Validation of Propulsion Technologies and New Engine Concepts in a Joint Technology Demonstrator Program

Jeffrey K. Schweitzer, John S. Anderson
Pratt & Whitney Division of United Technologies Corporation
400 Main St., East Hartford, CT, USA

Dr. Hermann Scheugenpflug, Dr. Erich Steinhardt
MTU Aero Engines GmbH
Dachauer Strasse 665, Munich Germany

ABSTRACT

This paper will describe the status of the Joint Technology Demonstrator Program (JTDP) being conducted by Pratt & Whitney (P&W) and MTU Aero Engines (MTU) and the technologies selected for implementation. It will include an overview of P&W's and MTU's future technology demonstration plans for the JTDP to support next generation engine product programs with specific requirements for performance enhancement, emission reduction, weight reduction, and reliability improvement.

INTRODUCTION

P&W and MTU have enjoyed a close working relationship since 2001 in jointly demonstrating and validating advanced technology gas turbine features intended for use in commercial aircraft engines in the JTDP. ***Figure 1*** shows the basic history time line of completing the previous two builds of the demonstrator and a schedule to complete the next build later this year. It shows the basic technology features included in each build. The first build of the demonstrator started with an engine taken from the PW6000 development program. The only technology feature included in that build was a six-stage high-pressure compressor (HPC) that was provided by MTU. That build was more successful in demonstrating HPC efficiency than the original five-stage HPC that was being certified in the engine production program. As a result, the MTU HPC was incorporated into the PW6000 Bill-of-Material (BOM).

The second build included two technology advancements: the incorporation of integrally bladed rotors (IBRs) into the MTU HPC, and the technology for low NOx (TALON III) combustor. That demonstration was instrumental in validating and lowering the development risk of both components. The technology readiness level (TRL) of both components was advanced to TRL 5 (*TRL 6 is necessary to enter full-scale development*).

The upcoming third build, scheduled for test in the 4th Quarter 2005, will include advanced technology features in the HPC and low-pressure turbine (LPT) provided by MTU. P&W will contribute the next generation of TALON combustors, efficiency and

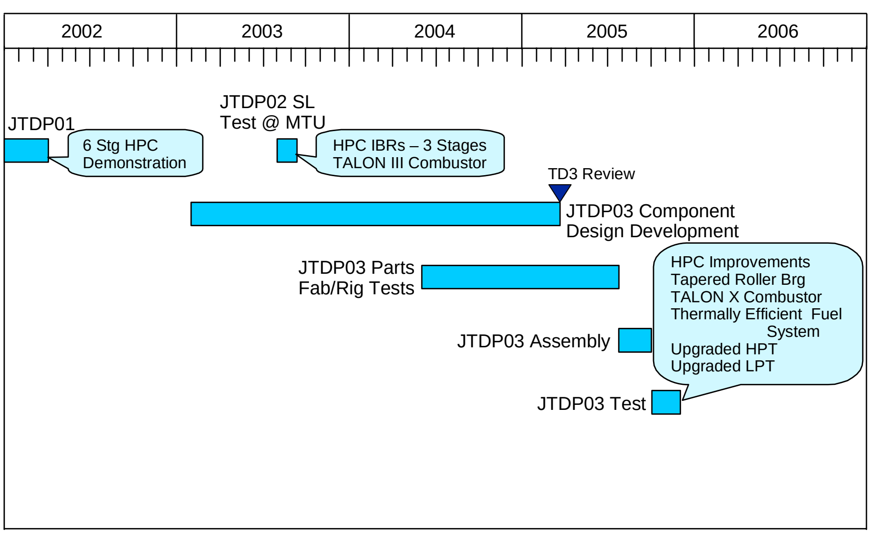

Figure 1. *JTDP Level I Plan*

cooling improvements in the high-pressure turbine (HPT), various mechanical features in the bearing compartment and an advanced, low cost thermally efficient fuel system. The configuration of JTDP03 is displayed in ***Figure 2***.

