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Development Status of a 50k LOX/Hydrogen Upper Stage Demonstrator

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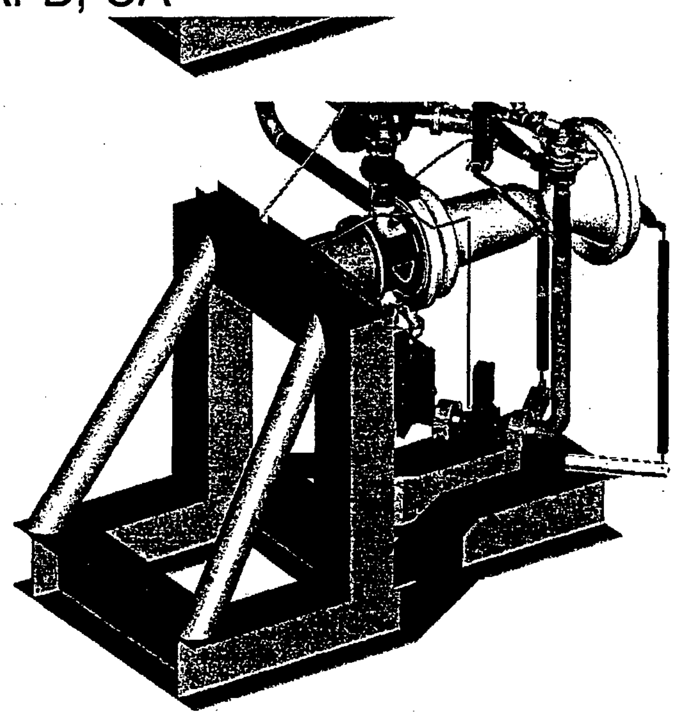

35th AIAA/ASME/SAE/ASEE
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ABSTRACT

This paper discusses design and systems integration status of a 50,000 pound (222.4 kN) thrust Oxygen/Hydrogen Upper Stage Engine Demonstrator (USD) being created by Pratt & Whitney Liquid Space Propulsion under contract for the United States Air Force Research Laboratory (AFRL) to support the Integrated High Payoff Rocket Propulsion 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. Scheduled to be the first of the IHPRPT program engine demonstrators, it is scheduled to be test fired in late 2000 and demonstrate a chamber pressure (Pc) capability of 1375 psia (9.48 MPa). 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 (Ref. AIAA 98-3676, *Design and Development of a 50k LOX/Hydrogen Upper Stage Demonstrator*). 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 98-3675, *Design and Development of an Advanced Expander Combustor*), and P&W provided Advanced Liquid Oxygen (ALO) turbopump.

The ALH turbopump was designed and fabricated by P&W for the AFRL under contract F04611-94-C-0008 and is currently undergoing component testing at P&W. 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 thrust chamber was designed and is being fabricated by P&W for the AFRL under contract F04611-95-C-0123 for component testing with a P&W provided 50k injector in late 1999. The AEC thrust chamber 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 contract effort, P&W is integrating the P&W provided ALO turbopump and 50k injector with the government furnished ALH turbopump and AEC thrust chamber, 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.

