REPORT DOCUMENTATION PAGE

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1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE** Technical Paper	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER** F04611-94-C-0008
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Pratt + Whitney	**8. PERFORMING ORGANIZATION REPORT**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20020828 200

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Leilani Richardson
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	A		**19b. TELEPHONE NUMBER** *(include area code)* (661) 275-5015

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

1 item enclosed

TP-1998-132

3058RCAW
F04611-
94C 0018

MEMORANDUM FOR PRR (Contractor Publication)

25 June 1998

FROM: PROI (TI) (STINFO)

SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-1998-132
A. Minick and S. Peery (P&W) "Design and Development of an Advanced Liquid Hydrogen Turbopump"
AIAA (Statement A)

AIAA 98-3681

Design And Development of an Advanced Liquid Hydrogen Turbopump

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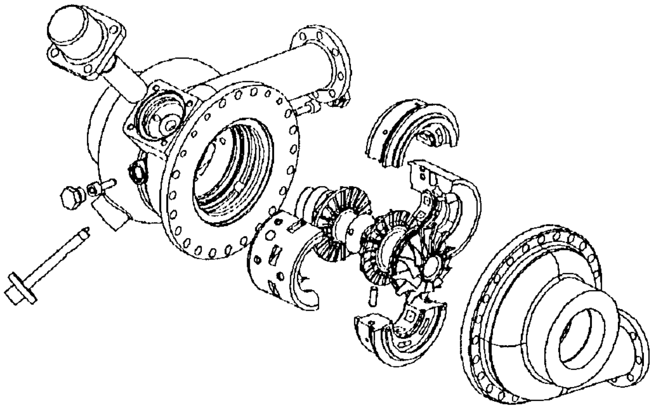
West Palm Beach, Fla.



34th AIAA/ASME/SAE/ASEE
Joint Propulsion Conference & Exhibit
July 13-15, 1998 / Cleveland, OH

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ABSTRACT

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This paper discusses design and development of an Advanced Liquid Hydrogen Turbopump for a 50,000 pound (22,679 kg) thrust Upper Stage Expander Cycle Engine being developed by Pratt & Whitney Liquid Space Propulsion under contract for the United States Air Force Research Laboratory (AFRL) to support the Integrated High Payoff Rocket Technology (IHPRPT) program. The Advanced Liquid Hydrogen Turbopump is designed to provide improved system thrust to weight, decreased hardware/support costs, and increased reliability. These benefits will be accomplished and demonstrated through design, development, and test of this high speed, high efficiency, two stage hydrogen turbopump capable of supplying 16 lbm/sec (7.3 kg/sec.) of liquid hydrogen at 4600 psia (323.4 kg/cm^2).

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 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 F04611-94-C-0008), is developing an Advanced Liquid Hydrogen (ALH) turbopump. This turbopump is designed to support the IHPRPT LOX/LH2 boost/orbit transfer propulsion area Phase 1 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 current state-of-the-art levels.

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 to the ALH turbopump.

DISCUSSION

As stated above, an advanced expander engine model, which met the IHPRPT Phase 1 system level goals was established, from which component goals could be determined. Since Pratt & Whitney has extensive history with the RL10A-3-3A, which is also the baseline for the IHPRPT goals, it was used as our 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 1, is used in each member of the RL10 family, covering the 16,500 to 24,750 pound (7484 - 11226 kg) thrust range. The advanced expander engine 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 maintaining the benefits of the RL10 family history.

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 combustor, 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 the advanced expander cycle.