Future plans call for a demonstration in the Engine Validation of Noise and Emissions Reduction Technologies (EVNERT) program of a gear driven fan configuration using the high-pressure core of the JTDP engine as the starting point. The general objective of that program will be to reduce noise and combustion emissions. P&W is planning to provide the new low noise fan and TALON X combustor, and is developing the fan drive gear system. MTU is planning to provide a high-speed LPT for that demonstration.

TECHNOLOGY DEVELOPMENT PROCESS

The JTDP is a part of the overall technology development process at P&W and MTU. The technology management process is used to ensure readiness prior to committing technologies into a product development program.

The process starts with a continuous review of market opportunities and customer requirements for future products or improvements to existing products. Customer and market needs are used as the basis for notional studies to assess new or revised product configurations and technologies to best meet customer requirements. The notional studies help identify and prioritize technologies, leading to a complete technology portfolio called the Advanced Technology Plan.

The process follows the widely known TRL 1-9 scale, where P&W and MTU require that technology achieve TRL 6 prior to start of detailed design in a product development program. TRL 6 requires that technology be validated in a system level relevant environment, most typically an engine test in the relevant design space, to validate Engineering Standard Work (ESW) for the technology. Explicit technology development plans (TDPs) are reviewed and approved for each technology in the portfolio. A TDP specifies all criteria and activities required to mature the technology and validate new Standard Work associated with achieving TRL 6. Upon achieving TRL 6 in demonstrator engine programs, such as the JTDP,

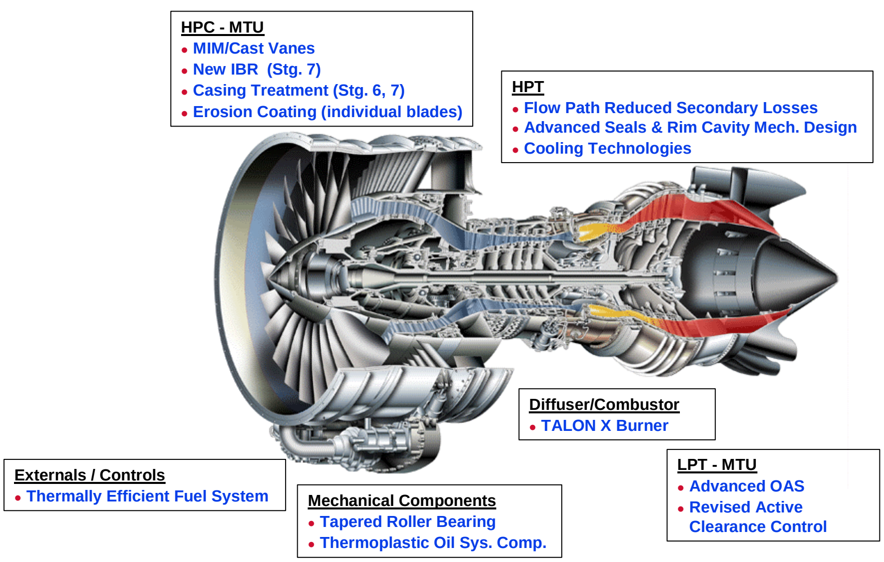

Figure 2. *JTDP03 Configuration*

technologies are approved for insertion into product development programs. The technology development process is illustrated in ***Figure 3***.

P&W/MTU BUSINESS RELATIONSHIP

A Memorandum of Agreement was negotiated at the beginning of the JTDP to establish the working relationship between P&W and MTU. Under that agreement, P&W provides the basic PW6000 engine and technology features in the fan/low-pressure compressor (LPC), combustor, HPT, mechanical systems and fuel, and control system. P&W also provides assembly of their own components and final assembly of the engine. MTU provides the HPC and LPT and the technology features in those components. MTU also provides assembly of their own components and the engine test in their Munich test facility.

JTDP01

PW6000 Base Engine

The first build of the demonstrator started with an engine taken from the PW6000 development program. The PW6000 builds on proven technology gleaned from other P&W advanced engine programs to deliver the lowest cost of ownership for 100-passenger aircraft operators. P&W has incorporated technological advances in the PW6000 that enable a reduction in part count. With fewer parts, the engine has a lower acquisition cost and a reduced maintenance cost.