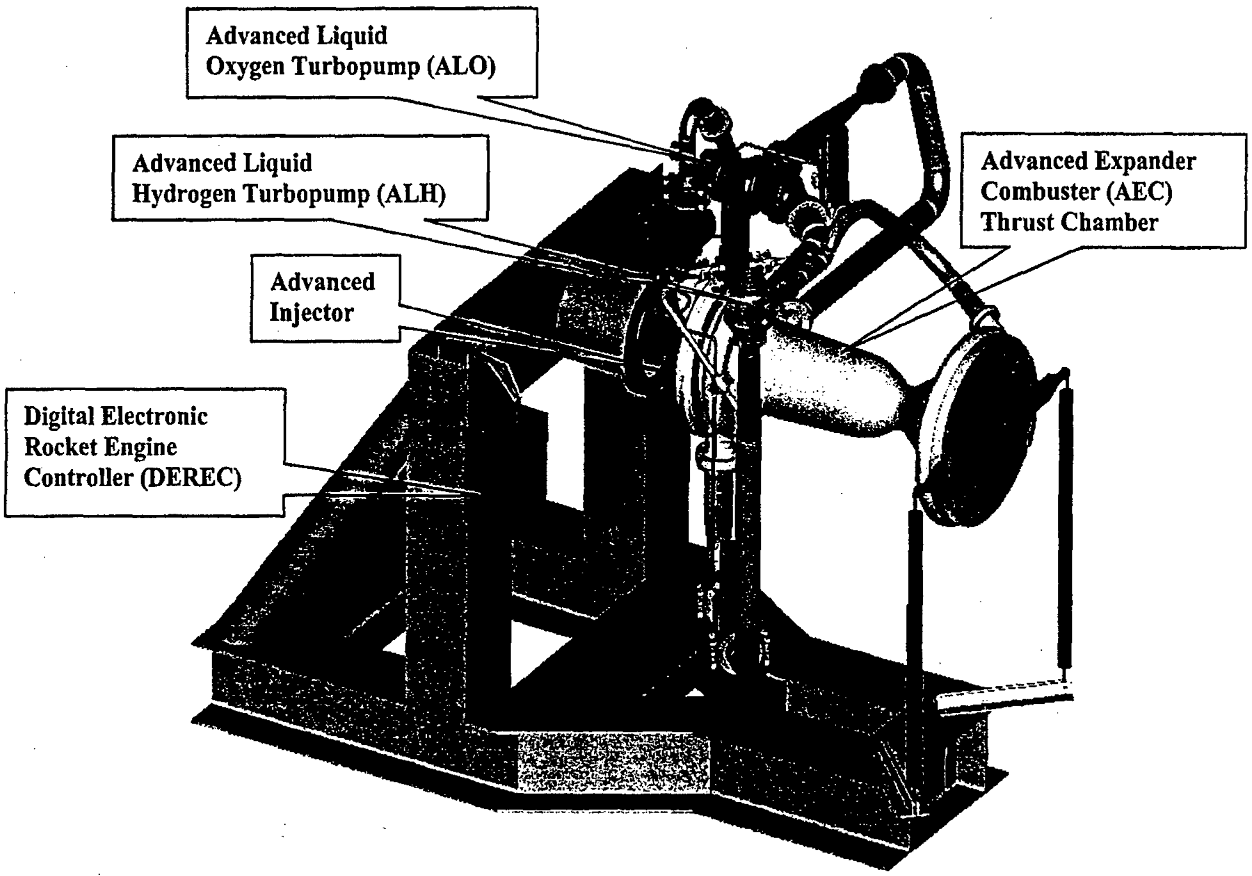


Figure 1. The IHPRPT Phase I 50k LOX/LH2 Upper Stage Demonstrator

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% reduction in failure rate relative to the current state-of-the-art engine baseline.

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 (9.48 MPa) at an engine flowrate to provide 50,000 lbf (222.4 kN) of thrust.
- Maintain the geometric envelope of the baseline (throat area, engine length and diameter, etc.)
- Traceable component weights to support an engine flight weight of 700 lb. (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 level goals could be determined. The P&W RL10 cycle (Ref. AIAA 98-3676, *Design and Development of a 50K LOX/Hydrogen Upper Stage Demonstrator)*, is the base for the advanced expander engine (Upper Stage Demonstrator - USD) cycle. The USD cycle allows growth to 50,000 – 80,000 lb. (222.4 – 355.9 kN) while maintaining the benefits of the RL10 family history. The USD flow schematic with 100 % Rated Power Level (RPL, Pc of 1375 psia (9.48 MPa) at an O/F of 6.0) propellant thermodynamic conditions identified at key locations in the cycle is shown in Figure 2.

In the USD expander cycle configuration liquid hydrogen is pressurized in the two stage ALH pump, delivered to the AEC thrust chamber 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 Oxidizer and Fuel 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 (O/F) is controlled by regulating the oxygen pump flow and back-pressure using the Oxygen Control Valve (OCV). Chamber ignition will be achieved using a gaseous hydrogen/oxygen igniter. 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 Fuel Shutoff Valve, FSV. The turbopumps will accelerate to 60% power level where the turbine by-pass valves will control the cycle operation. The USD cycle uses an oxygen lead chamber for engine start and a fuel rich chamber during engine shutdown. The controller has both open and closed loop control capabilities. In open loop control mode the controller will position the OTBV, FTBV and OCV to a position identified by the test facility. In closed loop control the controller will adjust OTBV and FTBV position to match a chamber pressure setpoint signal sent by the test facility.

