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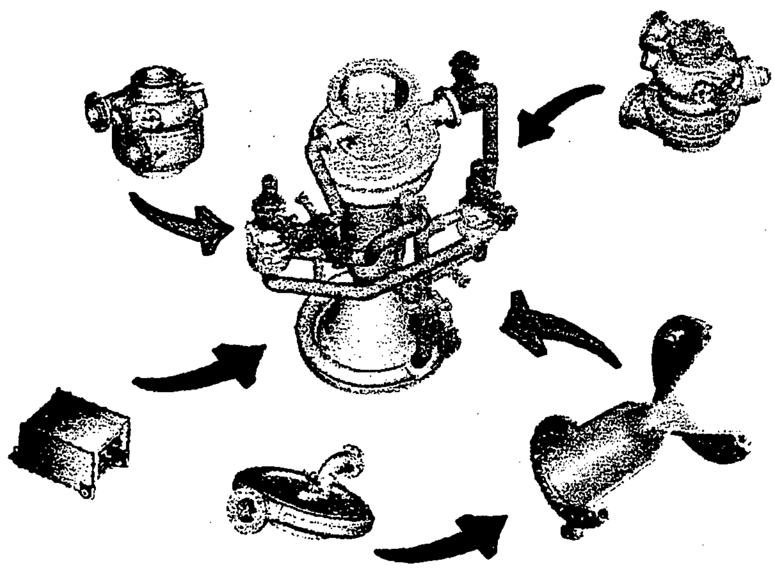
Design And Development of a 50k LOX/Hydrogen Upper Stage Demonstrator

S. Peery and A. Minick
Pratt & Whitney
West Palm Beach, Fla.



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ABSTRACT

This paper discusses design and systems integration of a 50,000 pound (222.4 kN) thrust Oxygen/Hydrogen Upper Stage Engine Demonstrator (USD) being developed by Pratt & Whitney Liquid Space Propulsion under contract for the United States Air Force Research Laboratories (AFRL) to support the Integrated High Payoff Rocket Technology (IHPRPT) program. The objective of this program is to integrate advanced technology components into an expander cycle engine configuration and demonstrate a 1% increase in specific impulse, a 30% increase in engine thrust-to-weight, a 25% reduction in failures per 1000 uses, a 15% reduction in required support costs, and a 15% reduction in hardware costs relative to current state-of-the-art levels (RL10A-3-3A). Scheduled to be the first of the IHPRPT program engine demonstrators, it is scheduled to be test fired in late 2000 and to demonstrate a chamber pressure capability of 1375 psia. This integrated 50k LOX/LH2 engine demonstrator will be used to evaluate individual component technologies as well as the system level mechanical, structural and thermodynamic interactions.

This technology program pushes the performance and operability envelope of existing expander cycle engines and provides the technology foundation to allow the development of the next generation of advanced space propulsion systems for upper stage and reusable booster applications. Additionally, through design, manufacture, and integration of the demonstrator new methods have been developed and adopted which will increase reliability and reduce component fabrication times.

INTRODUCTION

The Air Force, Army, Navy, and NASA have implemented a three phase, 15 year rocket propulsion technology improvement effort to "double rocket propulsion technology by the year 2010". This initiative, designated the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) established performance, reliability, and cost improvement goals for each of the three phases. These goals are to be met by advancing component technology levels through design, development, and demonstration, followed by an integrated system level engine demonstrator to validate performance to the IHPRPT system level goals. Pratt & Whitney Liquid Space Propulsion, under contract to the United States Air Force Research Laboratory (contract F04611-97-C-0029), is conducting a system level integration of a 50k LOX/LH2 upper stage demonstrator (USD) engine. The USD is comprised of the Advanced Liquid Hydrogen (ALH) turbopump (Ref. AIAA 98-3681, *Design and Development of an Advanced Liquid Hydrogen Turbopump*), the Advanced Expander Combustor (AEC) (Ref. AIAA 98-3681, *Design and Development of an Advanced Expander Combustor*), and a P&W provided Advanced Liquid Oxygen (ALO) turbopump, and Injector/Ignitor.

The ALH turbopump was designed and is being fabricated by P&W for the AFRL under contract F04611-94-C-0008 for component testing at P&W in early 1999. The ALH Turbopump incorporates an advanced fluid film rotor support system, unshrouded impellers, and a radial in-flow turbine to maximize pump discharge pressure at a minimum turbopump weight and production cost. The AEC was designed and is being fabricated by P&W for the AFRL under contract F04611-95-C-0123 for component testing in mid-year 1999. The AEC incorporates an advanced dispersion strengthened, high conductivity, copper alloy in a thermally/structurally compliant tubular design to significantly improve the capability of the expander cycle engine. For the demonstrator contracted effort, P&W is integrating the P&W turbopump provided ALO and AEC injector and the government furnished ALH and AEC, into a demonstrator assembly providing all required component physical and functional interfaces, ducting, valves, actuators, control system, instrumentation, and sensors, as illustrated in Figure 1.

