NASA/CR—2008-215266

The General Aviation Propulsion (GAP) Program

Williams International
Walled Lake, Michigan

July 2008

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Williams International
Walled Lake, Michigan

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TABLE OF CONTENTS

The General Aviation Propulsion (GAP) Program

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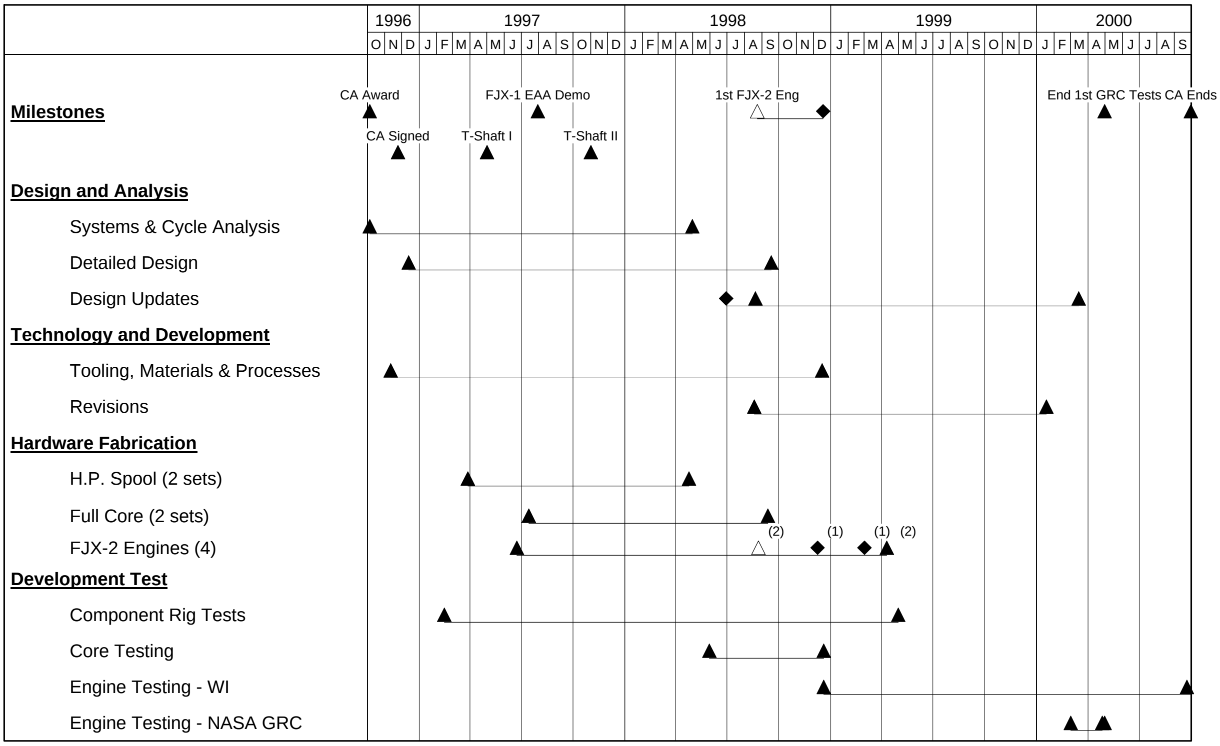
1.0 Program Objectives

The purpose of this Cooperative Agreement was to conduct a shared resource project to develop revolutionary technologies and manufacturing processes for low-cost, environmentally compliant, innovative turbine engine propulsion systems. Such technology would lead to the revitalization of the light (less than 6 seat, less than 5000-lb gross weight, greater than 200-knot design cruise speed) general aviation (GA) industry in the U.S.. The Master Schedule for the GAP Program is shown below.

GAP PROGRAM

FJX-2 Engine Demonstrator - Master Schedule



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The GAP Program Turbine Engine Element was focused on the demonstration of a new small turbofan engine, the FJX-2. This engine was to have a thrust level of at least 700 lbs. (sea level, static, standard day conditions) and to weigh less than 100 lbs. This would result in a thrust to weight ratio exceeding any turbofan engine in production at this time (Figure 1-1). Analysis conducted by Williams International showed that the FJX-2, along with a number of advanced avionics technologies, would allow a new generation of very light turbofan powered airplanes which would have performance comparable to present entry level business jets at acquisition and operational costs comparable to today's twin piston-powered planes. The outstanding thrust/weight characteristics of the FJX-2, coupled with its low fuel consumption, would enable these new GA jet planes to be half the weight of existing entry-level business jets.

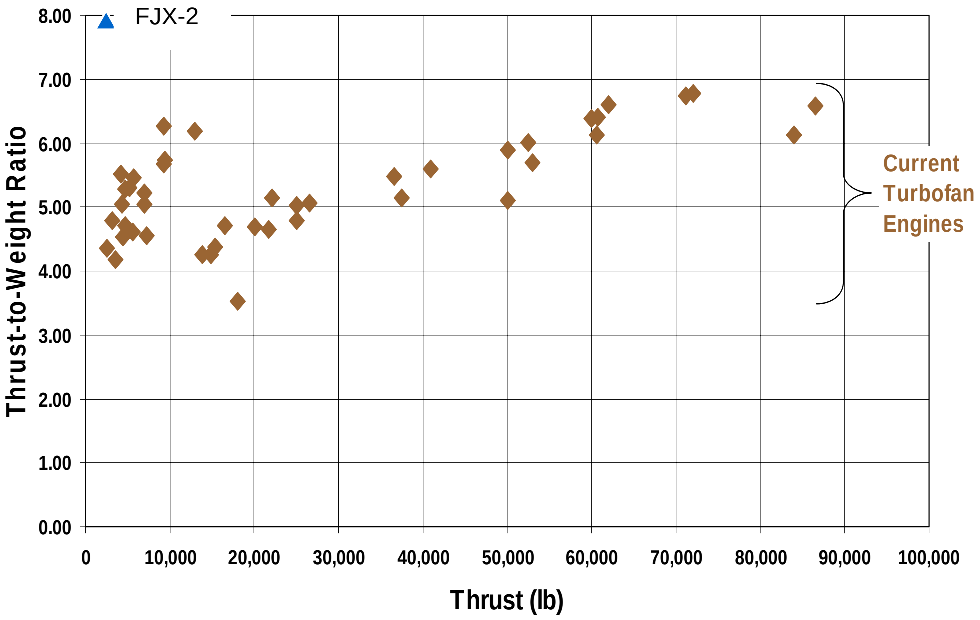


Figure 1-1 Thrust/Weight Ratios

NASA's goal to revitalize general aviation has been quantified as shown in Figure 1-2. For years GA sales had languished at less than 1000 planes annually after having reached over 17,000 planes delivered in the peak year of 1979. The NASA revitalization goal is to increase sales to 10,000 planes/year in 2007 and 20,000 planes/year in 2017.

NASA's investments in the GAP and AGATE (Advanced General Aviation Transport Experiments) Programs were intended to rapidly transition advanced technology into GA airplanes, providing a significant increase in aircraft safety and value, and accelerate GA sales.

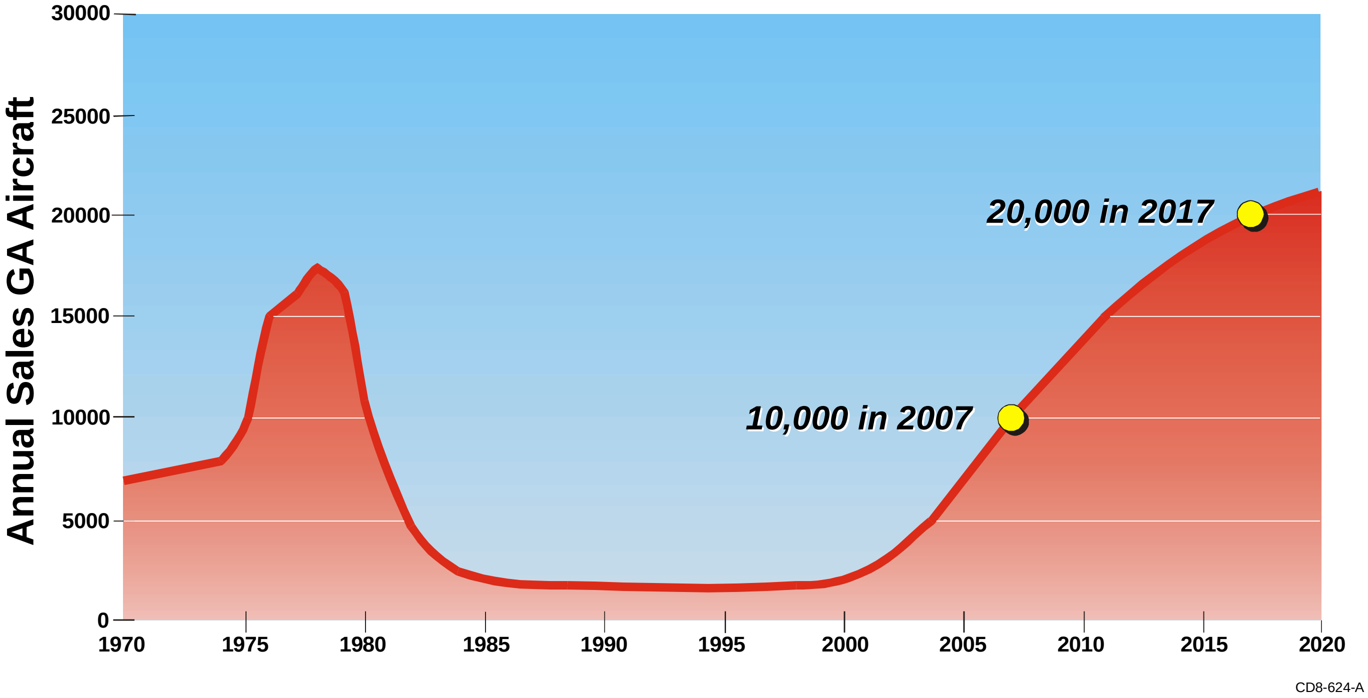


Figure 1-2 GA Annual Sales History

2.0 The FJX-2 Turbofan Engine

The history of powered aviation has shown that new engines enable new classes of airplanes. The focus of the GAP program was to design and demonstrate the FJX-2 turbofan engine combining high thrust/weight, low fuel consumption, and low acquisition/operational costs. The FJX-2 was to also comply with anticipated future noise and emissions requirements.

The detail design of the engine was initiated in the fourth quarter 1996 with rig tests of key components occurring in 1997. The first full engine test occurred in December 1998. Full engine and component tests were conducted throughout the remainder of the program.

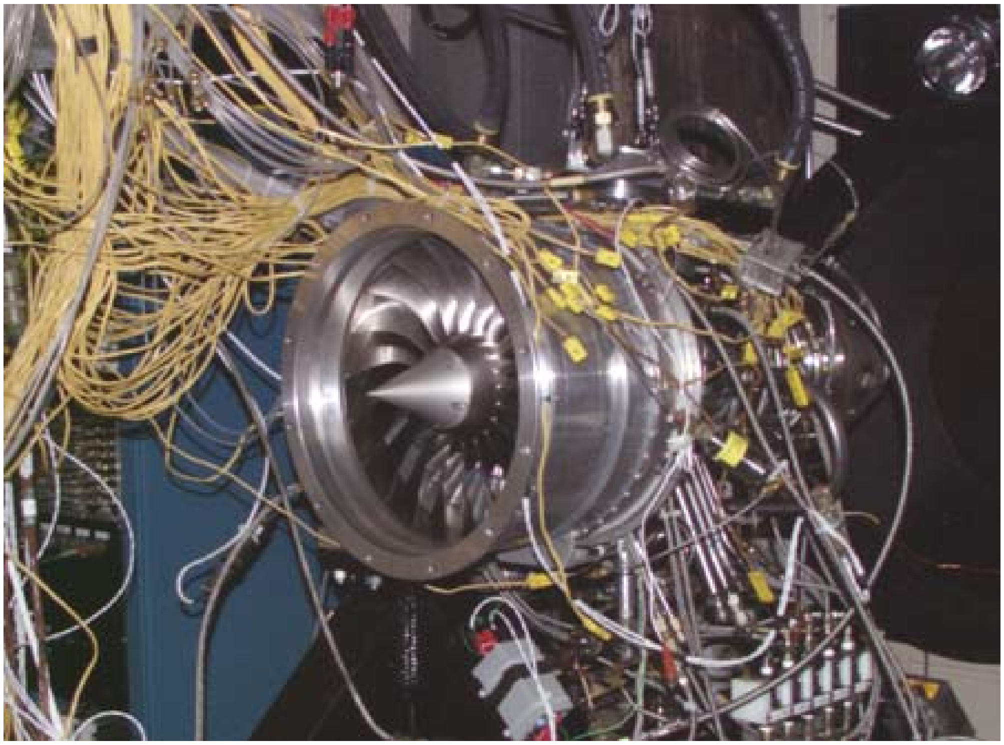


Figure 2-1 The FJX-2 Turbofan Engine Prior to the Initial test Run

The FJX-2 is a multi-shaft turbofan engine with a bypass ratio of 4:1 (Figure 2-1).

