Development Status of an Integrated Propulsion and Power System for Long Duration Cryogenic Spaceflight

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Proposed crewed and robotic exploration activities demand that high-performance, cryogenically fueled, in-space stages perform high delta-V missions that range from days to months in duration. In 2011 ULA presented a concept for the integration of in-space tank pressurization/vent, power-generation, attitude control and vehicle propellant settling functions into a single system based on the utilization of waste hydrogen and oxygen boiloff gases in a small, simple internal combustion engine and bipropellant thrusters. This system is called Integrated Vehicle Fluids or IVF. Much has been accomplished over the past months leading to further refinements and simplification of the system architecture. Flight-analogous engine and thruster hardware has reached a high maturity and could be considered for application beyond existing cryogenic stages.

Nomenclature

ACS	=	Attitude Control System
GH2	=	Gaseous Hydrogen
GHe	=	Gaseous 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

One year ago ULA revealed an innovative auxiliary power system for in-space and upper stages called Integrated Vehicle Fluids (IVF). IVF eliminates large batteries, pre-loaded high pressure helium and hydrazine or other secondary propellants and instead provides all these functions by using waste hydrogen and oxygen boiloff. It accomplishes this with two novel devices: a compact ullage gas burning thruster and a small internal combustion engine. Working together with simple generator, compressors and a compact battery it can not only support existing stage requirements but is imminently suited for safety-critical, longer-duration, high delta-V missions that cannot be effectively accomplished without enormous mass penalties.

The simplified schematic for a single IVF module is shown in Fig. 1. Two modules are used on a vehicle, illustrated in Fig. 2. The IVF engine consumes small amounts of H2 and O2 vent gases producing settling thrust as exhaust, shaft power for a generator and two pumps and waste heat which is rejected to incoming cold reactants for engine cooling. At higher power settings excess heat is used to vaporize liquid propellants for pressurization. These low pressure gases are pumped up using shaft power to 5-10 Bar and returned to the tank ullage spaces for pressurization. Vent gases are also consumed in gimbaling thrusters for vehicle settling and attitude control.

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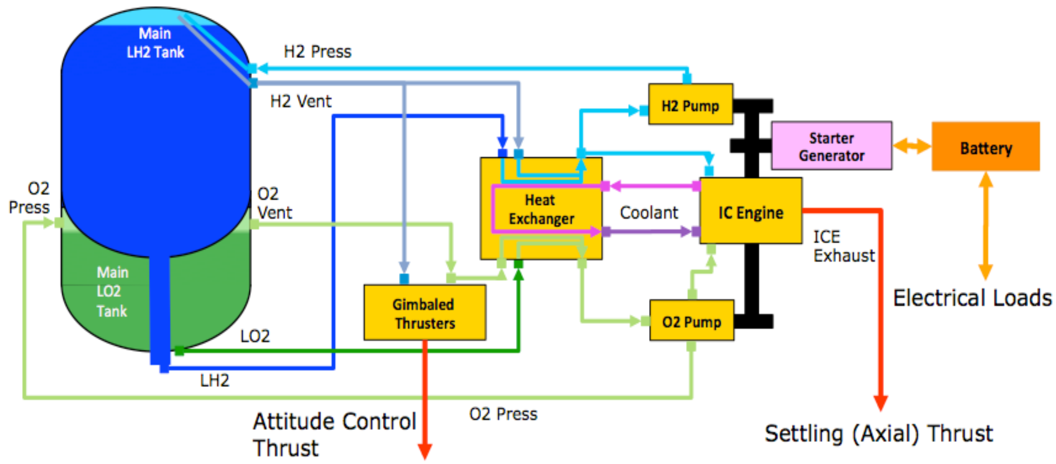

Figure 1. IVF Simplified Schematic

II. Hydrogen-Oxygen Thruster Development

Thruster development was commenced first in the evolution of the IVF system and the hardware has matured enormously. IVF initially required both high pressure short-pulse lateral thrusters and low pressure ullage-pressure fed axial settling thrusters. Work to date has shown that only four low pressure thrusters used in a gimbaling mode are required for all present hydrazine reaction control system functions. Further refinement of the IVF architecture has led to the thruster design shown in Fig. 3. This nominally 27 N thruster, fabricated principally of aluminum alloy, has been undergoing extensive vacuum hotfire testing with outstanding results. Consistent operation has been demonstrated over a range of mixture ratios from 1 to over 5. Typical Isp values are approximately 400 seconds – a substantial improvement over the 235 seconds of a typical monopropellant hydrazine system.

Three ignition exciter devices, two electronic and one piezoelectric, are still being traded based on test data but all have shown success. Testing has shown that with an effective injector design, the spark energy required for reliable ignition is extremely low; nearly an order of magnitude lower than anticipated at the start of development. This has lead to a significant reduction of exciter complexity, cost, and size.

