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JT9D Ceramic Outer Air Seal System Refinement Program-Phase II

by

L. T. Shiembob

UNITED TECHNOLOGIES CORPORATION
PRATT & WHITNEY AIRCRAFT GROUP
COMMERCIAL ENGINEERING

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NASA Project Manager, Mr. J. E. McAulay Project Engineer, T. N. Strom
Engine Component Improvement Office
NASA - Lewis Research Center, 21000 Brookpark Rd., Cleveland, Ohio 44135

16. ABSTRACT

The sprayed ceramic gas turbine outer air seal system was tested in two JT9D engines to substantiate the abradability and durability of the seals. Of particular significance was that one of the tests, a 150 hour 1000 cycle endurance program at nominal JT9D operating conditions, was completed with minimal effect on the seals and received Federal Aviation Administration cognizance with respect to potential field service use by the airlines. The other engine test completed 1825 endurance cycles at severe operating conditions and no burn-through or other serious defects in the structural integrity of a seal segment was observed.

These test results combined with other Pratt & Whitney Aircraft engine tests substantiate the potential of the ceramic outer air seal system to attain the durability goal of 5000 hour engine operating capability.

Both engine tests subjected the seals to intentional blade rubs and demonstrated good abradability with volume wear ratios greater than 100, far exceeding the design goal of 10. The improved volume wear ratio will allow the turbine tip clearance to be reduced, thereby resulting in an estimated thrust specific fuel consumption improvement of 0.3 percent.

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Foreword

The JT9D Ceramic Outer Air Seal Program is part of the Engine Component Improvement-Performance Improvement (ECI-PI) Project conducted by Commercial Engineering of Pratt & Whitney Aircraft, United Technologies Corporation, under sponsorship of the National Aeronautics and Space Administration-Lewis Research Center. The engine tests described in this report were completed by the end of 1981 and represent the final evaluation of the sprayed ceramic seal refinement, design and fabrication effort reported previously in NASA CR-165554.

Mr. J. E. McAulay and Mr. T. N. Strom of the NASA Lewis Research Center were the Project Manager and Project Engineer, respectively, for the contract. Dr. R. C. Bill of the United States Army Research and Development (R&D) Lab served as technical advisor.

Mr. William O. Gaffin was the Program Manager for Pratt & Whitney Aircraft. The program was under the technical direction of Mr. Lawrence T. Shiembob who was assisted by Senior Engineers David Cloud and James Hyland.

This report, which was prepared under the technical direction of Mr. Shiembob, has been assigned the Commercial Engineering, Pratt & Whitney Aircraft Internal Report Number PWA-5515-175.

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1.0 Summary

The sprayed ceramic gas turbine outer air seal system that resulted from the design and process refinements conducted under an earlier phase of the Engine Component Improvement-Performance Improvement (ECI-PI) program was tested in two JT9D engines. Both tests subjected the seals to: 1) intentional blade rubs to demonstrate the abradability of the seal and therefore the capability of improving engine performance by reducing engine clearances, and 2) endurance cycles to evaluate the durability of the seal system.

Of particular significance was that one of the tests was planned for, and received, cognizance by the Federal Aviation Administration (FAA) with respect to potential field service use by the airlines of the sprayed ceramic seal system.

Both engine tests demonstrated good abradability in the intentional rub tests with volume wear ratios (seal volume removed divided by blade tip wear) greater than 100. The volume wear ratio obtained far exceeded the design goal of 10 and will allow the turbine tip clearance to be reduced by at least 0.025 cm (0.010 in) relative to the JT9D bill-of-material seal system and result in an estimated thrust specific fuel consumption improvement of 0.3 percent.

