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JT8D High Pressure Compressor Performance Improvement

by

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FOREWORD

This JT8D Performance Improvement effort is part of the Engine Component Improvement (ECI) Project, which is part of the NASA Aircraft Energy Efficiency (ACEE) Program. The JT8D High Pressure Compressor Performance Improvement Program was conducted from September, 1978 through April 1981. The development and demonstration effort described in this report was conducted by the Commercial Products Division of Pratt & Whitney Aircraft Group, United Technologies Corporation, under sponsorship of the National Aeronautics and Space Administration - Lewis Research Center. Mr. John McAulay and Mr. Irving Sumner of the NASA Lewis Research Center were the Project Manager and Project Engineer respectively for the contract.

This report was prepared under the direction of William O. Gaffin, Pratt & Whitney Aircraft Program Manager, with the aid of the Pratt & Whitney Aircraft Engineering Department.

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1.0 SUMMARY

An improved performance high pressure compressor with potential application to all models of the JT8D engine was designed and demonstrated as part of the NASA sponsored Engine Component Improvement-Performance Improvement (ECI-PI) project. This improved compressor demonstrated specific fuel consumption and exhaust gas temperature improvement of 1 percent and at least 10°C relative to the bill-of-material compressor over the takeoff and climb power range in back-to-back sea level static engine tests. A thrust specific fuel consumption improvement of 0.7% at typical cruise conditions was calculated based on test results. Compressor rig tests showed a 1.2% efficiency advantage for the improved compressor at typical cruise operating conditions. Analysis of the results of the rig and engine tests showed a surge margin increase of 4% at high power conditions and a similar increase at idle and off-idle conditions. Since this extra surge margin is not needed for safe operation of the engine, it can be traded for additional fuel consumption and exhaust gas temperature improvements with further development. Sprayed abradable rubstrips exhibited excellent rub properties, abrading cleanly with insignificant blade tip wear.

The primary feature of the improved high pressure compressor is a trenched abradable rubstrip which seals the blade tips in each of the seven stages. This feature allows the blade lengths to be increased so their tips run at or near the optimum radius relative to the flowpath wall without the danger of damaging the blades during transients and maneuvers. The abradable rubstrips are porous nickel-chromium material applied to the stator outer shrouds by plasma spraying. This concept was referred to as the JT8D Trenched Tip High Pressure Compressor in Reference 1, but several other features are also significant. The outer portion of the blade airfoils are recambered in recognition of the aerodynamic effects of the reduced tip clearance. Flow guides are added to the forward edge of the stator inner shrouds to isolate the stator inner seal cavities from the flowpath. Manufacturing tolerances on the stator shrouds are revised to smooth the steps and bumps that occur in the flowpath walls when the bill-of-material compressor is assembled.

The demonstrated sea level performance of the improved compressor is slightly better than predicted in the 1977 ECI-PI Feasibility Analysis, but it's calculated performance at altitude conditions is somewhat poorer than predicted. These results, combined with the fact that fuel prices have increased faster than engine parts prices since 1977, would tend to improve the airline payback period by a small amount. This means that the concept would be very acceptable to the airlines as an integral part of new production JT8D engines, but would probably not be acceptable for retrofit in existing engines. However, current plans at Pratt & Whitney Aircraft do not include completing development of the improved compressor because of the shift in airline interest away from improving the JT8D engine family and toward replacing them with advanced, high bypass ratio engines.

2.0 INTRODUCTION

National energy demand has outpaced domestic supply, creating an increased U.S. dependence on foreign oil. This increased dependence was dramatized by the Organization of Petroleum Exporting Countries (OPEC) oil embargo in the winter of 1973-74. In addition, the embargo triggered a rapid rise in the cost of fuel which, along with the potential of further increases, brought about a changing economic circumstance with regard to the use of energy. These events, of course, were felt in the air transport industry as well as other forms of transportation. As a result of these experiences, the government, in conjunction with the aviation industry, initiated programs aimed at both the supply (sources) and demand (consumption) aspects of the problem.

An approach to the demand aspect of the problem is to evolve new technology for commercial aircraft propulsion systems which will permit development of a more energy efficient turbofan, or the use of a different propulsive cycle such as a turboprop. Although studies have indicated large reductions in fuel usage are possible with advanced turbofan or turboprop engines (e.g., 15 to 40 percent), any significant fuel savings impact of these approaches is still many years away. In the near term, the only practical fuel savings approach is to improve the fuel efficiency of current engines. Examination of this approach has indicated that a five percent fuel reduction goal, starting in the 1980-82 time period, is feasible for current commercial engines. Inasmuch as commercial aircraft in the free world are using fuel at a rate in excess of 80 billion liters of fuel per year, even five percent represents significant fuel savings.

Accordingly, NASA is sponsoring the Aircraft Energy Efficient (ACEE) Program (based on a congressional request), which is directed at reduced fuel consumption of commercial air transports. The Engine Component Improvement Program is the element of the ACEE Program directed at reducing fuel consumption of current commercial aircraft engines. The Engine Component Improvement Program consists of two parts: Engine Diagnostics and Performance Improvement. The purpose of the Engine Diagnostics effort is to provide information to identify the sources and causes of engine deterioration. The Performance Improvement effort is directed at developing engine components having performance improvement and retention characteristics which can be incorporated into new production and existing engines.

The Pratt & Whitney Aircraft Performance Improvement effort was initiated with a Feasibility Analysis, which identified engine performance improvement concepts, and then assessed the technical and economic merits of these concepts. This assessment included a determination of airline acceptability, the probability of introducing the concepts into production by the 1980 to 1982 time period, and their retrofit potential. Since a major portion of the present commercial aircraft fleet is powered by the JT8D and JT9D engines, performance improvements were investigated for both engines. The study was conducted in cooperation with Boeing and Douglas aircraft companies, and American, United and Trans World Airlines, and is reported in reference 1.

The study resulted in the selection of an improved high pressure compressor for the JT8D engine as one of the concepts for follow-on development. This concept, which was titled the JT8D Trenched Tip High Pressure Compressor in Reference 1, is described in Section 3.0.

Section 4.0 describes the test equipment, facilities, and procedures that were used to determine the performance improvement of the concept. Section 5.0 provides the results obtained from testing, Section 6.0 estimates the energy impact of the concept, and Section 7.0 provides conclusions drawn from the program.

3.0 COMPRESSOR CONFIGURATION DESCRIPTION

3.1 Introduction

The JT8D high pressure compressor was designed in the early 1960's and the general configuration, which is shown in Figure 1, has been retained into current production models. While refinements have been made in airfoil aerodynamics, the flowpath shape and sealing arrangement have not been changed. Recent research indicates that significant performance improvement should result if the hardwall blade tip seals were replaced with abradable material, allowing the blade tip clearances to be reduced without the risk of blade damage in case of rubs. Also, isolation of the large cavities around the stator inner seals, and general fairing and smoothing of irregularities in the flowpath walls would be expected to improve performance and stability. These concepts were incorporated in the design described below while minimizing the effect on the surrounding parts of the engine. This constraint was imposed to allow existing parts and production tooling to be retained wherever possible, enhancing the improved compressor's cost effectiveness and ease of retrofitting.

3.2 Bill-of-Material High Pressure Compressor

The bill-of-material high pressure compressor is a seven stage compressor, consisting of stages seven through thirteen of the complete JT8D compressor section. The seventh stage blades are attached by means of pin-roots, while the eighth through thirteenth employ dovetail attachments. The front hub and eighth disk are one piece.

Stationary metal rings which are actually extensions of the stator assembly outer shrouds seal the blade tips. Since blade tip rubs against these metal rings result in damage to the blades, the tip clearances are set conservatively. Rubs in airline service are rare, occurring only under extreme operating conditions.

The stator inner seals utilize knife-edges that are integral with the disk spacers. Deep seal cavities result from this arrangement because the rotor tie-bolts, which retain the spacers, must be located well inside of the highly stressed rim region of the disks. Consequently, a significant amount of disk pumping can occur in these cavities.

The stator vane rows are brazed into inner and outer shroud rings. The outer shroud rings of successive stages stack to form the outer flowpath wall, and are clamped together by the compressor case. Production tolerances in the machining and brazing operations result in small steps and angular discontinuities in the flowpath walls.

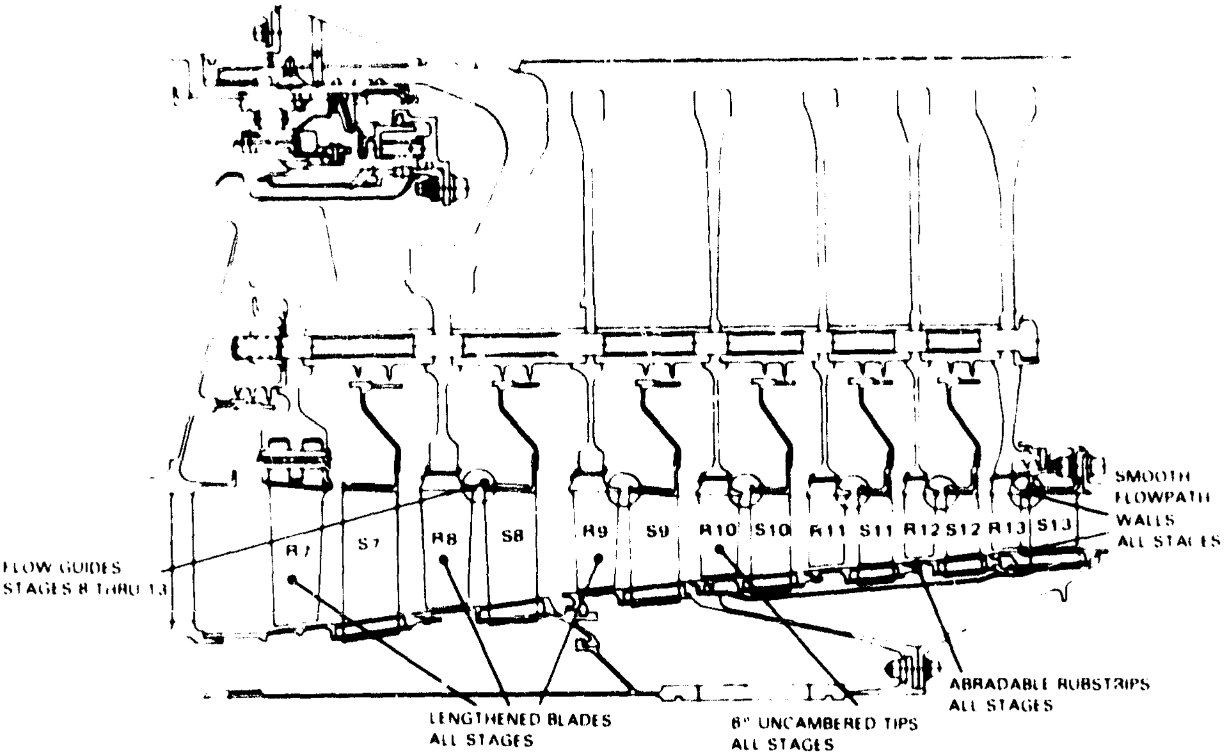


Figure 1 JT8D Bill-of-Material High Pressure Compressor. The locations of compressor improvement features are indicated. Rotor (R) and stator (S) stages are numbered starting from the first fan stage at the front of the engine.