The PW6000 meets all current and anticipated noise and emissions requirements to provide longevity and high residual value. Reduced noise provides better revenue benefits, since the PW6000 will enable flights into many airports that have curfews

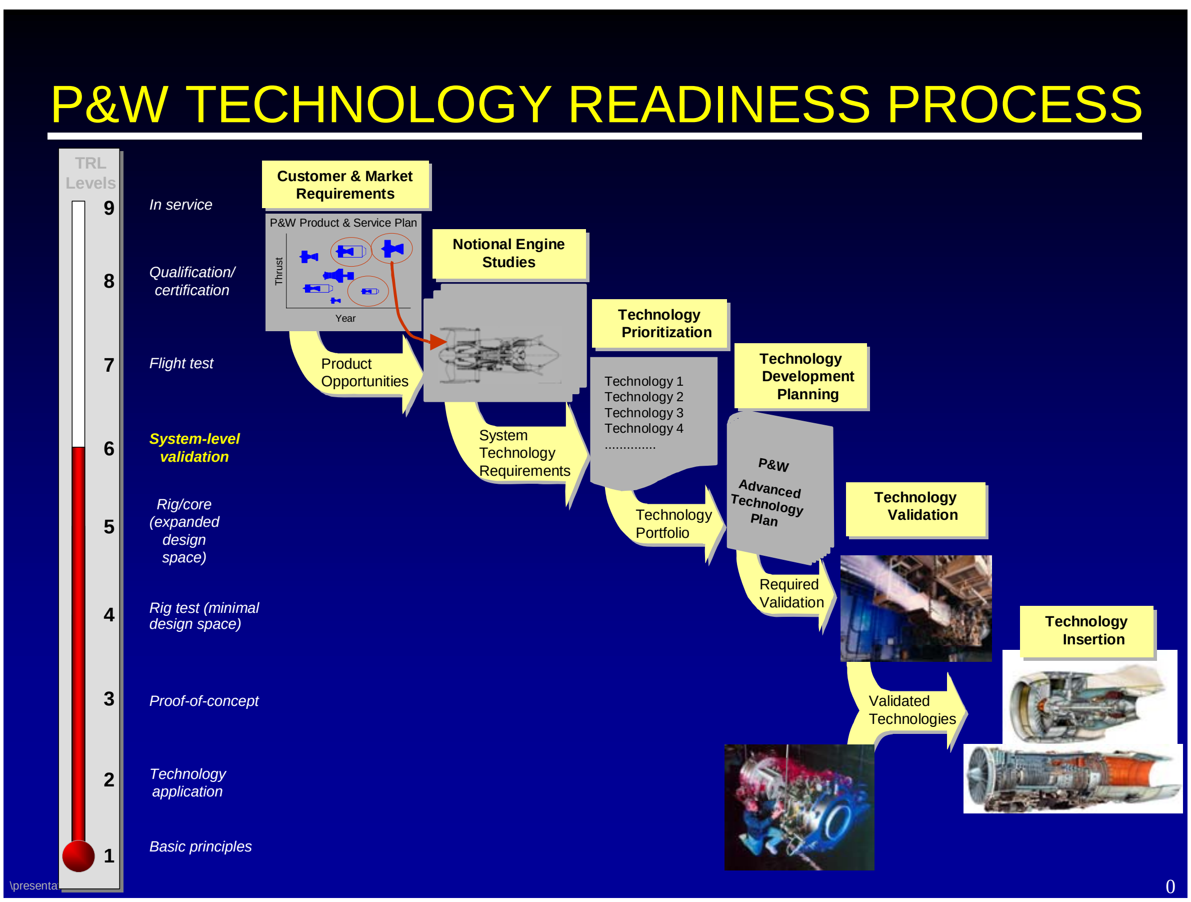

Figure 3. *Technology Development Process*

and noise quotas.