One of the engine tests, a 150 hour 1000 cycle endurance program at nominal JT9D operating conditions, was completed with minimal effect on the seals. A FAA representative inspected the seals before and after the engine test, satisfying that requirement for future FAA approval for field use. The other engine test completed 1825 endurance cycles at severe operating conditions which was substantiated by the condition of several engine components. An inspection of the condition of the seals after this test indicated that although spalling had occurred which would have negated some of the performance benefits attributable to the ceramic seal system, no burn-through or other serious defects in the structural integrity of a seal segment was observed.

These test results combined with other Pratt & Whitney Aircraft engine tests substantiate the potential of this seal system to attain the durability goal of 5000 hour engine operating capability.

The concept of a sprayed ceramic turbine gas path seal is making the transition from laboratory possibility to production reality. The benefits of improved engine performance and higher temperature capability, demonstrated under this program, provide the incentive for ceramic seals to be considered a desirable design feature by the Gas Turbine Industry for both future and current high performance gas turbine engines. As with any new design, however, incorporation of a ceramic seal system provides an additional risk to the engine manufacturer.

Studies can be conducted to assess the benefit and debit for each application. The risk to the manufacturer lies in the estimate of the durability of the ceramic seal for each application which, at this time, because of the minimal engine test information available, is relatively uncertain.

The uncertainty lies in the lack of a proven method to analytically predict the life of a ceramic seal system for a given application and, therefore, the possibility that engine endurance or field testing will indicate the need to redesign and retest.

An analytical model to define ceramic seal system durability for a given engine application is required to promote use of this design feature by the Gas Turbine Industry and, thereby, maximize energy conservation and minimize our dependence on foreign oil. Development of an analytical life prediction model for ceramic seals should be pursued. It is anticipated that the model will be capable of a life assessment of various forms of ceramic seal systems and utilize the extensive property, rig and engine test data already generated by this program to verify model accuracy.

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2.0 Introduction

National energy demand has outpaced domestic supply, creating an increased United States dependence on foreign oil. This increased dependence was dramatized by the 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 were felt in the air transport industry as well as other forms of transportation. As a result of these experiences, the government, with the support of the aviation industry, initiated programs aimed at both the supply (sources) and demand (consumption) aspects of the problem. The supply problem is being investigated by looking at increasing fuel availability from such sources as coal and oil shale. Efforts are currently underway to develop engine combustor and fuel systems that will accept fuels with broader specifications.

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 approach such as a turboprop. Although studies have indicated large reductions in fuel consumption usage are possible with advanced turbofan or turboprop engines (e.g., 15 to 40 percent), any significant fuel savings impact of these approaches is at least fifteen 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 (ECI) Program is the element of the ACEE Program directed at reducing fuel consumption of current commercial aircraft engines. The Engine Component Improvement (ECI) Program consists of two parts: Engine Diagnostics and Performance Improvement. 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. These concepts were then assessed for technical and economic merit. This assessment included a determination of airline acceptability (measured by the amount of time the concept would require to pay for itself, or "payback period"), 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 McDonnell Douglas aircraft companies, and American, United and Trans World Airlines, and is reported in Reference 1.

In the Feasibility Analysis, the JT9D Ceramic Outer Air Seal concept was selected for development and evaluation because of its fuel savings potential and attractive airline payback period. Under the feasibility study, the concept was predicted to have a potential fuel savings of 1,953,000,000 liters (516,000,000 gallons), and a payback period under a year for installations in both new and existing engines in all aircraft. This is well within the five year payback period defined as the acceptability limit in the study.

The goal of the Ceramic Outer Air Seal Program was to produce a cost effective and durable seal system that can reduce engine operating clearances by at least 0.025 cm (0.010 in). The seal should have a life of 5000 hours under typical engine operating conditions without compromising any of the other desirable properties of the bill-of-material configuration.

The first step in the ECI-PI sponsored program was a ceramic seal technology effort reported in Reference 2 which culminated in a test of ceramic outer air seals in a JT9D engine that demonstrated encouraging abradability (three ceramic seals were rubbed to a maximum depth of 0.060 cm (0.024 in) with an insignificant amount of blade wear) and good hardware condition (the seals sustained very minor laminar cracking).