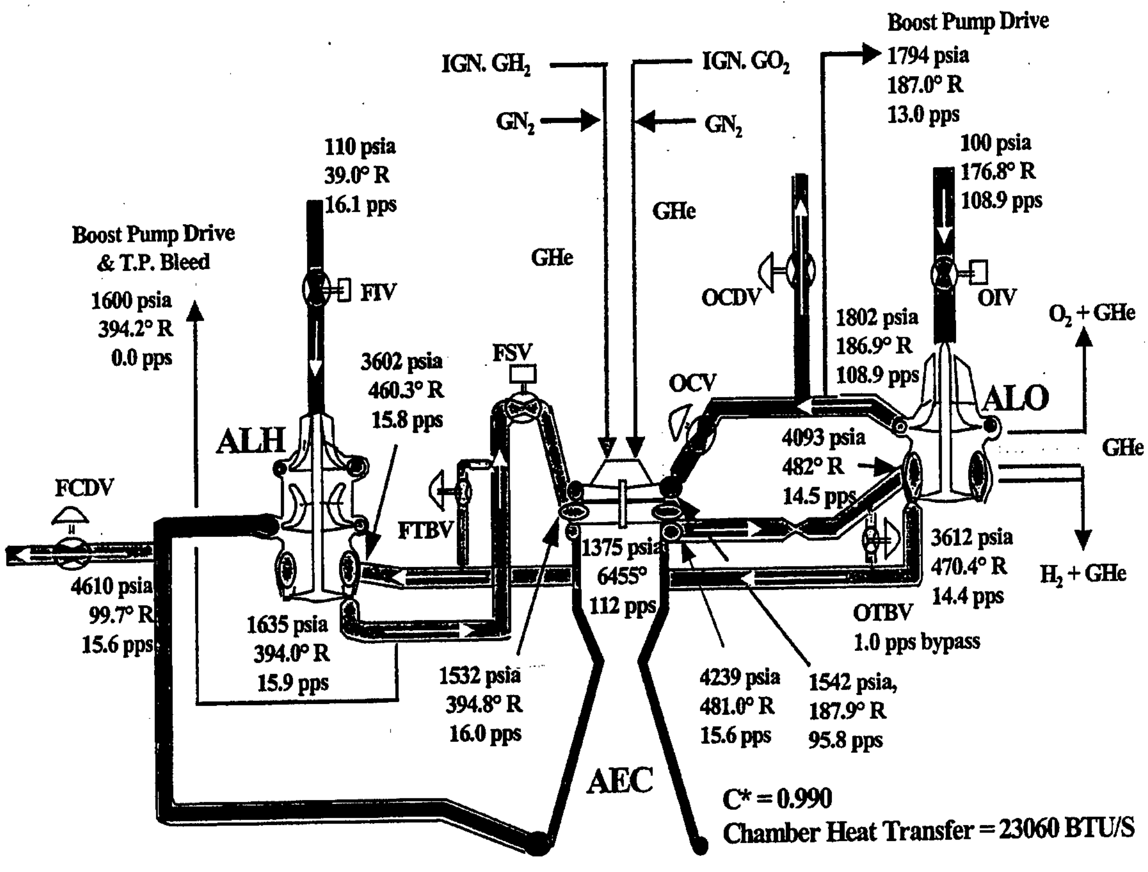


Figure 2. Upper Stage Demonstrator Cycle Schematic

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. System Preliminary Design Review was completed in December 1998 and the Critical Design Review is scheduled for August 1999. The rig will utilize Electro-mechanical Actuators (EMA) and a Digital Electronic Rocket Engine Control (DEREC) currently on-hand and developed during previous rocket engine programs. Design of the rig piping is in progress and is expected to be complete this summer. The four control and fuel shut-off valves will be furnished by Flodyne Controls Inc., Murray Hill, NJ. Design of the valves has been completed and manufacturing is in progress. The valves will undergo Design Verification Testing (DVT) during June – July, 1999 and delivery is scheduled for the third quarter 1999.

USD Math Model

A USD system math model has been created with the P&W/NASA MSFC ROCket Engine Transient Simulation (ROCETS) system. ROCETS consists of a library of module building-block codes, a processor to configure the modules into a user defined system simulation and a processor to execute the simulation as defined by the user. The module codes are non-linear mathematical representations of the rocket engine components with sub-modules containing characteristic maps of specific components and properties of fluids, metals and combustion. Design, off-design and transient characterization are provided with the simulation through the use of characterized component maps. The transient ROCETS model represents the engine cycle and the component to component interactions.

The USD ROCETS model has both transient and steady state capabilities. This math model is used to establish start, power level ramps, shutdown and steady state sequencing procedures; support test planning and pre-run predictions; support component and plumbing design; define valve requirements; and define control methodology. Valve sequencing is defined with the USD model to assure safe transient and steady state operation of the USD cycle. Operability considerations include:

- Avoid pump cavitation stall and overspeed caused by rapid flow acceleration, low inlet pressure and violation of suction performance.
- Minimize water hammer.
- Avoid injector flow reversals.
- Avoid nozzle throat over-temperature.
- Prevent AEC thrust chamber erosion.
- Track requested thrust and mixture ratio.
- Avoid excessive turbopump axial loads.