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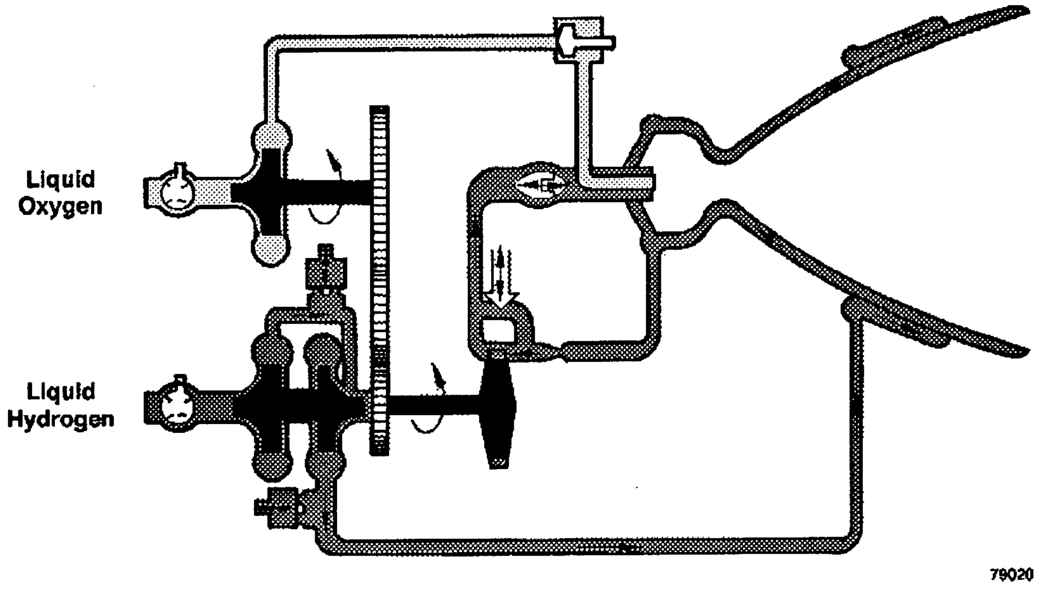


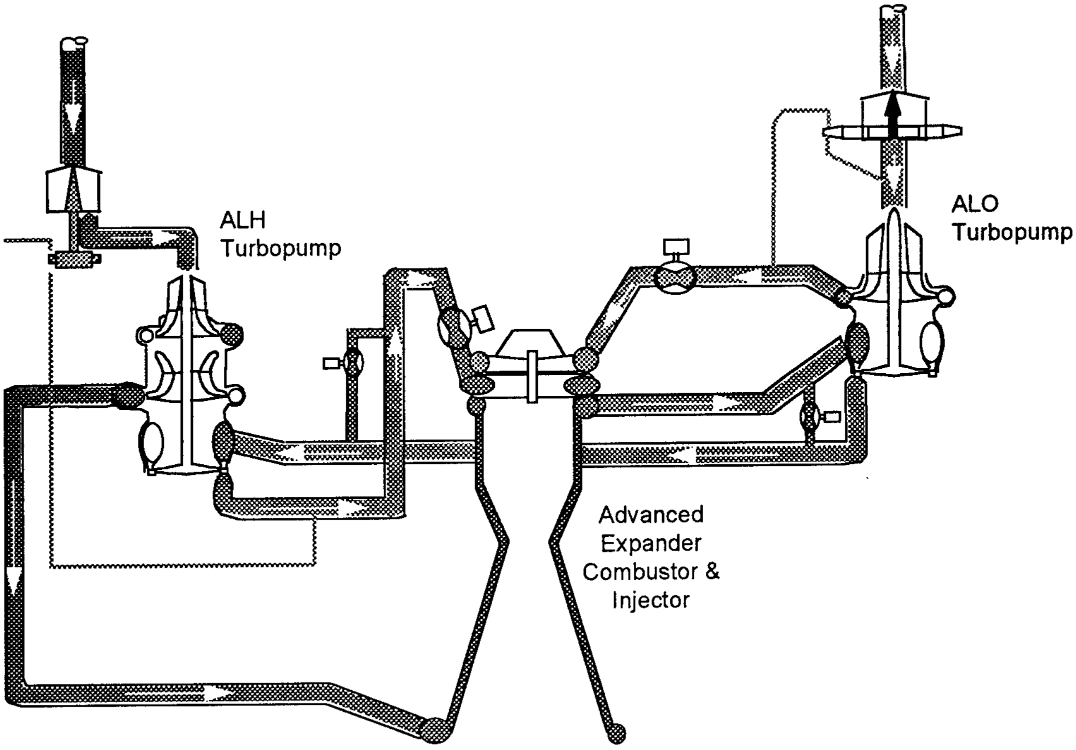
Figure 1 - RL10 Expander Cycle System with Geared LOX Pump

Until recently no significant improvement in thermal conductivity was available without an unacceptable sacrifice of material properties such as strength, Low Cycle Fatigue (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 (AEC) being developed for the AFRL on contract F04611-95-C-0123 uses PWA 1177 to provide the increased heat transfer and resultant energy required to support the advanced expander engine cycle (Ref. AIAA 98-3675, *Design and Development of an Advanced Expander Combustor*).