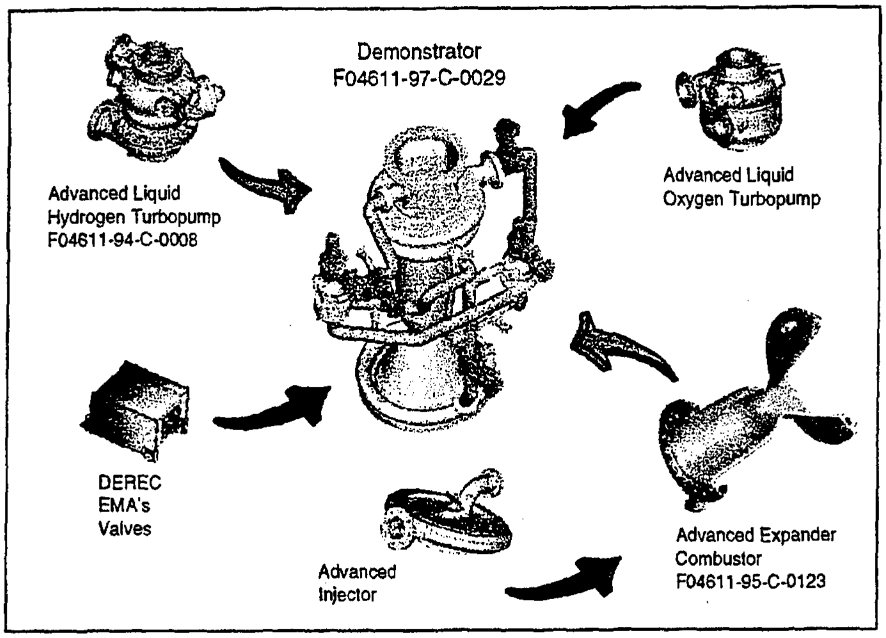


Figure 1. The IHPRPT Phase I 50k LOX/LH2 Upper Stage Demonstrator

The integration of these advanced technology components into an engine level system for test firing will demonstrate the IHPRPT LOX/LH2 boost/orbit transfer propulsion area phase I goals. These system level goals include; a 1% improvement in vacuum specific impulse, a 30% improvement in thrust to weight, a 15% reduction in hardware/support costs, and a 25% improvement in reliability relative to the current state-of-the-art engine baseline the P&W RL10A-3-3A.

Pratt & Whitney, in cooperation with the United States Air Force Research Laboratory, established an advanced upper stage expander engine model for the purpose of establishing the individual component requirements necessary to ensure the IHPRPT phase 1 system level goals are achieved. This cycle model was used to establish the performance, cost, weight, and thermodynamic operating requirements of the demonstrator engine. The component and engine level demonstration goals established for the 50k LOX/LH2 demonstrator to support the IHPRPT goals are:

- Demonstrate an engine chamber pressure of 1375 psia at an engine flowrate to provide 50,000 lbf of thrust.
- Maintain the geometric envelope of the RL10A-3-3A baseline (throat area, engine length and diameter, etc.)
- Traceable component weights to support an engine flight weight of 700 lbs. (318 kg).
- Demonstrate repeatable, safe, start, shutdown and steady-state operation.

DISCUSSION

P&W established an advanced expander engine model, which meets the IHPRPT phase 1 system level goals, from which component goals could be determined. The P&W RL10A-3-3A is the baseline for the IHPRPT goals and was used as the starting point for developing the advanced expander engine cycle. The RL10A-3-3A has 16,500 pound (7484 Kg.) vacuum thrust, Specific Impulse of 442.5 seconds, and a thrust to weight ratio of 53. It utilizes a two stage turbine driven by the expanded hydrogen from the combustor and nozzle cooling tubes. The RL10 turbine drives both the two stage hydrogen turbopump and, through a gearbox, the single stage Liquid Oxygen (LOX) turbopump. The ~~maximum~~ cycle pressure is approximately 1100 PSIA (77.33 Kg/cm**2) with a chamber pressure of 470 PSIA (33 Kg/cm**2). The expander cycle developed for the RL10, shown in Figure 2, is used in each member of the RL10 family, covering the 16,500 to 24,750 ~~pound~~ lb. (7484 - 11226 Kg.) thrust range. The advanced expander engine cycle, based on the RL10 cycle, established to support the IHPRPT phase 1 goals will allow further growth to 50,000 - 80,000 pounds (22,679 - 36,287 Kg.) while

psia
kg
lb.
lc
lower
cas

maintaining the benefits of the RL10 family history.