PW6000 Engine Characteristics

Fan tip diameter: 56.6 in.
Length (flange to flange): 108 in.
Takeoff thrust: 22,100 to 23,800 lb
Flat rated temperature: 86°F
Bypass ratio: 4.8 to 5.0
Overall pressure ratio: 26.1 to 28.2

The JTDP01 engine in MTU's Munich Test Facility is shown in ***Figure 4***.

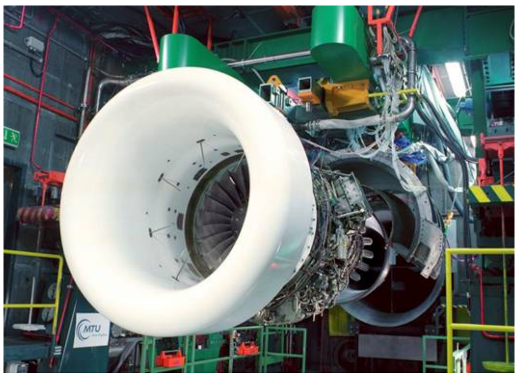

Figure 4. *JTDP01 in MTU's Test Cell*

HPC Design and Development

MTU developed the EJ200 HPC in the 1990s, which was based on advanced compressor design and production and numerous technology programs. P&W and MTU's joint studies showed that a derivative of the compressor would fit perfectly with the requirements of a regional aircraft engine core for the 20 to 24 klb thrust class and into a geared turbofan (GTF) up to 35 klb. By adding one and two stages to aerodynamic rigs representing the technology of the five-stage EJ200 compressor, MTU proved that pressure ratios up to 11 and beyond 12 and still getting excellent efficiency and stability margin. Based on these results, MTU developed a six-stage engine hardware compressor funded by the National E3E Program with a first test in 1997.

Following the desire and need to verify the six-stage compressor technology in a real engine environment to achieve TRL 6, MTU modified the compressor to fit directly into a PW6000 engine. New technology features like swept three-dimensional (3-D), low aspect ratio airfoils were introduced. The aerodynamic design of the HDV12 was performed using the 3-D Navier-Stokes Code jointly developed with German Research Center funding. It was the first time to include the effects of secondary flow through the inner airseals into the compressor design. From the E3E compressor test results, it had become obvious that this capability is essential for very highly loaded compressors.

The HDV12 compressor was successfully tested in a series of aero–rig tests from 2000 onwards at MTU's high temperature inlet compressor test facility.

The convincing aerodynamic characteristics of the rig tests finally triggered the decision to test the HPC in the JTDP engine, and gave the opportunity for proving the TRL. That rotor is pictured in ***Figure 5***.

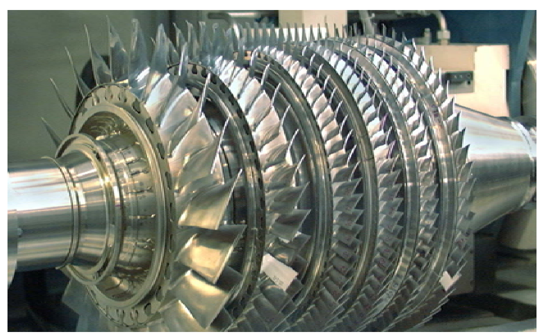

Figure 5. *HDV12 Rotor*

Finally, when the start button was pushed late in 2002, the engine started perfectly on the first try. Within a few days of testing, the joint team could provide all data required to the PW6000 program. Based on the JTDP01 results, the management of both companies decided that the HDV12 compressor should become the new HPC for the PW6000 engine. Based on the outstanding technology of the compressor, MTU received the Innovation Award of the German Industry in 2002.

As a follow-on activity, the JTDP01 hardware was tested at P&W's altitude test facilities to complete performance mapping and high power stability tests. The tests simulated low Reynolds Number conditions at the maximum cruise conditions and hot day takeoff conditions. A major focus was on cold day starting, handling tests, windmill relights to cover the critical performance, and integrity test points of a regular engine certification program.