The additional heat load capacity provides the required turbine input energy to support an increase in turbopump discharge pressures, 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 22,833 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 (Ref. AIAA 98-3676, *Design and Development of a 50K LOX/Hydrogen Upper Stage Demonstrator*) configured to meet IHPRPT Phase 1 goals is shown in Figure 2. The predicted advanced expander engine system performance is summarized in Table 1.

Once the advanced expander engine cycle model illustrated in Figure 2 and summarized in Table 1 was established, the performance and thermodynamic operating requirements of the individual components could be isolated from the system level characteristics to establish the design requirements of the ALH.



Note: Boost Pumps Not Included in Demonstrator

Figure 2. Advanced Expander Engine Cycle Schematic

Table 1. Advanced Expander Engine Cycle Summary

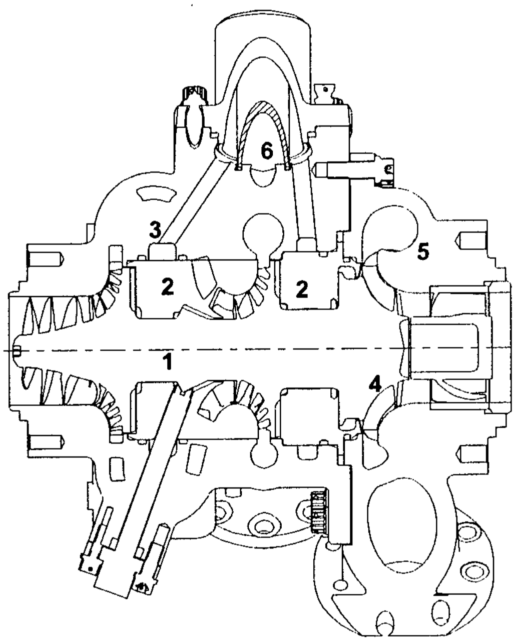
IHPRPT PHASE I ENGINE SUMMARY

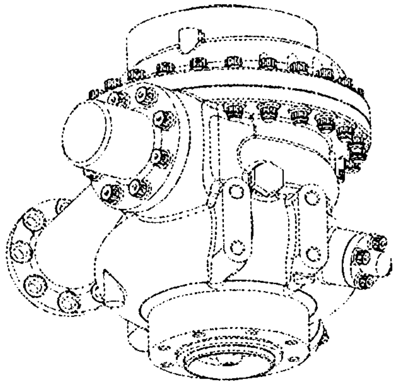
Vacuum Thrust, lbf	50,000	Chamber Pressure, psia	1375
Engine Mixture Ratio	6.0	Combustion C* Efficiency	0.99
Chamber Mixture Ratio	6.11	Chamber Coolant Q, Btu/s	22,833
Engine Flowrate, lbm/sec	112	Chamber Length, in	26
Del. Vacuum Isp, sec	450.5	Chamber Contraction Ratio	5.5
Throat Area, in**2	19.1	C*, 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

ALH TURBOPUMP DESIGN

The ALH turbopump design goals are to maximize pump discharge pressure at a minimum turbopump weight and production 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. Rotor speed has typically been limited by conventional bearing DN limits. The high leverage, enabling design feature of the ALH turbopump is the fluid film rotor support system. The ALH turbopump has been designed with a pressurized fluid film rotor support system to provide; high radial and axial stiffness, low cross coupled stiffness, optimized hydrodynamic and 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.

The required ALH turbopump design features were distributed to a design team including mechanical, pump, turbine, thermodynamic, hydrodynamic, rotordynamic, and fabrication specialists. This team further defined the requirements for the pump, turbine, static structure, and rotor support systems to establish an integrated parallel development approach for each element. Establishment of the physical design as well as integration of the individual sub-elements among the various specialists was the responsibility of the mechanical design specialist assigned to lead the team. The ALH turbopump is shown in cross section in Figure 3.