A cross-section of the bill-of-material compressor, showing the basic design features, is given in Figure 1. The locations of the modifications required for the improved version are indicated on this cross-section.

3.3 Improved High Pressure Compressor

The major design features of the improved high pressure compressor include the following:

- Trenched, abradable rubstrips
- Longer blades
- Reduced camber blade tips
- Inner flowguides, or seals
- An aerodynamically "smoother" flowpath

The purpose of these features is to increase the efficiency and stability of the compressor and so improve the fuel consumption, while maintaining the excellent durability and reliability characteristics of the JT8D engine. The trenched abradable rubstrips allow the compressor to run with reduced clearances and less leakage, while the longer blades actually reduce the clearance, and the uncambered tips increase surge margin. The smoother inner flowpath reduces aerodynamic losses. The flowguides force the air pumped from the stator inner seal cavities to re-enter the main flow in a downstream direction, reducing momentum losses and boundary layer growth.

3.3.1 Trenched, Abradable Rubstrips

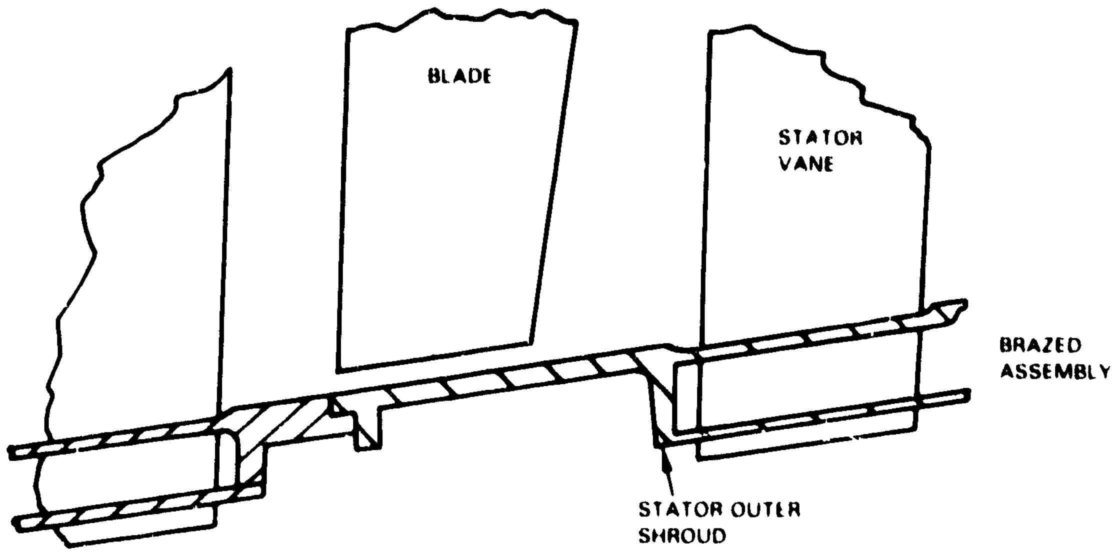
The abradable blade tip rubstrips consist of porous nickel-chromium material (nichrome) plasma sprayed into cavities in the stator outer shroud rings. The rubstrips, except in the seventh stage, are pilot trenched before assembly to limit the amount of material that must be abraded by the blade tips during operation, as shown in Figure 2. In the case of the seventh stage, which is the only stage with pin-rooted blades, the rubstrip was pre-trenched to the full extent of the blade incursion expected. This was done to minimize interaction of the blade tips with the abradable material under extreme conditions, eliminating the possibility of gouging.

The sprayed nichrome abradable was chosen from three candidate materials for its favorable abradability, durability and fabrication characteristics despite a lack of development experience with it. Sprayed nickel-graphite, which has been used in military engines, was rejected because of its durability limitations. Brazed Feltmetal^{R}, which is used in the JT9D high pressure compressor, was rejected because it would have forced a major redesign of the JT8D stator assemblies to accommodate the brazing operation.

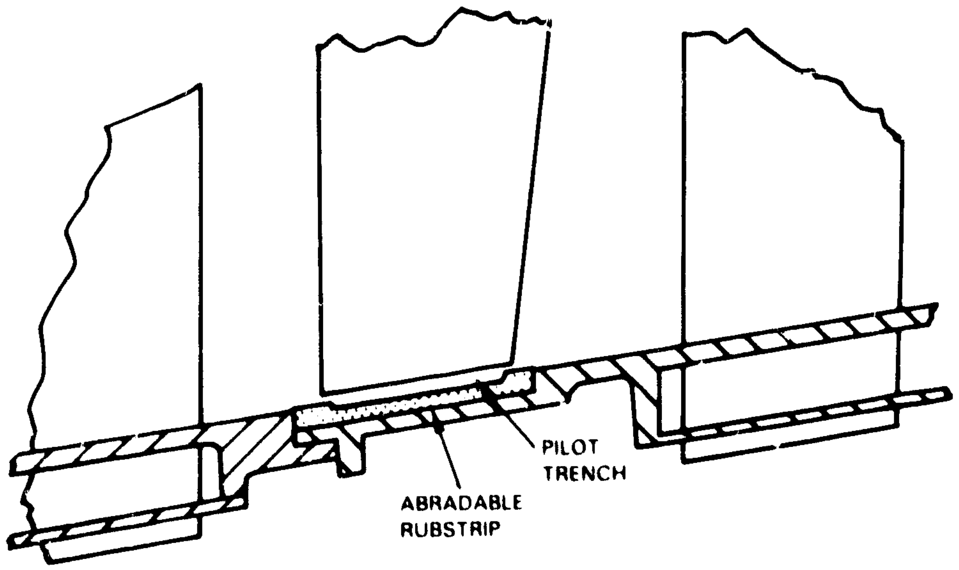
3.3.2 Longer Blades

The blades were lengthened relative to the bill-of-material blades to allow the blade tips to run in line with the projected flowpath wall at typical cruise conditions, where maximum efficiency is desired. The extra length required for each stage was determined analytically based on clearance data from the bill-of-material compressor rig test, from x-ray photographs of a bill-of-material compressor in an operating engine, and from airline experience with the engine. The length increases are shown in Table 1.

The blade airfoils were uncambered from mid-span to tip relative to bill-of-material blades to compensate for the radial flow shift expected with reduced tip clearance. All stages were uncambered 6 degrees at the tip trailing edge, with the angle change reduced linearly to zero at the 50% span location.



BILL-OF MATERIAL



IMPROVED

Figure 2 Comparison of Bill-of-Material and Improved Seals. The abradable rubstrip allows compressor blade tip clearances to be reduced.

TABLE 1

Increase in Blade Length for Improved Compressor

Stage No.	Blade Length Increase, cm (in.)
7	0.226 (0.089)
8	0.093 (0.037)
9	0.101 (0.040)
10	0.101 (0.040)
11	0.114 (0.045)
12	0.121 (0.048)
13	0.152 (0.060)
Avg.	0.130 (0.051)

3.3.3 Inner Flowguides and Smoother Flowpath

The smoother flowpath was accomplished by revising manufacturing tolerances and replacing square corners with bevels on the stator shroud ring details.

Flowguides were added to the forward edge of the stator inner shroud on stages 6 through 13, (see Figure 1). The flow guides, which are shown in Figure 3, partially seal the gap between the rotor and stator rows, and force the flow from the seal cavity to re-enter the main flow in a downstream direction. Similar flowguides would have been desirable on the rear edge of the stator inner shrouds, but these would have required extensive changes to the blades and the shroud forgings.

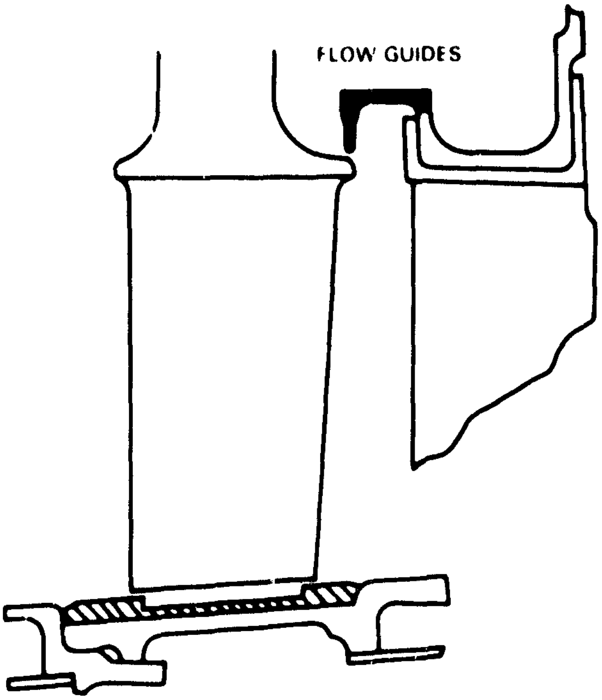


Figure 3 Flowguides. The flowguides block the perpendicular entry of disk cavity air, and cause it to be turned into the direction of the main air flow.

4.0 TEST PROGRAM

4.1 Overview

Back to back rig tests of the bill-of-material compressor and the improved compressor were conducted to establish the efficiency, stability, and structural integrity of the new design. Compressor blade tip clearances were varied for these tests by adjusting the compressor inlet air temperature. (A higher air temperature requires the compressor to operate at a higher mechanical speed to achieve the same corrected speed. The higher mechanical speed increases the elastic stretch of the blades and disks, reducing tip clearances.)

Back to back engine tests of the bill-of-material and improved compressors were then run to demonstrate the performance improvement of the concept. Both the compressor rig and engine test programs are discussed below, including descriptions of the facilities, instrumentation and procedures.

4.2 Rig Tests

4.2.1 Test Equipment and Facility Description

The rig evaluation was performed in a compressor component facility (X-27) designed to conduct performance and structural tests of multistage compressor units. Figure 4 is a layout of the stand.

The test compressor is driven by a modified Pratt & Whitney Aircraft PT-5 turboprop gas turbine engine rated at 11.2 MW (15,000 hp) at 6000 rpm. The PT-5 engine is coupled to the test rig through a step-up gearbox to produce rig speeds up to 18,000 rpm. The drive engine is completely automatic from start-up to idle. It is then switched to the rig supervisory control which sets speeds programmed by the test engineer. Speed is controlled by an electronic fuel control to ±5 rpm of set speed.

Airflow through the compressor is measured by a calibrated nozzle and controlled by throttling valves. The inlet air can be heated by directly fired burners up to a temperature of 232°C (450°F) for an airflow of 27.2 kg/sec (60 lbm/sec). A plenum chamber is located just ahead of the test compressor. Exhaust air is discharged into a collector duct and directed up and out through back pressure valves and an acoustically treated exhaust stack.