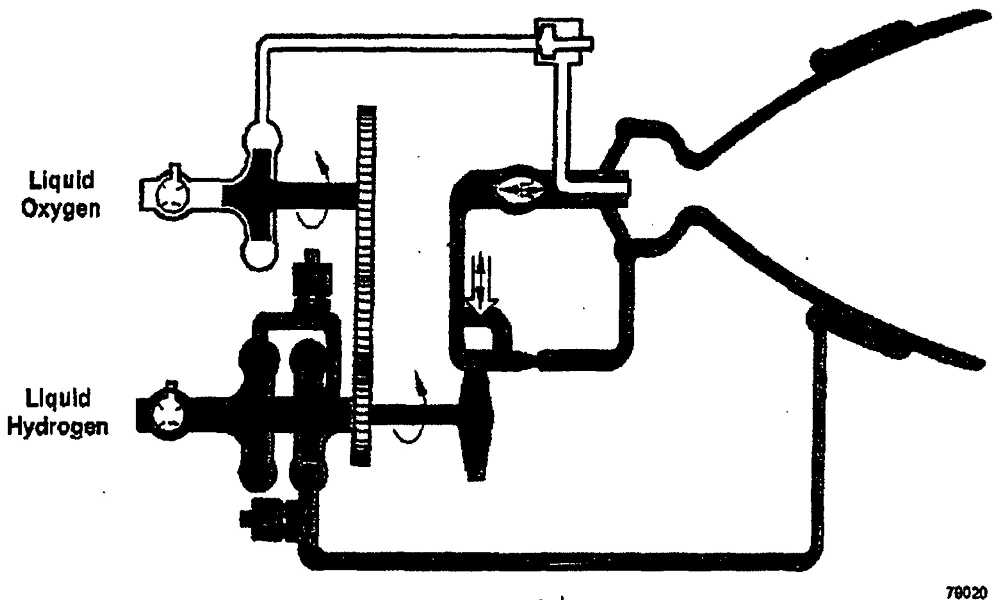


Figure 2. RL10 Expander Cycle Engine System

The growth potential of the current RL10 family is limited by the fuel pump discharge pressure which is in turn limited by the heat pickup capacity of the combustor and nozzle cooling tubes. While the tubular configuration provides better heat pickup than current milled channel combustors, the moderate conductivity of the RL10 steel tubes limits their heat load capacity per unit area and heat pick up. The ability to transfer more heat across the chamber cooling wall is essential to provide the increased energy required for higher turbopump output, chamber pressure, and thrust, in an advanced expander cycle engine.

Until recently no significant improvement in thermal conductivity was available without an unacceptable sacrifice of material properties such as strength, LCF characteristics, and oxidation/erosion capability. This problem has been solved by the development of PWA 1177 dispersion strengthened copper which provides improved material strength, LCF capability, and conductivity. The Advanced Expander Combustor being developed for the AFRL uses PWA 1177 copper tubes to provide the increased heat transfer and resultant energy required to support the high performance USD.