2.1 FJX-2 Engine Cross Section Review

The FJX-2 utilizes conventional aerospace materials, and advanced design and manufacturing techniques to produce superior performance in a lightweight, economical design. The FJX-2 engine design incorporated several revolutionary design concepts such as those listed below.

Shrouded Fan Rotor
Low Pressure Fuel System
Electrically Driven Fuel Pump
Blow Down Scavenge Lubrication System
No Engine Mounted Gearbox
High Speed Starter/Alternator

Airflow from the fan is divided into two separate paths. One flow enters the High Pressure (HP) compressor to be further compressed before entering the combustion section, where fuel is added and the fuel/compressed air mixture is ignited. The resultant expanding gases drive the turbines.

The other airflow path bypasses the engine core at a medium bypass ratio. The bypassed air permits the engine to use high cyclic temperatures and pressures in the core and still produce a low jet velocity at the exit. The bypass air and core exhaust flows are mixed, decreasing the velocity and temperature of the exhaust gases, creating high thermal and propulsive efficiency. In addition, the bypass air decreases the noise level and increases the power/weight ratio for a given engine thrust.

The FJX-2 Fan is a forward swept, shrouded rotor, integral blade-disk or blisk design. The fan contains a composite tip shroud wound from Hercules fiber in a matrix, with a titanium triple knife-edge labyrinth seal tip treatment. The Fan is integrally milled from Titanium forged material. The axial positioning of the Fan, the core flow splitter, the core flow stator, and the bypass stator were influenced by analysis to minimize the noise signature of the fan section.

The fan stage static structure is manufactured from Aluminum alloy. The stability during manufacturing of the alloy proved to be essential in the manufacturing of the Intermediate Case. The Intermediate Case incorporates two forward engine mounts, and utilizes a thin-walled, lightweight construction to structurally support the balance of the engine.

In order to aid in compressor development, the FJX-2 compressor design incorporated a variable Inlet Guide Vane (IGV); downstream of the fan core stator This IGV would provide maximum flexibility in rig, core, and full engine testing. As experience with the compressor was gained through this series of tests, the IGV was locked in a static position, and ultimately removed from the design all together.

The nine stages of axial compression are manufactured from a variety of Titanium as operating temperatures increase through the later stages. The rotors are manufactured from individual disk forgings that are Electron Beam welded into multi-stage rotors. Abradable rub strips are positioned between each of the blade rows on the rotor, and between the vane rows on the stator.

The axial compressor vane static structure is manufactured from SST in the intermediate-pressure (IP) section, and in the HP section. These stators are supported by a titanium Interstage Housing, that also supports the forward HP shaft bearing.

The cover and primary plate, which form the radial outflow, annular engine combustion chamber, are manufactured from sheet metal. Cooling to these surfaces is provided by a precise pattern of small diameter laser-drilled effusion cooling holes. The fuel is delivered to the primary combustion zone by way of a circumferentially uniform, slinger fuel distribution system. The fuel is introduced at the front of the HP shaft, and feeds along the length of the inner shaft in a thin film, finally being distributed into the combustor through the slinger that rotates with the HP shaft. The centrifugal force of the fuel exiting the slinger overcomes the compressor discharge pressure (CDP) in the combustor, allowing for lower pressure fuel delivery to the engine than would typically be required. Ignition in the FJX-2 is provided by way of a single spark igniter.

The first turbine rotor is an inserted blade design. The first stage turbine disk is manufactured from a forging, and the second stage disk is manufactured from a forging. Conventional nickel based materials are utilized in manufacturing both stages of turbine blades, CMSX single crystal alloy for the first stage, and Mar-M-247 for the second.

The low-pressure (LP) turbine rotors are high aspect ratio, shrouded blisk designs. The initial rotors were cast. The short chord length of the turbine blades made it difficult to fill the castings with the precision tolerance required to meet component performance goals. Later rotor designs were integrally machined from a forging, allowing for the high tolerance required. The LP Turbine group incorporates a rotating tailcone spinner, greatly reducing the weight and complexity of the engine rear bearing housing support.

The turbine section outer cases are manufactured from forged material. The turbine nozzles for all turbines are segmented designs, manufactured from castings. The two aft bearing housings are supported to the outer case by strods that provide structural support, as well as passage for oil/air services to the bearing housing.

The main shaft bearings utilize both conventional metals and hybrid ceramic materials for the ball and rolling elements. The use of ceramic materials provides for improved life, improved toughness during failure, and improved oil interruption capability over conventional metals. A combination of jetting, and under race lubrication, supplies Mil-L-23699 oil to these bearings. Under race lubrication is more efficient than jetting, and helps to avoid excess oil churning.

An HP Shaft driven high-speed starter/alternator provides three phase, 270-volt electrical power. The alternator rotor utilizes Neodynium/Iron/Boron magnets for optimum efficiency. A Power Conditioning Unit (PCU) transforms the high voltage power to 28 Vdc for aircraft use if desired by the airframer.

The FJX-2 engine did not incorporate a gearbox in its design. An electrically driven fuel pump provides fuel to the engine at pressures significantly lower than in conventional systems. The use of a rotating slinger to distribute fuel to the combustion chamber allows for this lower fuel delivery pressure. A schematic of the fuel system is shown in Figure 2-3.

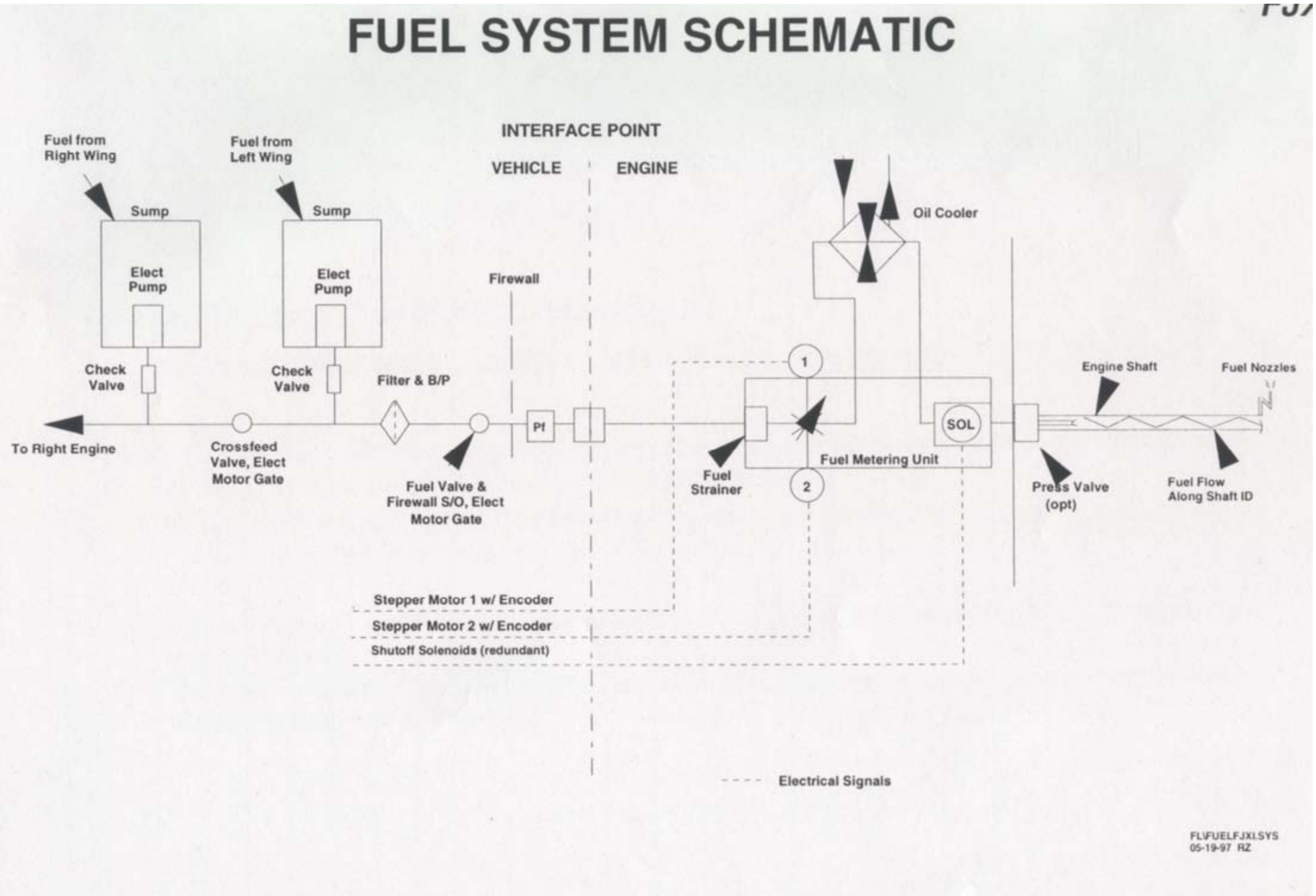


Figure 2-3 – FJX-2 Fuel System Schematic

A Fuel Metering Unit (FMU) controls the rate of fuel flow to the engine. The FMU utilizes a dual wound Stepper Motor with position encoder to locate a cam with respect to a metering orifice. Also incorporated into the FMU is a normally open Fuel Shutoff Valve (FSOV), which is energized during normal shutdown, or at times of overspeed detection. The dual wound stepper motor provides system redundancy for improved safety.

The FJX-2 lubrication system consisted of an electrically driven lubrication pump, containing supply as well as scavenge elements. In addition to pump scavenge, pressurized ‘blow-down’ scavenge is utilized for some bearing cavities. The oil tank for the engine is integral to the Intermediate Case. Less than a quart of usable oil is required to meet General Aviation type mission requirements.

2.2 FJX-2 Engine Detailed Design

Williams International has a long history of innovation in the area of gas turbines. Williams is recognized as a world leader in the advancement of small gas turbine engine technology. Prior to the FJX-2, the best existing small turbofan engine was the Williams FJX-1, which powered both the Williams V-Jet II GAP demonstration aircraft, and the Chichester-Miles Leopard II aircraft during their flight trials. The fuel consumption and cost of this engine, however, did not make it an attractive solution to the needs of the GA industry. The FJX-2 turbofan was designed from the ground up to be the low cost answer. In 1993, Williams International applied its expertise in turbine miniaturization, engine cycle analysis, advanced component and manufacturing technologies to initiate the design of what would become the FJX-2 Turbofan. By the outset of the GAP Program, the FJX-2 was ready for detailed design.

2.2.1 Design Tools

Williams International utilized a large array of analytical tools in the Detailed Design Phase for the FJX-2 Turbofan. The integrated engine design sequence is flowcharted in Figure 2-4.

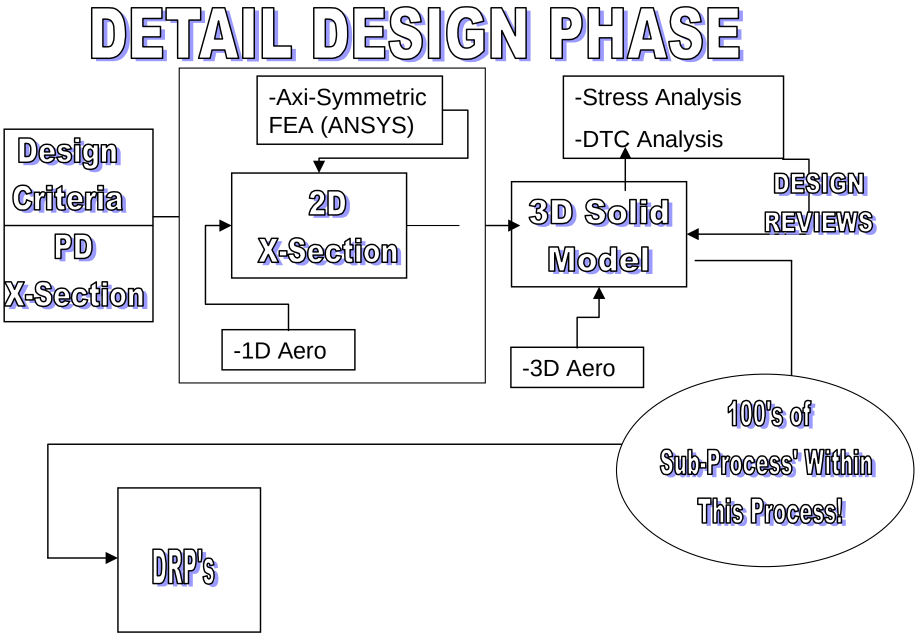


Figure 2-4 Integrated Engine Design Sequence

The Detailed Design Process was initiated from a Preliminary Design (PD) of the FJX-2 that satisfied Design Criterion based on a General Aviation application. The engine design is matured from a 2-dimensional cross section, to a complete 3-dimensional model. Williams utilizes Pro-Engineer for all solid model generation. A complete 3-D model of all components allows for assembly fits and interference to be totally evaluated as part of the layout phase of design.