With the maturation of the combustion and ignition devices the development focus has turned to the cryogenic propellant control valves. Making a light-weight, low-power valve with low pressure drop that can seal effectively with hydrogen at cryogenic temperatures and accomplish this with a lifetime measured in many thousands to millions of cycles has historically been difficult. Ongoing development is focusing on understanding the precise force requirements for leak tightness and vibration tolerance. Initial results are promising.

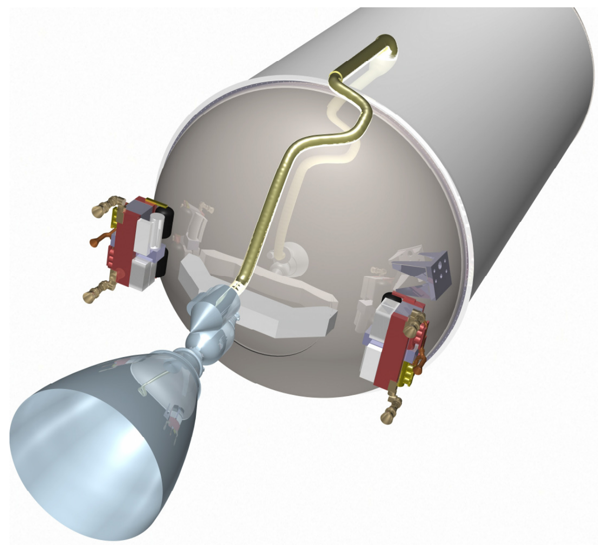

Figure 2. IVF Modules Mounted to Centaur Vehicle

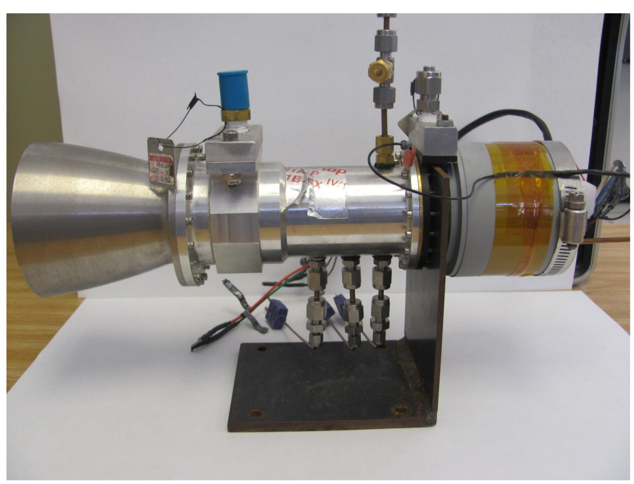

Figure 3. Low Pressure H2 Thruster

III. Internal Combustion Engine Architecture

Development efforts in 2010 and 2011 tested off-the-shelf single-piston and 200cc Wankel engines with pure H2/O2. Results were excellent and many lessons were learned. Chief of these being that burning hydrogen/oxygen at low mixture ratios in an IC engine was not only possible but imminently practical. In fact, the ignition and burn characteristics of hydrogen were astonishingly predictable with statistical variation in the combustion process being a small fraction of that seen with gasoline or even natural gas. The combustion process did not lead to detonation behaviors or pre-ignition. Exhaust gas temperatures at the low mixture ratios of interest were hundreds of degrees less that with gasoline, lessening the risk to exhaust system components.

The leading candidate for the flight design at the outset of testing was a Wankel configuration due to its very high power/mass ratio and lack of valve train. Inherent in the design of a Wankel is that there are no intervening "strokes" (as compared to a 4-cycle engine) to allow the combustion area to cool. The extremely rapid combustion of hydrogen and its high flame temperature lead to a tightly focused heating area around the spark plug. A drastic temperature variation was observed over only a few centimeters even with an aggressive external air cooling system. This would have lead to tight restrictions on the peak mixture ratio and established an undesirable thermal distortion of the engine case that would have inevitably lead to an extensive and costly development effort of the lateral and apex seal lubrication and cooling mechanisms.

The key engine requirement was to have a robust and simple design that would maximize use of commercial experience and off-the-shelf hardware. The design team traded high-performance configurations like the air-cooled Wankel, and decided that a liquid-cooled Inline 6 (I6) cylinder engine offered the best combination of weight, operating robustness, performance, heat rejection, redundancy and low vibration. Compared to the Wankel, it offered a well characterized lubrication system and had large areas for extracting waste heat via standard liquid cooling. Waste heat is used in IVF for propellant vaporization; the more available, the more robust the overall system design.

The multi-cylinder design also offered operational robustness since one or more cylinders could be disabled and the engine would continue to run. Because of the overlap of intake strokes in an I-6, the flow of gases through the intake system is more regular and can be more easily modulated with simple devices. This eases mixture ratio control and simplifies the electronic control system. Similarly, the power delivery is very smooth with minimal variation in output torque over 720° of crankshaft rotation. This meant that time-consistent power could be directed to pumps and generators. It also allowed the elimination of a heavy engine flywheel since the generator and other rotating devices were sufficient. The larger displacement allowed elevated power delivery even at moderate RPMs and also provided large margins to address any future loads or desired growth.