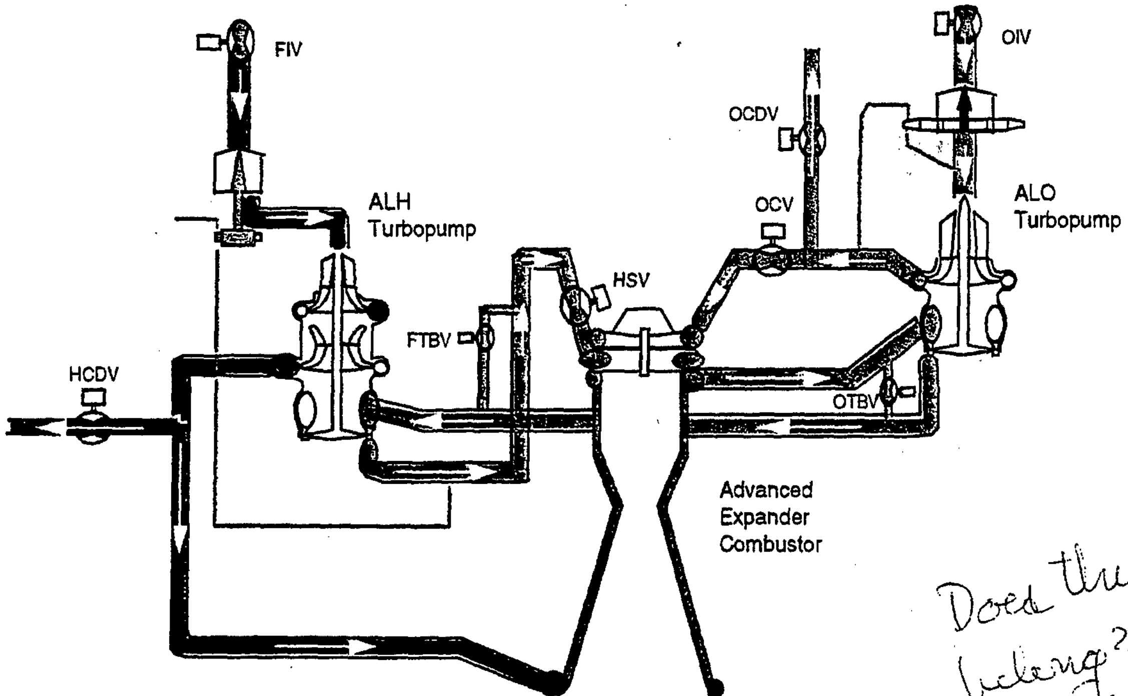
Spell out

The additional heat load capacity of the AEC provides the required turbine input energy to support the increase in turbopump discharge pressure of the ALH turbopump, allowing an increase in chamber pressure.

Analysis of an expander cycle with the improved heat load capacity supports a stable expander cycle operating at a chamber pressure of 1375 PSIA (96.7 Kg./cm**2) with a maximum cycle pressure of 4600 PSIA (323.4 Kg./cm**2) at the ALH fuel turbopump discharge. The final system balance provided a heat load capacity of 22,840 Btu/sec (24M N-M/sec) available to drive both the ALH fuel turbopump and the LOX turbopump with at least 5% margin remaining for roll control thrusters, boost pump drive, or equivalent bypass requirements.
The advanced expander engine cycle configured to meet IHPRPT Phase 1 goals is shown in figure 2. The predicted advanced expander engine system performance is summarized in Table 1. The measured operating conditions of the instrumented USD are expected to confirm these analytical predictions. The thermodynamic operating conditions of the IHPRPT Phase I engine at major station locations is displayed in Table 2.

Table 1. IHPRPT Phase I Advanced Expander Engine Cycle Summary

IHPRPT PHASE I ENGINE SUMMARY			
Vacuum Thrust, lbf	50,334	Chamber Pressure, psia	1375
Engine Mixture Ratio	6.0	Combustion C* Efficiency	0.99
Chamber Mixture Ratio	6.11	Chamber Coolant Q, Btu/s	22,833
Engine Flowrate, lbm/sec	112	Chamber Length, in	26
Del. Vacuum Isp, sec	450.6	Chamber Contraction Ratio	5.5
Throat Area, in**2	19.1	C*, Char. Velocity, ft/s.	7553
Nozzle Efficiency, Cs	0.995	Nozzle AR	64.5
Weight Estimate, lb	715	Nozzle Exit Diameter, in	39.6
Thrust to Weight	70.4	Turbine Bypass, %	5.4



Control: DEREC and EMAs
Note: Boost Pumps not included in Demonstrator

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Figure 2. Advanced Expander Engine Cycle Schematic

Table 2. IHPRPT Phase I Engine Conditions

ENGINE STATION CONDITIONS

Fuel System Conditions

Station	*Pressure* (psi)	*Temp.* (R)	*Flow* (pps)
Main Pump Inlet	100	38.6	16.0
Main 1st Stage Exit	2335	69.4	16.0
Main Pump Exit	4600	99.2	16.0
Chamber Coolant In.	4485	100.2	14.0
Chamber Coolant Ex.	4216	523.5	14.0
Turbine Bypass	4132	462.5	0.9
O2 Main Turbine Inlet	4132	462.5	15.1
O2 Main Turbine Ex.	3640	455.4	15.1
H2 Main Turbine Inlet	3585	457.3	15.1
H2 Main Turbine Exit	1641	382.9	15.1
Chamber Injector Inlet	1466	392.8	15.7
Chamber	1375		

Oxygen System Conditions

Station	*Pressure* (psi)	*Temp.* (R)	*Flow* (pps)
Main O2 Pump Inlet	100	176.7	96.0
Main O2 Pump Exit	1800	184.3	96.0
OCV Exit	1567	184.3	96.0
Chamber Injector Inlet	1540	184.3	96.0
Chamber	1375		

For the USD contracted effort, P&W will integrate the ALO and ALH turbopumps with the AEC into a demonstrator assembly providing all required component interconnects, ducting, valves, actuators, instrumentation, and sensors. P&W will provide the USD hardware and associated control system to the AFRL as an integrated assembly ready for testing.