4.2.2 Bill-of-Material Rig Test Instrumentation

Instrumentation was installed in the bill-of-material high pressure compressor rig to measure interstage and overall compressor performance. Table 2 summarizes the type and quantity of instrumentation used. In addition, instrumentation was included to monitor disk and engine cavity pressures and temperatures and to measure blade tip clearances. A summary of this instrumentation is given in Table 3.

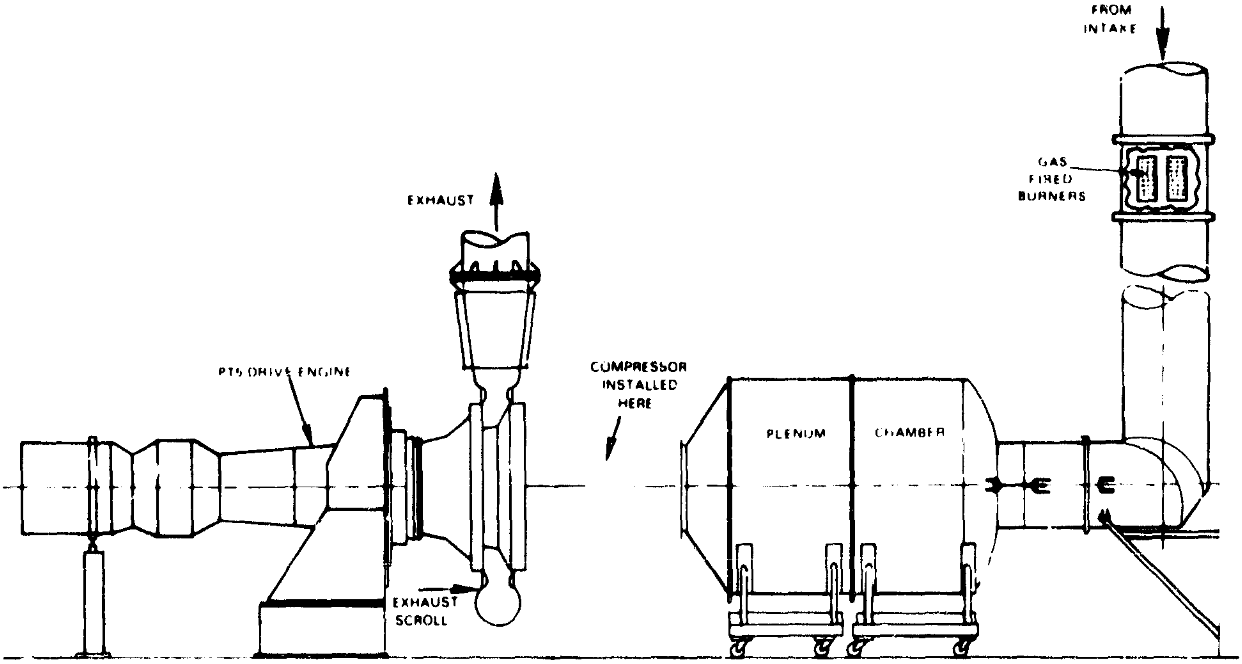


Figure 4 Layout of Stand X-27. The stand is designed for rig testing of compressors.

The overall compressor aerodynamic performance was determined from measurements of rig flow rate, compressor speed, and inlet and discharge total temperature and pressure. Indications of interstage performance, stage matching, and radial flow effects were determined from measurements of stator leading and trailing edge static and total pressures and temperatures.

Two "boundary layer" pole rakes, one measuring total pressure and the other total temperature, were used to define radial flow profiles near the compressor walls.

Six high-response static pressure sensors (Kulites) were located in the outer wall to detect transient pressure pulses which occur during surge. These sensors were at axial locations in the vicinity of those stages suspected of initiating surge.

TABLE 2
FLOWPATH PERFORMANCE INSTRUMENTATION

Instrument Location	Parameter	Instrumentation Quantity & Type	Notes
Intermediate Case	Total pressure	4 five element pole rakes	
	Total temperature	4 five element pole rakes	
	Static pressure	4 OD wall static taps	
Rotor 7 Inlet	Static pressure	4 OD wall static taps	
Stator 7 Inlet	Total pressure	7 vane L.E. Kiel heads	
	Total temperature	7 vane L.E. shielded TC's	
	Static pressure	3 OD wall static taps	
	Static pressure	2 OD wall high frequency response (Kulites)	
Stator 7 Exit	Static pressure	3 OD wall static taps	
Stator 8 Inlet	Total pressure	7 vane L.E. Kiel heads	
	Total temperature	7 vane L.E. shielded TC's	
	Static pressure	3 OD wall static taps	1
Stator 8 Exit	Static pressure	3 OD wall static taps	
Stator 9 Inlet	Total pressure	7 vane L.E. Kiel heads	
	Total temperature	7 vane L.E. shielded TC's	
	Static pressure	3 OD wall static taps	1
	Static pressure	2 OD wall high frequency response (Kulites)	
Stator 9 Exit	Static pressure	3 OD wall static taps	
Stator 10 Inlet	Total pressure	7 vane L.E. Kiel heads	
	Total temperature	7 vane L.E. shielded TC's	
	Static pressure	3 OD wall static taps	1
Stator 10 Exit	Static pressure	3 OD wall static taps	
Stator 11 Inlet	Total pressure	7 vane L.E. Kiel heads	
	Total temperature	7 vane L.E. shielded TC's	
	Static pressure	3 OD wall static taps	1
Stator 11 Exit	Static pressure	3 OD wall static taps	

TABLE 2 (continued)
FLOWPATH PERFORMANCE INSTRUMENTATION

Instrument Location	Parameter	Instrumentation Quantity & Type	Notes
Stator 12 Inlet	Total pressure	7 vane L.E. Kiel heads	
	Total temperature	7 vane L.E. shielded TC's	
	Static pressure	3 OD wall static taps	1
	Static pressure	2 OD wall high frequency response (Kulites)	
Stator 12 Exit	Static pressure	3 OD wall static taps	
Stator 13 Inlet	Static pressure	3 OD wall static taps	1
Stator 13 Exit	Static pressure	3 OD wall static taps	
Engine Exit	Total pressure	3 four element pole rakes	
	Total temperature	2 four element pole rakes	
Rig Exit	Total pressure	6 five element pole rakes	
	Total temperature	6 five element pole rakes	

Note: 1 Used in Bill-of-Material compressor rig test only

TABLE 3
SYSTEMS INSTRUMENTATION

Instrument Location	Parameter	Instrumentation Quantity & Type	Notes
Rotor 7 ID Cavity	Static pressure	6 probes	
ID Cavity	Air total temperature	4 TC's	
OD Wall	Metal temperature	2 TC's	
Disk	Metal temperature	6 rotating TC's	1
Disk	Metal temperature	4 rotating TC's	2
Case	Tip clearance	4 laser proximity probes	1
Case	Tip clearance	4 mechanical rub buttons	
Stator 7 ID Cavity	Static pressure	4 probes	
ID Cavity	Air total temperature	4 TC's	
OD Wall	Metal temperature	2 TC's	
ID Support	Metal temperature	2 TC's	
Outer Shroud	Metal temperature	2 TC's	

TABLE 3 (continued)
SYSTEMS INSTRUMENTATION

Instrument Location		Parameter	Instrumentation Quantity & Type	Notes
Rotor 8	OD Cavity	Static pressure	2 probes	
	ID Cavity	Static pressure	2 probes	
	OD Cavity	Air total temperature	2 TC's	
	ID Cavity	Air total temperature	2 TC's	
	OD Wall	Metal temperature	2 TC's	
	Tie Rod	Metal temperature	2 rotating TC's	
	Case	Tip clearance	4 laser proximity probes	1
	Case	Tip clearance	4 mechanical rub buttons	
Rotor 9	ID Cavity	Air total temperature	2 rotating TC's	1
	OD Wall	Metal temperature	2 TC's	
	Case	Metal temperature	6 TC's	
Stator 9	ID Cavity	Static pressure	4 probes	
	OD Cavity	Static pressure	2 probes	
	ID Cavity	Air total temperature	2 TC's	
	OD Wall	Metal temperature	2 TC's	
	Tierod	Metal temperature	2 rotating TC's	
Rotor 10	ID Cavity	Air total temperature	4 rotating TC's	
	OD Cavity	Air total temperature	2 TC's	
	Case	Metal temperature	2 TC's	
	OD Wall	Metal temperature	2 TC's	
	Disk	Metal temperature	12 rotating TC's	1
	Disk	Metal temperature	6 rotating TC's	2
Rotor 11	OD Wall	Metal temperature	2 TC's	
Stator 11	ID Cavity	Static pressure	4 probes	
	ID Cavity	Air total temperature	2 TC's	
	OD Wall	Metal temperature	2 TC's	
	Case	Metal temperature	8 TC's	
	ID Support	Metal temperature	2 TC's	
	Tierod	Metal temperature	2 rotating TC's	
Rotor 12	OD Cavity	Static pressure	2 probes	
	OD Cavity	Air total temperature	2 TC's	
	ID Cavity	Air total temperature	2 rotating TC's	
	OD Wall	Metal temperature	2 TC's	
	Disk	Metal temperature	6 rotating TC's	1
	Disk	Metal temperature	4 rotating TC's	2

TABLE 3 (continued)
SYSTEMS INSTRUMENTATION

Instrument Location	Parameter	Instrumentation Quantity & Type	Notes
Stator 12 Case	Metal temperature	2 TC's	
Rotor 13 ID Cavity	Metal temperature	2 rotating TC's	
OD Wall	Metal temperature	2 TC's	
Disk	Metal temperature	6 rotating TC's	1
Disk	Metal temperature	4 rotating TC's	2
Stator 13 ID Cavity	Static pressure	2 probes	
ID Cavity	Air total temperature	2 TC's	
Case	Metal temperature	2 TC's	
Diffuser ID Cavity	Static pressure	2 probes	
ID Cavity	Air total temperature	2 TC's	
OD Cavity	Air total temperature	2 TC's	
ID Wall	Metal temperature	2 TC's	
OD Wall	Metal temperature	2 TC's	
No. 3 Bearing: Race	Metal temperature	4 TC's	
Carbon Seal	Metal temperature	4 TC's	
No. 4 Bearing: Race	Metal temperature	8 TC's	
No. 5 Bearing: Race	Metal temperature	4 TC's	
Carbon Seal	Metal temperature	4 TC's	

Notes: 1 Used in Bill-of-Material compressor rig test only
2 Used in improved compressor rig test only

Thermocouples and/or pressure sensors were installed on disks and in stator cavities to allow calculation of thermal growth for all stages. These calculations were used to determine blade tip clearances.

The seventh and eighth stages each had four locations, spaced approximately 90° apart around the circumference of the case, where blade tip clearances could be measured. Laser probes, which can measure running clearances continuously using a reflected light technique, were installed in these locations through most of the test program. The primary clearance measurements were obtained with these probes. The accuracy of those measurements was verified by periodically replacing each laser probe with a mechanical clearance indicator, which forces an abradable button against the rotating blade tips. The button is later removed and measured to obtain a one-time clearance reading for that test run.

In addition, compressor vibration was monitored during all phases of the test program by vibration pickups mounted to sense horizontal and vertical movement of the rotor.