The math model represents the complete USD cycle through high fidelity physics and thermodynamics. Combustion properties are obtained from the NASA ODE database and real fluid properties from the NIST database. The USD model simulates:

- Volume dynamics;
- Pump inlet and discharge line inertia;
- Plumbing line losses;
- Design and off-design turbine an polytropic pump characteristics;
- Multi-node AEC heat transfer module;
- AEC injector areas;
- Proportional plus integral controller with digital to analog interface, second order actuator dynamics, sensor dynamics and open or closed loop capability;
- Valve characteristics;
- Fuel system venturi which suppresses propagation of potential turbine and Pc perturbations upstream affecting pump and AEC performance;
- Active injector purges;

Using the math model steady-state and transient operation were examined to develop control methodology and valve sequencing that would satisfy the operability considerations during start, power changes, steady-state and shut-down. To prevent an injector flow reversal the injector $\Delta P/Pc$ ratio was limited to no lower than 4%. Valve sequencing was optimized to minimize water hammer, avoid pump cavitation and similar turbopump related considerations, and reduce the potential of AEC thrust chamber erosion during transients. Control methodology studies were performed to identify chamber pressure and mixture ratio control valves, select controller gains and determine gain margins. Open and closed loop control simulations were run to validate the ability to control thrust and mixture ratio to the requested set-points. ALH and ALO turbopump performance maps will be benchmarked against component performance test results to assure sufficient cooling of the thrust chamber. The effects of injector purge timing and flowrates on propellant fill and flushing rates were examined. The math model enables customization of system control parameters to safely optimize USD operation.

Steady State Analysis

The USD math model was used to analyze the preliminary steady state performance at power levels ranging from 30% RPL (Pc of 413 psia, 2.85 MPa) at an O/F of 6.0) to the maximum power level (Pc of 1400 psia, 9.65 MPa at an O/F of 6.0), obtained with a fully closed FTBV. To safely satisfy all operational considerations, 60% RPL (Pc of 825 psia 5.69 MPa) with an O/F of 5.25) has been selected as the start point. A 60% RPL start reduces the risk of adverse USD cycle response to possible unknown system and controller interactions. Analysis of turbopump axial loads will be completed after ALH test data and ALO data is incorporated into turbopump axial load modules, to be used within the USD math model.

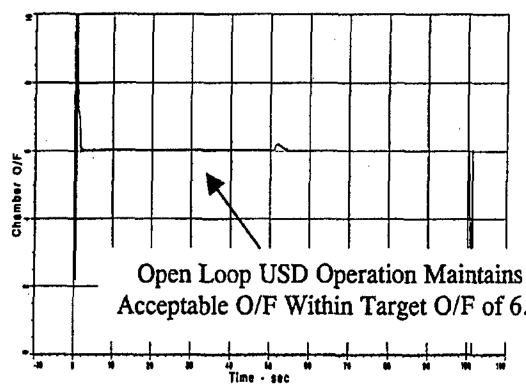


Figure 4. USD O/F Trace for Full Run

Transient Analysis

Transient analysis has defined the preliminary USD cycle operation and control methodology. The USD cycle uses a gaseous hydrogen/oxygen torch igniter for the engine chamber ignition device. The USD igniter operates at an O/F of 2 and is GH_2 cooled. The igniter will be activated prior to O_2 entering the engine chamber. The igniter will shut off and maintain fuel-rich operation throughout the duration of the hot fire, after engine chamber ignition is detected with Pc. As mentioned earlier, the USD cycle uses the bootstrap start procedure where the latent heat of the AEC hardware is sufficient to initiate turbopump rotation.

Transient analysis has shown open loop operation will provide acceptable start to 60% RPL, ramp to 100% RPL and shutdown from 100% RPL of the USD cycle. Figures 3 and 4 show the Pc and O/F characteristics during the full USD cycle operation.

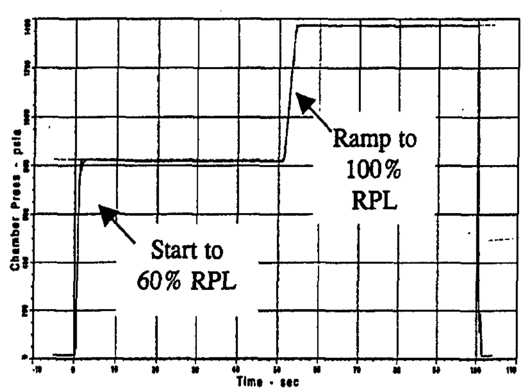


Figure 3. USD Pc Trace for Full Run

Optional closed loop control is available. This closed loop control will position the FTBV only to drive Pc to requested Pc. Also, an optional O/F trim will be available. This O/F trim will be a rate and authority limited manual control on OCV position only. The O/F trim will only be used at steady state operation to drive O/F to the target O/F.