Pro-Engineer provides a ready interface for structural analysis. Two codes are utilized for stress and heat transfer, providing integrated model evaluations under transient as well as static environments. Transient analysis of engine start-up, maximum compressor discharge temperature (CDT) operation, and engine shut down, supports material selection and disk sizing to meet cycle design life goals. The hot sections of the engine were designed with an operating life consistent with commercial engine duty cycles.

Structural and aerodynamic design are completed concurrently, with design trades continuously being made to satisfy structural requirements while optimizing aerodynamic performance. Compressor preliminary aerodynamic design is initiated utilizing a Williams in-house design code called SLC. Once basic design characteristics are insured, axi-symmetric analysis and blade generation is completed through the use of a modified version of the Air Force design code. Williams also utilizes an in-house design code called CASQ-3D for preliminary airfoil analysis. The design is matured through the use of the APNASA code, available from NASA, providing multi-stage compressor performance evaluation. The multi-stage capability of APNASA is a major step forward over the previously available Dawes single blade row analysis.

Accurate prediction of compressor performance across the entire operating range requires comprehensive compressor mapping. Prior to actual rig testing, analytically generated compressor maps are utilized to build predicted engine performance computer model or decks. In order to produce these maps, Williams generated an in-house code, OFFDES. This code made it possible to more easily create separable maps for the multi-stage axial compressors utilized in the FJX-2 design.

Aerodynamic design of flow through ducting such as inlets, interstage housings, combustors, and exhaust nozzles were completed through the use of CFD code. This code has developed sufficient fidelity to utilize it to predict the characteristics and mixing of the engine bypass and core flows. Use of CFD allowed this interaction to be incorporated into the design of the exhaust nozzle. NASA Glenn Research Center conducted a parallel combustor analysis effort utilizing ALLSPD/KIVA-II flow code supporting the combustor design.

The initial design of the FJX-2 turbine components was completed through the use of a commercially available CFD code called TASCFLOW. Efforts were also expended to attempt to use the compressor design tool APNASA for turbine component design with limited success. As will be indicated in later sections of the report, a shortfall in HP turbine performance prompted Williams to develop an in-house CFD code called WILLFLOW. WILLFLOW uncovered an unfavorable flow condition for the HP Turbine blade, and allowed for evaluation of multiple design iterations resulting in correction of the problem.

The secondary airflow system of the FJX-2 provides the necessary buffer air to all bearing compartments, as well as airflow necessary for component cooling. The entire engine system is evaluated by constructing flow network models using a Williams in-house design code called FINESSE. This analysis is critical to the evaluation of bearing thrust load, as well as evaluation of seal failure scenarios that need consideration during the design process.

Engine and component shaft first bend and rigid body modes are evaluated through the use of an FEM design code. IGES translated Pro-Engineer models, along with rotor mass properties, and beam stiffness evaluations of shaft structure are used to construct design models. Throughout its use in the FJX-2 and other engine development programs, this code has proven to be very reliable in the prediction of shaft modes. It also provides ability to evaluate bearing mounting stiffness impact on shaft dynamics, which is very beneficial in the assessment of shaft vibration.

All bearing and gear designs are influenced by multiple design codes. Rolling element bearing design is evaluated through the use of a TK Solver application of ABODE (Advanced Bearing Optimization Design and Evaluation), the Jones High Speed Ball and Radial Roller Bearing Analysis Program, the Shaberth Shaft Bearing Thermal Analysis Program, and ADORE (Advanced Dynamics of Rolling Elements) Program. Use of ABODE dramatically improved design productivity and optimized bearings designs. It allows for trade studies utilizing multiple ball and cylindrical roller bearings, at low speed, high speed, and high speed with implementation of raceway control theory.

Williams utilizes an in-house TK solver application based on AGMA design methodology for all gear design efforts. In addition, Williams also utilizes DANST (Dynamic Analysis of Spur Gear Transmissions), available from NASA. DANST is utilized for the optimization of gear tooth profiling, the minimization of dynamic loads and stresses, and the reduction of noise and vibrations.

Williams International and NASA Glenn Research Center engineers utilized two parallel approaches in evaluating the noise signature of the FJX-2. Williams utilized NASA provided semi-empirical noise prediction code NASANOISE in evaluation of the FJX-2. The code is typically utilized for propeller driven GA aircraft and small business jets, and is capable of evaluating noise levels at FAA FAR 36 certification conditions for takeoff, approach, sideline, and level flyover. NASA Glenn utilized upgraded versions of NASANOISE, specifically ‘Footpr’ and ‘Radius’ to conduct an independent assessment. Results of these evaluations will be reported in later sections of this report.

2.3 Turning Design into Reality

Achieving large engine performance in a very small size was one of the greatest challenges of the FJX-2 design, but this is a challenge that Williams International has successfully met in the past. The FJX-1 turbofan was similar in cycle to the large two-spool turbofans of its day, but it was much smaller and much simpler. To maintain the efficiencies of large engines when scaled down to such a small size, all features including clearances, tolerances, and surface finishes must also be scaled down. The design requirements for the HP Compressor to achieve performance are roughly two times as fine as those typically held on currently produced engines.

To address these challenges Williams International utilizes a fully integrated design approach within our engineering Component Process Teams. Each of Williams Component Process Teams contains all engineering disciplines required to insure that all component designs meet or exceed the design requirements for performance, weight, and cost.

Williams International enhanced the design process for the FJX-2 by the formation of a "Contractor-led Product Team" (CPT) to aid in executing the GAP Cooperative Agreement. This team included Boeing Helicopter, Cessna Aircraft, Chichester-Miles Consultants, Cirrus Design, Forged Metals, Lancair, New Piper, and VisionAire. Williams International met individually with CPT members, and jointly with NASA and

CPT members to determine the desired characteristics of the FJX-2 and TSX-2 (Turboprop version of the FJX-2) as well as identifying engine installation issues. The CPT also reviewed the market prospects of the FJX-2 and its shaft power derivatives, concluding that these engines could provide the incentive to launch a new generation of GA aircraft.

Williams and NASA also initiated conversations with the Federal Aviation Administration (FAA) at a very early stage of the design process. The design of the FJX-2 turbofan considered many revolutionary concepts to meet the aggressive design goals for the engine. This ongoing dialog with the FAA insured that all features of the FJX-2 design could be certified, or identified those areas were special exceptions may be required.

One of the struggles continuously facing the Process Team is the need to actually manufacture the hardware imagined by the designers on their computer screen. The thin walls and contoured shapes required to minimize weight, optimize performance, and satisfy structural requirements are often a challenge to manufacture.

Throughout its history, Williams international has been an innovator in working with machine tool manufactures to advance machining technologies. Machine advancements made over recent years have made it possible to manufacture the FJX-2 within its weight and cost targets. Williams International’s manufacturing engineers canvassed the industry to find the machining technology required to accurately remove material to the exacting tolerances required for the FJX-2. Examples of this advanced technology will be indicated in the following sections. Their efforts resulted in an FJX-2 design that weighed in at 96-lb as tested at the PSL altitude facility.

3.0 FJX-2 Engine Hardware Development

Throughout the design of the FJX-2, Williams International designers conducted extensive trade studies to optimize the engine design with respect to fuel economy, weight, cost, life and design simplicity. Any further improvement in fuel economy would be insignificant compared to the added weight, cost, and complexity of additional stages, and the reduced life or increased cost associated with higher temperatures.

Validations of these design efforts were accomplished by utilizing component rigs, core engine, and full engine. The program was structured to take a conservative approach in evaluating the capability of the FJX-2, a new engine, designed from the center-line out to be a major player in the revitalization of the General Aviation industry. Engine testing was structured to initially study all aspects of the engine performance at low speeds, attempting to fully understand the engine characteristics prior to moving upward in speed.

3.1 Component Testing

Development of the FJX-2 Turbofan engine began with component testing initiated in the third quarter of 1997. Component rigs were constructed for the Fan and the balance of the FJX-2 compressor section, the combustor, and the high-speed starter/alternator. Rig testing of these components documented efficiencies early in the development phase, prior to core and full engine testing. Verification, and in one case the validation of shortcomings, in design tools was a critical step in meeting the aggressive performance goals for the FJX-2 engine. With reliable design tools in place, modifications based on rig test results could be incorporated rapidly and with confidence.

3.1.1 HP Compressor Testing

Verification of compressor performance is best accomplished on a rig that provides for full variability of pressure ratios, shaft speeds, and the ability to incorporate high levels of steady state as well as transient instrumentation. This approach was utilized in the evaluation of the entire compressor section for the FJX-2 turbofan engine.

The heart of the FJX-2 engine is the HP compressor shown in Figure 3-1. This design was the culmination of extensive cooperation between NASA Glenn Research Center (GRC) and Williams International aerodynamicists utilizing the latest advancements in 3-D viscous flow analysis tools. The availability of NASA’s APNASA CFD code, data from compressor rig testing, and the expertise of NASA and Williams personnel was invaluable in the advancement of the compressor design. This collaborative effort between NASA and Williams resulted in a compressor that exhibited an adiabatic efficiency of 85%, the most efficient component of its size ever designed.

Figure 3-1 High Pressure Compressor Rotor

The component efficiency was achieved without the use of extreme tip speeds, extreme radius ratios, or variable geometry. Advanced finite element analysis was used to optimize the rotor bores for the lowest weight necessary to achieve design life.

A typical test arrangement for the FJX-2 compressor rigs is shown in Figure 3-2. The fan and compressor components were tested over their entire design speed range. Component operating line and stall margin was fully mapped.

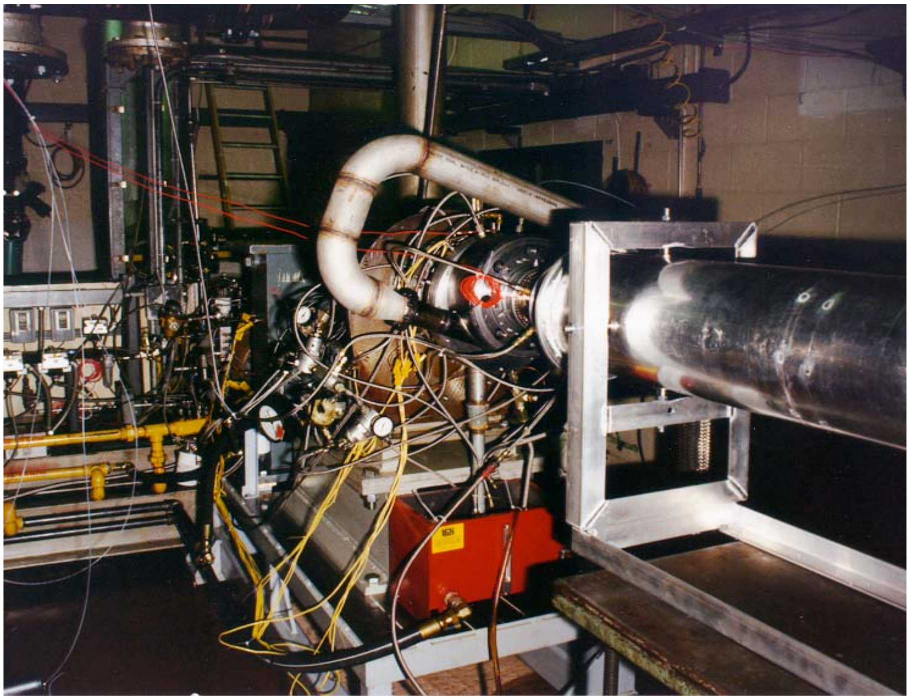


Figure 3–2 FJX-2 Compression Rig

The initial HP Compressor rotor and stator hardware manufactured to support component rig testing were found to be low in airflow and efficiency. A visual inspection of this hardware under magnification revealed the reason for the shortfall in performance.

The initial hardware tested in the HP Compressor Rig was manufactured on commercially available 5-axis milling machines. Such machines are totally acceptable for most engine hardware fabrication, but found to be inadequate for the increased accuracy required of the FJX-2 fabrication. This hardware lacked the surface contouring required for optimum performance. The rig test results reinforced the need for tighter machining tolerances on FJX hardware compared to typical engine requirements.

In order to achieve the machining tolerances required to properly manufacture this hardware, Williams International designed and manufactured a miniaturized five-axis milling machine. This machine was optimized for smaller rotating and static components such as those found on the FJX-2. It optimized spindle speed, machine head translation rates, data processing, and position feedback to obtain the high levels of accuracy required for the FJX-2 components.

The original stator hardware tested in the HP Compressor rig was replaced with the greatly improved hardware shown in Figure 3, and speed line calibrations were rerun. This new hardware showed significant improvement over the initial test. This data was adjusted for Reynolds number affects, accounting for the testing conducted at prevailing ambient conditions with inlet suppression. These corrections amounted to an adjustment of airflow by +1.2% and of efficiency by +1.4%.