The basic design of the Generation 1 development engine is shown in Fig. 4 and Fig. 5. The IVF ICE only displaces 600cc with a compression ratio of 6.5 and a redline of 8000 RPM. Renderings and photographs of the engine are consistently misleading – the engine is amazingly small, at less than 700mm long, despite no effort to remove excess material. No effort was applied to shed mass from the Generation 1 engine but it is likely it will weigh less than 50kg in flight configuration.

The ICE is effectively two three-cylinder engines which sandwich a common gearbox. The gearbox provides a 3:1 speed increase for the Integrated Starter-Generator which allows it to operate at higher speeds and improves its efficiency both during motor and generator modes. An intermediate power take-off drives the IVF compressors via clutches. Fig. 4 shows the central gearbox with the various power take-off provisions.

The design is a classic "flat head" which allows the entire valve train to be housed in the block/crankcase assembly. The valve train and gearbox cavities are segregated from the crankcase in separately lubricated sealed closed cavities – similar to many flight proven designs. Only the crankcase has a flow-through lubrication system which cools the pistons and lubricates the rolling-element connecting rod and crank bearings. The crankcase acts as an accumulator for the incoming hydrogen gas. Piston ring blowby gases are scavenged by this hydrogen and extracted from the case with the lube oil. A typical centrifugal separator allows recycling of lube oil and delivery of this gas to the engine intake manifold.

The “retro” design of the I6 is reminiscent of a classic Ford flathead V-8 design of the 1930s. These engines, while being incredibly tough, had a reputation for requiring oversized radiators since exhaust gas passages were close to block cooling passages and more heat than typical was transferred to the coolant. This heat rejection feature is much desired in the IVF engine since we wish to scavenge heat for tank pressurization. This allows us to eliminate the extraction of heat from the thrusters, a feature of earlier IVF designs, and keep all heat exchange functions within the engine. The engine head, which bridges the length of the engine, contains the heat exchange surfaces for rejecting heat to incoming hydrogen combustion gas, as well as vaporizing both liquid hydrogen and oxygen for tank pressurization.

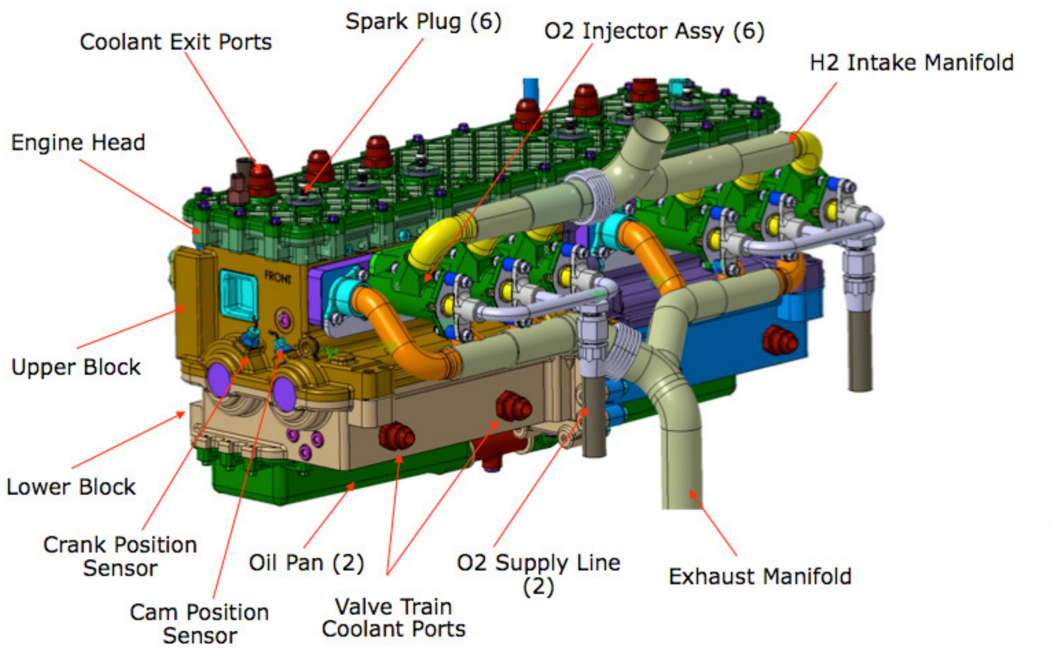

Figure 4. IC Engine Exterior Design – Gas Manifolding Provisions *Credit: Roush Industries*