The USD cycle will start with oxygen lead engine chamber sequencing via the OCV. Figure 6 shows expanded views of Pc and O/F during a typical USD cycle start to 60% RPL. The start signal is sent to open the OCV at T=0 seconds and O_2 enters the chamber within 0.050 seconds. At +0.2 seconds, the FSV is commanded open and about 0.05 seconds later GH_2 is introduced to the engine chamber and chamber ignition occurs at high O/F (<200). Chamber ignition results in a Pc increase to about 40 psia (0.28 MPa). The O/F can be seen decreasing at this time also. At about +0.55 seconds, the LOX injector primes and Pc increases rapidly as the turbopump speeds bootstrap up with the increasing AEC energy available to the USD cycle. The O/F increases at this same point in time, followed by a decrease as the ALH increases in power. The Pc and O/F achieve requested values within about +1.5 seconds, as the FTBV, OTBV and OCV move to their respective 60% RPL positions via open loop sequencing. All operational considerations are satisfactorily maintained throughout the USD start.

The transition from 60% RPL to 100% RPL is accomplished with open loop control. No operational considerations are violated during the power level ramp. Figure 5 shows the Pc tracking Pc request during the 3 second (13% Pc per second) ramp in Pc request from 60% RPL to 100% RPL. Pc tracks the request with no overshoot at 100% RPL. The O/F tracks the target value of 6.0, within 0.25 O/F units during the ramp. There are no adverse operational characteristics during the power level transition.

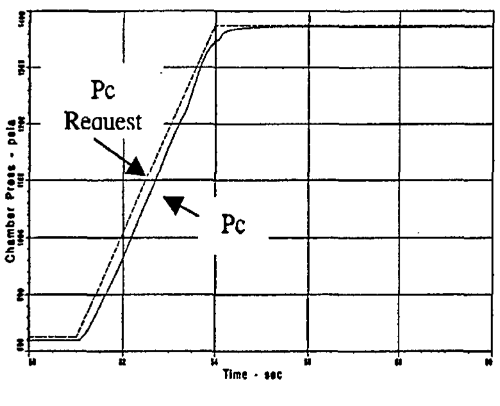


Figure 5. USD Ramp from 60% RPL to 100% RPL

Shutdown from 100% RPL uses the open loop controller. A fuel-rich shutdown is used to protect the AEC hardware from thermal distress. At the shutdown signal, time of 100 seconds in Figure 6, the FTBV is commanded open to reduce ALH turbine power, thus reduce ALH pump discharge pressure. At this same time the Oxidizer Cooldown Discharge Valve (OCDV) is commanded open to divert flow from the LOX injector to the overboard dump leg, thus reducing the O_2 to the injector and engine chamber. The Fuel Cooldown Discharge Valve (FCDV) opens after a short delay, which allows the H_2 to be diverted to the overboard dump leg without any adverse effects on AEC cooling or ALH pump performance (stall, cavitation, overspeed or water hammer). The OCV is also commanded closed after a short delay, allowing the O_2 supply to the LOX injector to be cut off with no adverse affect on the ALO pump performance (stall, cavitation, overspeed or water hammer). After the O_2 is depleted from the LOX injector (via ambient Helium purge), the FSOV is commanded closed. The engine inlet valves are both commanded closed about +2.0 seconds after shutdown signal is initiated. LOX depletion and engine chamber flameout occur within +1.2 seconds of shutdown signal, as shown in Figure 7. The turbopumps rotation stops by +1.5 seconds. At about +0.6 seconds, the Pc and O/F experience an increasing trend prior to final decay to levels resulting from only purge in the AEC injectors and chamber. This increase is due to an increase in ALH turbine pressure ratio, as the Pc decays quicker than the ALH pump discharge pressure. A resultant increase in power, pump exit pressure and mass flow to the chamber causes the Pc and O/F increase. All operational considerations are satisfactorily met through the USD cycle shutdown.

Advanced Expander Combustor (AEC)

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. Employing an advanced copper tubular geometry with an electroless nickel jacket, the AEC is expected to contribute 14% thrust-to-weight, 1% vacuum specific impulse and a 5% reduction in hardware and support costs towards the IHPRPT Phase I engine goals. Fabrication of the P&W provided AEC injector has been completed and the injector assembly has undergone waterflow testing at P&W's Florida facilities in March 1999 to measure the mixture ratio profile of the injector. AEC thrust chamber fabrication under AFRL contract F04611-95-C-0123, is currently in progress to support scheduled testing at Pratt & Whitney's Florida test facilities in late 1999.