Major Features:

1 One piece titanium rotor.
2 Split hydrostatic bearings.
3 Cast pump housing with integral crossover passages.
4 Radial inflow turbine.
5 Cast turbine housing with vaneless inlet volute.
6 Filtered bearing supply.

Figure 3. Cross section & External View of ALH Turbopump

Rotor Support System

Fluid film bearings are a key technology in developing long life, dependable rocket turbopumps. In contrast to rolling element bearings, the shaft and bearing do not come in contact after normal operation is achieved. Life limitations due to steady state wear of rotating components found in rolling element bearings are eliminated. The reduction in part count, roughly an order of magnitude, increases the component and overall system reliability and reduces complexity. The high levels of stiffness and damping found in fluid film bearings eliminates the need for additional damping devices, such as damper seals. System efficiency is also increased by employing a combination of radial and thrust bearings, thereby minimizing rotor excursions and maintaining reduced blade tip clearances.

The ALH turbopump has been designed to be insensitive to unbalance, impeller fluid forces, and destabilizing influences found in turbines and seals. This is achieved by providing a stiff shaft assembly, bearings optimized for dynamic performance, and a rigid housing. Rotor stiffness is achieved by compact rotor assemblies, high stiffness materials, large axial load paths through the rotor stack, and double pilots on major rotor components. Bearing dynamic behavior is optimized with the complete rotor/bearing system in mind. This avoids sub-synchronous instability and unbalance sensitivity problems. Rotor unbalance is minimized by analytically selecting the location of two balance planes and geometrically balancing shafts. Pratt & Whitney's rotor design experience has shown geometric rotor balance results in low synchronous response and a consistently reproducible configuration. The incorporation of fluid film bearings in the pump provides a reduction of synchronous response by eliminating critical speeds from the operating range, resulting in low dynamic stresses and rotor deflections. Additionally, the high levels of stiffness and damping available increases margin on the instability threshold speed and available rotor load support.

The ALH turbopump hydrostatic bearings use the pump discharge to generate a high pressure fluid film. This results in speed-dependent, high dynamic stiffness, and high damping forces. The bearing's ability to generate high levels of force, even in liquid hydrogen. has been documented by early tests and, more recently, by several analytical models.

Modal testing on the ALH rotor was conducted to verify modal analysis and to identify any natural frequencies which may be in the operating range for this turbopump. Four areas on the rotor assembly were studied: the impeller, 1st long, 2nd long, and turbine blades. Refer to Figures 4 through 6.

Holography was used to identify each natural frequency and mode shape. Modal analysis was also conducted on the inducer, 1st stage long and turbine blades. The modal analysis was used to verify the frequency of specific mode shapes. While there were some differences between the predicted analytical frequencies and the lab measured frequencies, the mode shapes in general were in good agreement.