4.2.3 Bill-of-Material Compressor Rig Test Procedure

The Bill-of-Material compressor rig was mounted in the test facility and all rig and facility systems were checked to insure their satisfactory operation.

Testing began with performance measurements over the entire compressor map with ambient inlet conditions to establish a baseline. In this test, the compressor discharge flow was throttled progressively from well below the operating line to surge at each of twelve rotor speed settings. Performance was then measured with a succession of increased inlet temperatures while holding a typical cruise operating point to simulate the effect of reducing compressor blade tip clearances. Next, performance was measured over the high speed portion of the compressor map with the inlet heated to simulate typical engine cruise conditions. This test was conducted at four selected rotor speeds with progressive throttling of the discharge flow, similar to the baseline test. Performance was also measured over the low speed portion of the compressor map with one, two, three and all four eighth stage bleeds open. Finally, performance was measured along four selected rotor speed lines (both higher and lower than cruise speed) with the inlet screen, which was used in all previous tests to simulate the low pressure compressor exit profile, removed.

4.2.4 Improved Compressor Rig Test Instrumentation

The improved compressor rig used essentially the same types and quantity of instrumentation as the bill-of-material rig to measure flowpath performance and systems parameters. The exceptions are noted on Tables 2 and 3. The improved compressor was also instrumented with strain gages on rotor blades in each stage to measure blade vibrational stresses.

4.2.5 Improved Compressor Rig Test Procedure

The compressor component rig was mounted in the test facility and all rig and facility systems were checked to ensure their satisfactory operation.

Testing of the improved compressor began with a stress survey program, consisting of a series of very slow accelerations along three compressor discharge throttle lines. Preliminary performance data was also obtained which was used mainly to check the instrumentation systems. At the completion of the stress program, stress records were reviewed to verify that stresses in the operating range were within acceptable limits.

A test was run to determine compressor performance with pilot trenches only in the abradable rubstrips. Following this test, the rubstrips were abraded to depths that would be expected in normal engine operation. This was accomplished by performing deceleration transients at increasing inlet temperature levels. More compressor performance testing was then done to define compressor performance with normal compressor wear. Trenches were rubbed-in further by forcing the compressor to surge at low speed with ambient temperature inlet conditions, and at high speed with heated inlet conditions. Performance was reevaluated in the same manner as before.

This testing was similar to that with the bill-of-material compressor in that both ambient and heated inlet air temperatures and screens which simulate upstream distortion in the engine were used.

4.3 Engine Testing

4.3.1 Test Equipment and Facilities

Engine testing of the compressors was accomplished using an experimental engine (X-372). The engine was built to an approximate JT8D bill-of-material configuration, but was instrumented to a much greater degree than a production engine.

The test facility used was X-234, a sea level test stand located in Pratt & Whitney Aircraft's Willgoos Test Facility in East Hartford. The X-234 stand is a gas turbine engine test facility designed to test turbofan and turbojet engines. Testing is conducted at sea level static inlet and discharge pressure conditions. Maximum engine airflow capacity is 249 kg/s (550 lbm/s).

The test engine is supported from an overhead thrust measuring platform. The thrust measurement system can handle up to 111,205 N (25,000 lbf).

Test data is recorded automatically and processed by an on-line computer.

4.3.2 Engine Instrumentation

Table 4 lists the instrumentation used in the engine test to measure compressor and overall engine performance. Static wall pressure taps, installed in stages 7 through 12, were used to evaluate the performance of each stage and the overall compressor efficiency. The taps were installed in the stator trailing edge plane between adjacent stators on the outside wall of the case, and were spaced approximately 120 degrees apart in each stage. The remainder of the instrumentation listed in Table 4 was used to determine engine performance or monitor engine condition. Instrumentation locations are shown in Figure 5.

TABLE 4
Instrumentation for Test Engine X-372

Engine Station or Location*	Parameter	Description
0.0	Bellmouth Screen Total Pressure	4 Kiel Probes
Front of Test Stand Bulkhead	Static Pressure	4 Taps (manometers)
Rear of Test Stand Bulkhead	Static Pressure	4 Taps (manometers)
1.0	Bellmouth Screen Total Temperature	12 Calibrated Thermocouples
1.0	Bellmouth Screen Total Pressure	4 Kiel Probes
2.0	Forward of Inlet Guide Vanes Total/Static Pressure	6 Pitot Static Probes
2.5	Fan Exit Guide Vanes Total Pressure	4 Pole Rakes With 5 Readings Per Rake
2.5	Fan Exit Guide Vanes Total Temperature	16 Individual Temp. Probes, Calibrated Thermocouples
3.0	Low Pressure Compressor Exit Total Pressure	4 Rakes With 5 Readings Per Rake
3.0	Low Pressure Compressor Exit Total Temperature	4 Rakes With 5 Readings Per Rake
4.0	High Pressure Compressor Exit Total Pressure	3 Rakes With 4 Readings Per Rake
4.0	High Pressure Compressor Exit Total Temperature	2 Rakes With 4 Readings Per Rake
Diffuser case	Combustor Static Pressure	1 Pressure Transducer
Diffuser case	Bleed Cavity Turbine Cooling Air Static Pressure	1 Pressure Transducer

TABLE 4 (continued)
Instrumentation for
Test Engine X-372

Engine Station or Location*	Parameter	Description
7.0	Low Pressure Turbine Exit Total Pressure	1 Manifolded Reading From 6 Probes With 6 Samples Per Probe
7.0	Low Pressure Turbine Exit Total Temperature	8 Rakes (Averaged) 1 Reading Per Rake
7.0	Fan Exit Total Pressure	6 Manifolded Pressure Probes
External Edge of Tail Pipe	Static Pressure	4 Taps (manometers)
Fuel Line	Fuel Flow	2 Turbine-Type Flow Meters
Flow Meters	Fuel Temperature	2 Probes
	Net Thrust	2 Strain Gage Load Cells
	Low Pressure Rotor Speed	1 Tachometer
	High Pressure Rotor Speed	1 Tachometer
	Thrust	Strain Gage Load Cell

*See Figure 5 for definition of engine station numbers.

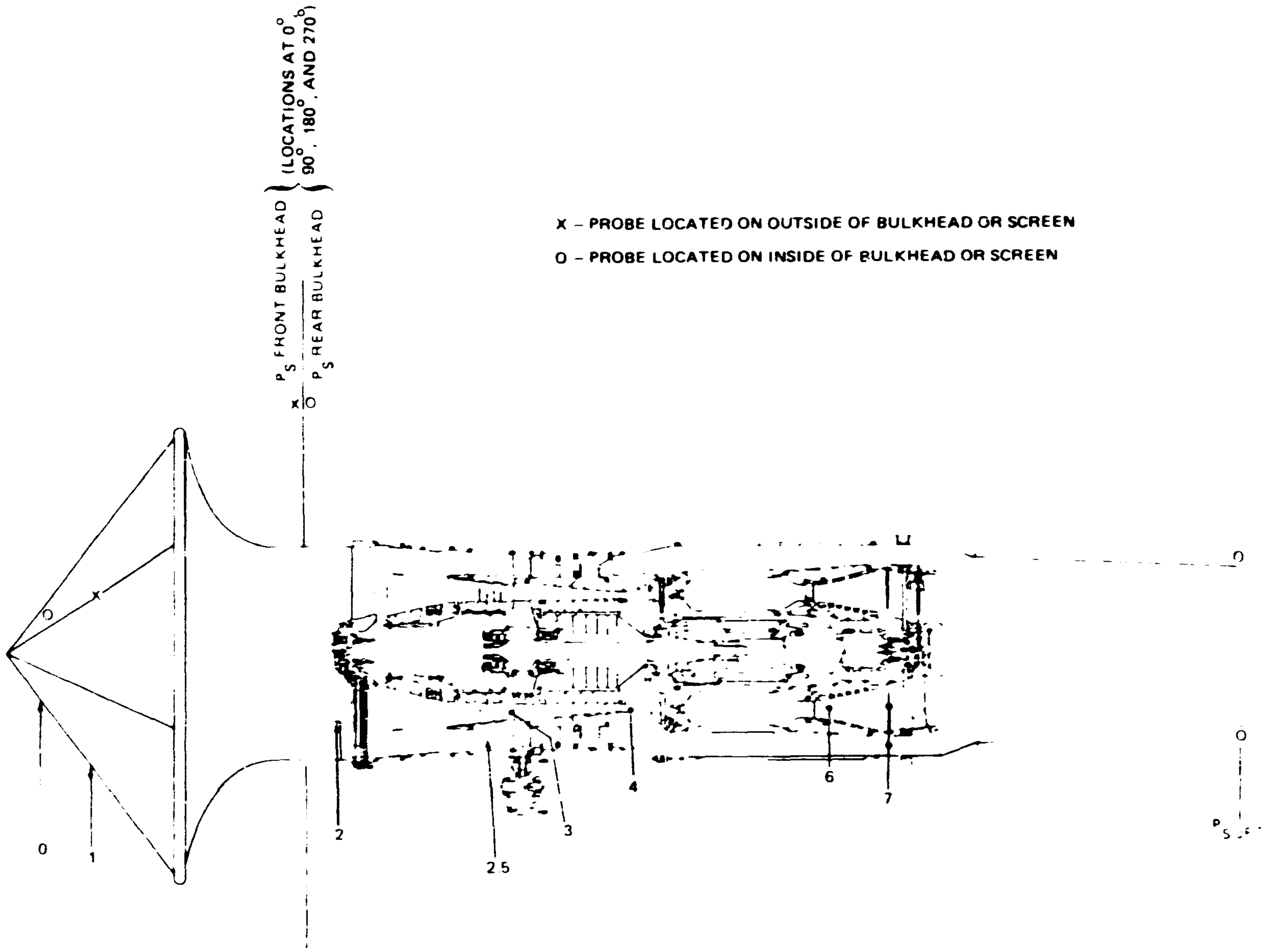


Figure 5 Cross Section of Experimental Engine X-372, Showing Station Numbers.

Measurements from engine instrumentation were collected and processed by an automatic data acquistion system. The system is capable of handling 250 individual millivolt signals, 16 frequency inputs, and up to 422 pressure inputs of various ranges. In addition, the system can produce a printout in engineering units of data collected at the time of testing. These "quick look" calculations consist of thrust specific fuel consumption (TSFC), corrected net thrust, corrected total engine airflow, corrected fuel flow, and corrected rotor speeds. The system has its own control console for use by test personnel to request a data point printout.

4.3.3 Test Procedure

The improved compressor and a bill-of-material compressor were tested back to back in the engine to determine the performance effect of the improved compressor. Calibration checks on the instrumentation and other stand systems were done before, during, and after testing. Testing was not done under humid conditions to avoid biased performance data.

The bill-of-material compressor was installed in the test engine first, and the engine mounted in the test stand. After snakedown testing and a stand systems check, the first five data points were taken at thrust levels from idle to takeoff in approximately 8,900 N (2000 lbf) increments. The engine was then shut down, systems checked, and then restarted. A second data acquisition run was made, taking data points at thrust levels from idle to takeoff in approximately 8,900 N (2000 lbf) increments, but at power levels staggered with the those used in the first five point data acquisition run.

