Program Status of the Pratt & Whitney RL60 Engine

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Abstract

Pratt & Whitney's RL10 engine, in a variety of models, has been the cryogenic powerplant for high-energy upper stages in US expendable launch vehicles for over thirty years. In preparation for future vehicle upgrades, Pratt & Whitney has started the development of a next generation cryogenic upper stage engine providing higher performance while maintaining the same installation envelope as the RL10. The Pratt & Whitney RL60 is an advanced liquid oxygen/liquid hydrogen (LOX/LH2) expander cycle engine incorporating several key technologies to increase performance and operability while maintaining RL10 reignition capability, life and reliability.

Engine performance is characterized by a thrust range of 40 to 60 k-lbf, with a 10% growth margin, and a specific impulse of 465 seconds. In order to meet the 60 k-lbf thrust requirement, the engine must be operated at much higher chamber pressures than any current expander cycle. This is made possible by the use of a copper tubular combustion chamber liner, a high heat load chamber technology specifically developed by Pratt & Whitney for expander cycle application.

The first phase of engine development, the RL60 demonstrator engine program, is currently under way and will demonstrate technology readiness for a reduced risk full scale development program. The RL60 engine design is defined, critical design review was passed for the demonstrator engine in the first quarter of 2002, and the engine program is on plan to conduct full power engine tests in 2003. The RL60 demonstrator phase is approved and fully funded by Pratt & Whitney and will serve as a basis for full scale RL60 engine development. Furthermore the RL60 demonstrator engine will be available as a testbed for future Air Force and NASA technology programs.

Introduction

There are two versions of the RL10 in production at Pratt & Whitney at this time. The RL10A-4 powers both the single engine version and the dual engine version of the Centaur upper stage for the Lockheed Martin Atlas II, Atlas III and Atlas V vehicles. The RL10B-2 powers the upper stage of both the Delta III and Delta IV vehicles, built by Boeing. As of this writing, 492 RL10's have been produced and have an accumulated 636 in-space firings.

Payloads have continued to grow in mass over the history of expendable vehicles, both because of need and because of improved vehicle capability. The new expendable vehicles have been developed to offer increased payload capability at lower launch costs, while incorporating improvements in reliability and safety. In concert with these vehicle developments, Pratt & Whitney has established a plan for development of a next generation cryogenic upper stage engine providing higher performance while maintaining the same installation envelope as the RL10.

The Pratt & Whitney RL60 is an advanced liquid oxygen/liquid hydrogen (LOX/LH2) expander cycle engine incorporating several key components and technologies to increase performance and operability. The RL60 development program will combine existing technologies with new technologies either developed under Integrated High Payoff Rocket Propulsion Technology (IHPRPT) programs with the US Air Force or independently by Pratt & Whitney. It will include components designed and developed specifically for the RL60 by rocket engine propulsion companies outside the United States. It is being developed to cover a broad range of thrust requirements, designed to operate at any thrust setting between 40,000 lbf to 65,000 lbf, thus covering a range of potential vehicle requirements. Figure 1 shows an overview of existing and planned cryogenic upper stage engines including the RL10 and RL60.

Based on the excellent track record of the RL10 expander cycle engine, this cycle was selected for RL60. The expander cycle is inherently safe because of its self-limiting power cycle. Additionally, because it uses no external combustion devices to drive turbomachinery, it is the best approach for in-space re-starts. The basic architecture of the RL60 also draws from studies conducted and lessons learned during the Upper Stage Demonstrator (USD) program, awarded to P&W by the Air Force Research Laboratory as part of the IHPRPT initiative. The USD program encompassed cycle balance and component performance trade studies, component and system design and integration activities, and component testing intended to lead up to a demonstrator engine. This program helped identify and/or reinforce the need for critical technologies and components, and provided pathfinders for fabrication technologies. The USD program also provided a key piece of information for an advanced expander engine, namely a test of a full-scale copper tubular combustion chamber (described in ref. 1)