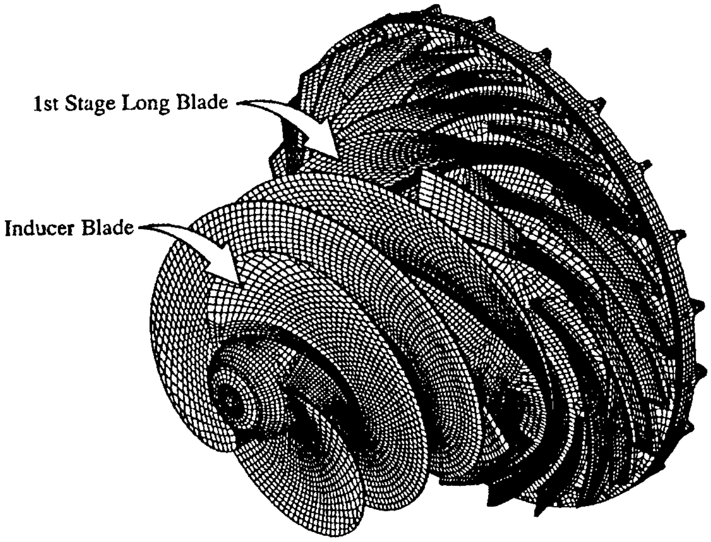


Figure 4 – ALH Inducer and 1st Stage Impeller

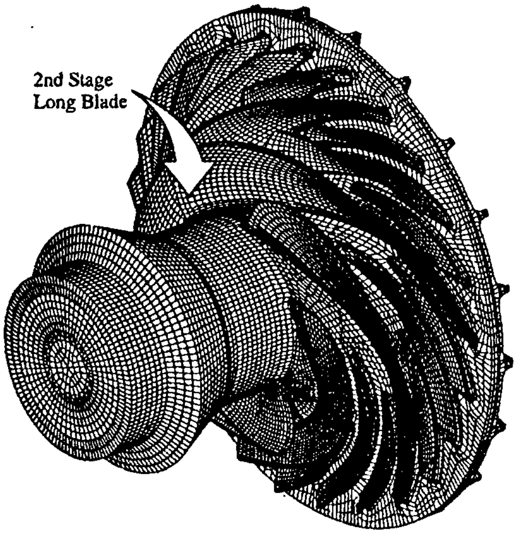


Figure 5 – ALH 2nd Stage Impeller

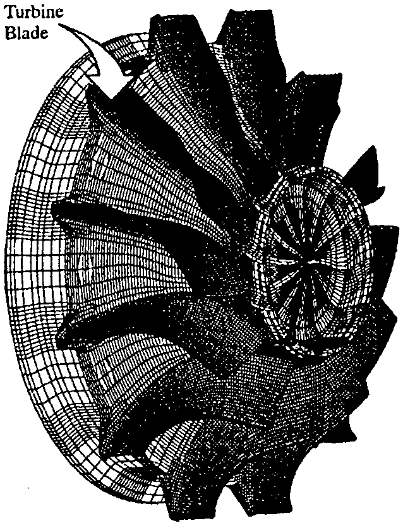


Figure 6 – ALH Turbine

Rotor axial thrust loads will be transferred to the static structure through a pressurized fluid film thrust bearing. This bearing is an integral part of the pump housing and is two-sided to provide precise rotor positioning and stability. One side of the bearing interacts with a small land on the back face of the second stage pump impeller; the other side interacts with the back face of the turbine rotor.

Start and stop cycles may produce momentary contact of the rotor bearing surfaces. It is only during these transient contacts that the hydrostatic bearing experiences wear. The effects of wear in the ALH turbopump are minimized by the selection of bearing surface materials. The hydrostatic bearing and mating rotors have fine surface finish and a combination of thin film hard coating on the rotor and sacrificial rub coatings on the static components to provide low friction, wear resistant surfaces. This prevents degradation of the surfaces and/or galling associated with conventional bearings. Use of extremely thin film coatings maintains accurate rotor positioning even if the sacrificial stator coating is consumed.

Pump Design

The two stage ALH turbopump uses a high speed inducer and high stage loading impellers to achieve low pump weight, low cost, high power density, and high efficiency. The ALH turbopump impellers have tip speeds of 2281 ft/sec (695.3 m/sec) at 174,240 rpm. This tip speed yields a headrise per stage of 74,128 ft (22594.3 meter), resulting in an overall pump pressure rise of 4,500 psid (306 kg/cm^2). This exceeds the current tip speed limit of 2000 ft-sec (609.6 m/sec) for shrouded impellers, requiring the use of unshrouded impellers to achieve the required tip speed. The first stage features an axial flow inlet and inducer, and a radial discharge unshrouded centrifugal impeller, to achieve good suction performance. The inducer has three highly swept blades with reduced leading edge blade thickness and incidence optimized to minimize cavitation. The impeller features 24 blades, including two sets of splitters. The first stage impeller discharges into a vaneless diffuser, followed by a channel type, internal crossover to diffuse and deswirl the flow before delivering it to the inlet of the second stage. The second stage consists of another unshrouded centrifugal impeller similar to the first stage. The second stage impeller also discharges into a vaneless diffuser. The flow is then collected in a scroll-type, single discharge volute with a splitter, followed by a conical diffuser.

The ALH turbopump design includes an internal interstage crossover between the first and second stages, which contributes to reduced weight and a compact design. This crossover design is of the channel diffuser type used successfully in the SSME/ATD fuel turbopump. The design features thirteen individual return channels. These channels act to diffuse and deswirl the flow exiting the first stage impeller and then deliver the flow to the inlet annulus of the second stage impeller.