After completing the bill-of-material testing, the engine was disassembled to allow installation of the improved compressor. While the engine was disassembled, minor repairs were made as required, but no modifications were made that would affect performance.

The engine with the improved compressor installed was remounted in the same test stand, and once again stand systems were shaken down and checked out before testing was started. The engine was then tested for performance with pilot trenches only in the abradable rubstrips. All accelerations and decelerations were done slowly to minimize blade tip interaction with the abradable material. Ten data points at equally spaced thrust settings were obtained in two separate data acquisition runs, as described for the bill-of-material test.

A 'run-in' procedure was performed to further trench the abradable rubstrips, while keeping the interaction rate low. Snap acceleration/ decelerations were done to increasing power levels, until a snap acceleration/deceleration had been done to full takeoff thrust. The trenches in the abradable rubstrips at this point simulated those expected in an 'in-service' engine.

Following the run-in procedure, performance data was obtained on the fully trenched compressor, using the same basic test procedure as was used with the bill-of-material configuration. The test was concluded, the engine removed from the test stand, and disassembled for inspection.

5.0 DISCUSSION OF RESULTS

5.1 Overview

The improved high pressure compressor improved thrust specific fuel consumption 1.0% over the full range of power settings at sea level static conditions, relative to an engine equipped with the bill-of-material high pressure compressor. Engine exhaust gas temperature (EGT), after correction for a temperature profile shift, decreased 10°C or more over the takeoff/climb power range at sea level static conditions. A cruise thrust specific fuel consumption improvement of 0.7% was estimated based on the sea level test results. Surge margin also increased as a result of a downward shift in the operating line observed in engine testing, and an upward shift in the surge line observed in rig testing.

5.2 Rig Results

Rig test results demonstrated a modest improvement in compressor efficiency, a significant improvement in surge margin, acceptable stress levels in the blades, and satisfactory abradability of the nichrome rubstrips. Together, these results encouraged continuation of the program to the engine test phase.

5.2.1 Performance Results

The compressor rig test efficiency results at a typical cruise rotor speed (9000 RPM) are summarized on Figure 6. The cruise design clearances in both compressors occur at an inlet air temperature of 127°C (260°F), where the data shows an efficiency advantage of 1.2 points for the improved compressor.

Since the corrected high pressure rotor speed in the engine at sea level static takeoff power conditions is also approximately 9000 RPM, Figure 6 can be used to determine the improvement at this condition as well. At 177°C (350°F) inlet temperature, which produces clearances expected at takeoff, the improved compressor shows an efficiency improvement of 1.4 percent.

The surge line advantage of the improved compressor is shown on Figure 7, which compares the two compressors at approximately equal inlet air temperatures. The comparison is made at higher temperatures at the higher rotor speeds, and at ambient temperature at the lower rotor speeds, to approximate the blade tip clearances encountered in an operating engine. The improvement shown is 1% at cruise conditions and about 4% in the idle and off-idle speed range, based on the NASA surge margin definition with no operating line shift. The engine test results showed that the operating line actually shifts downward with the improved compressor, which further improves the surge margin.

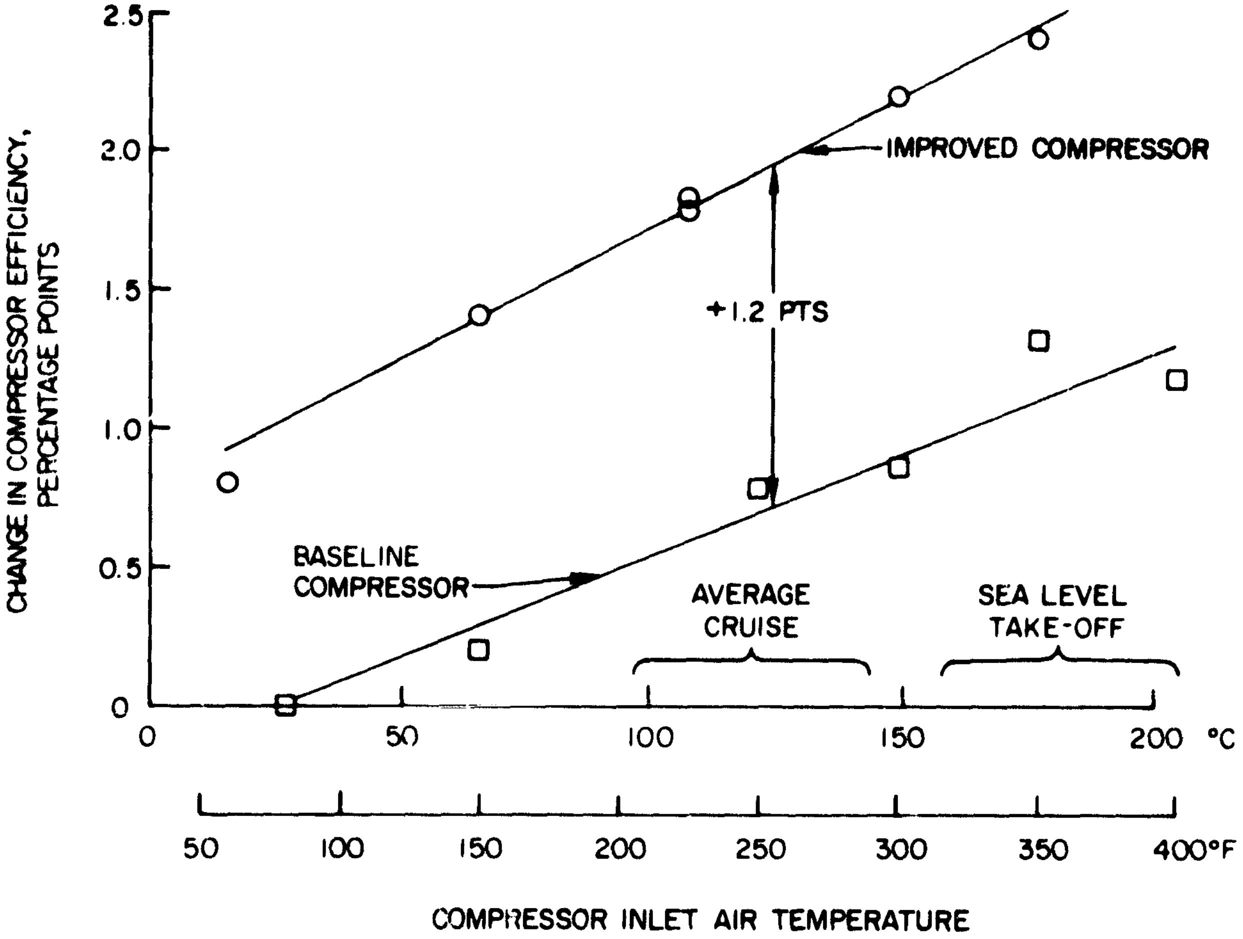


Figure 6 Compressor Efficiency vs Inlet Air Temperature (9000 RPM Corrected Rotor Speed). The efficiency advantage of the improved compressor is 1.2 points at average cruise conditions and 1.4 points at takeoff.

5.2.2 Stress Results

Strain gage readings taken during slow acceleration of the compressor along three discharge throttle lines showed that blade stresses in all stages were well within limits for safe operation in the engine. No highly stressed resonances or flutters were observed in the normal operating range. The highest stress measured was in stage 9, which was less than 30 percent of the acceptable limit. The strain gages were also monitored during the rub-in portion of the test program and did not indicate any significant change in the vibratory characteristics due to the rubbing. Based on these data no vibratory stress problems were anticipated for the engine test with this high pressure compressor.

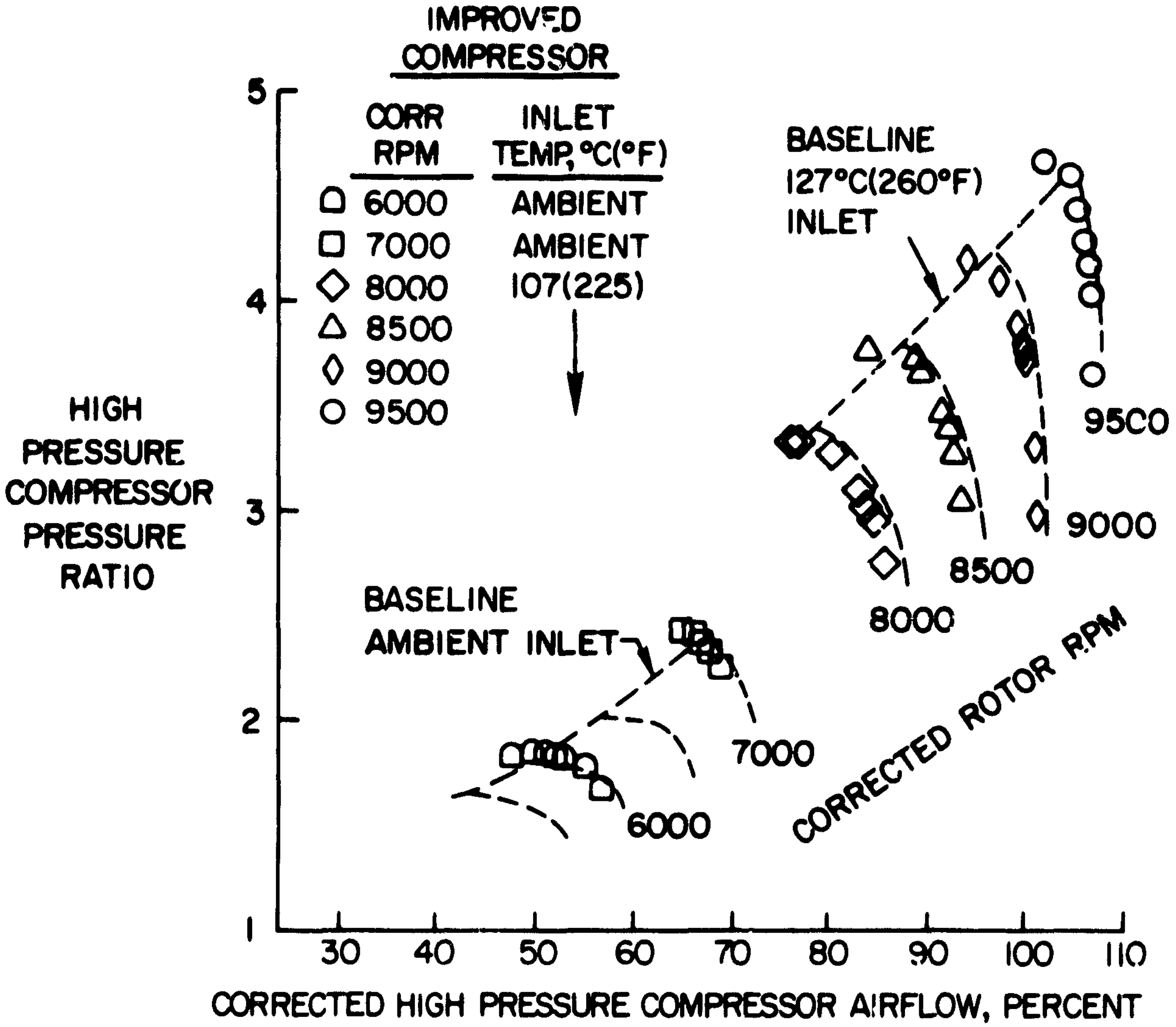


Figure 7 Comparison of Compressor Maps. The improved compressor has significant surge line advantage at both ends of the rotor speed spectrum. Inlet air temperatures shown result in blade tip clearances encountered in normal engine operation.