JTDP02

HPC IBRs

While all stages of the JTDP01 HPC include bladed rotors, the next build of the JTDP incorporated three stages of IBRs. Indications from rig testing of the HDV12 had already shown that sealing of the blade roots could improve the efficiency by a couple tenths of a percent. Furthermore, test results from a single-stage transonic rig indicate some potential for reduction of the shock losses in the first HPC rotor blade by advanced 3-D profiling and sweep. MTU designed three stages of IBRs to use the effects, and saved more than 20 lb of weight, in the process.

MTU could use the design and production technology for IBRs out of the EJ200 LPC and HPC programs for the first two titanium stages, but had to develop the production parameters for their first nickel IBR.

Within only 6 months, the bladed stages were replaced with the IBR as shown in ***Figure 6***, and tested in the JTDP02 engine. The results were more than satisfactory, and the IBR-HPC became the production standard. The customers were convinced that MTU and P&W possess excellent capabilities and technologies to design and manufacture IBRs. The expectations of the customer in terms of reliability

Figure 6*: IBRs Replacing Bladed Rotors in JTDP02*

requirements and maintenance costs will be met and may be exceeded.

The risks to the PW6000 certification program were significantly reduced by the technology validation that had taken place in the JTDP01 and JTDP02 programs. At this point the Technology Readiness was proven, and the responsibility for further maturation was transferred from Advanced Technology to the Engine Product Program Organization.

TALON III COMBUSTOR

Development of the TALON family of combustors was begun in the mid-1990s. The basic approach was to refine the traditional P&W rich/quench/lean (RQL) approach for commercial combustors, wherein the front-end of the combustor is designed to be *rich* or at a higher than stoichiometric fuel-air ratio at all power conditions. The rich products are diluted by quench air at the combustor mid-section down to the lean turbine entry conditions required by the engine cycle (combustor exit temperature). Having a rich front-end at lower operating conditions ensures a highly stable combustor. Conventional combustor design approaches, including optimized fuel-air stoichiometry, improved fuel injection, and mixing, were employed. The first TALON combustor was incorporated into the PW4098 engine. This combustor was improved through development testing at P&W with partial funding by NASA, and the first upgrade (TALON II) is available in the 94-in. and 100-in. PW4000s.

In early 2000, design changes incorporating the proven impingement film floatwall liner concept were made in the PW6000 TALON II combustor, which reduced complexity and lowered total part count by approximately 1/3. The TALON III combustor was tested in the JTDP02 engine in September 2003 with continuing development through a series of sector and full annular rig tests, and was partially funded by NASA. The TALON III combustor that was demonstrated in JTDP02 is shown in ***Figure 7***.

Figure 7. *TALON III Combustor*

The results of that demonstration validated that the TALON III combustor meets the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP)/6 emission with a significant margin. Also, carbon monoxide and hydrocarbons easily met the ICAO CAEP/6 rule with 60 and 95 percent margin, respectively. There was no visible smoke.

JTDP03

JTDP03 is the third build of the PW6000-based engine technology program. It is scheduled to be tested in October 2005 in three phases. The scope of technology features reach from emerging technologies to technologies that can easily be introduced into a product enhancement of the PW6000.

High Pressure Compressor

The technologies to be validated in the HPC are mainly focused on reducing the manufacturing cost and cost of ownership of the engine.

Advanced Manufacturing Process for IBRs

Advanced 3-D shaped IBR airfoils are primarily designed to meet aerodynamic requirements, yet they challenge current production capabilities. Single-pass flank-milling processes would cause a loss in efficiency on the order of one-half percent, whereas the regular point milling process used to date is still costly. Based on a new design tool, the aerodynamicists can now design airfoils while simultaneously simulating the manufacturing process. The output is computer code that can be directly transferred to the numerical controlled (NC) machine. Using this stripe milling design process, it is feasible to manufacture slightly swept airfoils without loss of efficiency or stability. The smoother surface will even give some potential for efficiency improvement and enhanced mechanical high-cycle fatigue (HCF) potential.