Concurrent with the FJX-2 development program, innovation in the area of CFD analysis was occurring at a rapid pace. Most notable, and of greatest benefit to the GAP Program, were the contributions of the analysis team at NASA Glenn Research Center (GRC), with their APNASA design analysis code. The NASA GRC team worked extensively with Williams International's aerodynamicists to refine the compressor design, optimizing component performance. Modifications introduced as a result of this analysis were validated in follow-on rig tests conducted during, and after the completion of the GAP Program.

The cooperative effort of the NASA – Williams team resulted in an improved meshing capability with the APNASA code. The ability to compare actual test results against the model predictions proved a valuable tool in the design process. This analysis resulted in the ability to more accurately represent reality with regard to the fillet radius of the blade and vane designs. It was found that stage matching between the forward and aft stages of the compressor was critical to optimizing performance. The ability of Williams Compressor Team to generate more accurate stage maps, through the use of the in-house design code OFFDES, allowed for more accurate modeling of the bleed flow between stages 2 and 3 of the HP Compressor. Throughout the series of design iterations, NASA Glenn personnel continuously implemented programming improvements to the APNASA Code, allowing for more rapid processing of individual design iterations.

3.1.2 Combustor Rig Testing

Two test facilities were used in evaluation and development of the FJX-2 combustor design. The initial testing was performed in a vacuum facility, and was structured to study ignition capability of the combustor design under a wide range of altitude and temperature conditions. The rig incorporated the entire engine fuel delivery system, as well as the proper aerodynamics for air delivery to the combustor.

The vacuum testing concentrated on the evaluation of light-off characteristics of the combustor. Testing was conducted across a wide range of anticipated conditions including variations in start fuel flow, altitude, ambient temperature, and igniter configuration and output energy. A wide variety of ignitor configurations ranging from conventional spark ignition to glow plug technology were evaluated in order to determine the most reliable design for use in the FJX-2. Primary zone mixing and recirculation were adjusted to produce light-off characteristics that were predictable and reliable, and would support core and full engine testing.

Igniter testing demonstrated that currently available off the shelf glow plug technology was not well suited to the fuel delivery and annular design of the combustor utilized in the FJX-2. Testing showed the glow plug life in the combustor environment of the FJX-2 to be of short duration, certainly unacceptable for a GA engine.

The second rig facility utilized pressurized, heated air to better evaluate the combustor performance at pressure and temperature levels experienced by the engine at power settings above idle. This rig installation is shown on Figure 3-3.
The pressurized rig completed testing over a wide range of pressure and temperature.

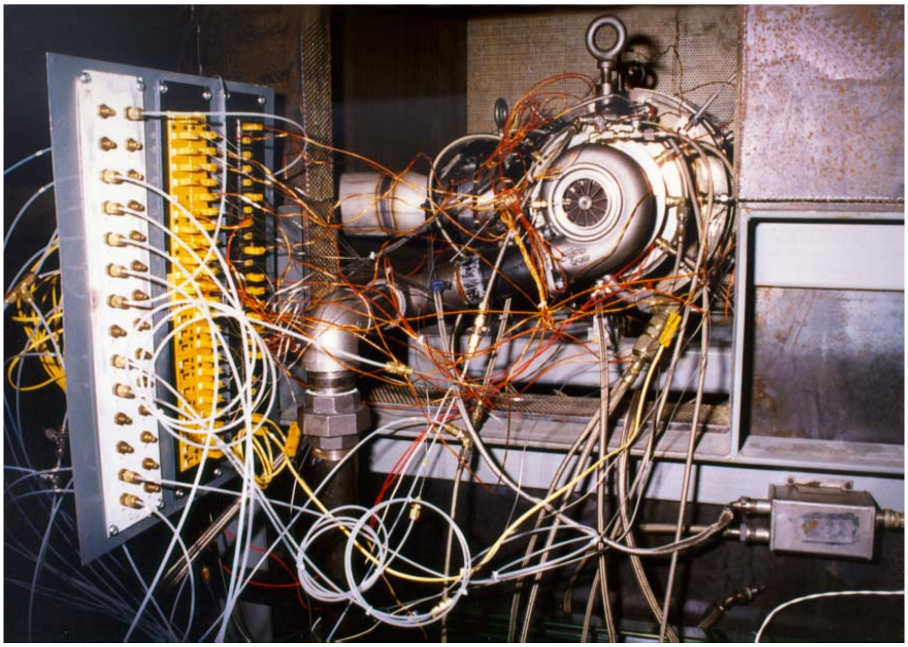


Figure 3-3 FJX-2 Combustor High Pressure Rig

Combustor modifications incorporated throughout the testing resulted in the combustor design exhibiting increased heat release and improving radial profile. These modifications were accomplished through the use of CFD modeling to make a detailed assessment of recirculation, fuel mixing, and thermal distribution. Testing indicated that the annulus velocities exiting the diffuser were too high to allow for proper filling of the primary air jets in the OD of the combustor cover. Test hardware modifications included the additions of air dams to the OD of the cover to better direct the airflow into the primary jets. These air dams provided a means of testing with the existing diffuser hardware. Design changes would be made to the diffuser to lower the exit velocity, allowing for the removal of the air dams on future hardware configurations.

The pressurized rig was limited in its ability to operate over long periods of time, and could not provide insight into the durability of the design. This durability would be demonstrated once the hardware was transitioned into core engine testing. The success experienced in both the ignition and high pressure combustor rigs greatly reduced the risk for the follow-on core and full engine testing.

3.2 Core Engine Testing

Following the completion of individual component testing, the core of the FJX-2 engine (full engine less Fan and Low Pressure Turbines) was assembled and tested. In addition to evaluating overall performance, this testing focused on evaluating lubrication system performance, secondary flow system performance, and shaft dynamics. Heated inlet air, along with a means of varying turbine exit area, was used to exercise the core over the maximum range possible of mechanical and corrected speeds.

The Core Engine accumulated a total of 5:55 hours and 48 starts during its test program. Testing of the engine Core was extremely beneficial in evaluating the secondary flow system of the engine, and it’s impact on the engine lubrication system. This Core testing demonstrated over 93% of maximum mechanical shaft speed, and over 98% of maximum inter-turbine temperature (ITT).

The use of inlet heating allowed for testing of the turbine section to 95.5% of the turbine design point. The HP turbine efficiency was measured at 80.7%, or 6 points in efficiency below the design target. Of those 6 points, excessive radial tip clearance, and a nozzle that was 7.4% over design flow could account for 2.9. Component operating conditions realized in the core versus a full engine accounted for 1.5 points slip in efficiency due to low Reynolds numbers.

An extensive review of test data versus design goals was conducted to determine the source of the 1.6 point lost in turbine efficiency. Concurrent with this investigation, Williams Expansion Team was creating a new in-house CFD code called WILLFLOW. The original HP turbine design was completed using a commercially available CFD code called TASCFLOW. Analysis of the tested turbine design, with the newly created WILLFLOW CFD code, revealed that the blade design contained a flaw at the blade tip, resulting in the formation of a shock wave, and the creation of a reverse flow field.

The turbine blade configuration was redesigned using the WILLFLOW CFD code to correct the reverse flow condition noted at the blade tip. The flow field produced by the new turbine design predicting a smooth transition of flow downstream through the turbine. This new blade design was initiated into manufacturing, and was incorporated into test during the full engine test program. A comparison of the efficiency for these two designs was accomplished.

3.3 Full Engine Testing

Following the completion of the core engine test program, the Fan Module and Low Pressure Turbine Module were married with the core engine in preparation for the first Full Engine run of the FJX-2 Turbofan. This initial run was completed at the end of December 1998. Figure 3-4 shows the engine installed in the test cell, just prior to the historic run.

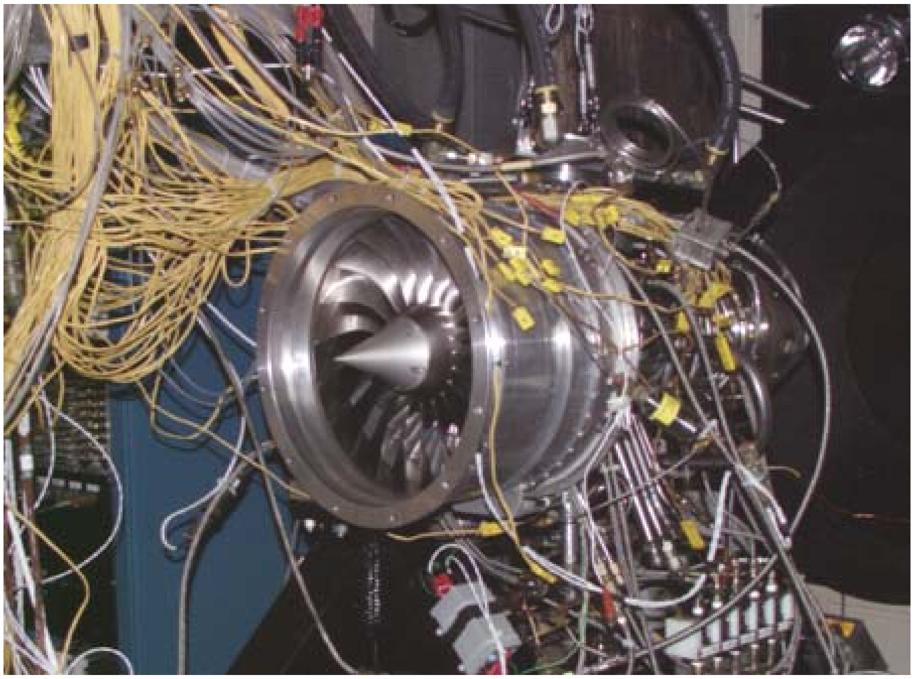


Figure 3-4 FJX-2 Prior to First Full Engine Run

Like the core engine, the investigation of the lubrication system and secondary flows took center stage in the initial, full engine test program. In addition, the engine start and fuel control systems, along with an investigation of overall performance were also conducted. Hardware builds were also dedicated to the evaluation of engine hardware durability.

Four FJX-2 engines (S/N 001 – 004) were used to complete the full engine test program. These four engines accumulated a total run time of 537:21 hours, with 896 starts during the period of the GAP Program, which completed in May 2001. Below are a summary of all engine builds runtime history, and a synopsis of test objectives and results.

FJX-2 Engine Test Summary

Engine S/N	Build	T Hours	T Starts	Start Date	Completion Date	Test Objectives - Notes
Engine 001Totals	1-3	3.42	109	18 Dec 1998	29 April 1999	**Objectives:** Initial FJX-2 Full Engine Build – Mechanical/Performance Checks, Starter/Alternator, Engine Starter/ Regulator (ESR) Development, secondary flow, and air turbine starter
Test Results: Establishment of control gains required for proper engine acceleration to idle. It was determined that the ESR interface to the Starter/Alternator required further development to raise voltage/current trip limits. **Test Result Impacts:** Design and fabricate an air turbine starter which would be utilized throughout the balance of the development program. Incorporate design changes to the HP shaft inner sleeve seal and IPC flashlight seal to eliminate SEAL , Modified HP Fwd Bearing squirt, HPT nozzle and blades.						
002	1-2	2.13	26	19 May 1999	15 June 1999	**Objectives:** Evaluate Lubrication system, secondary flow, HP Turbine performance.
Test Results: Shaft rub to the Fwd HP Bearing Laby seal noted during testing **Test Result Impacts:** Redesign the Fwd HP Bearing Laby seal to a carbon seal design						

<table>
<tr><th>Engine S/N</th><th>Build</th><th>T Hours</th><th>T Starts</th><th>Start Date</th><th>Completion Date</th><th>Test Objectives - Notes</th></tr>
<tr><td>002</td><td>3</td><td>8.52</td><td>34</td><td>23 July 1999</td><td>3 August 1999</td><td>Objectives: Evaluate carbon seals around HP Fwd Bearing cavity</td></tr>
<tr><td colspan="7">Test Results: Highest individual build hours to date. Noted excessive oil outside of #1 bearing cavity.
Test Result Impacts: Incorporate carbon seal design forward of the #1 bearing cavity</td></tr>
<tr><td>002</td><td>4</td><td>1.22</td><td>9</td><td>17 August 1999</td><td>18 August 1999</td><td>Objectives: Evaluate carbon seals forward of #1 Bearing cavity</td></tr>
<tr><td colspan="7">Test Results: Oil management in #1 bearing cavity improved. Turbine performance below requirements.
Test Result Impacts: Extensive inspection of 2nd stage Turbine blades and nozzle profiles lead to closing 2nd stage turbine blades 2 degrees to correct engine speed match.</td></tr>
<tr><td>002</td><td>5-7</td><td>59.69</td><td>175</td><td>28 August 1999</td><td>15 Jan 2000</td><td>Objective: Evaluate 2nd stage turbine closure by 2 degrees. Evaluate non-segmented turbine nozzles to determine leakage impact of segmented design. Evaluation Variable IGV .</td></tr>
<tr><td colspan="7">Test Results: Non-segmented nozzles showed some speed match impact, but little change to Inter Turbine Temperature (ITT).
Test Result Impacts: IGV not likely required in future engine designs.
Defined optimum turbine nozzle combinations.</td></tr>
<tr><td>002</td><td>8-9</td><td>53.22</td><td>114</td><td>9 March 2000</td><td>15 July 2000</td><td>Objectives: TSX Turboprop Gearbox configuration testing with McCauley Propeller</td></tr>
</table>