5.2.3 Hardware Condition

The improved compressor rig was removed from the test facility after completing 109.33 hours of testing. Following disassembly, visual inspection of the hardware indicated that the blades and abradable rubstrips were in good condition after the intentional rub-in of the compressor as shown in Figure 8 and Figure 9. All stages but the seventh stage rubbed. The seventh stage was not intended to rub due to its unique rotor attachment. The deepest rub occurred in the tenth stage as shown on Table 5. Table 5 also shows that except for the thirteenth stage all the rubbed stages achieved their desired rubbed-in depth within 0.015 cm (0.006 inches). The thirteenth stage was within 0.030 cm (0.012 inches).

TABLE 5
Improved Compressor Rig Trench Depths

Stage	Design Rubbed Trench Depth, cm (inches)	Actual Trench Depth, cm (inches)
7	0.097 (0.038)	0.097 (0.038)
8	0.069 (0.027)	0.066 (0.026)
9	0.069 (0.027)	0.066 (0.026)
10	0.069 (0.027)	0.079 (0.031)
11	0.069 (0.027)	0.053 (0.021)
12	0.069 (0.027)	0.053 (0.021)
13	0.081 (0.032)	0.051 (0.020)

5.3 Engine Results

Data from the back-to-back JT8D engine tests showed an advantage of 1.0% in TSFC for the improved compressor, but did not show a significant exhaust gas temperature improvement that should accompany the TSFC improvement. Analysis of the data led to the conclusion that the improved compressor changed the downstream flow profiles to the extent that the compressor exit and turbine exit thermocouple readings were not comparable with those in the bill-of-material compressor test. These inconsistencies were corrected by assuming that the only component efficiency change in the engine was in the high pressure compressor, and that parameters other than the compressor exit and turbine exit temperatures were measured correctly. The corrected results are discussed in the following paragraphs.

Figure 8 Compressor Blade Tip After Rubbing. The blades were in good condition after the intentional rub-in of the compressor.

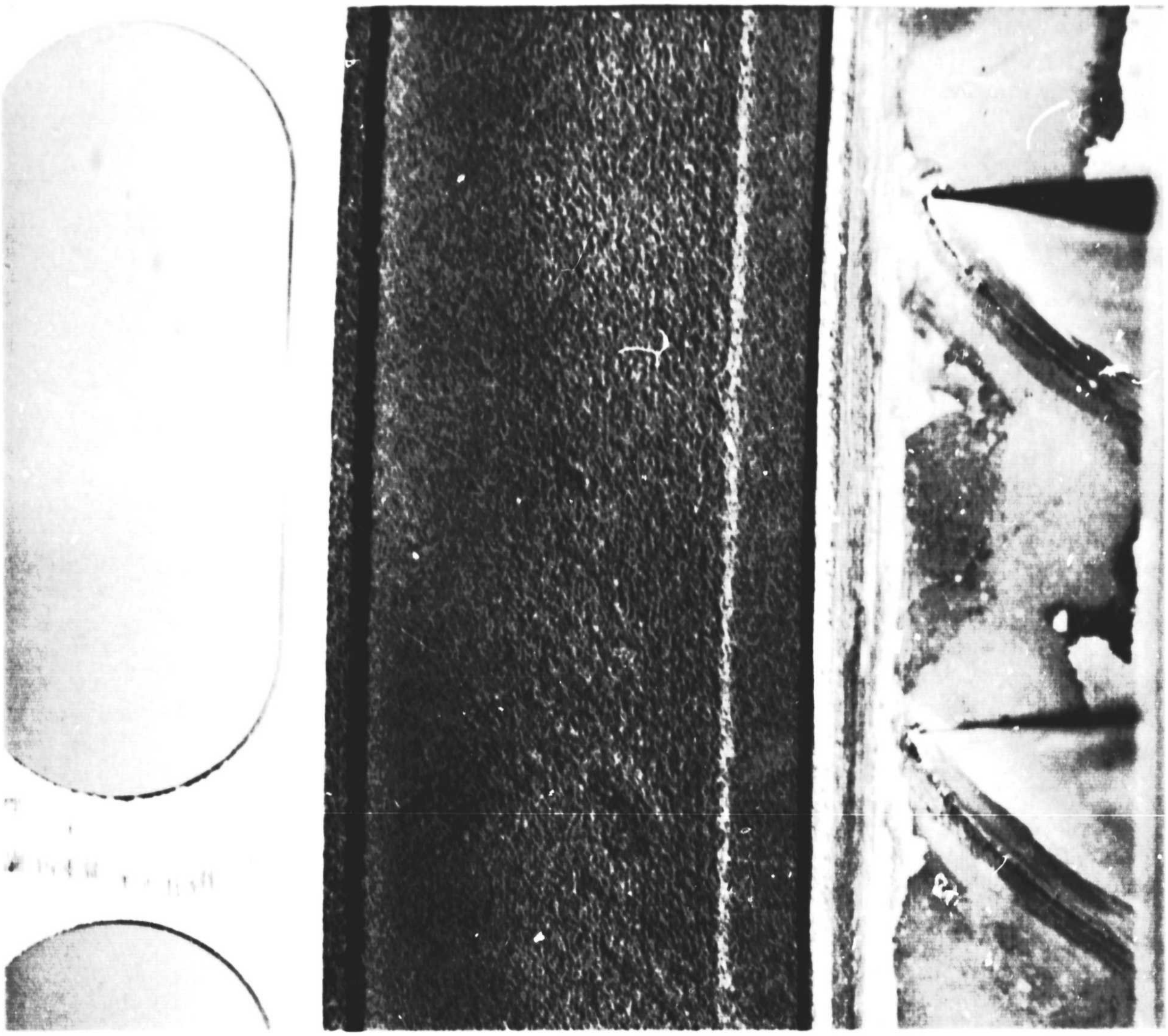


Figure 9 Typical abradable rubstrip after rig testing. The rubstrips were in good condition after the intentional rub-in of the compressor.

5.3.1 Performance Improvements

The 1% specific fuel consumption improvement stated earlier for the improved compressor was demonstrated over a wide range of engine thrust settings (see Figure 10) <u>after</u> the compressor abradable rubstrips had been rubbed-in to the extent expected in airline service. The pre-rub performance was considerably better, as shown in Table 6.

In Figure 11 the improvement or reduction in corrected exhaust gas temperature relative to the engine with the bill-of-material high pressure compressor is shown. Over the takeoff and climb power range at sea level static, the improvement is 10°C or more. At takeoff thrust (68,900 N or 15,500 lbf) the improvement is 11°C compared to the original prediction of 8°C.

The TSFC and EGT improvements at the critical operating conditions in typical airline service, as defined in reference 1, were estimated based on the test results at sea level static conditions. The results, presented on Table 7, showed a specific fuel consumption impovement of 0.7% at the typical cruise condition of 30,000 feet, 0.8 mach number, 90% maximum cruise thrust. A modern computer simulation of the JT8D engine cycle characteristics, reflecting the results of recent tests of JT8D engines in an altitude test facility, was used to make these estimates. The results are compared in Table 7 to the 1977 predictions for the Ref. 1 study, which were made using the less sophisticated simulation that was available at that time. The updated estimates show significantly less advantage for the improved compressor at the critical altitude conditions despite the fact that the demonstrated sea level advantage is better than predicted.

TABLE 6
Performance Effect of Intentional Abradable Rub-In

Thrust Specific Fuel Consumption Improvement, %

NET THRUST (SEA LEVEL STATIC)	PRE-RUB-IN TEST	POST RUB-IN TEST	LOSS DUE TO RUB-IN
68,900 N (15,500 lbf)	1.7	1.0	0.7
44,500 N (10,000 lbf)	1.4	1.0	0.4

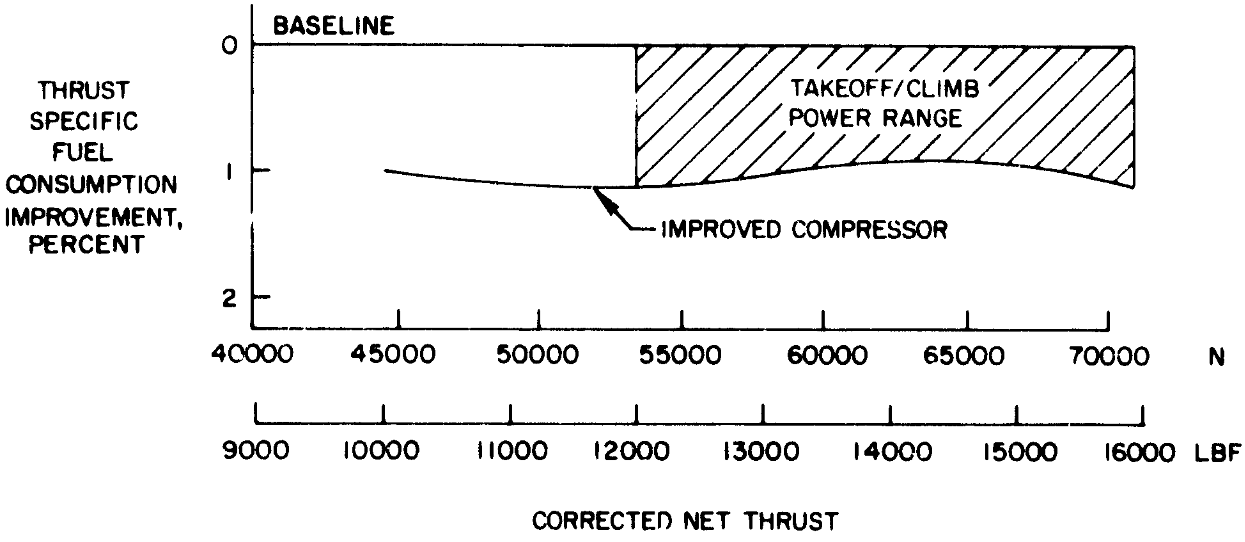


Figure 10 Thrust Specific Fuel Consumption Improvement at Sea Level Static Conditions After Rub-In of Abradable Rubstrips. The advantage of the improved compressor is essentially independent of engine power setting.