MTU has designed and produced one stage of the HPC, as shown in ***Figure 8***, to achieve technology readiness for this production process. Prior to the engine tests, the IBR underwent a series of mechanical tests.

Figure 8. *Stripe-Milled IBR*

Metal Injection Molding (MIM) and Casting of Highly Loaded Airfoils

While casting of compressor vanes is not new in the industry, highly loaded compressors, with an average stage pressure ratio of about 1.5, impose inherently high HCF loads on any airfoils. Although thorough frequency tuning and forced response calculations enable the designers to optimize the airfoil’s size and shape, the combination of static stress and HCF stress is critical to the materials applied. High strength forged nickel-based alloys were chosen for the PW6000 compressor. Milling or electro-chemical machining (ECM) manufacturing of the 3-D shaped nickel vanes is fairly time consuming and costly, whereas cast airfoils did not originally fulfill the requirements for HCF strength, nor could they guarantee acceptable quality for the thin leading and trailing edges.

For cast vanes, dampers may become necessary on some stages to solve the HCF challenge. The introduction of efficient vibration dampers, on the other hand, must not degrade the time on-wing because of wear in the friction damper. They should also be light and not cause extra leakage, which would be detrimental for the specific fuel consumption (SFC) of the engine. MTU will introduce a rainbow set of precision cast vanes with a particular small volume and light damper design in the JTDP03.

Vanes made by MIM somewhat compete with cast vanes. MTU has gathered experience in design and fabrication of MIM parts, including vanes themselves. In JTDP03, the vanes made from a high-temperature alloy will be tested (***Figure 9***). Specimen and rig testing indicates that the HCF properties will be very close to

Figure 9. *HPC MIM Vane Cluster*

those of forged material. For that reason, MIM vanes would combine the cost advantages of cast material with the strength of forged material and not require extra dampers. Together with a supplier, MTU undertook enormous efforts to develop the producibility of the vanes and to achieve the excellent material properties required. An excellent standard is now available and will go into the JTDP03 engine. This test is a key milestone to validate the design and production process under engine conditions and reduce the risk of introducing MIM vanes into any future production program.

MTU Casing Treatment

The PW6000 compressor has shown outstanding stability margins at part speed and full power conditions, as well as for any transient handling operations. The compressor only has three stages of variable vanes, including the inlet guide vanes, which is less than any other compressors in this class.

MTU has developed a casing treatment that can increase the stability margin at low speed up to 15 percent if applied over the first rotor stages. This additional margin can be used to eliminate one or two stages of variable vanes and still maintain performance over the whole range of operation.

Replacing the wear-sensitive variable systems, by using extremely rugged and durable casing treatments, would give a weight benefit of more than 10 lb and is an essential improvement in maintenance costs. The effectiveness of the MTU casing treatment has been shown on several rig tests and core engine tests. The JTDP03 testing will be the casing treatment’s first test under full power and is suited to investigate its impact on starting and transient engine operation.

TALON X Combustor

As the TALON III combustor was being prepared for the JTDP02 engine demonstration test, aircraft gas turbine engine combustor experts from P&W, academia, and independent consulting organizations met to assess next-step combustor technology direction for P&W low emissions combustors. Technology options were evaluated to achieve additional NOx reduction beyond TALON III. After studying the available advanced RQL data, the external experts concurred with P&W's position that the TALON family had not reached the end of the runway for further NOx emissions reduction, and the TALON X development program was launched. This decision came at a time when P&W had been conducting bench scale rig testing of promising lean direct injection (LDI) approaches. Lean combustion is widely used in industrial gas turbines to achieve low levels of NOx, but is very difficult to extend to aero engines due to the much wider operating envelope (much greater variation in maximum-to-minimum fuel-air ratio), stability and acoustic challenges, and higher cost and weight resulting from increased complexity.