The technology effort established a baseline for a seal system refinement effort reported in Reference 3 which resulted in substantial improvements in the thermal shock tolerance and abradability properties of the ceramic system. These improvements, which were demonstrated in rig tests, were obtained by refinement and optimization of the plasma spray process and the metal substrate design. Two engine sets of the improved seal system were fabricated for the JT9D engine test program which is the subject of this report.

Section 3.0 of this report describes the improved seal system. Section 4.0 describes the two engine test programs and test results. The energy impact of the ceramic seal system is discussed in Section 5.0. Program conclusions and recommendations are presented in Section 6.0.

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3.0 Seal System Description

The improved ceramic seal system consists of sprayed graded ceramic/metallic layers applied to a metal substrate, a special impingement cooling arrangement for the back side of the metal substrate, and abrasive tipped blades. These elements are described individually in the following paragraphs.

3.1 Seals

The sprayed ceramic seal segment is composed of a metal substrate, Inconel 713, upon which five layers of different materials are spray deposited. A sketch of the ceramic seal system is shown in Figure 1. Each of the five layers is identified with layer design thickness and composition of the powder used to form the layers, noted on the sketch. There are four different powders used in the fabrication of the ceramic system: 1) Zirconium Oxide stabilized by 20+ 1.5% weight of Yitrium Oxide, 2) CoCrAlY compound of approximately 68% by weight of Cobalt, 3) NiCrAl used as the bond coat, and 4) an aromatic polyester. As noted in Figure 1, the Zirconium and CoCrAlY powders are used in weight ratio mixtures of 40 to 60 and 85 to 15, respectively, to fabricate the intermediate layers. The Zirconium layer is covered by a top layer of porous ZrO_2 formed by spraying a mixture of the ZrO_2 powder and polyester and subsequently burning off the polyester before engine use to create the porosity. Details of the fabrication process may be found in Reference 3.

