to the vaporizers but if sustained heating demands are present several methods are available to keep up with the vaporization task. The simplest method uses lube oil electrical heaters which not only directly heat the oil but increase the load on the ICE thus producing more waste heat which is also acquired by the oil coolant. Alternatively, retarding engine timing and/or elevating MR reduces engine efficiency and increases exhaust gas temperature. Lube oil cools the exhaust manifold so greater heat is acquired in this area. By manipulating these parameters the accumulators can continue to deliver a consistent supply of gas at a steady pressure and temperature to both the thrusters and for tank pressurization.

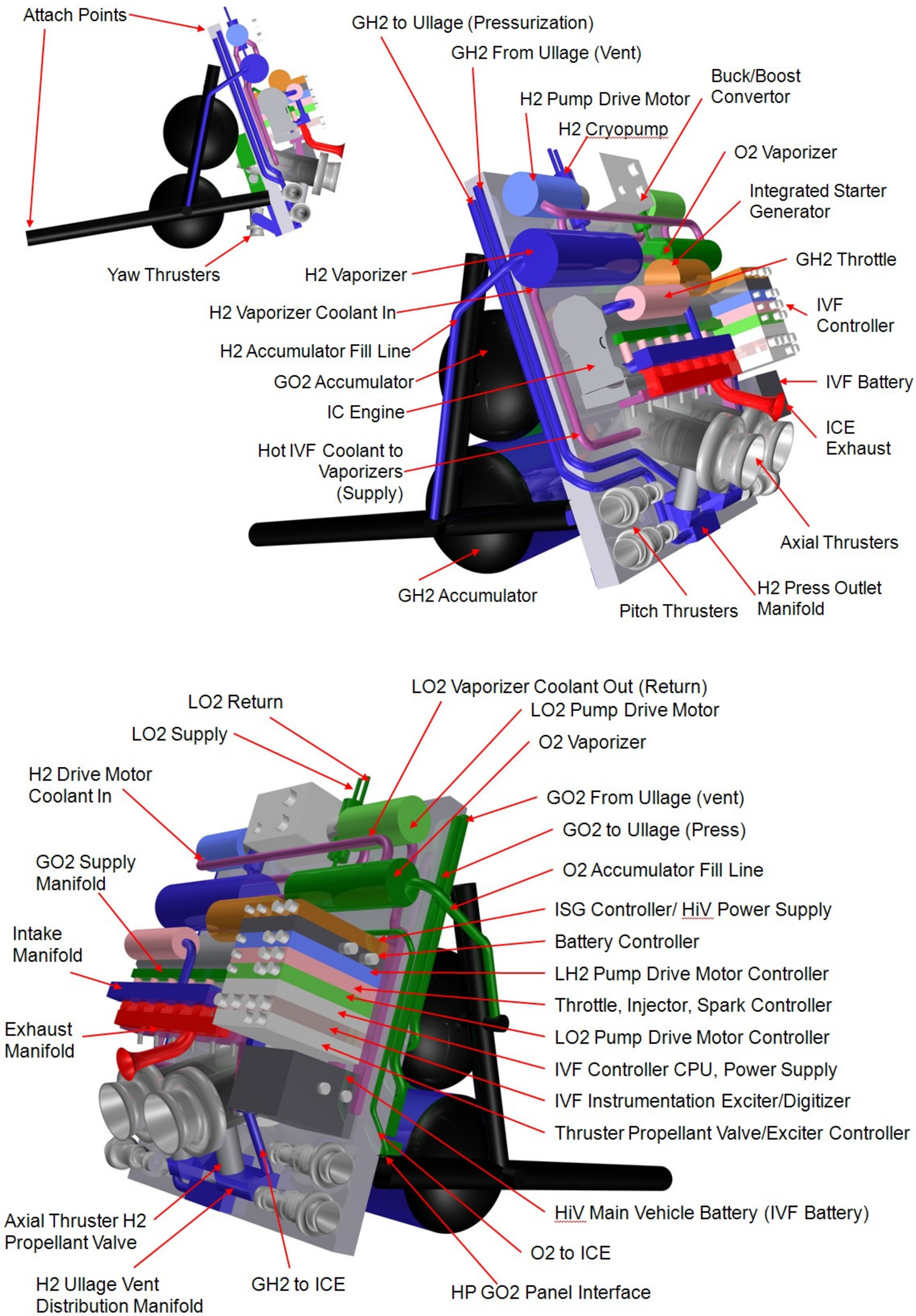


Figure 3 IVF Module Conceptual General Arrangement of Components

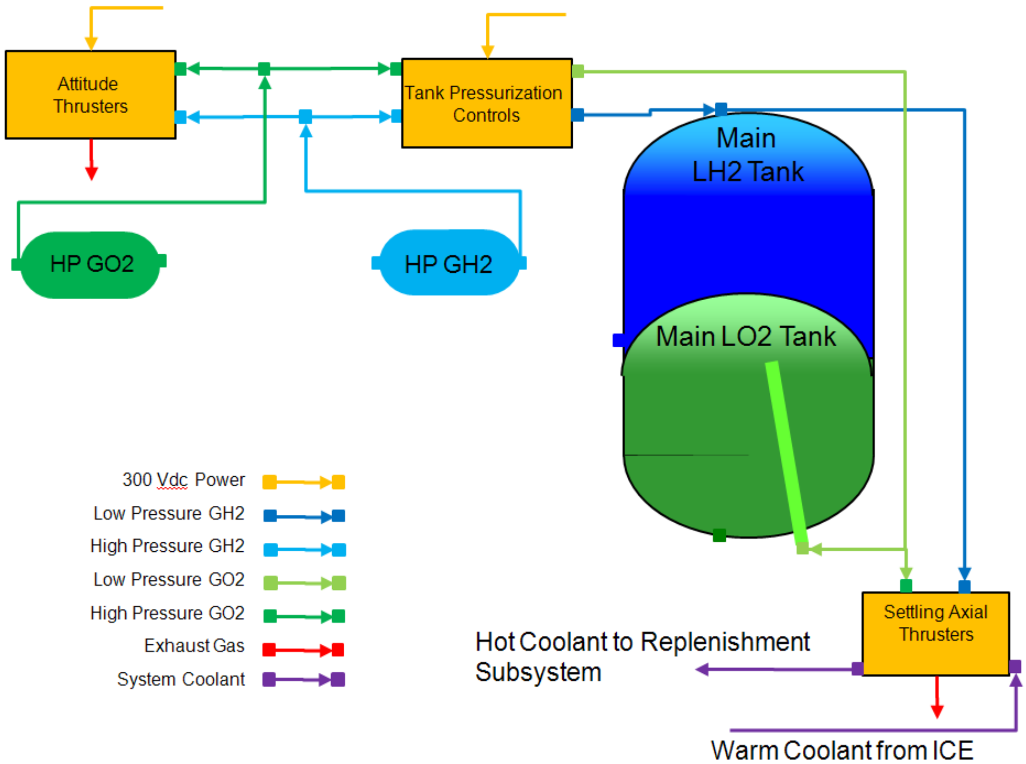


Figure 4 End Effector Subsystem Schematic

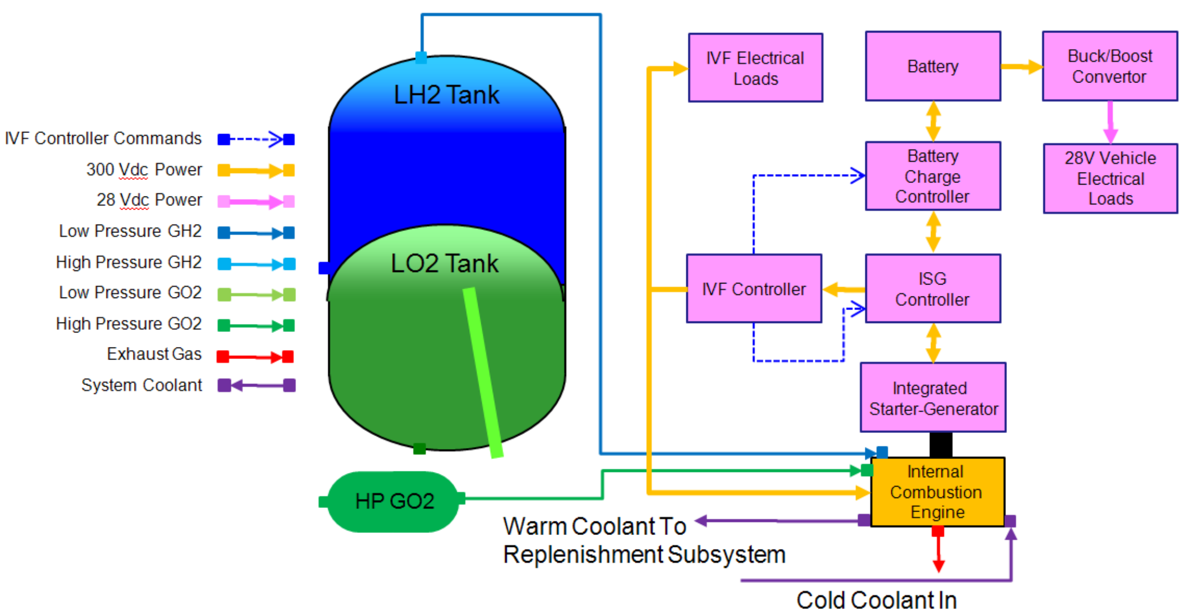


Figure 5 Power Generation Subsystem Schematic

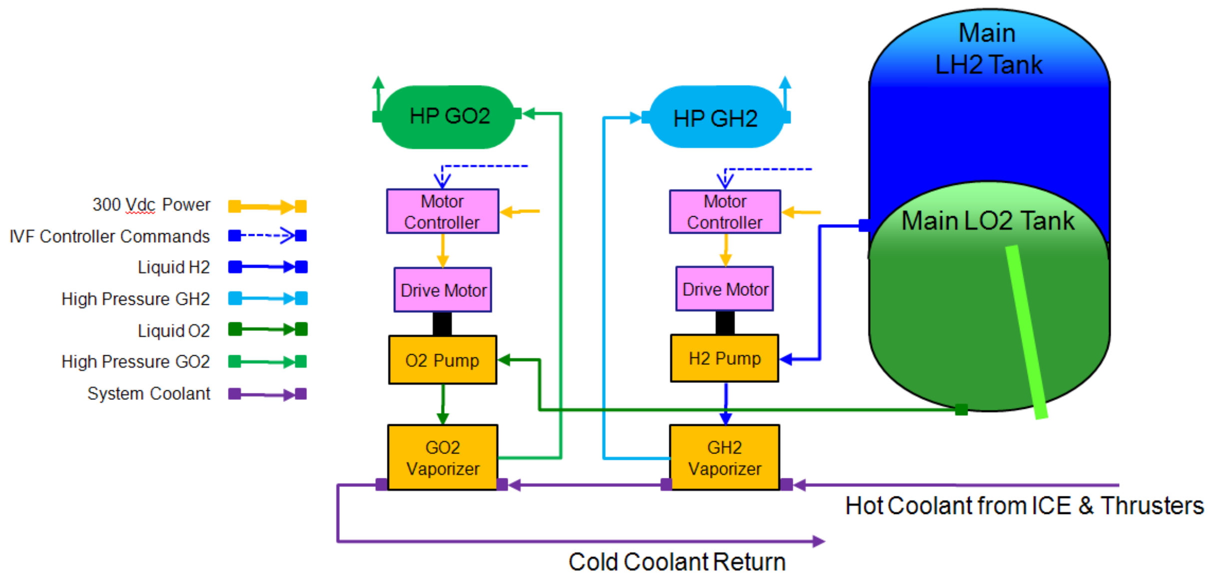


Figure 6 Replenishment Subsystem Schematic

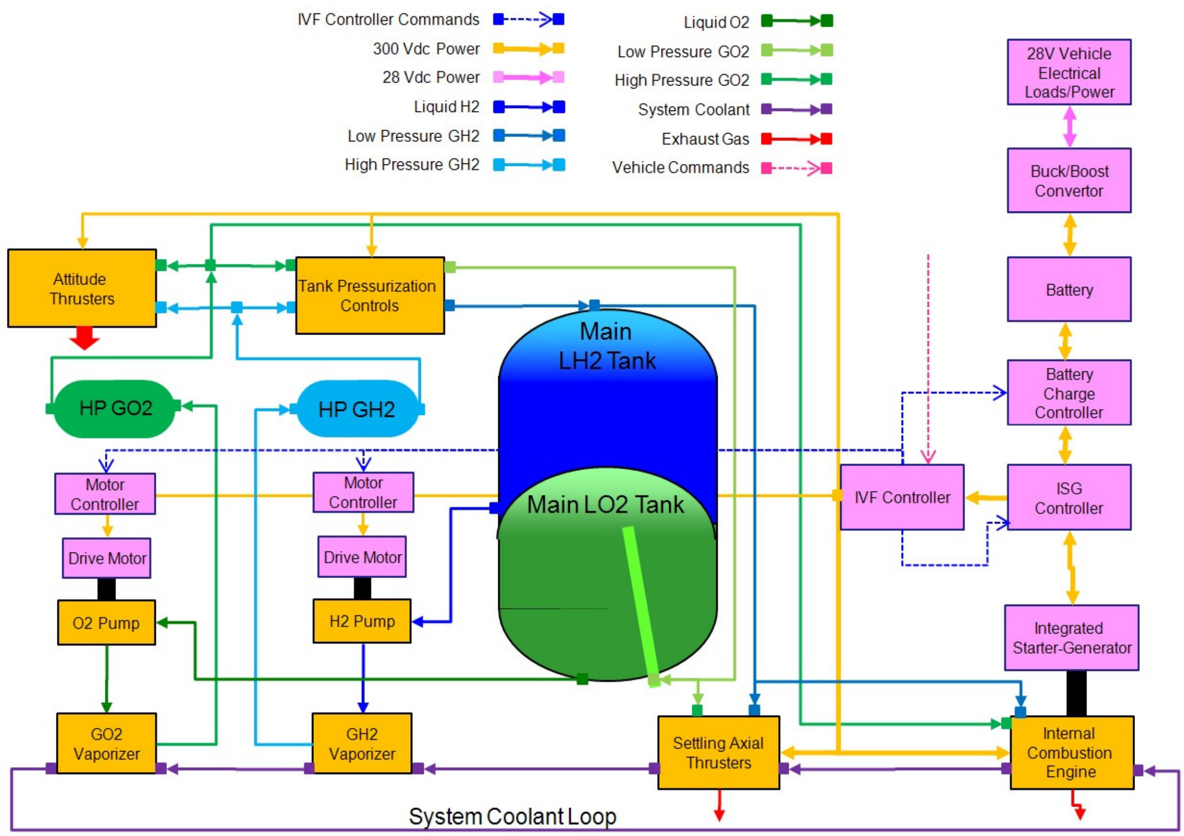


Figure 7 IVF Module System Schematic

IVF System Operation

Each IVF module (Figure 7) is commanded by the primary vehicle computer via a dedicated IVF controller to perform the required vent, pressurization, attitude control and settling functions. Under normal in-space coast circumstances with two IVF modules functioning, the IC engines are at a near-idle state and produce a combined 700-1000 W of electrical power for typical vehicle needs. Additional power demands may be present if the rechargeable batteries were discharged during prior high-load events. Coast is the ideal time to recharge these batteries.

The ICE exhaust settling thrust produced during these low power phases is very close to optimal for maintaining propellants in a fully settled condition. The amount of heat released in the ICE and transferred to the coolant is effectively balanced with the cooling capacity of the incoming cold hydrogen. If desired the overall hydrogen flow to the ICE can be modulated up or down by changing the engine mixture ratio. In general the vehicle tank pressures are held at a constant level by matching ICE consumption to boiloff. If desired the axial thrusters can be ignited to burn off excess gas.