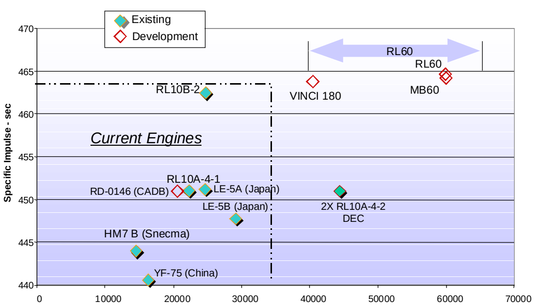

Figure 1: Existing and Planned Cryogenic Upper Stage Engines

The market for expendable launch vehicles has not met the predictions made just a few short years ago. The date envisioned for first launch of a next generation high energy upper stage engine has continued to move to the right. For this reason the RL60 Development Program has been divided into two parts. The first part, and the subject of this paper, is the RL60 Demonstrator Engine Program. Following the successful completion of this phase, and the establishment of launch vehicle commitment, the RL60 Full Scale Development (FSD) Program will be initiated.

Program Overview

The RL60 Demonstrator Engine Program is the first phase in development of the RL60 Cryogenic Upper Stage Engine. This program is funded by Pratt & Whitney. Its goal is to demonstrate the major components of the RL60 as a system in full scale at the 60,000 lbf operating condition.

This program has its beginnings in the original commercial Cryogenic Advanced Upper Stage Engine (cCAUSE) program of 1999. This program became the RL50 Engine Program, so designated to identify its 50,000 lbf thrust class (ref. 2). During the latter half of 1999 and early 2000, Pratt & Whitney and Snecma established a plan to develop a new cryogenic upper stage engine that encompassed the requirements and capabilities of both the RL50 and the Vinci. It was thought that effective cost management and economies of scale could be achieved by developing one engine to meet the future needs of US and European expendable launch vehicles. This engine was given the designation SPW2000, signifying the partnership and the new millennium. Unfortunately, it was not a program fully embraced by ESA, and was discontinued in June 2000. Since that event, Pratt & Whitney has re-established its own program, now designated the RL60 to identify its design thrust level. The RL60 Demonstrator Program was initiated at the end of 2000. Fig. 2 provides an overall RL60 program schedule, including the cCause, RL50 and SPW2000 efforts preceding the RL60.

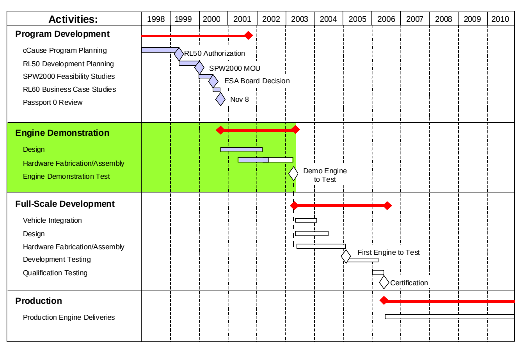

Figure 2: RL60 Program Schedule

The RL60 Demonstrator Engine incorporates all the design requirements of the full scale development engine. However, the Demonstrator Program will concentrate solely on the "core" components. The RL60 Demonstrator will include the combustion chamber, injector, regeneratively cooled nozzle and both main propellant turbopumps. It will include the highly reliable RL10 dual direct spark ignition system and flight-type thrust control valves. Plumbing and on/off valves will be rig type hardware designed to flight-type operational and performance requirements. The RL60 Demonstrator will not include the propellant boost pumps or the radiation cooled extendable nozzle and its deployment system.

Although the Demonstrator Engine does not include all the components of the full scale development engine, it is being designed with attention to flight-type requirements. Even where program limitations forced the use of less-stringent requirements, the status of the engine design relative to the original requirements is tracked on a monthly basis. Engineering responsibilities are shared by systems level and component-level engineering teams, with a core team of personnel assigned to the program. Naturally, representatives for the Operations (Manufacturing, Assembly, Test, Quality Assurance) branches of the company are also participatory in the design process. System and component level requirements are derived from program (vehicle) requirements, and are formally documented and tracked in the same manner as they would be for a full scale development program, adding rigor to the design process, and positioning the engine for a smooth transition to full scale development.