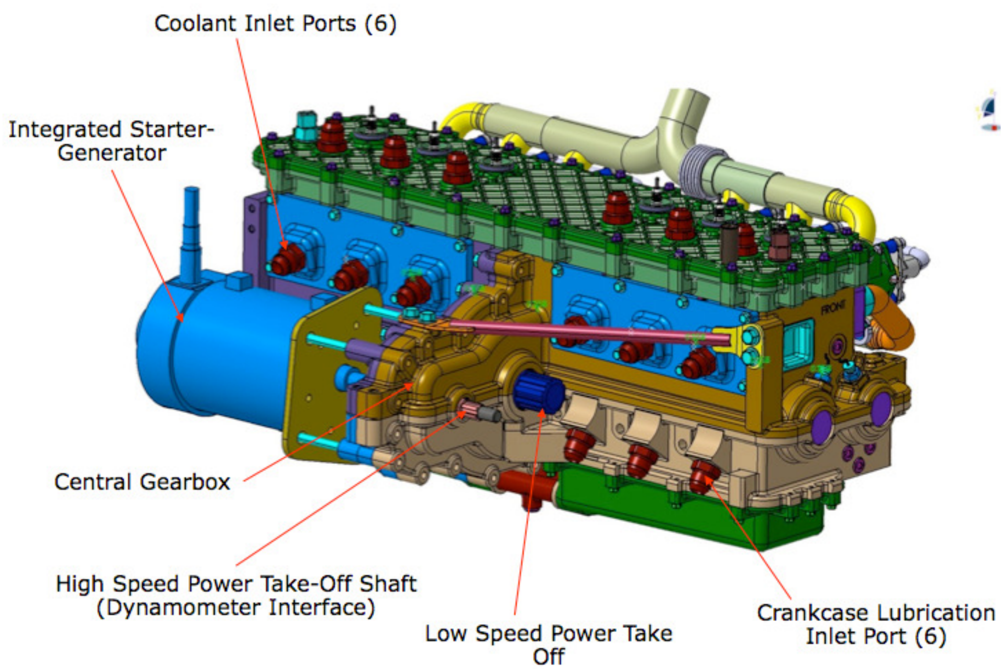

Figure 5. IC Engine Exterior Design – Power Take Off Provisions *Credit: Roush Industries*

The engine valve system was designed for simplicity, robustness and reliability. The valve-in-block design allowed a direct gear drive for the camshafts from the crankshaft without intervening belts or chains. The cams directly actuate the valves via a simple tappet thus avoiding rocker arms or other mechanisms. As might be imagined there has been little performance optimization work done on flathead engines in recent decades so analytical tools were of limited benefit. The valve lift and head internal geometries were optimized based on direct flow testing. Small contour changes in the head had significant benefits to performance.

For initial testing the engine will use a commercial coil-on-plug ignition system. Follow-on configurations will likely be derivatives of the electronic ignition options being tested on the hydrogen thruster. Based on prior testing there should be no need to create custom spark plugs.

Accustomed as we are to atmospheric IC engines which pump nearly 80% inert gas, the mass flow rates of hydrogen and oxygen for the IVF ICE are surprisingly low. Approximately 2 kg/hr of hydrogen and half that amount of oxygen will be consumed at low power settings ranging up to 12.5 kg/hr at peak power. Metering such low flowrates and pressures required a change of technique from traditional plate-in-bore throttles seen on automobiles. Testing with these throttle geometries showed that the low pressure H2 simply bypassed the metering element by passing through clearances. Instead a device akin to a medical respirator controller is used to meter the flow of hydrogen into the engine. These devices exhibit the required precision required to modulate hydrogen both at low and high flowrates. The throttles establish the effective mass of hydrogen present in the combustion chamber and this is matched by injecting O2 to establish the desired combustion mixture ratio.

Analogous to an automobile fuel injector the IVF injectors are capable of variable on-time to deliver precise amounts of oxygen to each cylinder. At peak RPMs a given injector will be firing more than 60 times a second for durations on the order of a millisecond. Working with Roush, Moog has extended their no-slip-fit coaxial solenoid valve line to perform this function in pure oxygen and do it for 18 million cycles.

Integrated Starter-Generator (ISG) hardware developed in 2010 for the testing of the off the shelf IC engines on hydrogen was redesigned and refurbished to support the higher shaft speed and greater starting torque associated with the I6 engine. The ISG produces approximately 300 Vdc in generation mode and requires 270 Vdc during motor mode. Start up of a six cylinder flat head engine with hydrogen as the primary manifold gas falls somewhat outside the historical background of IC engine cranking experience. Conservative analytical assumptions were applied to assure a robust engine start capability. Accordingly the ISG was improved to be able to supply this and also to be capable of providing up to 4 kW of electrical power.