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 109 lb/s (49 kg/s) liquid Oxygen with a pressure rise of 1760 psia (12.13 MPa) 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.

The design continues the evolution of the turbopumps developed for the RD-0124 used on the Soyuz and the RD-0120 used on the Energia launch vehicles. The Preliminary Design Review was completed in August 1998 and the Critical Design Review will be held mid-1999. Fabrication of long lead hardware is in progress and delivery is scheduled for the end of 1999.

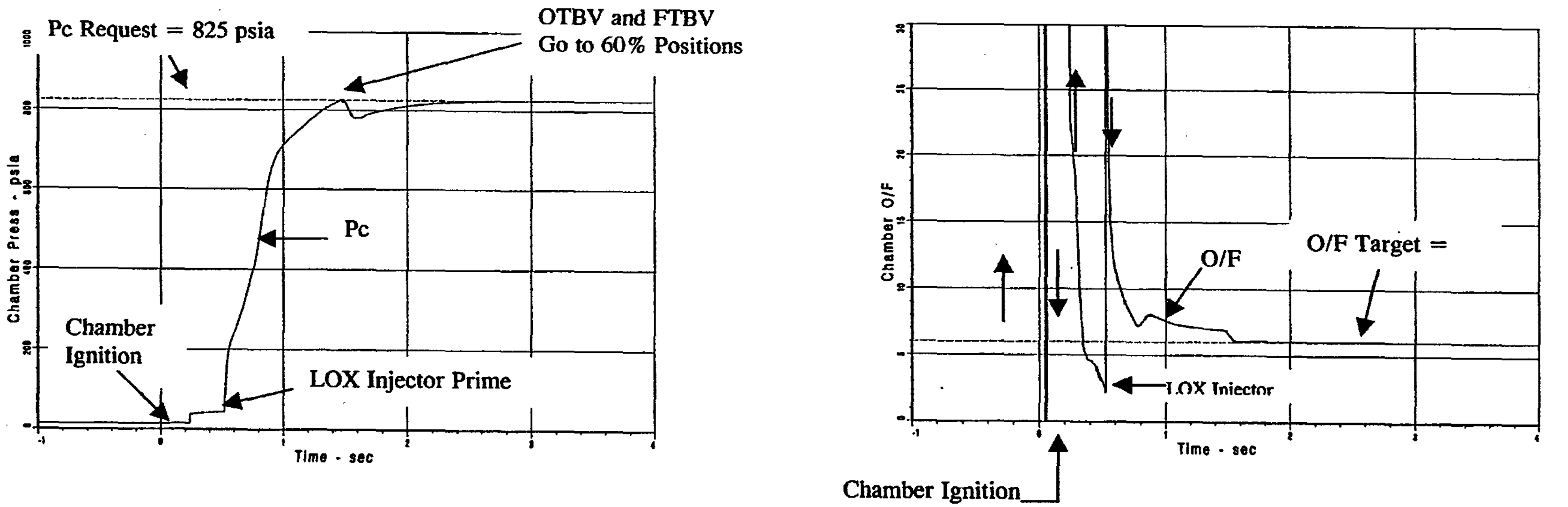


Figure 6. USD Cycle Start Pc and O/F Characteristics

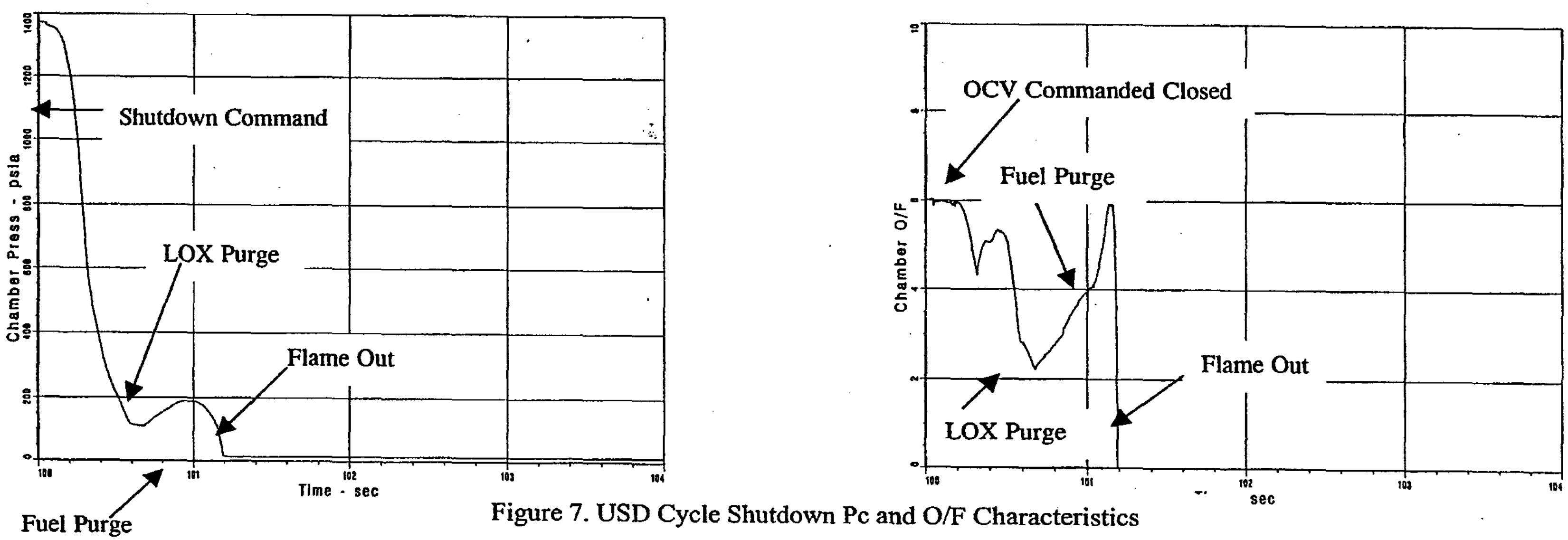
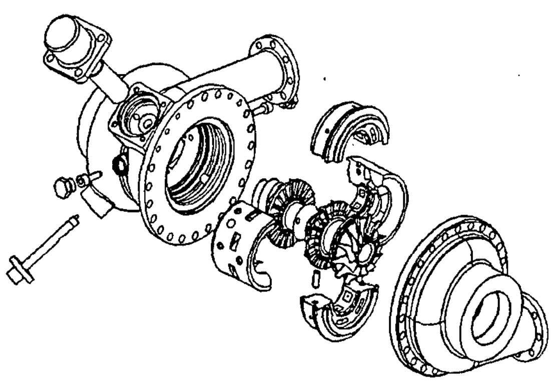


Figure 7. USD Cycle Shutdown Pc and O/F Characteristics

Advanced Liquid Hydrogen (ALH) Turbopump

The ALH turbopump, Figure 8, was designed and fabricated by P&W for the AFRL under contract F04611-94-C-0008. Component testing at P&W started in late 1999. The ALH turbopump delivers 16 lb/s (7 kg/s) liquid hydrogen with a pressure rise of 4500 psia (31.02 MPa) to support the 50k LOX/LH2 expander cycle engine and provide engine level contributions of a 10% thrust-to-weight increase, 5% cost reduction, and 7% reduction in failure rate toward the IHPRPT Phase I engine goals.