Prior to an engine burn, tank pressures must be increased and higher settling thrust is required. The replenishment system pumps are activated and liquid propellants are gasified as the pressurization valves flow stored gases from the accumulators into the main tank ullage spaces. Naturally the pump demands will increase electrical power needs and the ICE increases power to match this need. More settling thrust is thus generated and more waste heat is available to vaporize the propellants. This engine prestart event represents the peak load condition for IVF. As H_2 tank ullage pressures rise, the hydrogen inlet pressure to the ICE also increases and the engine becomes increasingly supercharged. Its power delivery capability thus also increases just at the time when it is most needed. However because the replenishment subsystem is pumping liquid propellants up to a low pressure the total electrical demand can be handled by a single IVF module. The bulk of the energy required for pressurization and the ACS is provided by the waste heat from either the ICE, axial thrusters or both. Hence there is no premium placed on extremely high ICE or generator efficiency- greatly simplifying the hardware design. Two fully functioning modules merely complete the pressurization task at a higher rate. The time for pressurization can be further foreshortened by discharging the batteries to support this high-load event.

During engine burn the IVF modules continue to supply gaseous oxygen pressurant to the LO_2 tank and LH_2 tank pressurization is handled by a gaseous bleed from the main engine as is done today. However the IVF system is fully capable of performing LH_2 tank pressurization if desired. High power demands associated with main engine operation such as thrust vector control or engine valve operation are readily addressed by the Power Subsystem.
Following engine shutdown the axial thrusters can be used to rapidly vent the tanks down or simply operating the ICE at low MR will effectively consume the excess gases and return the tank pressures to their coast levels. Tank pressure control both in vent and pressurization modes is thus far more robust with greater hardware redundancy but with little impact to hardware complexity or system costs.

If zero-G conditions are desired, such as for spacecraft separation, the IVF system can be completely shut down and the vehicle will continue to run on with redundant power supplied from the small IVF batteries. The system can be sized to operate in alternating “battery-only” then “ICE-generator” mode if tank heating and power demands are low. In this way mission duration can be drastically extended within the limits of the propellant storage capacity and thermodynamics. If desired the IVF power supply function can be completely halted so that a solar array or other long-duration power source can be used. Even with the ICE shut down vehicle settling can be maintained via the axial thrusters in a pulsed or continuous duty mode thus maintaining propellant position and conditioning.
The ICE is sized to permit ample power generation even with hydrogen tank pressures that are well below existing vehicle levels. The use of hydrogen whose saturation pressure is below 1 Bar, as might be useful for a long-duration cryogenic vehicle, is readily supported.

IVF Hardware Development Status

J. Hydrogen –Oxygen Thrusters

IVF development commenced four years ago with the design, fabrication and hotfiring of the lateral thrusters (Figure 8). The greatest challenge was to achieve reliable operation with a low-cost ignition system. At the time, all space- demonstrated engine ignition systems were extremely bulky and costly. At present two viable low-cost, compact ignition systems exist and have been demonstrated in the lateral thruster. An innovative system using piezoelectric spark generation is the prime candidate and is presently being developed for NASA by the supplier. The third generation of lateral thruster is presently being designed and is expected to be hotfired in 2012.