The astonishing pace of Lithium battery technology evolution has been hugely beneficial to the design of the IVF battery. Operating at approximately 270V the battery takes advantage of the 300Vdc output of the ISG to maintain charge. This is very similar to a hybrid auto system and indeed it operates in an analogous fashion. Unlike in traditional launcher batteries or even a hybrid auto the total energy stored is not the principle driver since the energy demand is very low. Under a failure condition an IVF battery would be asked to deliver approximately 115 W-Hr during an engine shutdown event before recharge Engine startup consumes only 15 W-Hr. What is critical is the peak power which is demanded during brief (< 10 sec) transients- the worst being ICE start. What is desired is a small capacity battery with a high discharge rate and reasonable charge rate. Preliminary estimates suggest a very simple battery configuration with an approximate mass of 6% of today's battery is practical.

The IVF pumps are based on designs which have been in testing for over a year with excellent results. This critical element has proven to be a straightforward design with robust performance. Capable of handling both liquid and gaseous hydrogen and oxygen the pumps are coupled directly to the engine power take off shafts using clutches just as in an automobile air conditioning compressor.

Under nominal mixture ratio conditions of 1.0 and feed pressures typical of ullage conditions the ICE will produce on the order of 20kW (26HP) of shaft power- approximately the total electrical power available on a Shuttle orbiter. It achieves this at a combustion hydrogen flow rate that is less than the typical boiloff rate of existing in-space stages. Waste heat released by the engine for vaporization will on the same order so in effect the engine delivers effective enthalpy at a surprisingly high rate. For the task of increasing propellant tank pressure shaft power and waste heat are effectively combined to do the work of pressurization. Since the energy in the exhaust is applied to produce vehicle settling thrust it can be argued that the overall conversion efficiency approaches 100%.

If desired even higher power levels can be achieved by simply using part of the hydrogen compressor output to feed the ICE instead of drawing from the ullage. The ICE then becomes effectively supercharged with attendant gains in power output. Within practical limitation of the hardware power could likely be doubled.

IV. Engine Manufacturing

Manufacturing of the Generation 1 engine was straightforward and used common industrial processes. The greatest difficulty was in addressing the small size of the valves, ports, seals and seats. To speed manufacturing the upper and lower blocks, crankcase, heads and head cover were integrally machined from solid aluminum alloy billet. This imposed complexities in the formation of hollow passages for coolant and lubrication which required welded-on closeout plates. Fig. 6 shows the upper block assemblies after initial machining and ready for weld closeouts. Most of these closeouts would be eliminated by using simple castings for rate production.

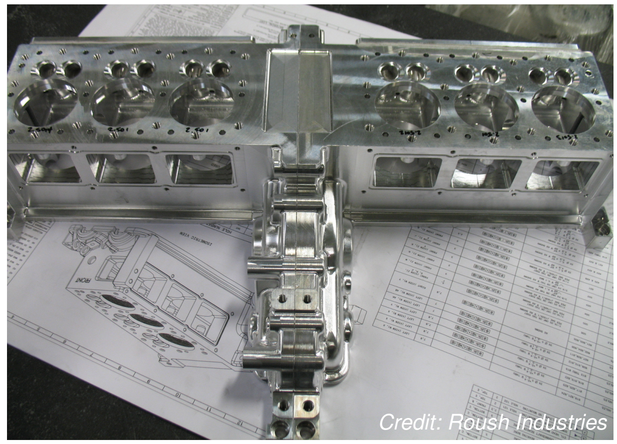

Figure 6. Rough Machined Upper Blocks

All bearings are short lead-time common industrial hardware due to the low loading and rotational speeds. The pistons are typical aluminum alloy (Fig. 7) and ride in cast iron cylinders with a standard arrangement of piston rings. Connecting rods two-piece stock items from a high power application. Crankshafts, camshafts and gearing were all custom designs to match the engine requirements but are fabricated from standard steel alloys, Fig. 8.

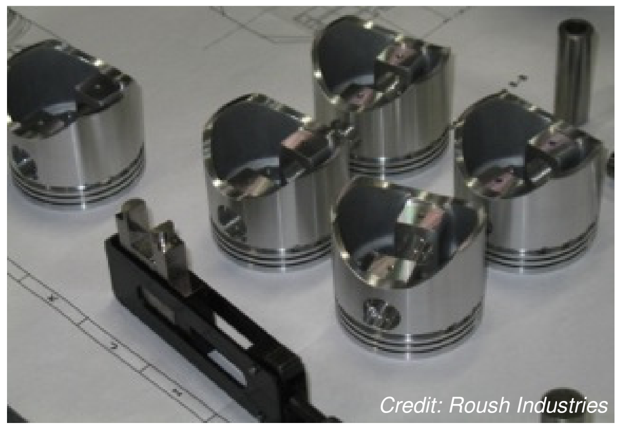

Figure 7. Pistons In Inspection

Exhaust and intake manifolds are fabricated from welded austenitic stainless steel- no exotic nickel alloys are required, Fig. 9. Wherever practical redundant seals were used to reduce the risk of hydrogen leakage.