Turbine Design

To meet the ALH turbopump design objectives the turbine must achieve maximum performance while minimizing cost, size, and weight. The ALH turbine uses an advanced compact radial turbine to achieve a 13% increase in speed capability, a 10% improvement in turbine performance, and reduce turbine cost and weight. A toroidal inlet volute manifold provides improved performance compared to the constant cross-sectional area toroidal housing used in the baseline. The toroidal inlet volute minimizes the circumferential static pressure and gas angle gradients entering the turbine rotor minimizing the total pressure loss in the volute. This assures a volute with maximum performance and minimal impact on the turbopump shaft radial side loads.

The reduction in turbine radial side load was accomplished by using advanced computational fluid dynamics analyses to design the volute manifold flowpath to achieve a constant circumferential static pressure, thereby eliminating the side load on the rotor shaft. By configuring volutes using advanced design tools, the excess area incorporated in the constant area toroid is removed, reducing the housing weight by approximately 12 percent. Also, by removing this excess area, large regions of separated flow are eliminated and velocity gradients are maintained throughout the manifold, reducing the pressure loss by at least two percent. The result is a high performance and low weight inlet volute manifold. By integrating the radial inflow turbine inlet volute designs the need for an inlet guide vane is eliminated.

The ALH turbine was designed with reduced thru-flow velocities, increased reaction, and increased airfoil loading relative to previous expander turbines. The increased blade load reduces the airfoil count and provides a blade with a low aspect ratio and a high degree of camber, assuring a stiff blade capable of high speed operation.

Mechanical Design

The mechanical design approach for the ALH turbopump has been to promote simplicity via low parts count. Low parts count has proven to improve maintainability, cost, and reliability, and reduce weight. Lower parts count also minimizes the dimensional tolerance stack-ups that are critical to turbopump performance and pressurized fluid film bearing operation. To minimize parts count the turbopump design uses a single piece rotor, two cast housings, and two split hydrostatic bearings for a total of only 5 primary parts. The increased speed of the ALH allows the pump and turbine diameter to be reduced to approximately 3.2 inches, with a shaft length of only 7 inches. The reduced size and increased simplicity of the ALH fuel turbopump compared to the RL10A-3-3A baseline is exhibited, to scale, in Figure 7. These improvements provide an Hp /Weight ratio of 141 for the ALH compared to 11 for the RL10 baseline.

RL10A-3-3A
Fuel Turbopump
Part Count 135,
Rolling-Element Bearings

ALH Fuel Turbopump
Part Count 29,
Hydrostatic Rotor Support

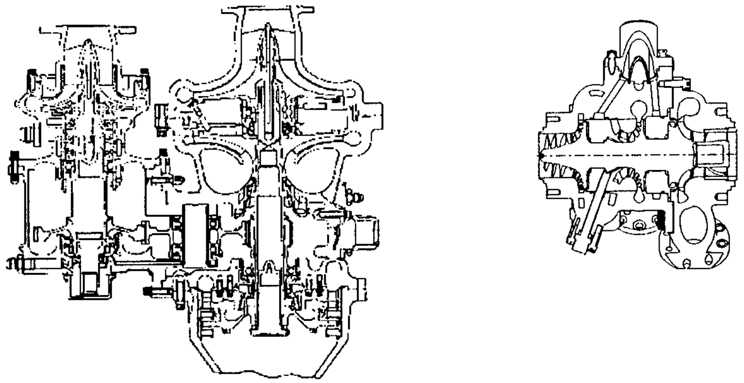


Figure 7. Scaled Comparison of Baseline to ALH Turbopump

The PWA 1240 titanium single piece rotor consists of an integral inducer, first and second stage pump impellers, and an integrally bladed radial inflow turbine. The journals for the pressurized fluid film bearings are positioned on the shaft between the pump impellers, and between the 2nd stage pump impeller and the turbine rotor, respectively. The axial thrust bearing face is adjacent to the aft bearing journal on the front face of the turbine rotor.