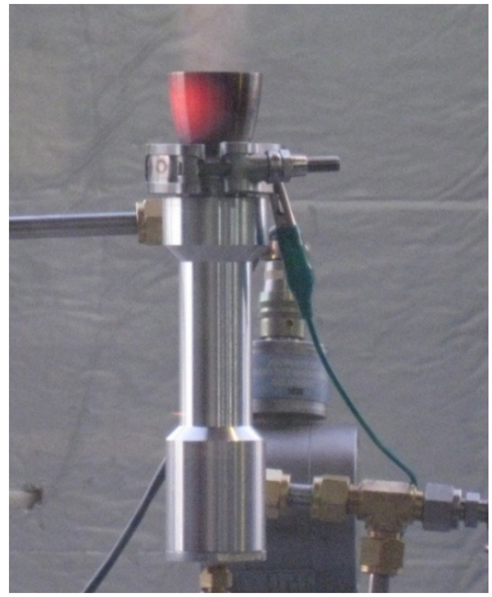


Figure 8 Lateral Thruster Test

The axial thruster (Figure 9) was developed second since it has a very low combustion chamber pressure and requires a specialized vacuum test facility. This facility was completed in 2011 and extensive firing of the first generation axial thruster was conducted with excellent results. The Generation One axial thruster had a double wall cooling system to enable direct measurement of the heat extraction capability since this is the source of heat for propellant vaporization. Results were better than expected. The Generation Two thruster is already in design and is also expected to be hotfired in 2011.

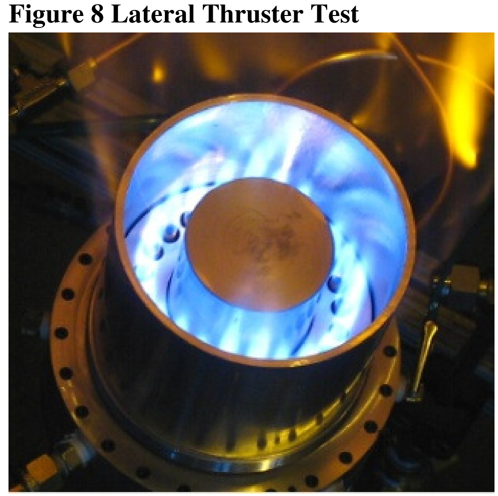


Figure 9 Axial Thruster Test

K. Hydrogen-Oxygen Internal Combustion Engine

The Internal Combustion Engine (ICE) at the heart of IVF has its roots in a DARPA/NASA project of the early 1960s. A team from Vickers designed, built and tested a H_2/O_2 burning single-cylinder engine (Figure 10) for 500 hours with excellent results. ULA and Roush Industries leveraged this historic work and built and tested two engines in 2010 burning H_2/O_2. A single cylinder piston engine (Figure 11) and a single rotor Wankel engine (200cc displacement) were both subjected to “hotfire” testing with very good results. Multiple H_2/O_2 mixing methods were used and operation was performed over a range of mixture ratios, power output, spark timing, intake conditions and engine speed. The behavior of H_2/O_2 combustion in the engine was directly compared to gasoline/air. H_2/O_2 was shown to be not only readily ignitable even at very low mixture ratios but exhibited amazingly consistent and rapid burning as compared to gasoline. A very detailed thermal survey was conducted on the Wankel with over 75 thermocouple channels (Figure 12) to understand the heat loads across various parts of the engine. This is pivotal since the engine is regeneratively cooled. The results of these efforts lead to the selection of an inline six-cylinder as our baseline engine design. This engine is presently in design and manufacture is expected to be well underway by year's end.

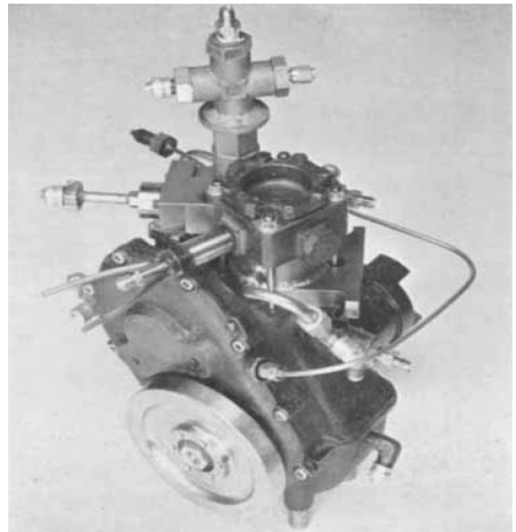


Figure 10 Vickers H2/O2 ICE

L. Cryopump & Vaporizers

The liquid oxygen and hydrogen cryopumps are derivatives of test work performed by ULA and XCOR Aerospace in 2009 and 2010. Effectively XCOR has shown that liquid cryogens, including hydrogen, can be readily pumped with high efficiency in simple, long-life, positive displacement pumps at low net positive suction pressure. This groundwork has enabled the design of smaller pumps for IVF which include all the salient features of the larger pumps which we have already tested. These components are already in design and should be in test in 2012.