The Generation 1 engine was optimized for experimentation and hence has external cooling and lubrication systems. Each cylinder has a dedicated coolant supply. Multiple return ports are present so that flows can be adjusted and balanced. In a similar fashion separate lubrication supply ports are provided for each cylinder. Varying configurations of lubrication injection hardware can be tried and injection pressures and flowrates controlled.

The all up engine was completed in August 2012 and is shown in Fig. 10 and Fig. 11.

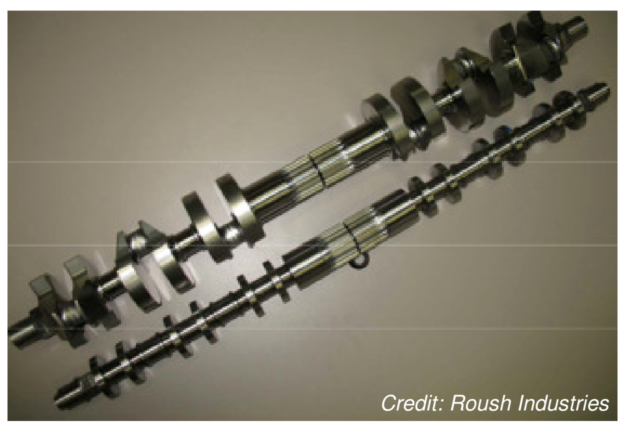

Figure 8. Rough Machined Cranks and Camshafts

V. IVF Architecture Alternatives

The use of a simple piston-in-cylinder engine on an ultra high performance in-space stage seems to be out of place in a technology landscape dominated by high speed turbomachines, fuel cells and solar panels. Didn’t we move into the jet age? How could this possibly be a good solution? At the outset we, too, felt like we had wandered into a technological twilight zone.

The key to understanding is that the high workload task for the system is not producing electricity or turning a shaft to drive a hydraulic pump. Tank pressurization is the dominant activity and it demands the delivery of enthalpy to the main tank ullage spaces – whatever the source. The IVF engine is superior to other lower temperature systems in that its waste heat is of high quality and is sufficient to turn cryogenic liquids into vapor. Half of the inefficiency of a heat engine is put directly to work pushing enthalpy into a working fluid for pressurization and the remainder is used to produce the small amount of thrust required to settle propellants.

A turbine could be used for such an application but it would be exquisitely small with extremely high rotating speeds to produce only 20kW with low density hydrogen as the working fluid. Provisions for heat and shaft power extraction could be made but the overall developmental complexity of cooling, lubrication, ignition, control and power take off at this very low power level seemed daunting compared to the IC engine. The use of such small turbines on ground based installations is virtually unheard of. Virtually a whole new technology would have to be developed at substantial cost and risk.

Figure 9. Exhaust Manifold

Similarly a fuel cell could be used to drive IVF with the advantage of no high speed machinery and an extensive history of spaceflight. Proton Exchange Membrane (PEM) cells have shown a tremendous amount of promise in recent years. However, 20kW is a relatively large fuel cell for flight applications and because all power is produced as electricity (as compared to perhaps 10% for the IC engine) it must be converted via motors to shaft power with their attendant switching systems and losses. This grows the fuel cell to address conversion efficiencies. Reactants are only consumed at a mixture ratio of 8 – which is generally insufficient for regenerative cooling so unless a bulky and costly radiator system is employed a larger flow of hydrogen must be brought to the fuel cell to maintain thermal stasis. From a consumables standpoint the fuel cell loses its advantage over the IC engine. The PEM cell efficiency is founded on low operating temperature which produces condensed liquid water which must be disposed of without providing any