The ALH turbopump completed several tests and has demonstrated hydrostatic bearing technology to 35% rated power. Additional testing to demonstrate operation above 35% power is planned for 3rd quarter, 1999.



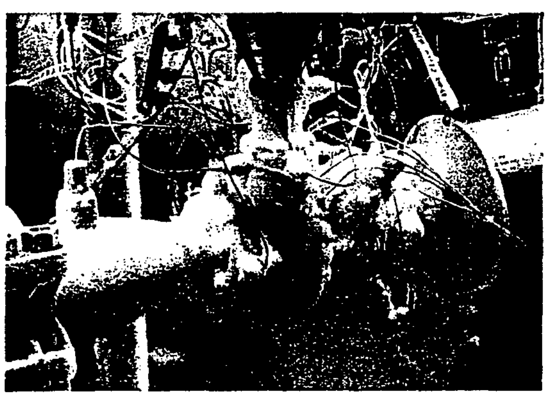


Figure 8. The Advanced Liquid Hydrogen Turbopump

Digital Electronic Rocket Engine Control (DEREC)

The 50k engine demonstrator will be configured with an "on-engine" electronic control system. The engine control system will be comprised of a Digital Electronic Rocket 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. While both the DEREC and EMA's have two fully redundant channels, only one channel will be active for the demonstrator test program. Use of a DEREC with EMAs with redundant channels is expected to provide an IHPRPT Phase I engine with a 45% reduction in failure rate, through improved engine control, electrical signal redundancy, and elimination of the pneumatic actuation system. The demonstrator DEREC will communicate with the test facility through a MIL-STD-1553 data interface through an Engine Control Module (ECM). An abort discrete can be sent directly from the test stand computer to terminate the test should the facility health monitoring system detect an out-of-limit condition.