Engine S/N	Build	T Hours	T Starts	Start Date	Completion Date	Test Objectives - Notes
Test Results: Demonstrated TSX gearbox operability with regard to geartrain and lubrications systems. Demonstrated powerhead operability with the gearbox, and propeller combination. Single build runtime record to date. **Test Result Impacts:** Demonstrations to perspective Turboprop airframers that the TSX was a viable power system for future Turboprop airframes.						
Engine 002 Totals		124.78	358			
003	1 - 2	0.78	14	12 Oct 1999	16 Nov 1999	**Objectives**: initial build of new hardware set, Improve oil system performance
Test Results: Waterfall plots of vibration data indicated 0.84E excitation of the HP shaft. **Test Result Impacts:** Internal oil leakage resulting in collection of oil in the compressor drum, implement weep holes in the rotor to provide drainage during operation Initiate investigation of alternative abradable materials as well as vane and blade tip treatments.						
Engine S/N	**Build**	**T Hours**	**T Starts**	**Start Date**	**Completion Date**	**Test Objectives - Notes**
003	3 - 4	11.71	64	20 Dec 1999	17 Jan 2000	**Objectives:** Continue oil system evaluations and mechanical checkouts. Evaluate machined LP turbines
Test Results: Refined understanding of engine oil/secondary flow systems. Documented impact of fully machined vs. cast LP turbine rotors.						
003	5	4.27	21	11 Feb 2000	16 Feb 2000	**Objectives:** Performance evaluations

						and NASA control system checkouts in preparation for altitude testing
003	6-8	54.2	81	22 Feb 2000	27 April 2000	**Objective:** Altitude Testing at NASA Glenn PSL facility - Cleveland
Test Results: See Altitude Test Summary in this report						
003	9	7.17	31	9 July 2000	30 August 2000	**Objective:** Post Altitude test performance evaluations – compressor tip clearance studies
Engine S/N	**Build**	**T Hours**	**T Starts**	**Start Date**	**Completion Date**	**Test Objectives - Notes**
003	10	2.53	19	3 Nov 2000	17 Nov 2000	**Objectives:** Evaluate reduced squeeze film support to #2 bearing
003	11 - 13	321.55	167	8 Jan 2001	16 April 2001	**Objectives:** Engine Durability
Test Results: The engine successfully completed three (3) 100-hour endurance cycles demonstrating the increasing maturity of the FJX-2 development engine design						
Engine 003 Totals		402.21	397			
004	1 - 2	6.94	32	19 Jan 2000	18 March 2000	**Objectives:** initial build of new hardware set

<table>
<tr><td colspan="7">Test Results: The 3rd stage compressor blades failed at the roots. Failure was attributed to a 6E downstream excitation source and engine operation within the interference speed range.
Hardware requirements for engine S/N 003 to support altitude testing forced the retirement of S/N 004 following the initiation of flight cycle testing.
Test Result Impacts: Short-term corrective action clipped the blade tips to move the 1st mode frequency out of the run range.
Long term corrective action - initiate a blade redesign to move the 1st mode out of the run range and maintain performance and stall margin.</td></tr>
<tr><td>Engine 004 Totals</td><td></td><td>6.94</td><td>32</td><td></td><td></td><td></td></tr>
<tr><td>FJX-2 Totals</td><td></td><td>537.35</td><td>896</td><td></td><td></td><td></td></tr>
</table>

Like any new engine design, the FJX-2 did encounter growing pains as exhibited in the test summary. Design changes were incorporated as required to bring the engine operability and performance to the desired levels. Other than the incidents of seal rub noted in the test summary, the vibration performance of the FJX-2 was outstanding from the outset of testing, with vibration levels so low as to produce a very comfortable environment within an aircraft cabin.

The test summary indicates design modifications made to replace labyrinth seals with carbon seals forward of the No. 1 Bearing cavity. These changes resulted in a reduction in oil loss from the cavity. It has been previously noted that the FJX-2 lubrication system utilizes blow-down scavenge for some of it’s bearing cavities. The test program highlighted the need to maintain proper pressure control on both sides of the seals that retain oil within the various bearing cavities. The secondary flow system of the FJX-2 was designed to maintain very small delta pressures across all of the bearing cavity seals, maintaining oil containment, and minimizing leakage that would reduce engine performance.

One element of the fuel delivery design that exhibited difficulties during sea level and altitude testing was the HP shaft fed fuel delivery system. As described in Section 2.1, the fuel is introduced at the front of the HP shaft between walls held concentric by supporting cross-struts. The fuel feeds along the length of the inner shaft in a thin film, finally being distributed into the combustor through the slinger that rotates with the HP shaft. Engine testing showed that at higher shaft speeds it was difficult for all of the fuel introduced at the end of the shaft to pass through the rotating cross struts, limiting the fuel that could be delivered to the combustor. Modifications made to the cross-strut design helped to reduce this blockage, allowing operation at higher shaft speeds.

The durability of the FJX design was demonstrated through the completion of the three (3) 100-hour endurance cycles by engine S/N 003. Each 100-hour cycle was completed on a single build of the engine hardware. Engine performance was maintained throughout the endurance completed on build 12, and little change noted from the beginning, to the end of the second 100-hour endurance cycle on build 13.

3.3.1 700-lb Thrust Demonstration Run

The culmination of the test program was the sea level static demonstration of over 700-lb. thrust completed in March of 2001 at Williams International's Walled Lake test facility. This test confirmed the ability of the hardware design to satisfy the program goals with regard to engine produced thrust. Plots of Corrected LP Shaft Speed vs. Corrected Thrust and Corrected HP Shaft Speed vs. Corrected ITT, for this performance calibration were made and compared.

The test article for this demonstration was a follow-on engine to the four FJX-2 engines utilized throughout the Development Program. Engine S/N 111 was built in support of the FJ22, the first productionized version of the FJX-2 turbofan engine. More detail on the commercialization of the FJX-2 will be included in later sections.

The engine utilized in the thrust demonstration run weighed in at 96-lb, demonstrating a thrust-to-weight ratio of 7.52.

3.3.2 Altitude Testing - NASA Glenn Propulsion Systems Laboratory (PSL)

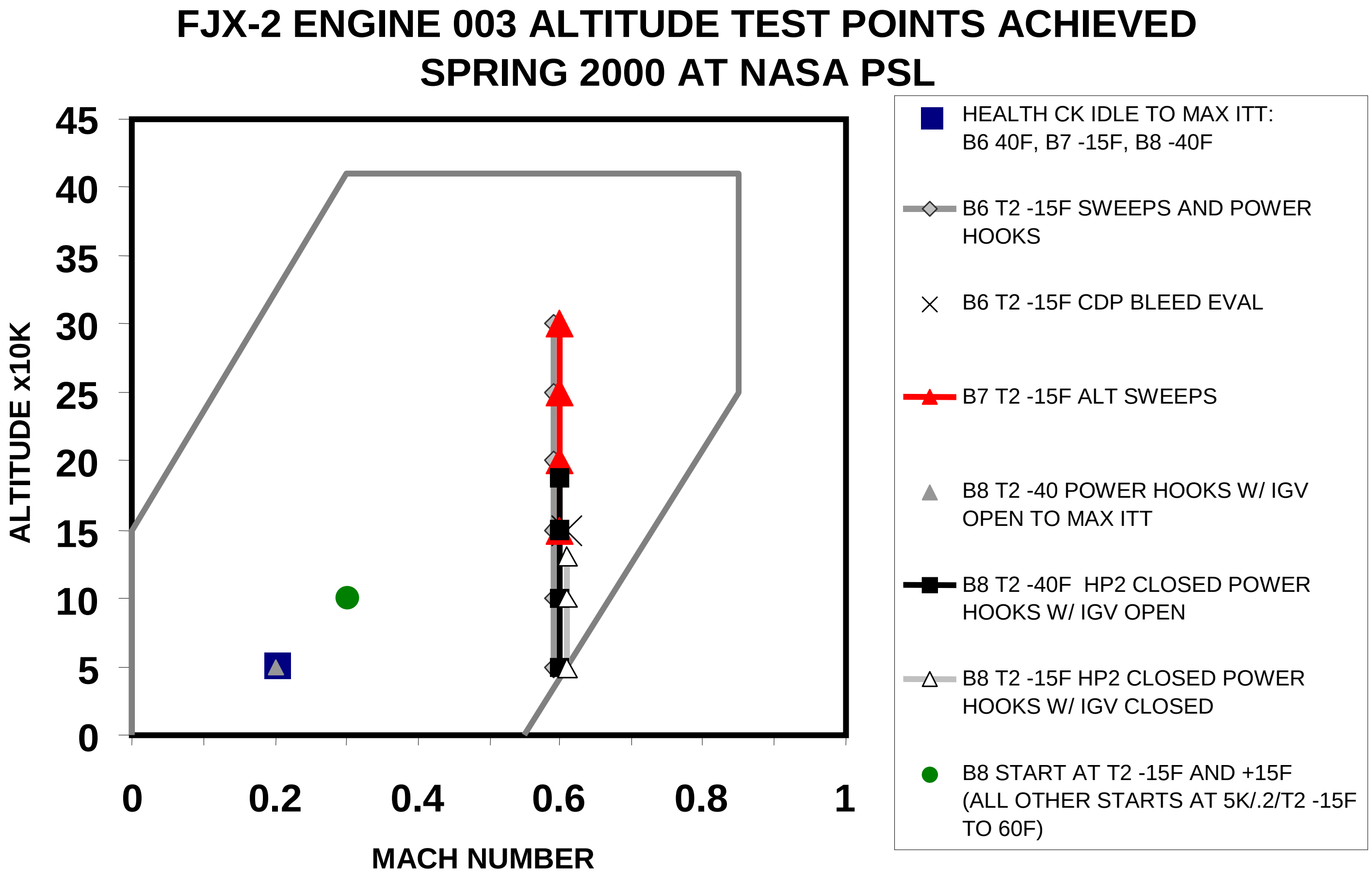
An essential portion of the FJX-2 engine test program was the completion of altitude testing in the Propulsion Systems Laboratory (PSL) facility at GRC. This testing was completed in March to April of 2000.

Testing in an altitude facility allows for engine operation at higher corrected shaft speed, higher airflow, and higher compressor discharge pressure (CDP) than is capable at sea level static conditions. In addition, one of the most critical elements of the test program dealt with understanding the impact of Reynolds Number affects. Reynolds Number is associated with changes in fluid density and viscosity, and their impact on the smoothness of flow over objects such as compressor and turbine blades. At higher altitudes, this impact can be critical for hardware components as small as those in the FJX-2 engine. Figure 3-5 shows the FJX-2 engine being installed in the PSL facility.

Figure 3–5 FJX-2 Installation into PSL Altitude Facility

The altitude test program at NASA GRC was completed using engine S/N 003 in 41:34 hours of engine running in PSL, accumulating 34 starts. This testing was performed at altitudes ranging from sea level to 30,000 feet, and at Mach numbers from static to 0.6.

Figure 3-6 – Summary of Altitude Test Points



A summary of accumulated test data is graphically shown in Figure 3-6. Three builds of Engine S/N 003 were used to complete the altitude test program. A summary of those engine builds is included below.

The configuration of engine S/N 003 incorporated the Shrouded Fan rotor utilized throughout the engine development program. The third stage compressor was clipped as a result of the blade failure experienced during the initial build of engine S/N 004. The variable IGVs, which had been incorporated as an aid to development testing, were locked at 25 degrees angle of incidence for the majority of the test program. The engine utilized shaft fuel feed delivery, along with a single spark plug for engine ignition. The most optimum HP turbine configuration, established through development testing was incorporated. The LP turbines were of the machined configuration.

The engine accessories included an air turbine starter, and a palletized fuel and oil pump system. A remote air-to-water HP Compressor bleed cooler was utilized to reduce the bleed air temperature prior to the reintroduction of the air into the secondary buffer air system. Electrically actuated handling bleeds were utilized. Customer bleed was routed through to a remote valve and measuring station. The engine control systems consisted of a PC based interface to a stand alone single-channel digital engine control. This control interfaced with the P2/T2, P0, ITT and speed sensors, Fuel Metering Unit (FMU) stepper motor. A composite tailpipe was utilized throughout the test sequence.

Testing conducted on build 6 of the engine experienced an engine surge and shaft lock-up during testing conducted on March 28, 2000. The engine was removed from the cell and returned to WI for investigation.