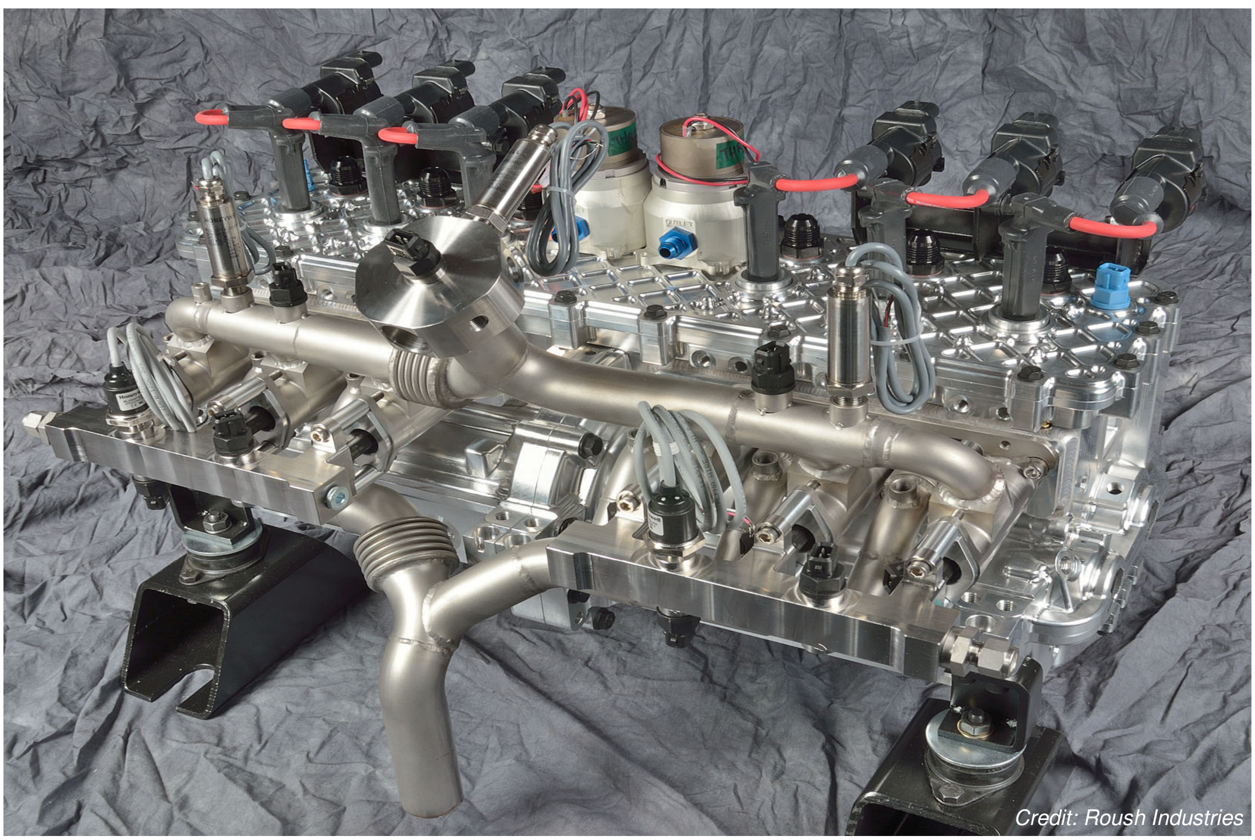

Figure 10. IVF Engine Assembled – Fluids Handling Side

benefit for vehicle settling. In general, the use of a fuel cell system would be most advantageous for crewed vehicles