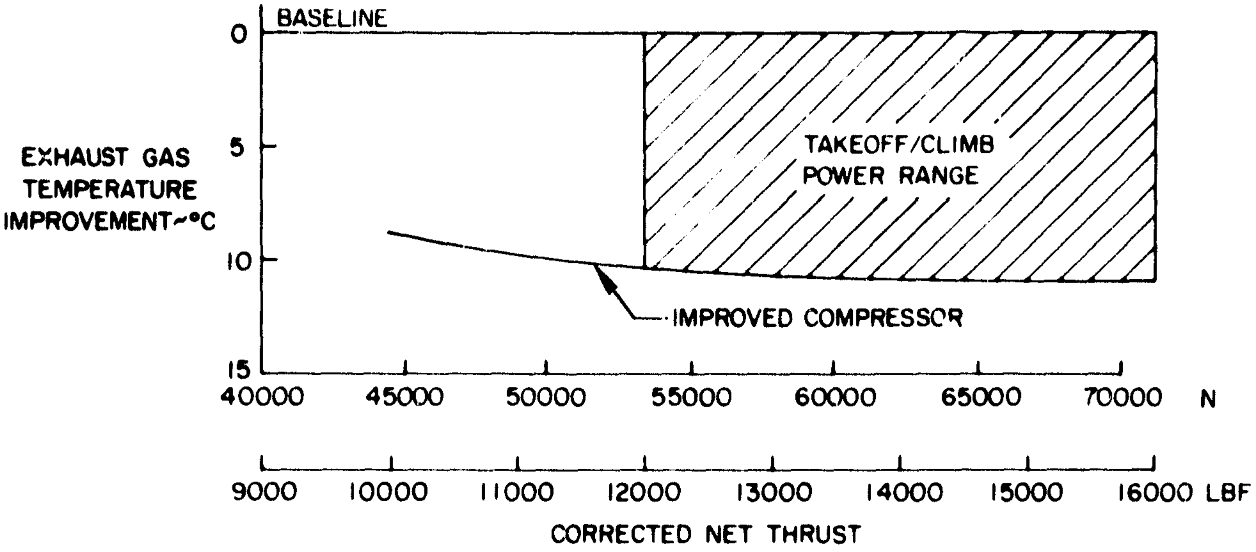


Figure 11 Corrected Exhaust Gas Temperature Improvement at Sea Level Static Conditions. The advantage of the improved compressor is nearly constant over the takeoff and climb power range.

5.3.2 Compressor Operating Line Shifts

An operating line shift in the high pressure compressor, which results from the engine rematch effect of the improved compressor efficiency, was observed in the engine testing and is shown on Figure 12.

This downward shift of the operating line combined with the surge line improvement demonstrated in the rig tests resulted in a surge margin increase of approximately 4% in the rotor speed range used for takeoff, climb, and cruise operation of the engine.

A downward operating line shift was observed in the low pressure compressor and is shown on Figure 13. This shift, which increased surge margin 2% or more over the normal operating range, is a further manifestation of the increased efficiency of the improved compressor.

The demonstrated surge margin increases in both compressors indicate that the operating stability of the JT8D engine would be enhanced with the improved compressor. However, the JT8D engine does not really need enhanced stability, and the extra surge margin can be traded for additional TSFC improvement with further design and development effort. Compressor efficiency can be increased further while lowering the surge line by means of relatively minor aerodynamic modifications in the high pressure compressor. Engine cycle efficiency can be increased by adjusting turbine nozzle areas to raise the operating lines on both compressors. These trades were not accomplished under the subject program because of schedule and budget constraints.

TABLE 7
Performance Improvements at Critical Airline Operating Conditions

		% Thrust Specific Fuel Consumption Improvement		Exhaust Gas Temp. Improvement, °C	
Condition	Mach No.	1977 Prediction	Test Results	1977 Prediction	Corrected Test Results
Sea Level Takeoff (66,700 N or 15,000 lbf)	0	0.9	1.0	8	11
Max. Climb (7,900 m or 26,000 ft.)	0.7	0.9	0.5*	8	7*
90% Max. Cruise, (9,100 m or 30,000 ft.)	0.8	0.9	0.7*	-	-
40% Max. Cruise, (Hold) (3,000 m or 10,000 ft.)	0.45	1.4	1.0*	-	-

*Calculated based on test results using computer simulation

5.3.3 Compressor Condition After Engine Test

The improved compressor was removed from the engine and disassembled after completing 18.41 hours of performance testing. Visual inspection of the hardware indicated that it was in excellent condition except for the the twelfth stage rubstrip which had three locations where excessive cratering of the abradable material occurred. The abradable material in this stage is believed to have encountered damage during assembly and broke away during subsequent running. The blades and other abradable rubstrips were in excellent condition after the break-in and performance test program. All stages rubbed except the seventh stage, which was designed to avoid rub. The deepest rubs occurred on stages 10, 11, and 12. Rubbing was encountered over the entire rub strip circumference and over the entire blade tip surface except for stage nine. Only the leading edge portion of the ninth stage blade tips rubbed.

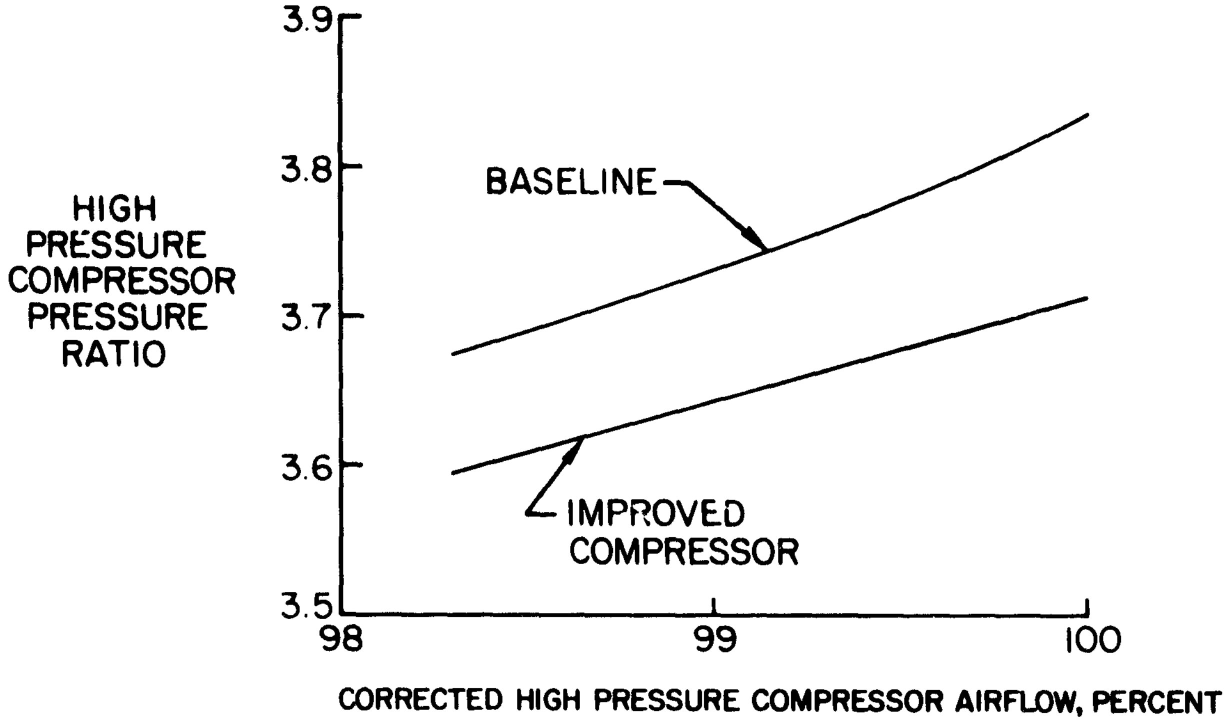


Figure 12 High Pressure Compressor Operating Line Comparison. The operating line was lowered significantly by the engine rematch that resulted from the increased efficiency of the improved compressor.

The boundaries of the pilot trenches were fully engaged (except for the seventh and ninth stages) by the engine break-in testing, indicating proper sizing and positioning of the pilot trenches.

The first two columns of Table 8 show that the depth of the post-test trench achieved the nominal design depths within 0.015 cm (0.006 inches), indicating that the blade tips were running near the desired line-on-line position at the equivalent cruise condition. Subtracting the pilot trench depth from the post test trench depth indicates the extent of rubbing, which may be seen in the last column. The results indicate that the engine test accomplished the desired degree of rubbing. This fact, combined with the excellent condition of the blade tips and rubstrips verifies the abradability characteristics of the sprayed nichrome material in the engine environment.

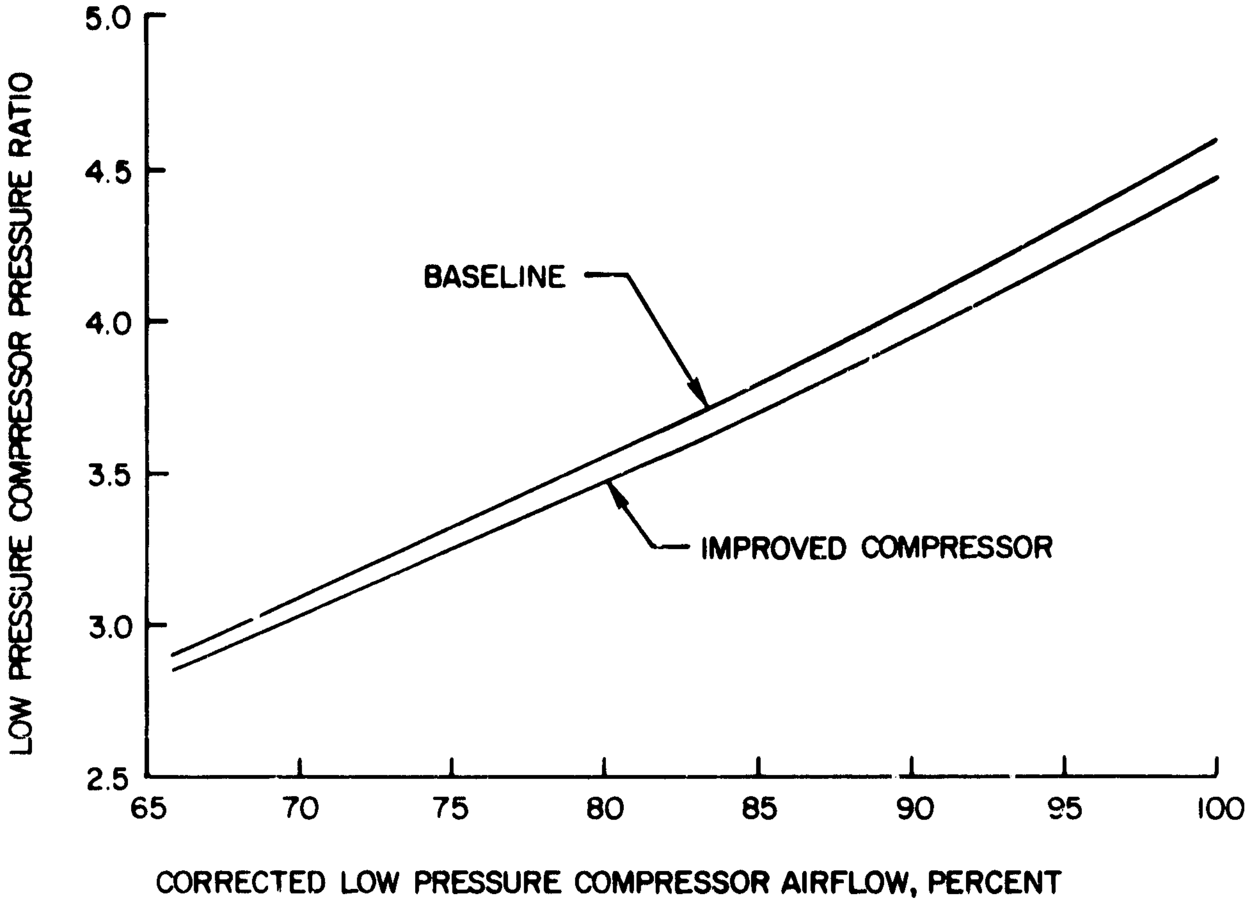


Figure 13 Low Pressure Compressor Operating Line Comparison. The operating line was lowered significantly by the engine rematch that resulted from the improved high pressure compressor.