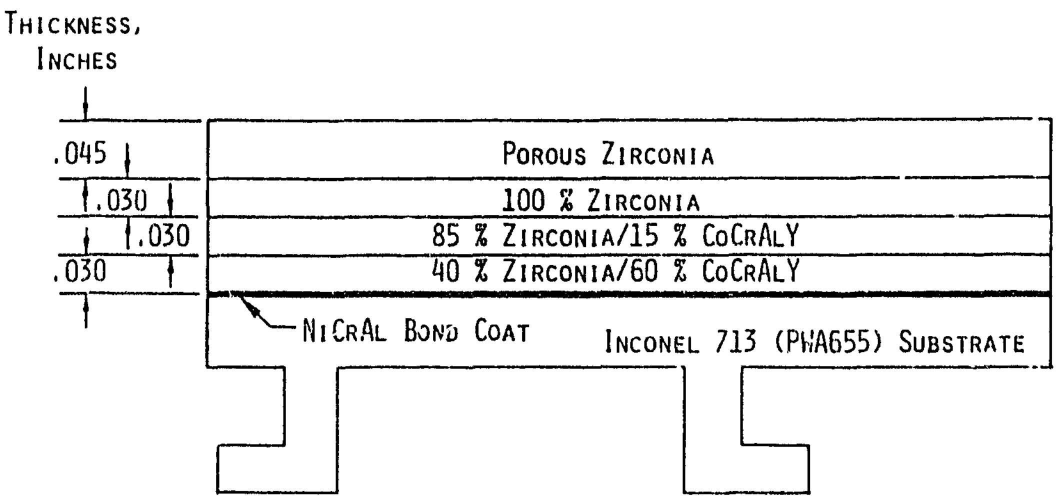

Figure 1 Sprayed Ceramic Seal System is Composed of Five Layers of Material

Two different size segments of the improved design were engine tested. The first, 5.46 cm (2.15 in) long, is the same length as the advanced models of the JT9D engine which utilizes 60 segments in the first turbine stage seal. The second design evaluated is twice as long, requiring only 30 seal segments for a turbine stage. The longer segment was designed and tested to evaluate the effects of increasing seal segment size, with its attendant cost reduction benefits, on rub performance and durability. Both seal segments are pictured in Figure 2. Although somewhat obscured, several of the layers of the ceramic system are noticeable by directing attention to the machined sides of the ceramic seal. Another feature of the seal design noticeable in Figure 2 is the large slots or "scallops" machined into the attachment rails. These scallops were incorporated to optimize the stiffness of the metal substrate to reduce thermal stresses during engine operation.

Details of the ship-lap design are highlighted at A and B in Figure 2. The ship lap reduces leakage between the seals and is the same approach taken for this sealing in the current JT9D engines.

The seals were designed to be compatible with current JT9D attachment hardware.

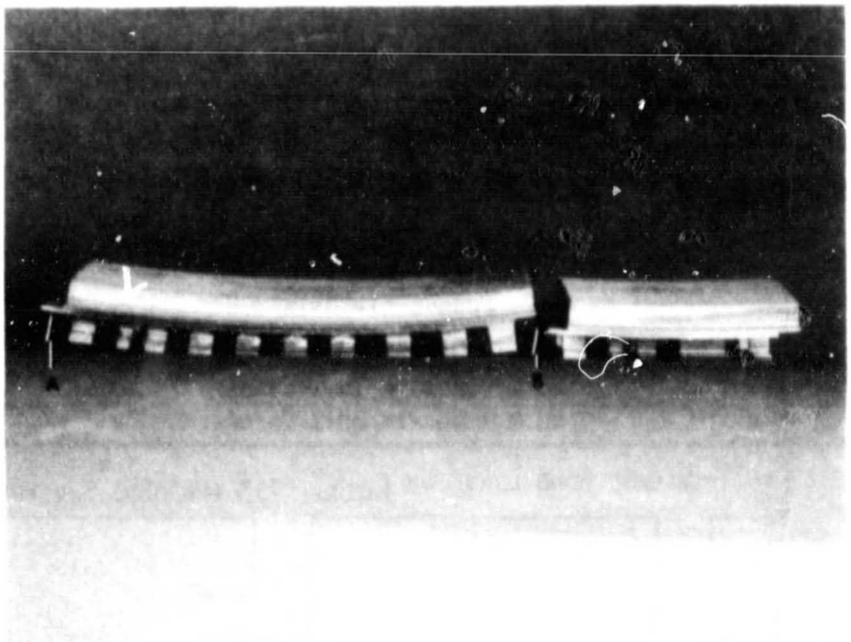

Figure 2 Two Different Size Seal Segments Tested in the JT9D Engine

3.2 Seal Cooling

The current JT9D turbine seal cooling design, illustrated in Figure 3, utilizes an impingement plate through which cooling air is flowed to impingement cool the back of the segment. The cooling air is then metered through holes in the support rails to cool the front and back of the segment. The necessity of scalloping both the front and rear attachment rails of the segment to reduce thermal stresses in the ceramic required design of an alternate method of cooling air management. The design selected, shown in Figure 4, provides a cooling air annulus between the attachment rails of the segment. The annulus is formed by five cooling plate sub-assemblies connected circumferentially by tabs as highlighted in the figure. The inner diameter of the annulus is the back of the seal segment, as highlighted by point A in the figure. The cooling air flow used for the JT9D turbine seals was used for the ceramic system.

Sealing of the five seal plate sub-assemblies to the outer diameter or back of the seal segment is accomplished by a spring fit resulting from the design height of the sub-assembly (H) and the mating surfaces at points B and C. Holes were incorporated in the seal plates, D, to match the cooling air flow of the JT9D engine. Holes were incorporated in the side plates to appropriately distribute cooling air to the front and back of the seal.