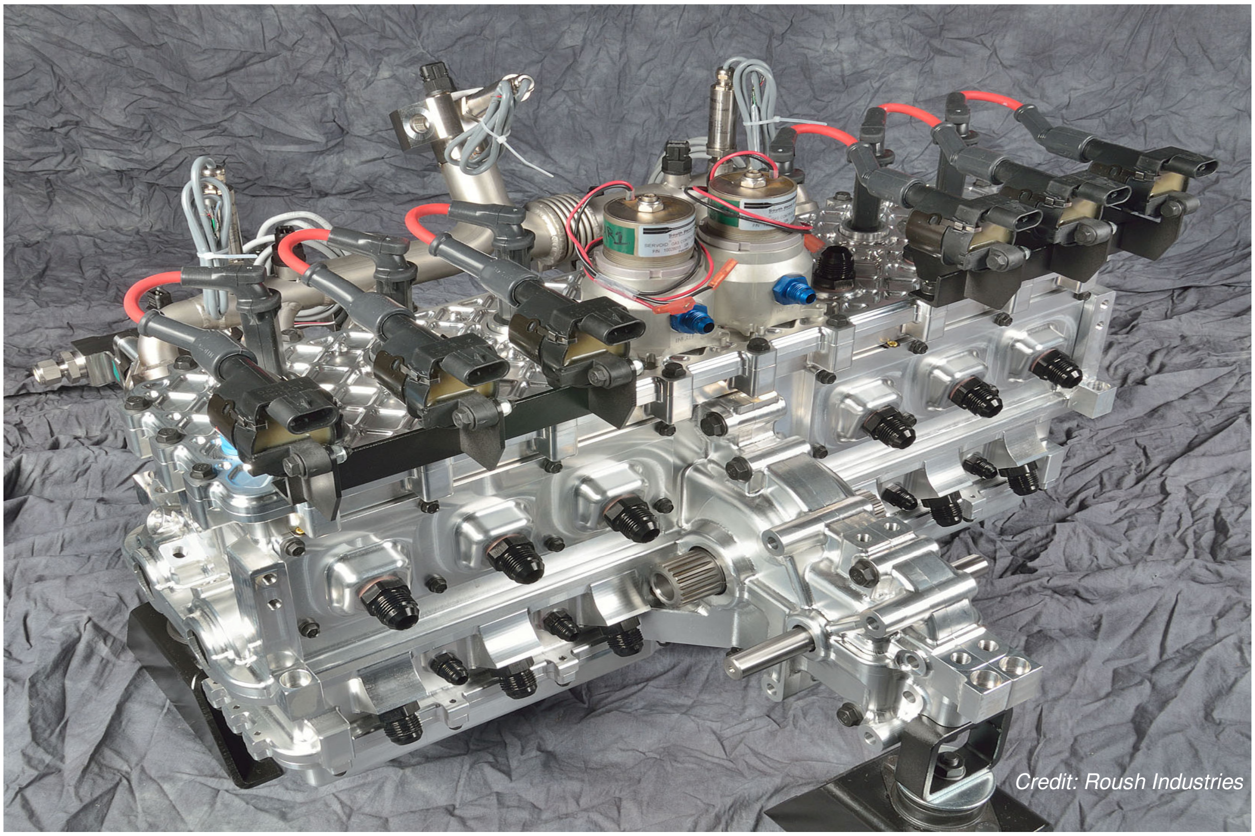

Figure 11. IVF Engine Assembled – Power Take Off Side

where the water produced has a strong positive influence on vehicle mass. For cryogenic propulsive stages the cost differential between IC engines and fuel cells likely favors the former.

VI. IVF Applications

The effects of IVF on upper stage performance are remarkable. An existing Centaur goes from a vehicle with nominal two main engine burns and 8 hour flight duration to one capable of 10+ burns and flight durations measured in multiple days. Burnout mass is reduced by 10% and propellant residuals can be used to dispose of the stage without mass or cost penalty.

The effects on future designs which can fully leverage IVF are shown in Fig. 12. The left image shows a next generation upper stage aft equipment shelf with traditional systems. The image on the right shows the identical vehicle using IVF. The system mass reduction for this configuration is in excess of one ton.

The availability of a light weight system which can take low pressure ullage gases and turn them into substantial heat and power at high efficiency with relatively mundane hardware opens the doors for many applications beyond the initial usage on existing upper stages for pressurization, attitude control and power generation. IVF can be used to directly drive cryogenic pumps for a small scale rocket engine without requiring power extraction from engine nozzles. A single IVF module could readily drive a 5300N (1200 lbf) thrust hydrogen engine while simultaneously doing tank pressurization and thruster operations. Complete systems integration could then be accomplished including the main engines. Cryogenic pump technologies can be used to rapidly transfer propellants both in space and on planetary surfaces. Airlock depressurization, storage bottle filling, vehicle refueling can all use these technologies which are essentially direct extensions of ground systems used for decades. We think the utility of this system is as limitless as the application of IC engines has been over the past century.

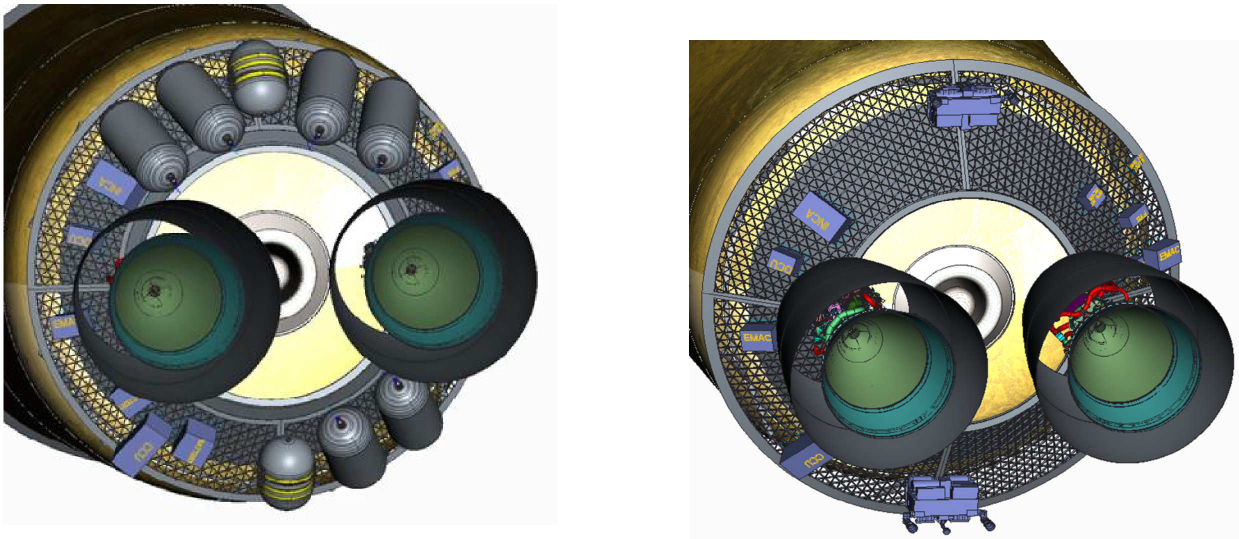

Figure 12. Advanced Stage Systems Hardware – Traditional vs IVF Systems

VII. Conclusion

Over the past year the IVF system concept has become even simpler, more robust, and more capable. Much of the hardware has already seen extensive testing and many more elements are on the verge. We believe this is a linchpin technology for the future and expect to use it on flight vehicles before this decade is out.