DEREC software has been written and bench checkout of the software is in progress using a Verifier System to simulate the engine and EMA's (Figure 9). The embedded software will control the demonstrator through all phases of operation – prestart conditioning, start, steady state, and shutdown, and will include limited self-health monitoring, fault detection, and fault accommodation functions. While both chamber pressure and mixture ratio control functions will be open loop with command set-point being issued by the Test Conductor, the DEREC software will include a limited closed loop trim function that can be activated during testing.

The Verifier System has a real time model that simulates chamber pressure and EMA feedback for all phases of engine operation. Test cases are being run to verify DEREC self-health monitoring and the limited fault detection and accommodation for the EMA's and chamber pressure sensor along with closed loop control of chamber pressure. The Verifier System will also be used for test simulation during demonstrator testing. Prior to loading the command sequence into the DEREC the test will be simulated using the Verifier to validate safe operation.

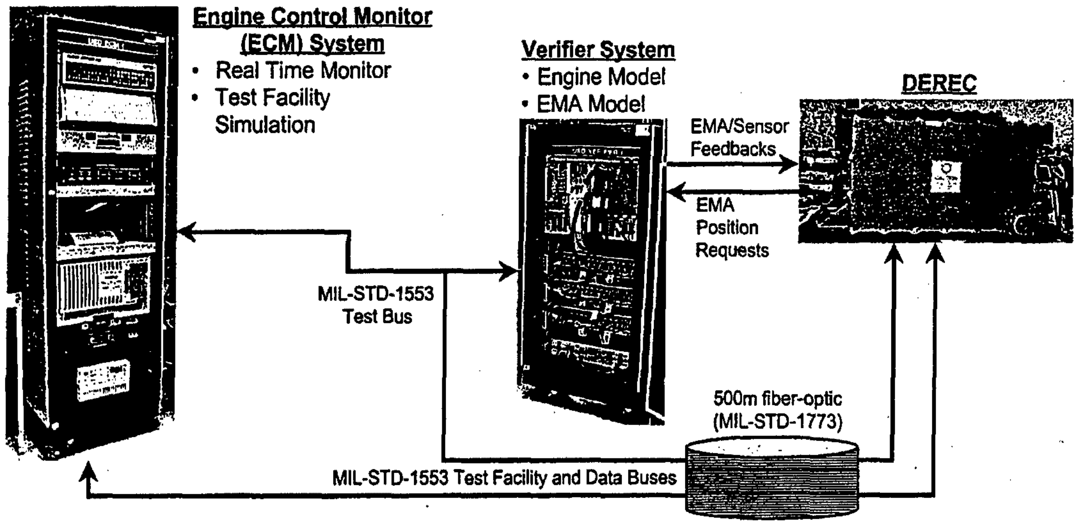


Figure 9. The DEREC Software Verification System

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 primary enabling technologies (hydrostatic bearings, high-heat transfer chamber, and digital controls) will demonstrate significant benefits for rocket engine components regardless of cycle or propellant combination. Future vehicles such as the Space Operations Vehicle and Space Maneuvering Vehicle will need very high performing propulsion systems. The USD provides a demonstration of advances that can benefit these propulsion systems.

While the USD was designed to provide an IHPRPT Phase I upper stage demonstrator, it was sized to meet future launch system demands. The thrust level for the upper stage demonstrator is based on future launch vehicle demands. This is already evident on Atlas and Delta heavy lift configurations that use two RL-10 engines. An engine based on the USD will be able to replace these two engines in the same envelope of just one RL-10. By reducing the number of engines, the vehicle reliability will be higher and reduce the overall vehicle cost.

With cost being one of the primary focus areas of the IHPRPT goal, the USD has also developed procedures and manufacturing techniques which will reduce the overall cost to launch vehicles in both hardware and support requirements. This directly supports the goal of the EELV program of reducing launch costs by 25 to 50%. The EELV schedule currently shows the Initial Operating Capability (IOC) in 2002. Engines based on the USD technology will directly benefit any future upgrades to EELV launch vehicles. The higher thrust level and maintaining the same operational envelope of the RL-10 also supports the demands of the heavy lift EELV slated for IOC in 2003.

SUMMARY AND CONCLUSION

The USD will demonstrate the operation of a high conductivity chamber, fully supported fluid film bearing turbopump and digital controls 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 engine capable of replacing existing RL10 upper stage engines. The USD will lead to robust engines for future expendable applications.