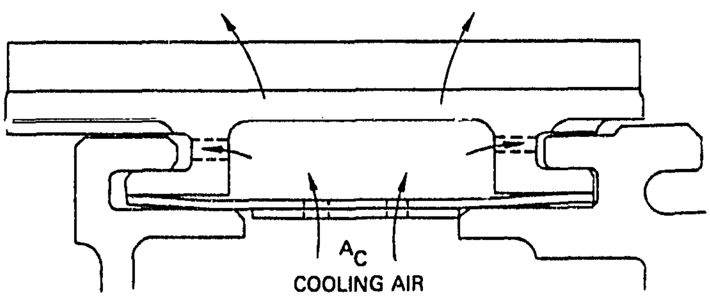

Figure 3 Current JT9D Turbine Seal Cooling Design

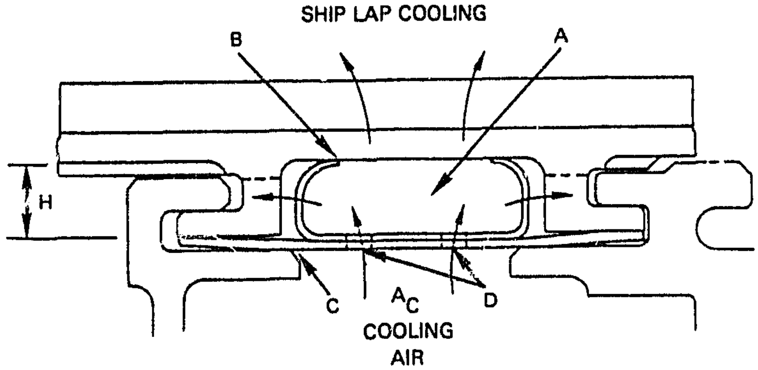

Figure 4 Ceramic Seal Cooling Design Utilizes a Cooling Air Annulus Between the Attachment Rails of the Segment

The basic difference of this cooling air management design is that it replaces the metering of cooling air through holes in the seal segment rails with holes through side plates of a cooling air annulus located between the seal segment attachment rails. A picture of the actual engine hardware showing the cooling system is presented in Figure 5.