In the USD expander cycle configuration liquid hydrogen is pressurized in the two stage ALH pump, delivered to the AEC for cooling and heat pick-up, expanded across the ALO and ALH turbines providing power to drive the pumps, and delivered to the injector. Liquid oxygen is compressed by the single stage ALO pump and delivered to the injector for combustion. Cooldown valves, located downstream of the pumps, are open during engine cooldown, before engine start, to allow fluid flow through the pumps for thermal conditioning. The turbine bypass valves (OTBV and FTBV) are used to independently regulate the flow through the turbines thereby controlling turbopump speed, pump discharge pressure, chamber pressure, and thrust. The engine mixture ratio is controlled by regulating the oxygen pump flow and back-pressure using the Oxygen Control Valve, OCV. After engine chilldown, prior to start the USD system is filled with hydrogen up to the closed Fuel Shutoff Valve, FSOV. The USD uses the bootstrap start procedure where the latent heat of the AEC hardware is sufficient to initiate turbopump rotation with the opening of FSOV.

A USD system transient model has been created and is being used to develop the start, shut-down, and steady-state characteristics to determine valve sequencing and control logic. Figures 3 and 4 display the predicted chamber pressure and engine mixture ratio transient profiles for a typical USD run sequence. Studies continue to optimize the start and shut-down sequences and timing to ensure safe, stable, and repeatable USD testing. Based on these studies test stand control requirements, computer logic test plans, and test facility operation requirements will be defined. Interface definition will be provided by the model for design and operability analysis allowing test bed instrumentation requirements to be determined.