Another challenge being addressed in the RL60 program is that of replacing a highly-reliable, mature engine, the RL10, which has a demonstrated reliability record, with a clean-sheet engine design. Obviously, the goal of the new engine is to provide increased reliability. In the RL60 engine, this is being addressed from the ground up. Reliability and hazard assessments are included in the Demonstrator Engine program, and will be continuously updated going into full scale development. Producibility and inspectability are being designed into the RL60's components. Pathfinders are being used to demonstrate new technologies and processes before they are committed to the design. Design requirements include adequate margins to ensure a robust design, and modern inspection techniques are applied where appropriate.

In order to take advantage of technologies and capabilities throughout the industry, the RL60 includes components designed and fabricated by key non US space propulsion partners. IHI, the center of excellence for rocket engine turbomachinery in Japan is designing and building the main fuel turbopump. CADB of Russia is responsible for the main LOX turbopump. And Volvo Aero of Sweden is providing the regeneratively cooled (regen) nozzle incorporating their laser welded sandwich technology. Pratt & Whitney is responsible for system design and integration, engine controls and combustion devices.

The RL60 Demonstrator Program is well underway and has passed its Critical Design Review. Hardware is in fabrication and the majority of components will have completed all component level testing by the end of 2002. The engine assembly will begin in early 2003 with first engine test scheduled before the end of the second quarter, 2003.

Engine Overview

RL60 engine performance data are summarized in table 1. The engine has over twice the thrust of the RL10B-2 version, while fitting into the same geometrical envelope. Vacuum specific impulse will be higher than the current RL10B-2 value, and life and reliability will be at least the same. NPSP values are lower compared to current RL10 versions, providing overall stage system performance benefits. A 10% thrust growth margin is being incorporated into the design.

Figure 3 shows the RL60 engine cycle schematic and mechanical arrangement. The flow schematic is basically the same as the current RL10 except that the oxidizer turbopump is driven by a separate turbine and turbine bypass valve instead of a gear drive system. The RL60 also includes hydrogen and oxygen boost pumps to accommodate lower propellant inlet pressures and allow higher main pump rotational speeds for high efficiency, lower weight and lower cost. The oxidizer boost pump is driven by a hydraulic turbine which is fed by LOX tapped off of the main LOX pump discharge. The hydrogen boost pump is driven by turbine discharge GH_2. The boost pumps are not part of the demo program and will not be described further in this paper. The main turbopumps features will be summarized in the turbomachinery section of the demonstrator engine description.

	RL10B-2	RL60
Thrust, (lb.) vac.	25,000	60,000
Isp (sec.) vac.	462	465
Weight (lb.)	664	1,100
Chamber pressure (psia)	640	1,200
Propellants	LOX / LH2	LOX / LH2
Inlet mixture ratio	5.0 to 6.0	5.0 to 6.0
NPSH (psia) LOX / H_2	6.0 / 6.0	2.0 / 1.5
Maximum diameter (ft.)	7.5	7.5
Installed Length (ft.)	7.3	7.3
Growth margin	0	10%
Life		
– Firings (starts)	15	45
– Time (sec.)	3,500	4,050
Reliability	0.998	0.998