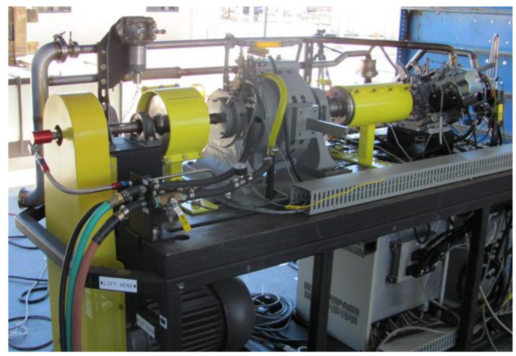


Figure 11 H2-O2 Burning Single Cylinder Engine on Dynamometer Test Stand

M. Technology Infusion & Evolution

While the eventual full implementation of IVF will be revolutionary in its impacts, ULA has learned by costly lessons that an evolutionary approach to vehicle design is mandatory for maintaining reliability. Fortunately the entire IVF system does not have to be simply dropped into the vehicle in a single step. Substantial portions of IVF can be used to solve pressing and immediate needs without demanding the wholesale removal of major existing flight-proven systems. Flight experience can be gradually accumulated with elements of IVF until by the time the final configuration is installed a high confidence level will have been achieved based on flight data.

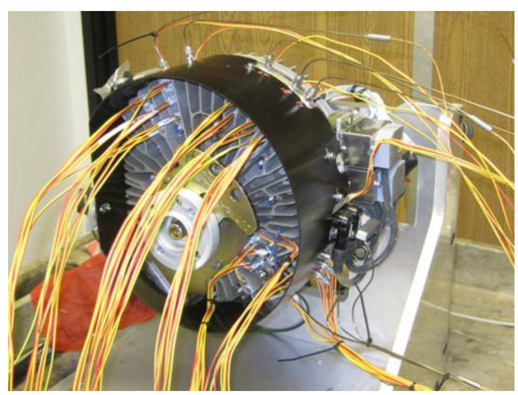


Figure 12 H2-O2 burning Wankel engine thermal survey instrumentation

N. Vehicle Disposal, Mission Extension and Performance Amplification

Current policy requires appropriate disposal of upper stages for NASA and Department of Defense missions. Most missions currently are granted waivers due to the high cost (both in terms of performance and dollars) to dispose of these stages. It is increasingly obvious to policymakers that we must begin to dispose of upper stages and reduce overall orbital debris release in order to avoid potential catastrophic damage to high value orbital assets. The difficulty lies in delivering an accurate and substantial delta velocity to the spent upper stage at precise orbital locations without incurring large penalties to the overall vehicle performance and cost. The residual propellants within an upper stage such as the Centaur vehicle weigh at least 150kg and on many missions much more. If properly burned they could readily produce the required delta V for disposal. The application of the IVF axial thrusters to existing vehicles would permit these residuals, which are typically dumped, to be burned following spacecraft separation to achieve upper stage disposal. Hence only a portion of the End Effector Subsystem is required to provide an immediate benefit to a launch vehicle system.

If it is desired to perform multiple disposal thruster firings in a typical Hohmann transfer maneuver, then mission duration must be extended by up to 12 hours. The addition of the power generation system can readily provide this capability while remaining inert up to the point of spacecraft separation. Hence the ICE and electrical power generation elements could be used in a mode which does not place the primary spacecraft at risk.
The emplacement of axial thrusters for continuous settling during long coast periods such as those for direct to geostationary orbit missions can significantly reduce propellant boiloff as compared to zero-G flight. This is due to the segregation of heat sources away from the liquid propellants. If a set of axial thrusters were installed in addition to existing hydrazine thrusters, then the hydrazine typically used for settling could be eliminated. By reducing propellant lost to boiloff and reducing hydrazine mass required the overall vehicle performance would be enhanced. Once again the application of the ullage-burning axial thrusters would provide an immediate and significant benefit to a launch system.