Teardown inspection of the engine identified primary cause of the event as #2 bearing retainer excessive wear, allowing the compressor rotary group to move forward 0.042 of an inch. This forward movement allowed the tapered compressor rotor blade tip to contact the stator abradable, causing a heavy tip rub. The displaced material generated a hole in rotor abradable area measuring 0.200 X 2.5 inch around the circumference of the rotor, creating excessive group unbalance. The unbalance loads caused an HP shaft rub, and subsequent shaft lockup.

Build 7 of the engine completed repairs, rebuild and check run in WI's test cell B1 prior to return to PSL. The engine configuration included modification to the design of the #2 bearing retainer incorporating a larger contact surface and a more hardened material. Compressor and shaft seals were replaced. Instrumentation for shaft group thrust balance analysis was incorporated.

Continued testing at NASA PSL accumulated 4:38 hours and 5 starts before experiencing an ECU commanded shutdown due to an over temperature of the ITT. Analysis of the event on both the facility safety tape, and the data logging capability of the PC based interface to the ECU, indicated that the control had commanded an increase in fuel flow to counteract a perceived decrease in HP shaft speed. HP shaft speed is measured at the air starter, and the apparent decrease in speed was a result of a failure in the air starter drive system, which decoupled the starter from the engine.

The engine was returned to WI, and disassembly revealed a failure of the starter shaft bevel gear. Analysis of the failure indicated that thrust loads imparted by the air start turbine caused it. Build 9 of the engine incorporated new bevel / pinion gears, along with a new design low thrust air start turbine. The new design also featured new HP speed sensor target to improve the speed sensing capability of the ECU. Build 8 testing at PSL had experienced compressor instability traced to increased tip clearances due to worn abradables. A very tight test window at PSL forced the return of the engine into test without the ability to replace the abradable. In order to provide some improvement to the engine stability, a functioning variable IGV was incorporated.

Build 9 testing completed the altitude phase of testing on the FJX-2. The new HP speed sensor demonstrated much better signal stability than had been seen previously. A maximum power data point was achieved while running to a 1500F ITT limit at a flight condition of 5000 feet, Mach Number 0.2, and inlet temperature of -40F. At this flight condition, the engine attained a measured thrust of 770 lbs. corrected to sea level static.

Considering all the factors that drove overall engine performance during the test program, there was nothing that showed the Reynolds Number analytical modeling too be far off from reality. Progressive tip clearance deterioration, along with improper engine spool speed match, contributed to the loss of operational stability and very limited operational range. Efforts to precisely model a continuously changing engine proved to be quite challenging. If Reynolds effects were not adequately modeled this would have been further exacerbated.

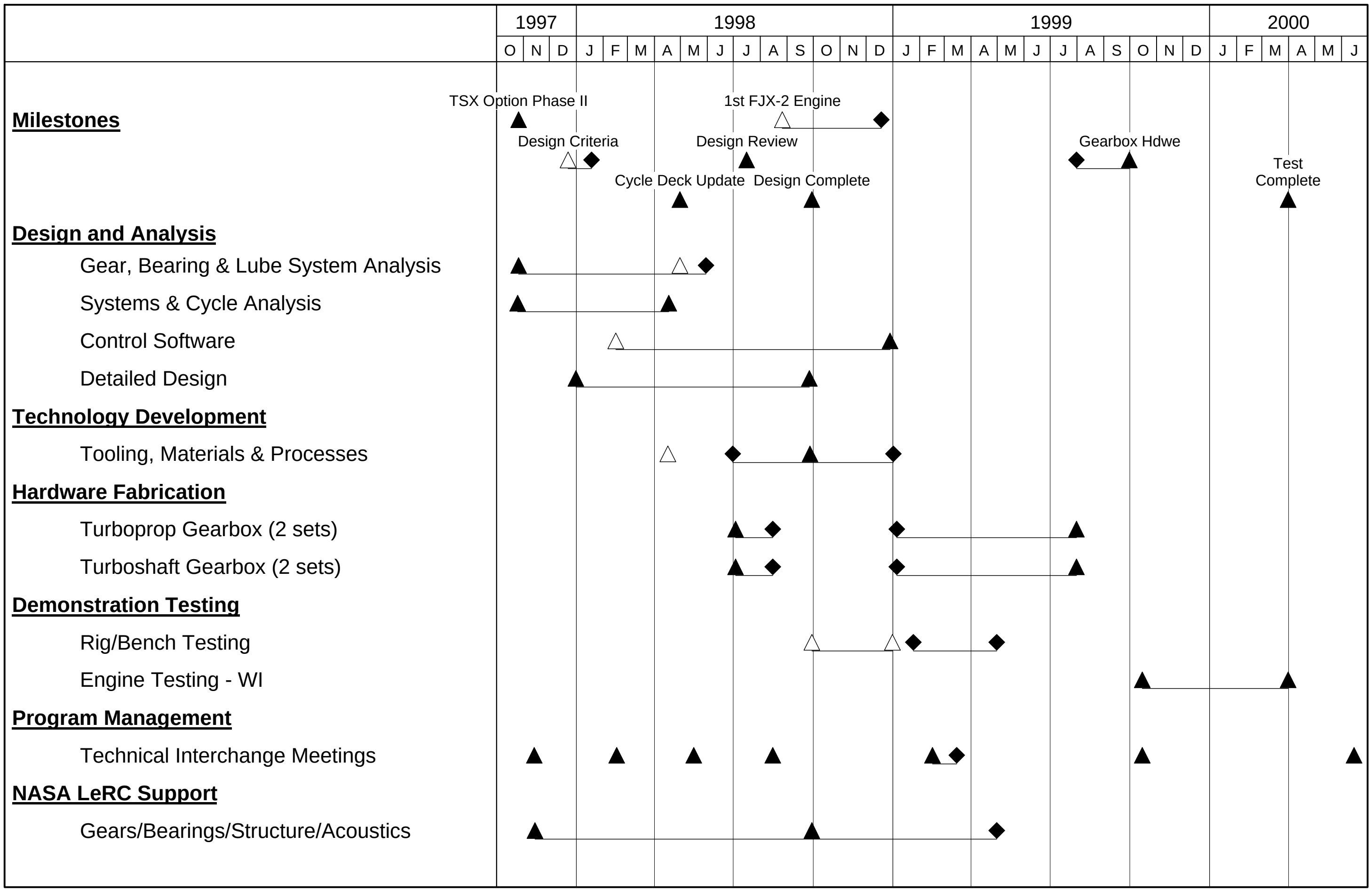
Altitude sweeps conducted with engine builds 6 and 7 were compared to status models. Projected production engine performance was superimposed on these plots to provide comparison with Reynolds Number predictions.

4.0 TSX-2 Turboprop Engine

It was recognized at the beginning of the GAP program that building large quantities of engines was key to achieving low acquisition costs. The FJX-2 turbofan was designed to be readily converted to a turboprop or turboshaft configuration that could support the sizable market for turboprop aircraft that exists today. The GAP Cooperative Agreement included an option to design, build, and test a turboprop version of the FJX-2 turbofan if both NASA and Williams International agreed. This option was exercised and the resulting turboprop engine was designated the TSX-2. The schedule for the TSX portion of the program is shown below.

GAP PROGRAM

Turboshaft Option Phase II - Detail Design and Demo Schedule



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The TSX-2 was configured to maintain a high degree of commonality with the FJX-2 to aid in achieving the goal of reduced engine acquisition cost. The fan was removed from the low pressure shaft of the FJX-2 and a gearbox was added to the front of the engine. The remainder of the engine was kept common to the FJX-2.

Two different gearboxes were designed; one for a turboshaft application with 6000 rpm output shaft speed, and a derivative one which further reduced the output shaft speed to 2000 rpm, appropriate for a turboprop application.

The turboprop configuration of the gearbox was fabricated and rig tested over its full speed spectrum (Figure 4-1). 6:06 hours of rig testing were conducted.

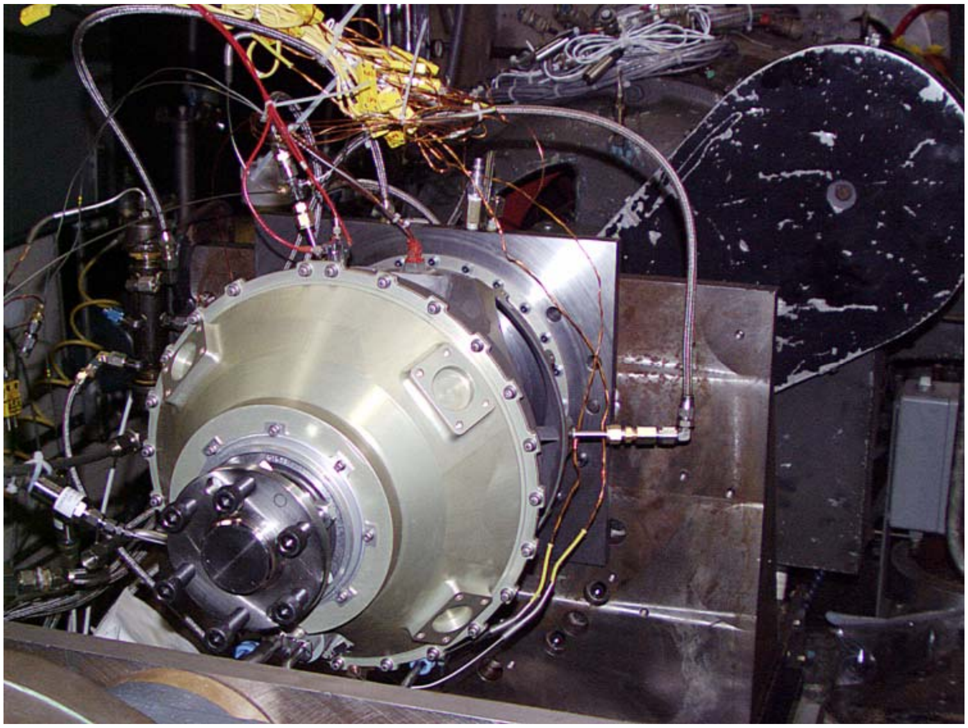


Figure 4-1 TSX-2 Gearbox in Rig Testing

The TSX-2 engine was then built and demonstration testing ensued. The engine and gearbox were installed at the Outside Test Facility (OTF) at Walled Lake (Figure 4-2). The test program required 49:21 hours of engine running to complete, with 106 starts. Along with validating the design of the gearbox drive train and lubrication system, the test program also demonstrated the suitability of the lightweight design of the powerhead and gearbox of the TSX-2 for use in the vibration environment created by a 195-lb propeller capable of absorbing 550-HP.