P&W conducted a series of high-pressure sector rig tests in 2003 at the NASA Glenn Research Center's Advanced Subsonic Combustor Rig (ASCR) and in 2004 at the United Technologies Research Center (UTRC) Jet Burner Test Stand (JBTS). Results were very encouraging and indicated that further NOx reductions beyond TALON III were achievable and that TALON technology was capable of meeting NASA's Ultra Efficient Engine Technology (UEET) goal within the bounds of all the other requirements for a commercial engine combustor.

During 2004, additional sector rig testing was conducted that explored various embodiments of the earlier sector rig testing with more realistic geometries. The results confirmed the additional NOx reduction potential and an engine-quality TALON X combustor was designed and fabricated. Initial annular rig testing was completed in January 2005. That configuration is now installed in JTDP03 and is ready for engine validation of the predicted emission reduction.

High-Pressure Turbine

The HPT in the JTDP03 engine incorporates a number of key turbine technologies currently under development at P&W.

In the area of aerodynamics, secondary flow and shock losses have been reduced by using contoured endwalls and leading edges. These features were developed through cascade and rig testing, and have been incorporated in the JTDP03 HPT for engine validation.

Another key aerodynamic technology in the JTDP blade is P&W's patented *tip blowing* for reducing aerodynamic losses due to turbine running tip clearances. The benefits of this system were demonstrated on rig tests. Results from these tests formed the basis for the multi-disciplinary optimization carried out for executing the JTDP design.

In the area of turbine sealing and rim cavity design, the JTDP03 HPT will demonstrate a number of innovative P&W technologies.

A P&W-patented system for capturing parasitic turbine leakage air, recovering the dynamic head of this air through contoured plenum in the rim cavity and then reintroducing this air with increased momentum and at exit swirl that better matches the main flow reduces the overall aerodynamic mixing losses and improves cycle performance by extracting a greater proportion of work from the leakage air.

Platform sealing and damping was a challenge with the contoured endwalls requiring a new and more efficient seal and damper design for the JTDP03. The HPT to be tested in this engine has this improved concept seal and damper design and is estimated to provide reduced platform leakage while meeting the blade damping requirements.

In the area of turbine cooling, JTDP03 will demonstrate the latest P&W-patented cooling technologies in the HPT blade and blade outer airseal (BOAS). Both of these components incorporate a number of P&W-patented cooling and manufacturing technologies developed through supporting static and rotating rigs, as well as prototype casting and machining facilities.

Low-Pressure Turbine

The JTDP03 is very important in supporting the MTU technology roadmap as it is the first vehicle to demonstrate conventional LPT technology in advance of new engine programs.

High-Temperature Outer Airseals

High-temperature outer airseals are important to maintain tight tip clearances on LPT blades over more than 15,000 flight hours. The thin-walled honeycombs need to be properly coated to withstand the corrosive environment in the exhaust stream, but should not damage the thin tip fins when rubbing at transient engine operation.

MTU has developed a new lower cost material for the honeycombs funded by a European program, which will be tested in the JTDP03 demonstrator engine to reach a TRL of 6. A section of this outer airseal is shown in ***Figure 10***.

Advanced Active Clearance Control (ACC)

The tip clearance of LPTs can be matched to the operating conditions by switching cooling air from the LPC through holes on a couple of tubes

Figure 10. *Outer Airseal With Low Cost Honeycombs*

wrapped around the LPT casing. The air impinges onto the casing and shrinks it in cruise conditions to achieve the optimum performance. Conventional ACCs are fairly heavy and increase the outer diameter (OD) of the LPT, which affects fan air passage.

An advanced ACC will be tested for the first time on the JTDP03. The new system is smaller and lighter and uses less air than current systems. This could improve the engine cycles further to the direct impact on the LPT. Apart from the efficiency, durability of the new design principle will be the main focus of the test program.

Mechanical Systems

The JTDP03 mechanical systems high-technology components consist of a No. 2 position low rotor main-shaft bi-directional tapered roller bearing, and a thermoplastic material No. 2 bearing oil nozzle assembly. These mechanical systems components maintain a high degree of design commonality with the existing No. 2 ball bearing and oil nozzle assembly, since the same PW6000 design space and thrust loads were used to design and procure the tapered roller bearing. The oil nozzle assembly is basically the same shape and has the same oil flow requirements as the current aluminum oil nozzle assembly. The only differences are the change to Torlon 7130 thermoplastic material and embedded washer inserts to interface with the oil nozzle assembly retention bolts.