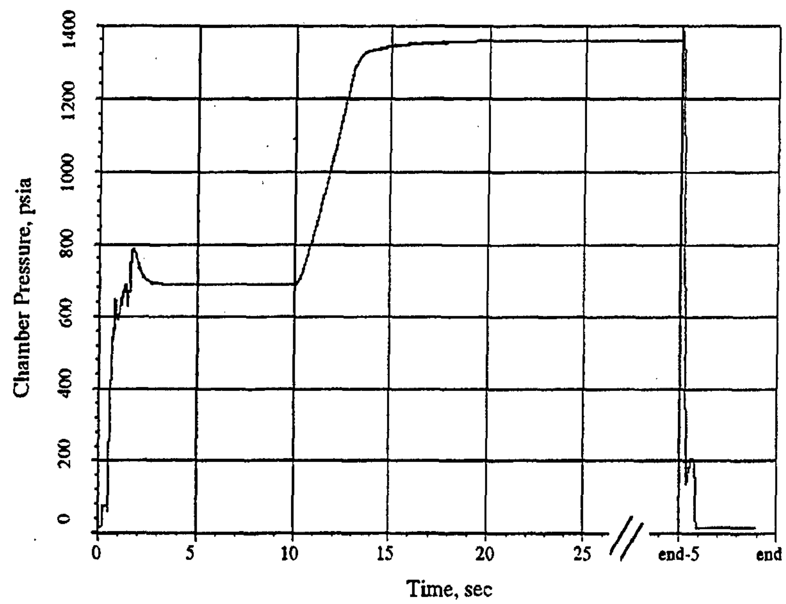


Figure 3. USD Chamber Pressure Transient Profile

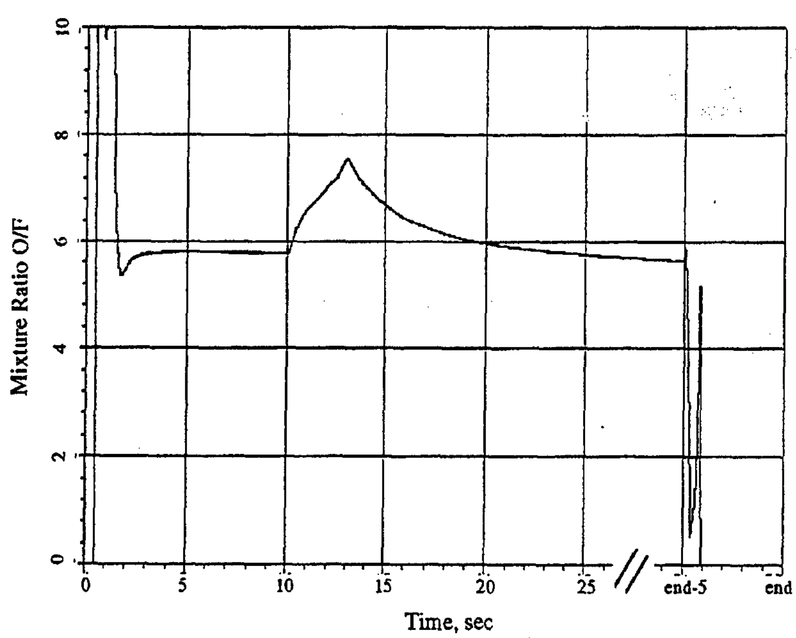


Figure 4. USD Mixture Ratio Transient Profile

Advanced Expander Combuster (AEC)

The AEC was designed and is being fabricated by P&W for the AFRL under contract F04611-95-C-0123 for component testing in mid-year 1999. The AEC,

Figure 5, incorporates an advanced dispersion strengthened, high conductivity, copper alloy in a thermally/structurally compliant tubular design to significantly improve the capability of the expander cycle engine. The AEC is expected to contribute a 12% increase in engine thrust-to-weight, and the 1% increase in specific impulse required for the Phase I goals.

The primary power constraint of current expander cycle engines is the heat delivery into the thrust chamber coolant per unit length of thrust chamber assembly. The AEC, Figure 5, makes use of recent improvements in material properties to enable the transfer of larger quantities of heat into the expander cycle coolant. The AEC uses an advanced copper alloy tubular geometry chamber to provide the heat to support the USD engine cycle. In doing so, higher pump pressures, higher chamber pressures and subsequently higher specific impulse levels at reduced weight can be achieved.

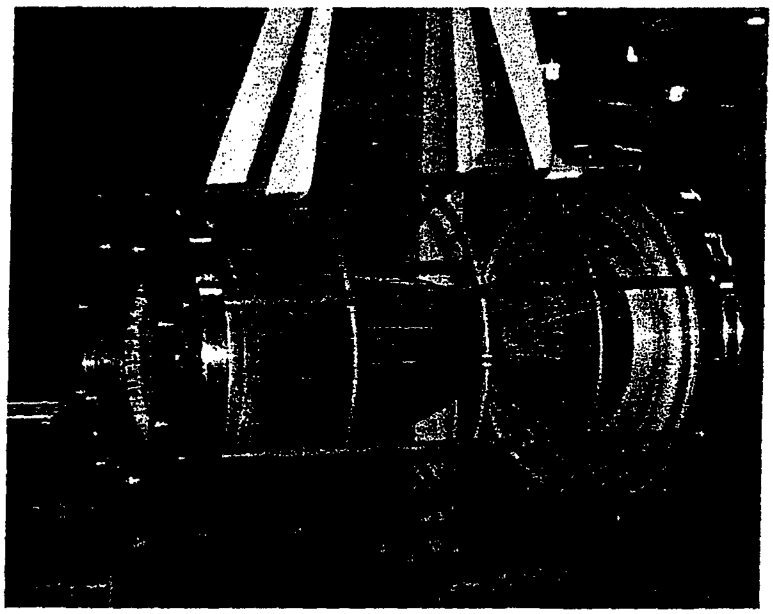


Figure 5. The Advanced Expander Combustor tube bundle prior to braze

The AEC is on schedule for testing at Pratt & Whitney's Florida test facilities in mid-year 1999. The design has been completed and the hardware fabrication is nearing completion. The AEC test requirements are being integrated with the Air Force Research Laboratory in parallel with fabrication to ensure the facility is ready to support testing of the AEC on schedule.

Pratt & Whitney's Advanced Expander Combustor integrates state-of-the-art materials, a high performance thrust chamber geometric configuration, and advanced fabrication approaches into a thrust chamber unit that supports the USD and IHPRPT phase 1 goals.

Advanced Liquid Hydrogen (ALH) Turbopump

The ALH turbopump, Figure 6, was designed and is being fabricated by P&W for the AFRL under contract F04611-94-C-0008 for component testing at P&W in early 1999. The ALH turbopump delivers 16 lb/s liquid hydrogen with a pressure rise of 4500 psia to support the 50k LOX/LH2 expander cycle engine and provide engine level contributions of a 10% thrust-to-weight increase, 10% cost reduction, and 11% reduction in failure rate toward the IHPRPT Phase I engine goals.