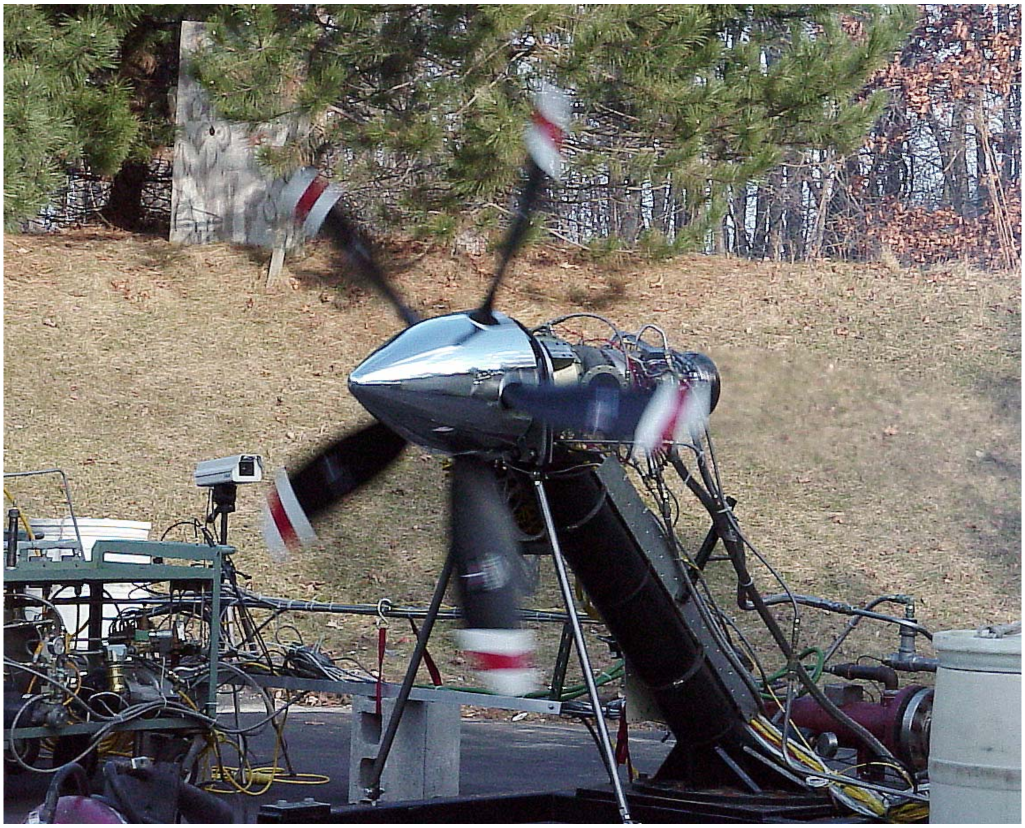


Figure 4-2 TSX-2 and McCauley Propeller in Test at OTF

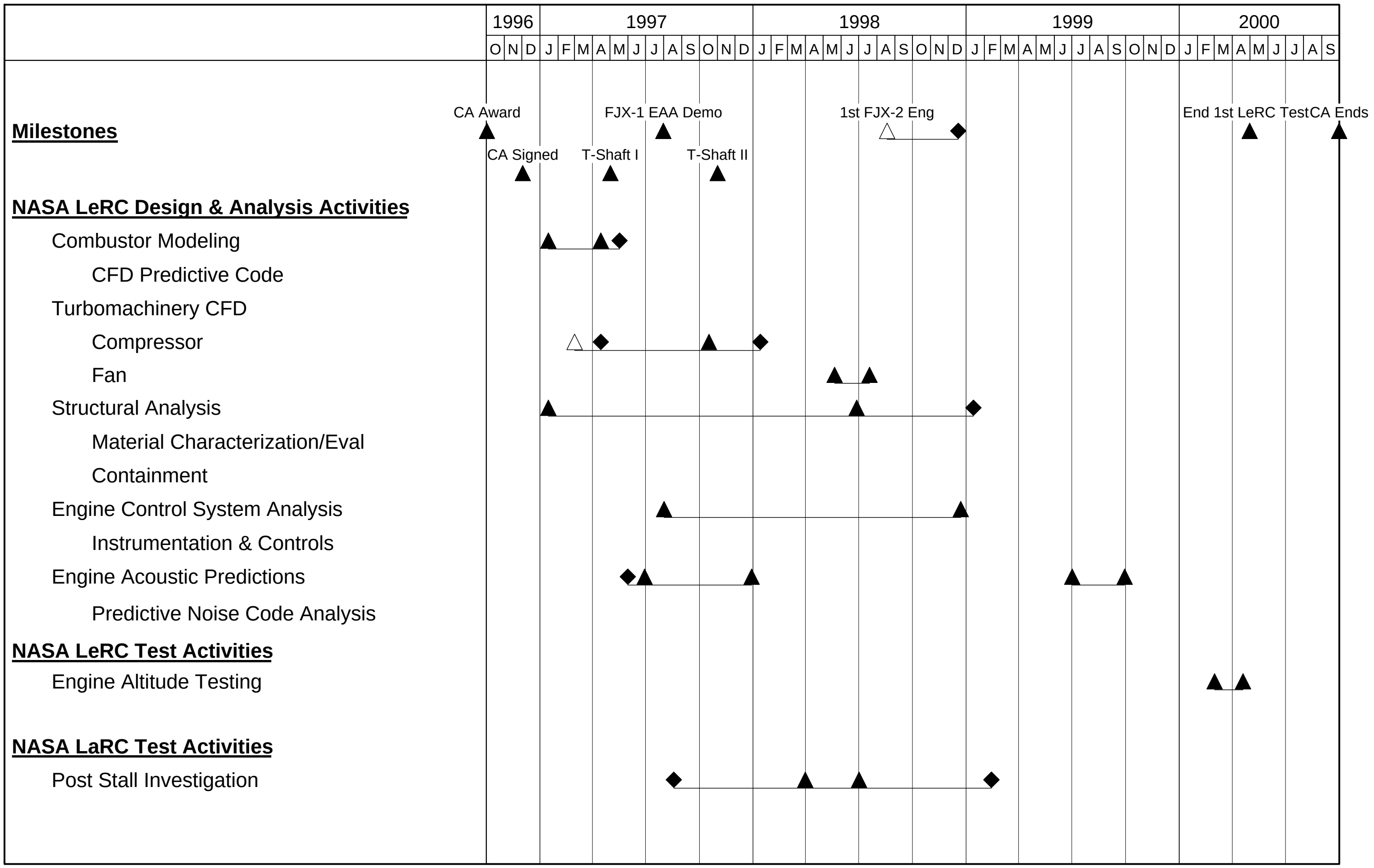
The TSX-2 demonstration engine weighed 130-lb without the propeller. Some additional accessories would be needed dependent upon the requirements of each specific application. The TSX-2 would be rated at 550 hp on a sea level, static, standard day. The engine is very attractive from a weight and fuel consumption viewpoint. It would compete very well in the light helicopter market and the light turboprop market. It's future is dependent upon the success of the FJX-2. The high degree of commonality between the engines will allow a low TSX-2 acquisition price when a high annual sales rate is achieved with the FJX-2.

5.0 NASA and Industry Working Together

The Turbine Element of the GAP Program leveraged the talents and facilities of NASA along with Williams International to further the advancements in technologies supporting General Aviation. The areas of impact are highlighted below in a summary schedule of the NASA facility efforts.

GAP PROGRAM

FJX-2 Engine Demonstrator - NASA Centers Support Schedule



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5.1 A Quieter and Cleaner Engine Solution

The next generation of GA engines will need to be environmentally friendly in the areas of noise and emissions. These characteristics will be essential if we are to begin to utilize jet aircraft at the hundreds of smaller airports across the country. NASA engineers at GRC, along with engineers at WI, conducted noise analysis of the FJX-2 engine installed in the V-Jet II demonstration aircraft. The analysis was conducted utilizing NASA provided codes NASANOISE, Footpr, and Radius. These codes were validated through comparison of analysis and actual test results for Williams FJ44-1A powered Cessna CitationJet. The results, reported in NASA Noise Analysis Report NASA/TM-1999-208908, show the FJX-2 to have a lower predicted noise signature (Figure 5-1) than the existing Effective Perceived Noise Level (EPNL) requirements, with a total margin of 63.9 dB. It is anticipated that future requirements will reduce the combined rule by 11 dB, still leaving the V-Jet II, and aircraft like it, with a 52.9 dB margin.

	Sideline	**Community**	**Approach**
Fan	65.3	59.2	65.9
Jet	72.0	68.8	48.3
Core	67.6	64.6	66.5
Airframe	46.5	55.6	39.3
Total	74.9	71.5	70.7
Rule	94.0	89.0	98.0
Variance	-19.1	-17.5	-27.3

Figure 5-1 EPNL Predictions for the V-Jet II vs. Existing standards

Along with reduced noise signatures, the next generation of GA Aircraft will also need to generate low exhaust emissions. The current FAA regulations require engines of the size of FJX-2 to have smoke numbers of less than 50. Estimates for the FJX-2 engine, based on analysis and testing of the Williams FJ44 business jet engine, would indicate smoke numbers well below this requirement with values of between 10 and 20.

5.2 Scaled Aircraft Model Testing

The model makers and engineering staff at the 14 X 22 foot low speed wind tunnel facilities at NASA Langley supported the GAP Program through testing of a quarter scale model of the FJX-2 demonstration aircraft, the V-Jet II, shown in Figure 4-2.

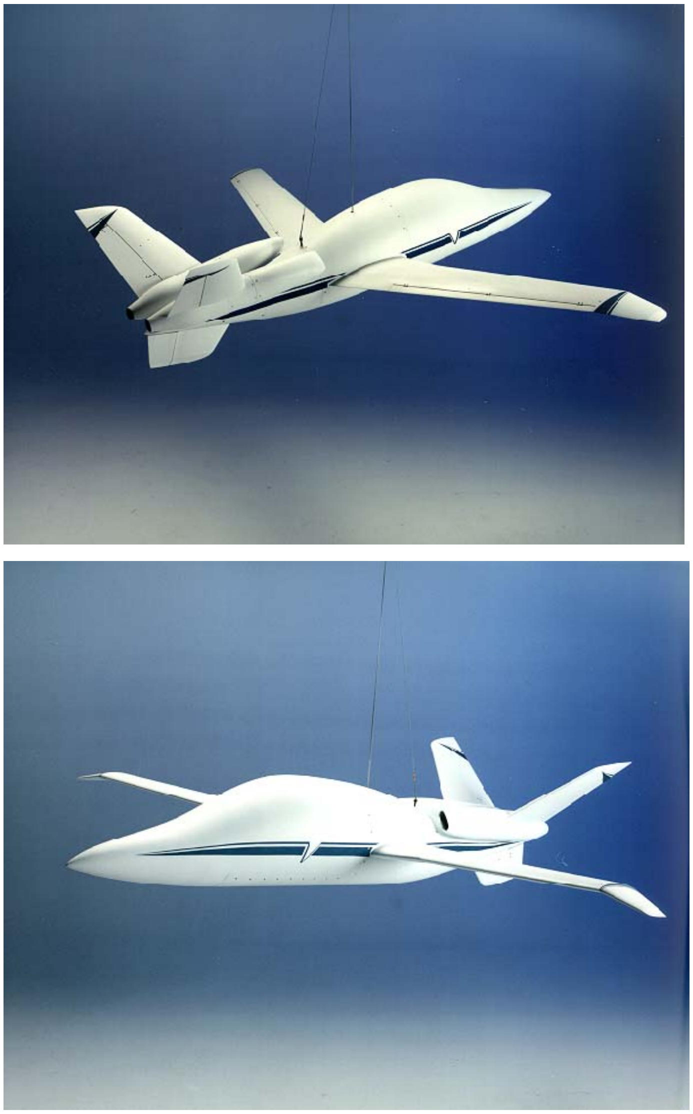

Figure 5-2 Quarter Scale Wind Tunnel Model of V-Jet II Demonstrator Aircraft

α	β	Power	δf, left	δf, right	δr, left	δr, right	δv	Comments
A1	0, ±5, 15	OFF	0	0	0	0	0	Baseline configuration
TBD	B1	OFF	0	0	0	0	0	Baseline configuration, check for deep stall
A1*	0	OFF	0	0	0	0	0	Baseline configuration
A1	0, ±5	OFF	-14, -5, 5, 10, 22	-14, -5, 5, 10, 22	0	0	0	Flaperon pitch control, symmetric
A1	0, ±5	OFF	0	0	-22, -10, -5, 5, 14	-22, -10, -5, 5, 14	0	Ruddervator pitch control, symmetric
A1	0, ±5	OFF	TBD	TBD	TBD	TBD	0	Combined pitch control, validate use of superposition (2 deflections)
A2	0	OFF	-5 to 10 by 1	-5 to 10 by 1	0	0	0	Flaperon map
A1	0, ±5, 15	OFF	-14, -5, 5, 10, 22	0	0	0	0	Flaperon roll control, every 10º between max & min deflections
TBD	B1	OFF	-14, -5, 5, 10, 22	0	0	0	0	Also generates data for math model of flaperon effectiveness
A1	0, ±5, 15	OFF	0	0	-14, -10, -5	5, 10, 14	0	Asymmetric ruddervator (yaw control)
A1	0, ±5	OFF	0	0	-36, -25, -15, -5, 5, 15, 28	0	0	Ruddervator control, every 10º between max & min deflections
TBD	B1	OFF	0	0	-36, -25, -15, -5, 5, 15, 28	0	0	Also generates data for math model of rudervator effectiveness
A1	0, ±5	OFF	0	0	TBD	TBD	0	Combined yaw-pitch control, validate use of superposition (2 deflections)
A1	0, ±5	OFF	0	0	0	0	0	Alternate wing tip dihedral
A1	0, ±5	OFF	0	0	0	0	0	Alternate nacelle inlet
A1	0, ±5	OFF	0	0	0	0	-30, -20, -10	Ventral control
TBD	B1	OFF	0	0	0	0	-30, -20, -10	Also generates data for math model of ventral effectiveness
A1*	0, ±5, 15	T1	0	0	0	0	0	Baseline configuration
TBD	B1	T1	0	0	0	0	0	Baseline configuration
A1*	0	T1	0	0	0	0	0	Baseline configuration
A1	0, ±5	T1	0	0	-14, -10, -5	5, 10, 14	0	Asymmetric ruddervator (yaw control)
A1	0, ±5	T1	0	0	-36, -25, -15, -5, 5, 15, 28	0	0	Ruddervator control, every 10º between max & min deflections
TBD	B1	T1	0	0	-36, -25, -15, -5, 5, 15, 28	0	0	Also generates data for math model of rudervator effectiveness
A1	0, ±5	T1	0	0	TBD	TBD	0	Combined yaw-pitch control, validate use of superposition (2 deflections)
A1	0, ±5	T1	0	0	0	0	0	1 Engine out
A1	0, ±5	T1	0	0	0	0	0	Alternate nacelle inlet

A1: -4, -2, 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 28, 32 (17 points) **A1***: A1 alpha sweep extended as necessary to document deep stall characteristics

A2: TBD (to be used for flaperon map)

B1: -15, -12, -10, -8, -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 8, 10, 12, 15 (21 points)

T1: Thrust required for inlet mass flows of 1 and 2 lbm/sec per engine

Remaining TBD items will be determined during the test based on obtained data.