Table 1: RL60 Engine Requirement

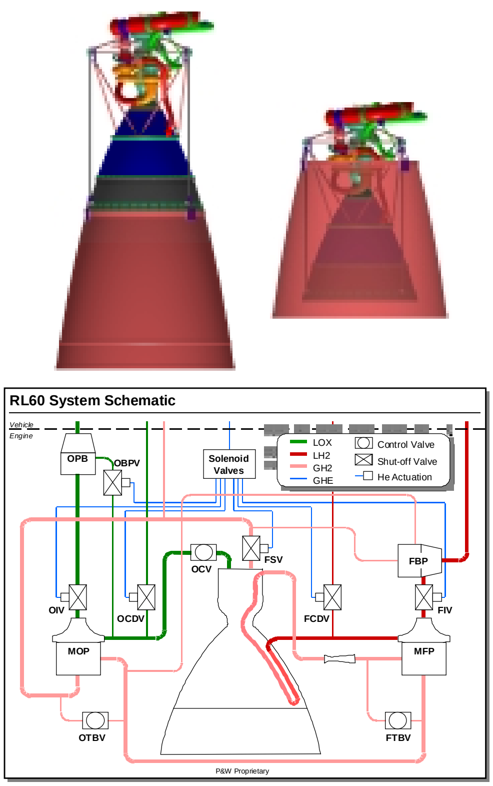

Figure 3: RL60 Engine Cycle and Mechanical Arrangement

Key to achieving the high performance in the RL60 engine is the use of a copper tubular combustion chamber which allows to operate the engine at about twice the chamber pressure of an RL10 or LE5 engine while maintaining adequate chamber life. The steel tube chamber technology used in those engines do not support engine operation at the RL60 chamber pressure levels due to life limitations. The copper tube chamber liner technology is thus the main enabling technology. This technology has been developed within an Air Force program sponsored under IHPRPT and has been demonstrated successfully in a full size chamber test, see ref. 1. Demonstrating full power conditions at the 60 k-lbf design point in hot fire tests will be the ultimate proof of suitability and readiness of this new technology. Main design characteristics of the combustion devices, including injector/igniter, combustion chamber itself and regen nozzle will be provided in the combustion devices section of the demonstrator engine description.

The radiation cooled nozzle extension is similar in size and profile to the existing RL10B-2 nozzle which uses high temperature compatible Carbon/Carbon material and is made by Snecma of France. This nozzle is considered existing technology and is not needed for the demonstration of the RL60 core engine in the Demonstrator Program; it will not be described here.

RL60 Demonstrator Engine

Overview

The RL60 demonstrator engine represents the core of the RL60 engine and is designed to RL60 engine requirements. It does not include the boost pumps or the radiation cooled nozzle and its deployment system. The demonstrator engine program will be used to demonstrate key technologies, components and engine architecture supporting the RL60 engine cycle by designing, fabricating and testing a full scale demonstrator engine. Using key components designed to flight engine requirements and configuration, the demonstrator engine will reduce the risks of the FSD program. Critical components such as the thrust chamber assembly and main fuel turbopump are designed to flight-type configuration to increase the fidelity of the demonstration. Other components such as the main LOX turbopump and valves are designed to FSD performance and operability requirements.

At every step of the demonstrator engine program an identified path exists to meet FSD engine performance, weight and cost goals. The demonstrator engine will be tested at full power conditions, representative of 60,000 lbf FSD thrust conditions, on Pratt & Whitney's E-8 vacuum test facility.

Fig. 4 shows the RL60 demonstrator engine configuration, its major components, and the partners participating in this program. Pratt & Whitney is responsible for all system engineering aspects such as mechanical arrangement, performance, operations, engine assembly and test. At the component level, Pratt & Whitney is responsible for injector & igniter, combustion chamber, and controls, valves and plumbing. Volvo Aero of Sweden provides the regen nozzle, IHI of Japan provides the fuel turbopump, and CADB of Russia supplies the LOX turbopump. All major subsystems except the regen nozzle, will be tested at subsystem level prior to demonstrator engine assembly, to verify subsystem performance and validate engine system models prior to engine test.