The cast Inconel 718 pump housing contains internal diffuser passages from the first stage impeller discharge to the second stage impeller inlet, a volute to collect the pump discharge flow, and positioning features for both Incoloy 909 hydrostatic bearing sets. The pump bearing is a unique split fluid film bearing with the second stage impeller inlet incorporated into the bearing to facilitate assembly and reduce parts count. The turbine bearing is a more conventional split fluid film bearing which includes the thrust bearing adjacent to the turbine rotor. Both of the split fluid film bearings are contained in the pump housing, allowing a lightweight, structural method to provide the housing stiffness important to pressurized fluid film bearing operation for a subcritical rotordynamic design. The dimensional tolerance stack up affecting rotor to stator alignment are minimized by mounting both bearings in the same housing.

The cast weldable waspaloy turbine housing incorporates an as-cast volute inlet manifold and locating features for the exit guide vane required for development testing only. The turbine housing bolts to the pump housing to complete the ALH assembly once the rotor and bearings have been installed. Figure 8 provides an exploded view of the ALH to facilitate understanding of the assembly.

The ability to machine the close tolerances necessary to control clearances and assure performance is essential to the success of this approach. Clearance control is facilitated by the low parts count, i.e., reducing the stack-up accumulation of tolerances. For example, the integral pump and turbine impeller tip contours are dimensioned directly from the bearing journal and thrust piston faces with no intermediate part stack-ups. This allows tighter clearance control for the unshrouded impellers which are easier to manufacture than shrouded impellers. Figure 9 shows the finished, precision machined rotor. Other manufacturing considerations include use of matched pump housing and split bearing assemblies. These parts will be pre-assembled with circumferential and axial indexing features. The concentricity controlling diameters for both of the bearings will be machined concurrently in the pump housing to ensure accurate rotor to stator alignment.

The materials for the ALH turbopump are state-of-the-art relative to P&W and industry rocket experience. The cast Inconel 718 pump housing was chosen for producibility and structural integrity. The cast weldable waspalloy turbine housing provides these same benefits as well as improved material properties at elevated temperatures. The selection of PWA 1240 titanium, an advanced low interstitial oxygen alloy for the impellers is driven by fracture toughness and strength-to-weight for rotor dynamics considerations.

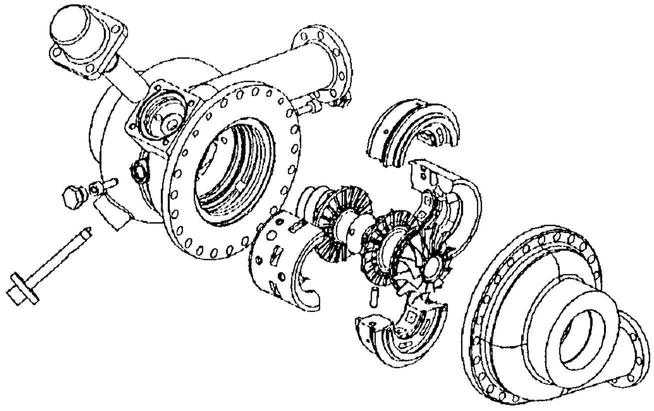


Figure 8. Exploded View of ALH Turbopump

The difference in the coefficient of thermal expansion between the Inconel 718 pump housing and the Incoloy 909 split hydrostatic bearings will allow the use of reasonable (less than 500 F°/ 260 C °) thermal differentials to ease assembly and disassembly.

The design of the pump housing, with its internal diffuser passages and volute, and the volute turbine housing requires the use of complex castings. Typical casting methods require a large investment in tooling which is not compatible with the demonstrator nature of the IHPRPT phase 1 programs. Pratt & Whitney's Rapid Prototyping Center in East Hartford, Connecticut has matured several procedures which avoid the need for a high initial tooling investment. For the ALH turbopump, stereolithography models generated using Quickcast$_{TM}$ software are used to generate the wax patterns. A curable ceramic is then injected into the stereolithography wax pattern to generate the cores for the internal crossovers, volutes, and other internal features, in situ. The combination of these procedures allowed the first development casting to be generated from the 3D solid computer model in only 6 weeks for less than one tenth the cost of a conventional development casting.