O. Flight Experimentation for System Maturation

Because of its compact size and low mass a single complete IVF module could be flown as a flight experiment on the Centaur. It could be installed in the location called the Aft Bulkhead Carrier position as a secondary payload. The experimental IVF system could remain inert until spacecraft separation so as not to compromise launch reliability. Extensive and long duration end-to-end functional tests could be performed with the IVF module interacting with the residuals in the expended upper stage. Effectively the full system functionality could be demonstrated in a true extended duration space environment thus raising the IVF concept to Technolgy Readiness Level 9.

IVF Bottom Line Benefits

IVF effectively eliminates multiple heritage systems with an associated benefit for a existing Centaur-class vehicle on the order of 5-10% of dry mass which directly translates to payload capability. On a Centaur this equates to over 200kg of payload- nearly the same benefit as adding a fifth solid rocket motor to an Atlas booster. The greatest benefit though lies in the reduction in losses to the main vehicle propellants and the elimination of secondary fluids, their mass margins and residuals. These benefits are dependent on mission type with the greatest gains accruing to long duration missions such as the direct injection to geostationary orbit mission which includes a coast duration on the order of five to six hours. The benefits for this moderate coast duration mission exceed 500kg when provisions for orbital disposal are factored in. The benefit for earth departure stage vehicles whose primary structure is not yet designed and which can take full advantage of IVF-driven pressure reductions, whose propellant masses are 60 tons or more and with orbital coast durations measured in days to weeks, could be many tons. The cost benefits are effectively proportional to the orbital cost per kilogram- meaning that savings range into the multiple tens of millions per mission.

Unlike today's systems IVF provides an unprecedented level of robustness and retained capability even in the face of multiple hardware failures while simultaneously allowing us to validate its integrity for extended periods and right up to the point of launch. No other system has had this sort of capability. The use of main propellants stores is powerfully enabling. Margins for pressurization and ACS no longer need to be meticulously analyzed; our margins are in the hundreds of pounds. IVF can tolerate leaks and hardware failures that would doom existing systems while simultaneously eliminating high pressure gas which is the biggest driver for leakage. Total electrical energy capacity and power is taken to a new level as is the performance of thrusters in terms of specific impulse, variability of impulse bit and total delivered impulse. Whole days are recovered from a launch campaign since hypergolic propellants no longer have to be pre-loaded, batteries do not have to be activated and pyrotechnics are eliminated.

From a lifecycle standpoint one of most beneficial aspects of IVF is that it does not require endless redesign and requalification testing to address unforeseeable but inevitable growth requirements. A common IVF module can be used on any H_2/O_2 vehicle without significant scaling of mass or change in complexity. The same system can support a vehicle with a 60 ton propellant capacity or a 20 ton capacity. Larger thrusters, increased electrical demand, bleeds for breathing air, provisions for vehicle propellant cooling or heat rejection from spacecraft, etc, can all be accommodated without wholesale redesign. IVF can support any transport architecture and is especially valuable for depot based concepts. It enables medium duration flight of propellant delivery tankers for rendezvous with an orbital depot and is an obvious tool for transferring propellants directly between vehicles under positively-settled, thermodynamically controllable and predictable conditions.

Summary

We believe that the Integrated Vehicle Fluids system represents a new level of capability in terms of cost, mass, reliability and mission design. No other approach has given us the holistic benefits to vehicle design that IVF has shown to date. The system architecture is an essential element in any future affordable, long duration, in-space cryogenic stage. Such stages are key to not only accomplishing current missions more effectively but open the door to exploration , commercial and government missons that today simply cannot be done . ULA intends to continue IVF development with the goal of fielding a full scale system later in this decade.