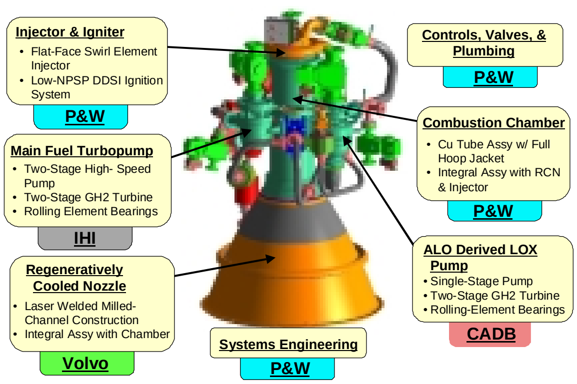

Figure 4: RL60 Demonstrator Engine Configuration and Major Components

<u>Engine System</u>

The mechanical arrangement and packaging of the components consider not only the demonstrator engine but also all FSD components (e.g., boost pumps and thrust vector control actuators) and integration into future upper stages. Component mount arrangement and propellant manifolds were designed to represent a flight engine which increases the fidelity of the demonstration. The demonstrator engine essentially represents the first development unit of the RL60 engine development program.

Steady state and transient performance models of the RL60 were created to establish component performance requirements and a baseline for the engine system. These models which are continuously being updated as new component performance data becomes available, were used for all design and off-design studies and to define margins. Engine thermal conditioning and start and shut-down methodologies were determined from transient analyses. Engine operational philosophy has been established and valve sequencing has been defined for all phases of engine operation, i.e., cooldown, ignition, start, steady-state operation, and shut-down. Furthermore, the control logic requirements have been established and the control software development plan has been defined.

The demonstrator engine includes a full suite of control and shutoff valves to mimic FSD engine operation. Valve performance requirements, such as propellant temperature, pressure, flows, slew rate, opening and closing times, and fail safe position, were derived from performance analysis models and system requirements. The turbine bypass valves are designed to FSD requirements and use EMAs while the OCV and all shutoff valves will be electrohydraulically operated on the demonstrator engine. For the FSD engine it is foreseen that the OCV will be EMA operated, and the shutoff valves will be pneumatically actuated.

The RL60 demonstrator engine and all its components have passed CDR in March of 2002. System and component designs have been frozen and manufacturing has been underway for some time, to support engine assembly in the first quarter of 2003. In the following paragraphs a brief summary of the combustion devices, turbomachinery, and engine testing will be provided.

<u>Combustion Devices</u>

The RL60 thrust chamber comprises the injector with igniter, the combustion chamber and the regen nozzle. Both the injector and the regen nozzle are welded to the combustion chamber to form the thrust chamber assembly.

The RL60 will use a flat-face, transpiration cooled injector with integral igniter.

Manufacturing of the injector has been completed at this time. Fig. 5 shows the finished injector, which will be tested at nominal RL60 design point operating conditions in the second quarter of 2002. The igniter is a slightly redesigned version of the RL10 Dual Direct Spark Igniter (DDSI). A series of ignition tests has verified safe and reliable ignition under the reduced NPSP conditions required for RL60. Fig. 6 shows the test rig used.

Figure 5: RL60 Injector

Figure 6: RL60 Ignition Rig Testing

The combustion chamber uses a copper tubular liner and a full hoop structural jacket. The high heat load copper tubular chamber is the enabling technology for RL60, providing much higher turbine drive power than conventional chamber technologies, thus enabling higher pump outlet and chamber pressures than previously achieved in any expander cycle engine. Chamber design is based on Pratt & Whitney material and fabrication technologies demonstrated in previous technology programs. Fig. 7 shows the actual hot fire test of the AEC chamber demonstrating the copper tube liner technology for the first time in a full size chamber operation, see ref. 2 for details.