Flow visualization, both tufts and smoke flow, will be conducted at the end of the test. Conditions will depend on test results.

Configurations may be added or deleted depending upon test results.

Test plan as shown represents approximately 360 runs.

Figure 5-3 NASA Langley Model Test Matrix

The Test Matrix shown in Figure 5-3 was conducted concurrent with the aircraft flight test program that allowed for the safe investigation of deep stall characteristics at high angles of attack (60 degrees alpha). The test program also concentrated on investigation of the aircraft’s combination flap/aileron or flaperon utilized as a flap only. The command authorities of the aircraft’s combination rudder/elevator or Ruddervator, as well as a ventral fin design were also characterized. The model was constructed to allow for flexibility to also investigate wing tip droop variations from the flight configuration anhedral design, to a level wing tip, to an equivalent dihedral tip design.

5.3 Material and Material Processes Evaluation

The metallurgy and processing of the FJX-2 turbofan allowed for extensive cooperation between NASA Glenn and Williams in completing evaluations conducted in the following areas.

Due to the small physical size of the FJX-2 components a study was conducted to determine the best Non-Destructive Test (NDT) methods to use on these components as well as assemblies. The investigation concentrated on 3 main areas; Titanium billet inspection, semi-finished machined component inspection, and assembled weld joint inspection. The goal of the investigation was to find defects measuring 0.010” or less in the detection-limiting dimension. A secondary challenge was to find defects in hidden areas of assembly joints. The ability to detect smaller flaws will directly impact the ability to accurately life components.

Mockups used for the investigation had artificial defects machined into the parts for inspection purposes. Flat bottom EDM holes and notches machined to set depths were used to simulate internal defects. Titanium mockups contained a 0.030” hole, and a 0.010” hole in the flat section of the disk. Two edge defects in the bore, 0.010” X 0.010” and a 0.005” X 0.005” were also machined. Small tungsten inclusions were added in the hub contour area by filling EDM holes with tungsten powder, welding the holes closed and HIP’ing the parts.

NASA Glenn provided Computer Aided Tomography (CAT) scans for the titanium samples and some conventional ultrasonic testing. Williams worked with inspection vendors such as Sonoscan Inc. to evaluate additional processes. A summary of the methods used, and the results are shown below.

	RESULTS							
METHOD	COMPRESSOR ROTOR FLAWS DETECTED				TURBINE ROTOR FLAWS DETECTED			
	.010”	.030”	HD	EDGE	.010”	.020”	.030”	SLOPE
Acoustic Micro Imaging	X	X	X	X	X	X	X	(1)
CAT		X	X		NA	NA	NA	NA
Eddy Current (2)	NA	NA	NA		NA	NA	NA	NA
Conventional Ultrasonics		X		NA		(3)	(3)	
Conventional Radiography		X	X			X	X	(4)

Summary of Component Defect Inspection Results

NA = Not Applicable

(1) Could detect flaws in tapered area only from the open side

(2) Not used to look for sub-surface defects – could not detect edge defects, will detect other surface flaws

(3) Flat areas only

(4) Sizes of defects in tapered region indeterminate

The most promising inspection method for finding flaws in near net machined hardware appears to be Acoustic Micro Imaging. This method detects smaller flaws in more areas than any of the other methods studied. Additional results and recommendations for further investigation are summaries in the table below.

PARTS/MATERIALS	**REQUIRED CAPABILITY**	**CURRENT CAPABILITY**	**ADDITIONAL WORK REQUIRED**
Ti Billet	.010”	.032”	Billet structure refinement or software development
Compressor Rotors	.010”	.010”	Correlation studies between conventional and Sonoscan methods
HP Compressor Welds	.010”	.020”	Investigation of Smart Eddy system, eddy current probe development
HP Turbine Rotor	.010”	.010”	Correlation studies between conventional and Sonoscan methods
HP Shaft Welds	.030”	.030”	Probe development to access restricted areas
Rotor Edge Defects	.005” X .005”	.010” X .010”	Investigate Sonoscan method to yield consistent detection of .005” x .005”

NDI Inspection Methods - Results and Recommendations

NASA Glenn and Williams jointly performed material characterization studies of compressor component materials. These materials included disks, welds, and titanium welds. This testing encompassed an evaluation of tensile properties, high cycle and low cycle fatigue (HFC/LCF), creep rupture, and creep growth rate both with and without dwell

NASA also provided great assistance in the evaluation of a variety of turbine nozzle and blade casting coatings to evaluate their oxidation/corrosion benefits. This testing subjected the test samples to a maximum temperature of 1900 ^{0}F, with 60 sec of 1 PPM sea salt, 59 minutes w/out salt, 10 min cool down prior to initiation of the next cycle.

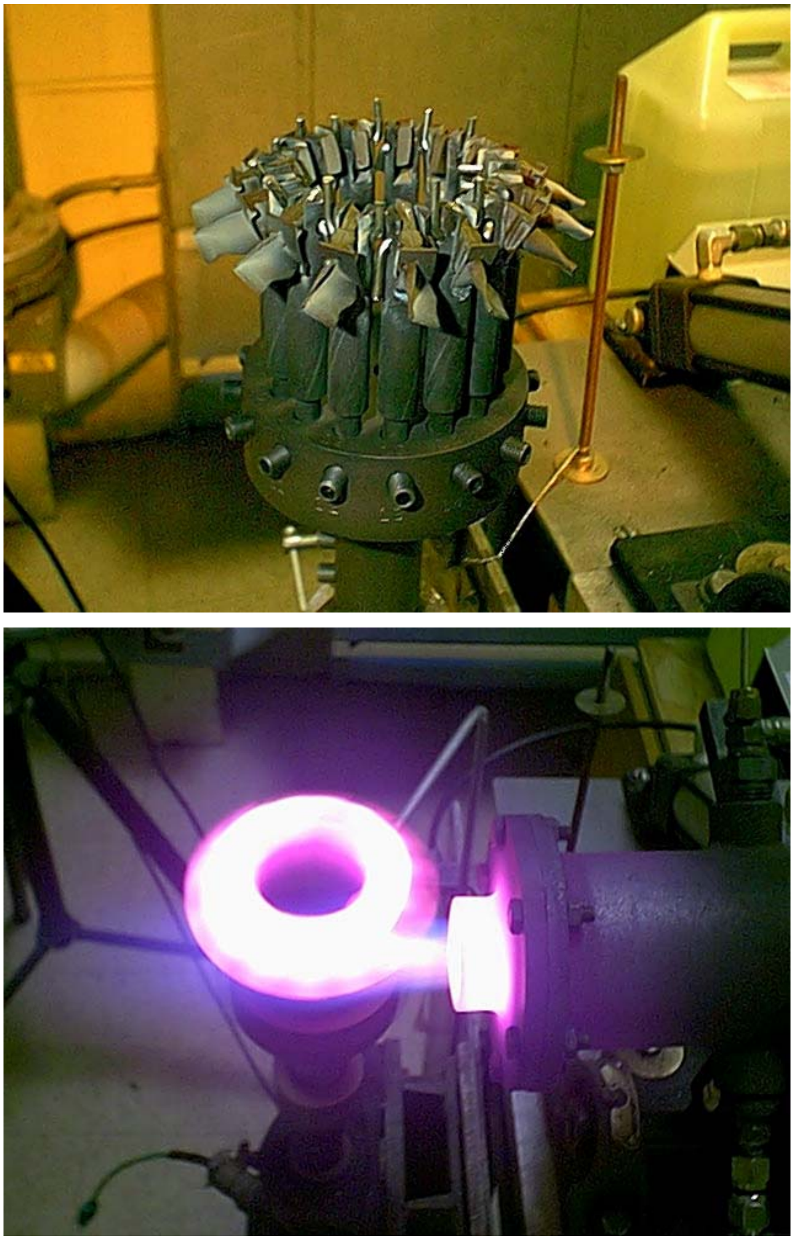

Figure 5-4 – Carousel Test Fixture for HP Turbine Blades – NASA Glenn Research Center

Figure 5-4 shows the test arrangement assembled at NASA Glenn to complete this evaluation. A compilation of the testing and results are shown in Figures 20 - 22 in Appendix A of this report.

6.0 Cost

The success of the FJX-2 design cannot be measured only in its ability to meet its performance and weight goals. One of and quite possibly the most important success criteria for the FJX-2 and its successors is its ability to be manufactured at a cost which will make possible the revitalization of the GA Industry envisioned by the GAP Program. Design to Cost (DTC) is a critical element for all of Williams International turbine engine designs, and the FJX-2 was no exception. Cost analyses conducted by Williams International show that at production rates consistent with NASA's GA sales goals, the FJX-2 would be cost competitive with the 300 horsepower, turbocharged, piston engines of today. NASA commissioned an independent cost analysis performed by Aviation Analysts International, Inc. which reached the same conclusion. A summary of the cost model for the production version of the FJX-2 engine is shown in Appendix B.

This success is due to many factors influenced by the integrated design process. Cost saving begin with raw material, and minimization of raw material is a key to low cost engine manufacturing. This is one of many areas in which the close relationship between Williams International and its Contractor-led Product Team (CPT) member, in this case Forged Metals, resulted in cost saving measures. Forged Metals delivered tooling and manufacturing techniques required to produce low cost, close shaped forgings, minimizing raw material.

The ability to remove material economically and accurately is also critical to the cost of the manufacturing process for the FJX-2. Williams International currently utilizes highly automated, unmanned, high rate, highly flexible machining cells in the production of turbine components. This approach will continue for the FJX-2 engines. Williams also investigated options for automated assembly of the FJX-2 engine in a production environment.

The FJX-2 has demonstrated the potential for a production, general aviation, turbofan engine that can enable a new class of airplanes that will provide outstanding value to the general public. The GAP program brought the engine to a point where a commercial engine certification program could be initiated.

7.0 Commercialization

The ultimate success of the GAP Program will be determined by the ability of FJX-2 technology to be commercialized, i.e., to be certified and incorporated into a new generation of airplanes with outstanding safety and value. Williams International formed a "Contractor-led Product Team" (CPT) to aid in executing the GAP Cooperative Agreement. This team included Boeing Helicopter, Cessna Aircraft, Chichester-Miles consultants, Cirrus Design, Forged Metals, Lancair, New Piper, and VisionAire. Williams International met individually with CPT members, and jointly with NASA and CPT members to determine the desired characteristics of the FJX-2 and TSX-2 as well as identifying engine installation issues. The CPT also reviewed the market prospects of the FJX-2 and its shaft power derivatives, concluding that these engines could provide the incentive to launch a new generation of GA aircraft.

While it was not a requirement of the GAP Cooperative Agreement, Williams International and NASA understood that the final confirmation of commercialization would be the launch of a new certified airplane program based on the FJX-2. It was believed that this new engine would enable a new generation of airplanes unlike those presently available. These new planes would be the size of today's twin piston powered airplanes but with performance comparable to today's entry level business jets.

It was decided it would be necessary to demonstrate to aircraft manufacturers and the public the new type of airplane enabled by the FJX-2. Williams International conducted the preliminary design and funded the detailed design, fabrication, and flight test of the V-Jet II concept airplane as part of the GAP Cooperative Agreement. Burt Rutan and his team at Scaled Composites fabricated and flight tested the V-Jet II. It was flown at the Experimental Aircraft Association Oshkosh Fly-In in 1997, utilizing available Williams International's turbofan engines of approximately FJX-2 size. These engines were heavier than the FJX-2 and had significantly higher TSFC.

The V-Jet II was a very effective concept plane. It attracted public attention and clearly made the point that the engine being demonstrated in the GAP Program would lead to significant improvements in light plane safety and value.

Seating	**6**
Length	**31.1 ft**
Height	**9.8 ft**
Span	**35.3 ft**
Mean TO Weight	**3,800 lb**
Empty Weight	**2,200 lb**
Take-off Distance	
SL/Std Day	**2,300 ft**
5000 ft/ISA (25°C)	**3,000 ft**
Climb Rate (SL)	**3,200 fpm**
Time to Climb	**8 min to 18 kft**
Performance	
High Speed Cruise	**370 ktas**
Range - Max Fuel	**2600 miles**
4 on board	**1800 miles**
Fuel Economy	**15 mpg**

V-Jet II Performance Summary

The GAP Program has achieved far more than the objectives cited in the Cooperative Agreement. It has demonstrated engine technology which has motivated the development and certification of the first of a number of new, safe, comfortable, high value airplanes, which will revolutionize general aviation.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The General Aviation Propulsion (GAP) Program Turbine Engine Element focused on the development of an advanced small turbofan engine. Goals were good fuel consumption and thrust-to-weight ratio, and very low production cost. The resulting FJX-2 turbofan engine showed the potential to meet all of these goals. The development of the engine was carried through to proof of concept testing of a complete engine system. The proof of concept engine was ground tested at sea level and in altitude test chambers. A turboprop derivative was also sea-level tested.

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