Mechanical systems components have been substantiated and validated by analysis and rig testing, and are deemed ready for the JTDP03 engine test. For the tapered roller bearing, those rig tests included a bearing reverse load and run-in test that simulated engine loads, speeds, oil flows, temperatures, and pressures. For the thermoplastic oil nozzle assembly, the tests included material property verifications, burst pressure tests, proof pressure tests, creep testing, vibration testing, dimensional stability, and oil targeting testing.

The JTDP03 demonstration is considered to be a proof-of-concept demonstration of the tapered roller bearing; therefore, its potential benefit will not be realized since it has not been integrated into the existing PW6000 engine design. In a new centerline engine, significant weight and cost reduction could be achieved since this design eliminates the need for a separate engine thrust balance system.

Thermally Efficient Fuel System

Development of the thermally efficient fuel system began in 2003, and follows a rich tradition of pumping systems development by Hamilton Sundstrand (HS). Future engine and air vehicle trends point toward higher temperature fuel systems that demand thermally efficient pumping solutions. Traditional pumps are sized to cover a specific point in an operating envelope while pumping excess fuel at off-design conditions. This unnecessary pumping introduces heat into the fuel system that complicates air vehicle and engine thermal management strategies. P&W and HS are anticipating a significant system cost reduction and increased fuel system reliability when such a system is incorporated into a future product.

HS developed a unique concept that provides required fuel with no excess energy injected into the fuel. The concept underwent coupon testing in late 2004 followed by design finalization and part procurement. System-level testing was completed earlier in 2005. The system is now installed on the JTDP engine and is ready for validation of the predicted performance.

FUTURE DEMONSTRATOR PLANS

P&W, in cooperation with NASA, is currently designing a ground-test version of a fan-drive geared turbofan. This demonstrator is being funded, in part, by a partnership with NASA under their EVNERT program. P&W is teaming with MTU, Fiat-Avio, and Volvo for parts of the engine and core hardware that will be used for this test. A new low-noise fan, a high-speed low compressor, and the fan-drive gear system (FDGS) will be designed and manufactured to mate with PW6000 core hardware. The resulting engine will demonstrate drastically reduced noise at approximately 35 dB below the ICAO Chapter III standard, reduced NOx at approximately 70 percent less than the CAEP/II standard as a result of the TALON X combustor technology, and enhanced engine performance enabled by the resulting cycle change associated with a geared turbofan high bypass configuration. The engine will feature advanced thermal management and lubrication system configurations integrated like an actual engine application, as opposed to previous testing with special test equipment to mimic parts of the thermal management or lube systems.

Engine testing is scheduled for late 2007 at P&W test facilities in West Palm Beach, Florida. Post-test modification to the ground-test engine will be made to accommodate potential flight testing planned during 2008.

Figure 11 is an artist concept of the EVNERT ground demonstrator engine.

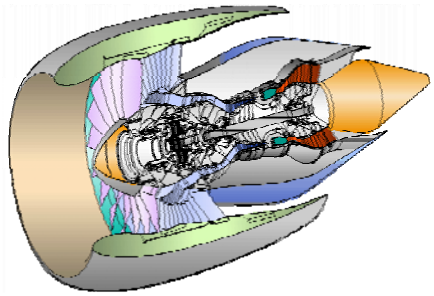

Figure 11. *EVNERT Engine Concept*

SUMMARY

The results of the close working relationship between P&W and MTU have been realized over two very successful builds of the JTDP. Both P&W and MTU expect the third build will be equally successful with even more technology features than in the first two builds. This success has set the stage for continued cooperation in gas turbine technology development in the future. P&W and MTU also believe that such activities significantly reduce the risk of introducing improvements into future engine development programs.

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