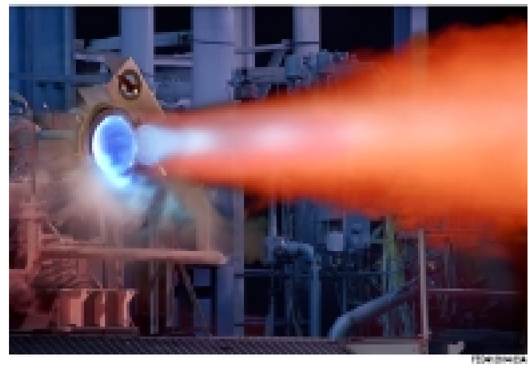

Figure 7: AEC Copper Tubular Chamber Test

Fig. 8 shows a sketch of a section of the copper tubular chamber, and the first set of tubes to be used for the first RL60 chamber assembly. An extensive development program incorporating a number of manufacturing pathfinders was needed to establish the tube forming, brazing and spray technologies needed for the construction of this chamber. A component test of the injector/combustion chamber assembly is foreseen for the first quarter of 2003, prior to engine testing.

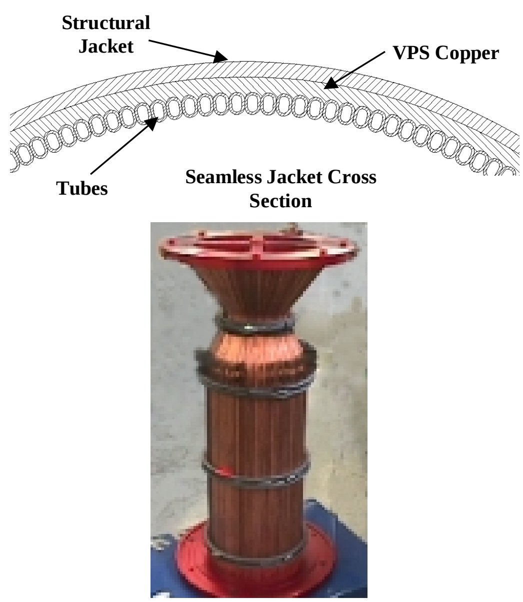

Figure 8: RL60 Combustion Chamber

The regeneratively cooled nozzle is being developed by Volvo Aero in Sweden using their proprietary new sandwich nozzle technology. This technology, which has been successfully demonstrated at subscale level under representative chamber operating conditions, employs a laser-welded milled channel construction. Fig. 9 shows a schematic of the RL60 regen nozzle and RL60 nozzle cones during manufacturing. Details of the sandwich nozzle technology and the RL60 regen nozzle design features may be found in ref. 3. The regen nozzle will be welded to the injector/chamber assembly to form the thrust chamber, prior to engine assembly.

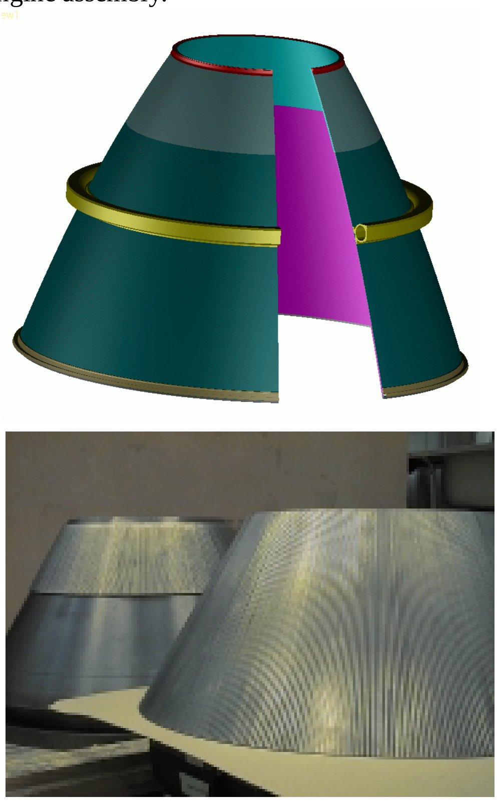

Figure 9: RL60 Regen Cooled Nozzle Extension (Volvo Aero, Sweden)

Turbomachinery

Fig. 10 shows the turbomachinery package as installed on the engine. The main fuel pump, developed by IHI in Japan, is a two-stage high speed pump with a two-stage turbine and conventional rolling element bearings. Component bench tests on both turbine and pump have been performed to support design optimization. Overall turbopump testing with hydrogen will take place this summer in Japan.