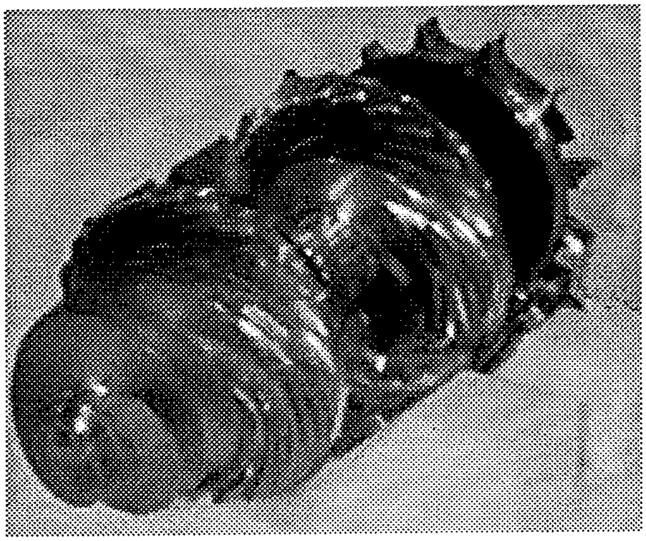


Figure 9. ALH Rotor

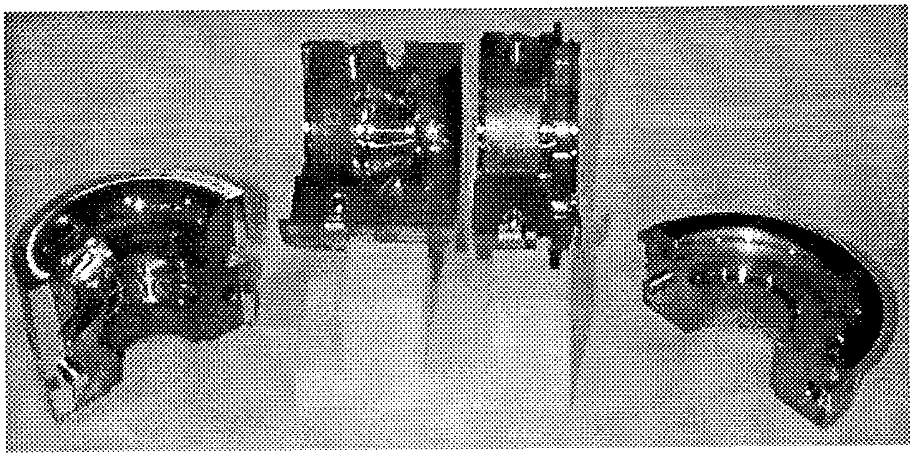


Figure 10. ALH Pump and Turbine Bearings

Advanced Rotor Sensor

Measurement of the rotor speed and condition in turbomachinery is useful to support health monitoring, provide performance data and provide over-speed protection. The speed sensor provided for the ALH will measure speed accurately over the entire operating range. Low speed monitoring provides initial spin-up characteristics, while high speed monitoring ensures safe turbopump operation. The ability to monitor the full speed allows improved health monitoring by exposing radical changes in turbopump torque during spooldown.

The ALH includes a dual channel sensor which monitors orthogonal surfaces on the rotor. This sensor is supplemented by a single channel sensor positioned 90 degrees around the pump. These sensors measure shaft proximity to establish position and deflection. One of the surfaces monitored includes controlled slots that can be used to establish the rotor speed. A signal conditioning module provides electrical signals to the data recording and position monitoring system.

SUMMARY AND CONCLUSION

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. Test performance parameters have been established to verify the ALH turbopump design characteristics listed in Table 2. 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.

Table 2. ALH Turbopump Design Characteristics

PUMP	100%	50%
NUMBER OF STAGES	2	2
EFFICIENCY	0.67	0.66
INLET VOLUME FLOW (GPM)	1600	795
HORSEPOWER	5900	1080
SPEED (RPM)	166,700	96,400
HEAD RISE (ft)	136,700	49,500
DIAMETER (in)	3	3
TIP SPEED (ft/sec)	2182	1262
HEAD COEFFICIENT	0.462	0.500
FLOW COEFFICIENT	0.147	0.128
NSS	17,000	6200
TURBINE		
NUMBER OF STAGES	1	1
EFFICIENCY (T/T)	0.78	0.66
HORSEPOWER	5900	1080
SPEED (RPM)	166,700	96,400
DIAMETER (in)	3.2	3.2
TIP SPEED (ft/sec)	2327.4	1345.1
U/C (ACTUAL)	0.633	0.503
PRES.RATIO (T/T)	2.16	1.56