The ALH turbopump was designed to a nominal discharge pressure and flowrate to support the USD at a minimum turbopump weight and cost. The combination of high pump discharge pressure and low turbopump weight requires maximum rotor speeds to attain high impeller tip speeds at a minimum impeller diameter. The breakthrough design feature of the ALH turbopump is the fluid film rotor support system. The ALH turbopump has been designed with a hydrostatic rotor support system to provide; optimized rotordynamic operation, accurate rotor position control, minimized rotor stresses, bearing loads, and operating clearances. Additionally, the use of fluid film bearings drastically reduces the turbopump part count, directly reducing costs and improving reliability.

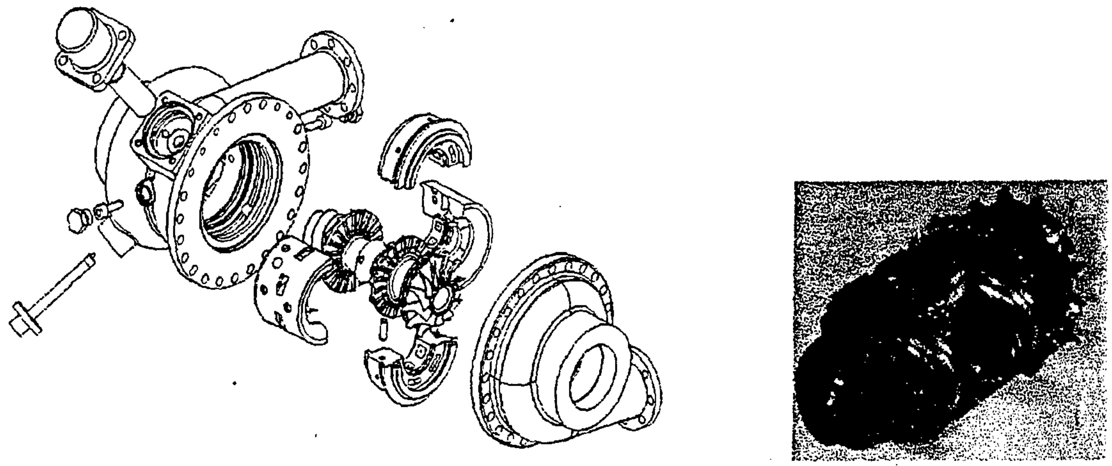


Figure 6. The Advanced Liquid Hydrogen Turbopump

The ALH program is on schedule for testing at Pratt & Whitney's Florida test facilities in the fourth quarter of 1998. The design and hardware have been completed. Structural verification of the rotor response has been accomplished. The ALH turbopump test requirements have been defined and are being verified with the integrated facility and test article model required for safe testing of high response devices such as the ALH turbopump. Pratt & Whitney will conduct the ALH testing in cooperation with the AFRL, including comprehensive analysis of the ALH turbopump's performance upon completion of testing.

Pratt & Whitney's Advanced Liquid Hydrogen turbopump integrates state-of-the-art materials, an advanced compact radial inflow turbine, advanced high pressure fluid film bearings, and a high performance inducer and impellers into a unit that supports the IHPRPT phase 1 goals.

Advanced Liquid Oxygen (ALO) Turbopump

The ALO turbopump is being designed and fabricated by Chemical Automatics Design Bureau (CADB), Voronezh, Russia, under contract to P&W. The ALO turbopump delivers 96 lb/s liquid Oxygen with a lc pressure rise of 1700 psia to support the 50k LOX/LH2 expander cycle engine and provide engine level contributions of a 5% thrust-to-weight increase toward the IHPRPT Phase I engine goals.

Digital Electronic Rocket Engine Control (DEREC)

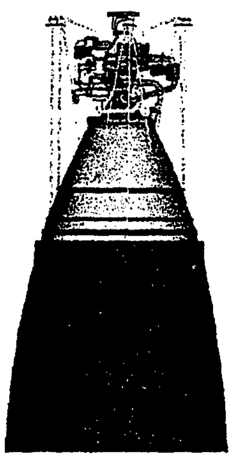
The 50k engine demonstrator will be configured with an "on-engine" electronic control system to control all operating aspects of the engine. The engine control system will be comprised of a Digital Electronic Rocket lc Engine Control (DEREC) system and electromechanical actuators (EMAs) to control the engine valves. EMAs eliminate the need for conventional hydraulic actuators and pumps, supply lines, and associated ground support equipment, directly supporting the IHPRPT cost, weight, and reliability goals. The DEREC receives thrust and mixture ratio commands from the test stand computer and modulates the rig EMAs to achieve the desired test article response. The use of a DEREC with EMAs is expected to provide a 45% reduction in failure rate, through improved engine control, electrical signal redundancy, and elimination of the pneumatic actuation system. The proposed DEREC is a modular unit which can be easily modified in later programs to further enhance the electronic engine control system performance and include enhanced engine health monitoring features and technologies.