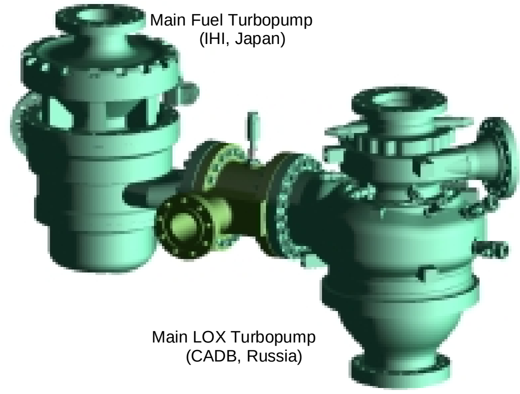

Figure 10: RL60 Main Turbopumps

The main LOX pump is under development by CADB in Russia and is a derivative of the existing Advanced Liquid Oxygen (ALO) turbopump previously supplied to Pratt & Whitney by CADB, see ref. 4. It is a single-stage pump with a two-stage turbine and rolling element bearings. Component tests will take place this summer at CADB test facilities in Russia.

Engine Testing

The test program for the RL60 demonstrator engine will be conducted on Pratt & Whitney's E-8 test stand in the second quarter of 2003. The engine will be mounted in the vacuum cell currently used for RL10 production engine acceptance testing. Fig. 11 shows the E-8 vacuum facility in its current configuration. Major test stand modifications are under way to accommodate the higher mass flows and pressure levels of the RL60 engine. The current test plan foresees five tests in its first phase as covered by the RL60 demonstrator engine program. The goal of the test program is the demonstration of safe engine operation at full power (i.e. 60 k-lbf equivalent flows) conditions.

Figure 11: Pratt & Whitney E-8 Vacuum Test Facility

Summary and Conclusions

The RL60 engine is being developed by Pratt & Whitney as a high thrust, high performance, high reliability engine for future cryogenic upper stages. The first phase of engine development, the RL60 Demonstrator Engine Program, is currently under way and will demonstrate technology readiness for a reduced risk full scale development program. This demonstration will be achieved by full power tests of the demonstrator engine at Pratt & Whitney's vacuum test stand in the second quarter of 2003.

The RL60 engine design is defined, critical design review was passed for the demonstrator engine in the first quarter of 2002, and the engine program is on plan to conduct full power engine tests in 2003. The RL60 demonstrator phase is approved and fully funded by Pratt & Whitney and will serve as a basis for full scale RL60 engine development. Furthermore, the RL60 demonstrator engine will be available as a testbed for future Air Force and NASA technology programs.

References

1) Cooley, C., Fentress, S., and Jennings, T., "Hot Firing of a Full Scale Copper Tubular Combustion Chamber", AAAF-2002-S.18.02, 6th AAAF International Symposium: Propulsion for the XXIst Century, Versailles, France, May 2002.

2) Brown, J.R., Bullock, J.R., Parsley, R.C., and Popp, M., "Development Status of the Pratt & Whitney RL50 Upper Stage Engine", AIAA-2000-3786, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, Alabama, July 2000.

3) Johansson, L., Ryeden, R., Häggander, J., and Damgaard, T."Laser Welded Sandwich Nozzle Extensions for Expendable and Reusable Engines", AAAF-2002-S.18.03, 6th AAAF International Symposium: Propulsion for the XXIst Century, Versailles, France, May 2002.

4) Dimitrenko, A.I., Ivanov, A.V., Kravchenko, A.G., and Minick, A.B., "Advanced Liquid Oxygen Turbopump Design and Development", AIAA-2000-3878, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, Alabama, July 2000.