TABLE 8
Engine Running Trench Depths

STAGE	Nominal Design Trench Depth, cm (in)	Post Test Trench Average Depth, cm (in)	Pilot Trench Depth, cm (in)	Extent of Rubbing, cm (in)
7	0.114 (0.045)	0.107 (0.042)	0.107 (0.042)	0
8	0.061 (0.024)	0.051 (0.020)	0.038 (0.015)	0.013 (0.005)
9	0.061 (0.024)	0.051 (0.020)	0.038 (0.015)	0.013 (0.005)
10	0.061 (0.024)	0.076 (0.030)	0.038 (0.015)	0.038 (0.015)
11	0.061 (0.024)	0.064 (0.025)	0.038 (0.015)	0.025 (0.010)
12	0.061 (0.024)	0.071 (0.028)	0.038 (0.015)	0.033 (0.013)
13	0.066 (0.027)	0.066 (0.026)	0.051 (0.020)	0.015 (0.006)

6.0 ENERGY IMPACT

The ECI-PI Feasibility Analysis conducted in 1977 (Reference 1) estimated that the improved compressor would result in a 1 percent fuel saving in a typical airline route system using the "Originally Predicted" specific fuel consumption improvements listed in Table 7. The 1977 study also predicted that the concept would be very acceptable to the airlines in new engines, but only marginally acceptable as a retrofit for existing engines. This prediction was based on the 1 percent fuel saving estimate, the engine cost effects shown in Table 9 and the airline payback period evaluation results shown on Table 10. When the airline acceptability results were combined with the then current engine market projection, the cumulative fuel saving for the world fleet of JT8D powered airplanes shown in Table 11 was estimated.

TABLE 9
1977 Engine Cost Effects Evaluation
(From Reference 1)

Parameter	Effect
Engine Price Change, $	10,000
Kit Price, $	43,000
Maintenance Cost Charge, $/man-hour	
Materials	0
Labor @ $30/man-hour	-1.90
Base Fuel Price (Domestic), 1977 dollars/gallon (dollars/liter)	0.35 (0.09)

Applying the engine specific fuel consumption improvements that resulted from the improved compressor test program (Table 7) to the typical airline route system shows a fuel saving of 0.7 percent, compared to 1 percent predicted. The airline acceptance of the concept cannot be reevaluated quantitatively because engine hardware price effects have not been updated. Qualitatively, based on the fact that fuel prices have increased much faster than engine parts prices since 1977 and allowing for the smaller percent fuel saving, it is estimated that airline payback periods will stay the same or improve slightly relative to the 1977 results. However, since 1977 there has been a shift in airline interest away from improving the JT8D engines and toward replacement with advanced, high bypass ratio engines. Because of this shift, current plans at Pratt and Whitney Aircraft do not include completing the development of the improved compressor.

TABLE 10
1977 Airline Cost Evaluation
(from Reference 1)

Parameter	Boeing 727-200	Douglas DC-9
Total Operating Cost Change, $/year	-31,450	-18,430
Required Airline Investment Change, $		
New Buy	+37,050	+ 25,900
Retrofit	+159,320	+111,370
Payback Period, years		
New Buy	1.2	1.4
Retrofit	5	6

TABLE 11
1977 Fuel Saving Evaluation
(World Fleet of 727 and DC9 Aircraft, from Reference 1)

Parameter	
Fleet Fuel Saved, percent	1.0
Start of Service Date	3/81
Number of Engines Affected	
New Buy	560
Retrofit	1660
Total	2220
Cumulative fuel saved, 10^6 liters (10^6 gallons)	
New Buy	310 (82)
Retrofit	723 (191)
Total	1033 (273)

7.0 CONCLUDING REMARKS

The improved JT8D compressor has demonstrated its ability to reduce the fuel consumption and exhaust gas temperature of JT8D engines significantly. It also demonstrated a large excess of surge margin that can be converted to additional performance improvements by refinements in the compressor and engine rematching. However, current plans at Pratt & Whitney Aircraft do not include completing development of the improved compressor because of the shift in airline interest away from improving the JT8D engine family and toward replacment with advanced, high bypass ratio engines.

APPENDIX A

PRODUCT ASSURANCE

INTRODUCTION

The Product Assurance system for this program provided for the establishment of quality, reliability, safety, and maintainability requirements and determination of compliance with these requirements, from the design stage through the procurement of hardware until the completion of the experimental test. The system ensures the detection of nonconformances, their proper disposition, and effective corrective action.

Materials, parts, and assemblies were controlled and inspected to the quality requirements of the JT8D High Pressure Compressor Performance Improvement Program. A full production-type program requires inspection to the requirements indicated on the drawings and pertinent specifications. On experimental programs such as this one, Engineering may delete or waive noncritical inspection requirements that are normally performed by Experimental Quality Assurance.

Parts, assemblies, components and end-item articles were inspected and tested prior to delivery to ensure compliance to all established requirements and specifications.

The results of the required inspections and tests were documented as evidence of quality. Such documents were made available upon request to designated Government Representatives for on-site review.

Standard Pratt & Whitney Aircraft Commercial Products Division Quality Assurance Standards currently in effect and consistent with Contractual Quality Assurance Requirements were followed during execution of this task. Specific standards were applied under the contract in the following areas:

1. Purchased Parts and Experimental Machine Shop
2. Experimental Assembly
3. Experimental Test
4. Instrumentation and Equipment
5. Data
6. Records
7. Reliability, Maintainability and Safety

1. PURCHASED PARTS AND EXPERIMENTAL MACHINE SHOP

Pratt & Whitney Aircraft has the responsibility for the quality of supplier and supplier-subcontractor articles, and effected its responsibility by requiring either control at source by Pratt & Whitney Aircraft Vendor Quality Control or inspection after receipt at Pratt & Whitney Aircraft. Records of inspections and tests performed at source were maintained by the supplier as specified in Pratt & Whitney Aircraft Purchase Order requirements.

Quality Assurance made certain that required inspections and tests of purchased materials and parts were completed either at the supplier's plant or upon receipt at Pratt & Whitney Aircraft.

Receiving inspection included a check for damage in transit, identification of parts against shipping and receiving documents, drawing and specification requirements, and a check for Materials Control Laboratory release. Positive identification and control of parts was maintained pending final inspection and test results.

The parts manufactured in Pratt & Whitney Aircraft Experimental Machine Shop were subject to Experimental Construction procedures to ensure that proper methods and responsibilities for the control of various quality standards were followed.

Drawing control was maintained through an engineering drawing control system. Parts were identified with the foregoing system. Quality Assurance personnel are responsible for reviewing drawings to ensure that the proper inspection requirements are indicated.

Non-conforming experimental articles involved in this program were detected and identified by Experimental Construction, by vendors, or by Experimental Quality Assurance. Non-conforming articles were reviewed by Engineering and Experimental Quality Assurance personnel in deciding disposition. Records of these decisions, including descriptions of the non-conformances, were maintained by Experimental Quality Assurance and reviewed by the cognizant Government Quality Assurance Representative.

2. EXPERIMENTAL ASSEMBLY

In Experimental Assembly the compressor rigs and test engines were assembled for evaluation of performance in accordance with the program requirements. Established Experimental Construction procedures were employed to perform the work and to ensure that proper responsibilities and methods for the control of various quality standards were followed.

3. EXPERIMENTAL TEST

The rig and engine performance and stability tests were performed under Experimental Test Department procedures which cover sea level stand testing. Instrumentation was provided by the Instrumentation Development Department. All equipment was monitored and controlled by Experimental Test Procedures.

4. INSTRUMENTATION AND EQUIPMENT

Instrumentation and equipment were controlled under the Pratt & Whitney Aircraft Quality Assurance Plan which includes controls on the measuring and test equipment in Experimental Test to specific procedures. All testing and measuring equipment carries a label indicating its status (controlled, monitor or calibrated) and, when applicable, the date of calibration and next due date.

The accuracy of gages and equipment used for quality inspection functions was maintained by means of a control and calibration system. The system provided for the maintenance of reference standards, procedures, records, and environmental control when necessary. Gages and tools used for measurements were calibrated utilizing the aforementioned system.

Reference standards were maintained by periodic reviews for accuracy, stability, and range. Certificates of Traceability establish the relationship of the reference standard to standards in the National Bureau of Standards (NBS). Calibration of work standards against reference standards was accomplished in environmental-controlled areas.

Initial calibration intervals for gaging and measuring equipment were established on the basis of expected usage and operating conditions. The computerized gage control system provided a weekly listing of all gages and equipment requiring calibration.

5. DATA

Performance and stability data from the sea level rig and engine stands were recorded on the Steady State Data System. This system is certified to procedures which specify calibration intervals for the components requiring laboratory certification. During each data acquisition the system recorded certified reference parameters, providing an "on-line" verification that the systems were performing properly.

These "confidence" data were reviewed at the time of the run and were later analyzed to provide an overall assessment of the system operations.

6. RECORDS

Quality Assurance personnel ensured that records pertaining to quality requirements were adequate and maintained as directed in Experimental Quality Assurance procedures and in accordance with contractual requirements.

Engine build and operating record books were maintained in accordance with Engineering Department requirements. In addition, a consolidated record of operating times for each component test article used in the experimental program was maintained.

7. RELIABILITY, MAINTAINABILITY AND SAFETY

Standard production engine design techniques and criteria, which consider product reliability and maintainability in context with all other requirements (such as performance, weight and cost), were used in defining the parts for the improved high pressure compressor. Production fabrication standards were waived in some cases to allow rework of Bill-of-Material forgings and semi-finished parts to obtain the desired configuration for rig and engine tests with minimum program cost and lead time. The structural adequacy of such parts for the relatively short test program was checked by analysis and confirmed by successful completion of the tests without encountering reliability problems.

The compressor improvements were designed with maintainability features similar to the bill-of-material parts. However, these features were not demonstrated as part of the subject program.

The safety activities at Pratt & Whitney Aircraft and as considered on this program are designed to fully comply with the applicable sections of the Federal Aviation Regulations, Part 33 Air Worthiness Standards: Aircraft Engines, as established by the Federal Aviation Administration.

REFERENCE

1. Gaffin, W. O. and Webb, D. E., "JT8D and JT9D Jet Engine Performance Improvement Program Task 1 Feasibility Analysis Final Report", NASA CR-159449, April 1979 (PWA-5515-38)