TECHNOLOGY TRANSITION TO PRODUCTS

The operating conditions and design features of the USD components were selected to demonstrate IHPRPT Phase I goals. The IHPRPT goals are broad based and were selected to focus efforts to improve all aspects of rocket propulsion systems. Successful completion of the program will provide the confidence and design validation to transition the demonstrated advanced technology components into existing and future propulsion systems. The configuration and thrust size of the USD was selected to maximize technology transition opportunities while assuring the demonstration of Phase I goals.

The Common Cryogenic Advanced Upper Stage Engine

The Common Cryogenic Advanced Upper Stage Engine (CCAUSE) is the near-term high priority opportunity to transition the USD into a product for commercial, civil, and military applications. CCAUSE, Figure 7, is a 40,000 lbf thrust class upper stage engine designed to provide over 470 seconds of impulse in the same dimensional envelope as the current RL10. The CCAUSE design uses USD technologies in a configuration biased toward maximizing specific impulse. CCAUSE will provide payload delivery improvements of approximately 20% on current and near-term medium lift launch vehicles. P&W is currently working with vehicle primes to optimize thrust levels and is conducting preliminary design of the CCAUSE components and plans an Initial Operating Capability of ~2003.



Cryogenic Advanced Upper Stage Engine

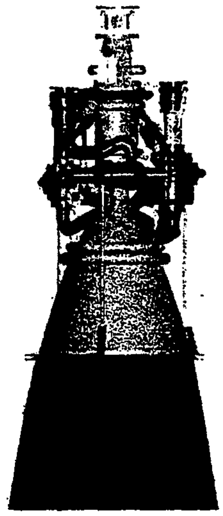
Inlet Mixture Ratio	5.5
Thrust (lb) Vac	43.500
Isp (sec) Vac	472
Area Ratio	370:1
Chamber Pressure (psia)	1250
Vacuum Thrust-to-Weight	60
Exit Diameter (in)	90
Engine Length, Stowed (in)	90

Figure 7. The Cryogenic Advanced Upper Stage Engine

A Highly Reusable Booster Engine, The RL200

Long-life and safe operability will drive the design of future booster engines for Reusable Launch Vehicle lc (RLV) applications. The P&W RL200, Figure 8, is a mid-size (150K - 350K lb) thrust class LOX/LH2 expander cycle engine designed to provide airline-type operability and safety for a military or commercial RLVs. The USD provides the technology foundation to allow long-life and sufficiently high chamber pressure at high thrust levels for sea level to vacuum operation.

The robustness and operability of the expander cycle results from the benign engine operating conditions and the simplicity of the configuration. The RL200 provides assured safety since any component failure simply results in a benign loss of energy to the cycle, eliminating the occurrence of catastrophic failures. The USD provides the first step toward demonstrating the capability of generating high chamber pressures in a booster class expander cycle engine while retaining expander cycle safety,operability, robustness and affordability.



P&W RL200 Reusable Engine

Inlet Mixture Ratio	6.0
Thrust (lb) Vac	300,000
Thrust (lb) SL	250,000
Isp (sec) Vac	450
Engine Life, cycles	> 250
Critical Failure Modes	none
Sea Level Thrust-to-Weight	75
Exit Diameter (in)	90
Engine Length, Stowed (in)	100

Figure 8. The RL200 Booster Class Reusable Engine

SUMMARY AND CONCLUSION

Successful completion of the 50k LOX/LH2 upper stage engine demonstrator will provide traceable validation of Phase I IHPRPT goals. The technologies required to attain a 1% increase in specific impulse, a 30% increase in engine thrust-to-weight, a 25% reduction in failures per 1000 uses, a 15% reduction in required support costs, and a 15% reduction in hardware costs relative to current state-of-the-art levels (RL10A-3-3A) will be demonstrated upon completion of this program. Successful completion of the program will provide the confidence and design validation to transition the demonstrated advanced technology components into existing and future propulsion systems.

The USD will demonstrate the operation of a high conductivity chamber and a fully supported fluid film bearing turbopump in an engine configuration. This technology demonstration, schedule for testing in late 2000, will push liquid rocket engine performance to new levels. This technology base will provide a highly reliable, low cost upgrade to the existing RL10 upper stage engines and lead to a robust engine for future RLV applications.

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