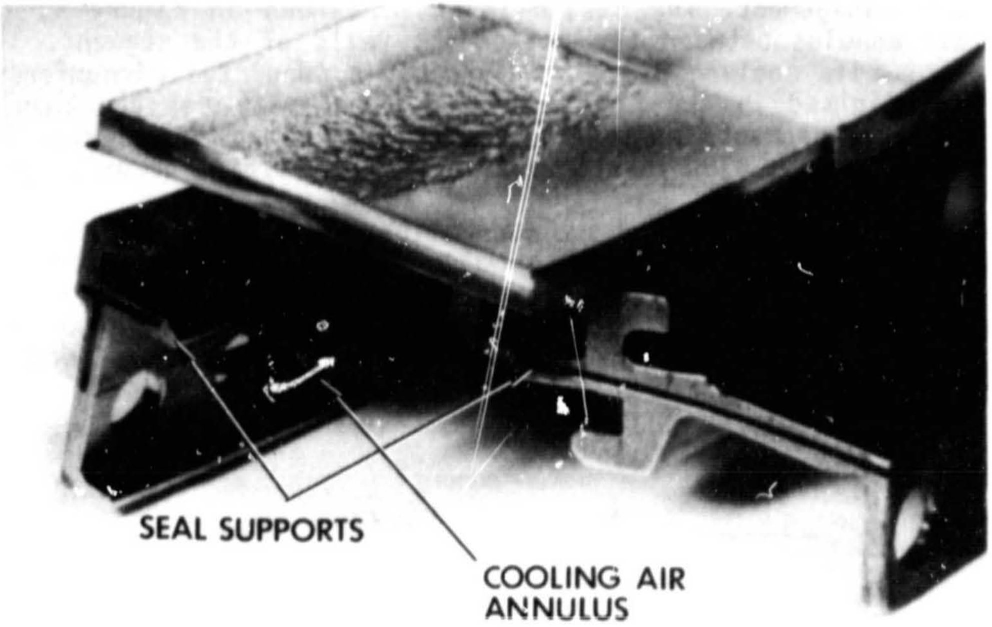

Figure 5 Cooling Air Annulus Hardware

3.3 Abrasive Blade Tips

The abradability of the ceramic seal system which allows clearances to be reduced and, thereby, engine performance to be improved, results in part from abrasive tip treatment of the turbine blades. This treatment provides a blade tip surface of exposed silicon carbide grits which preferentially wear the ceramic seal during rub contact. Figure 6 shows a typical JT9D blade with silicon carbide grits exposed prior to test.

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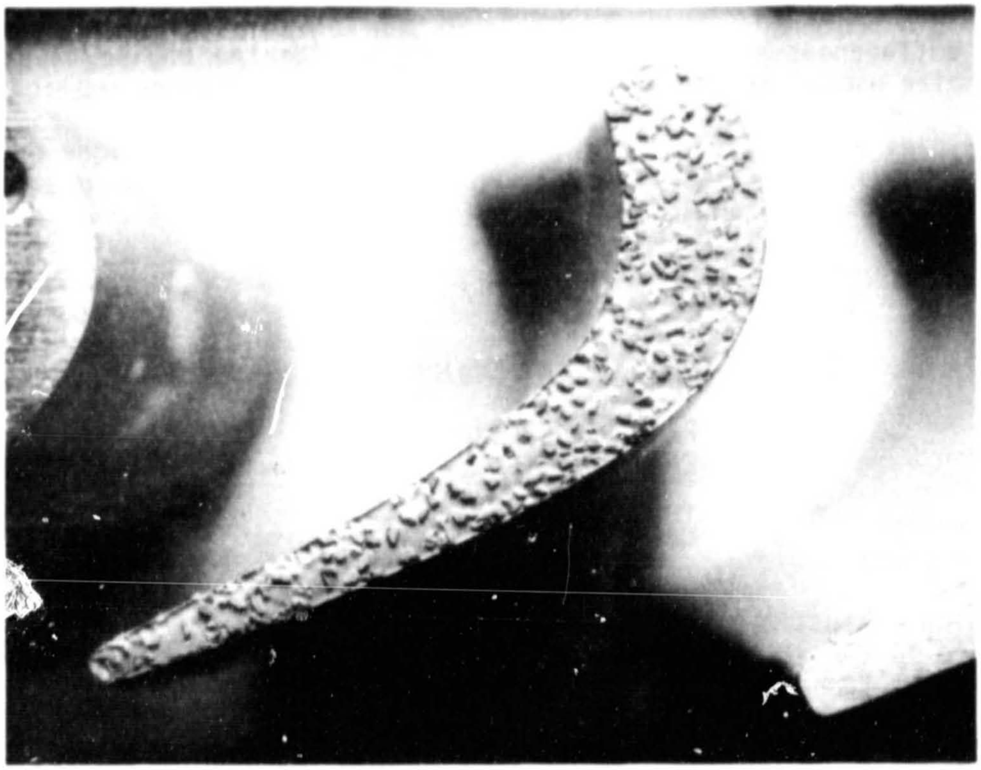

Figure 6 Typical JT9D Blade with Silicon Carbide Grits Exposed Prior to Test

The tip treatment involves an abrasive tip cap fabricated by hot isostatically pressing (HIP) Tipaloy[R], a NiCrAl material, matrix with 20 volume percent of silicon carbide grits which are approximately 0.04 cm (0.015 in) in diameter. The silicon carbide grits are coated with a thin cover of aluminum oxide to prevent carbide migration and resulting grit disolution at high temperatures. The abrasive tip cap is bonded onto the blade and blended to conform to the airfoil. After blade tip grinding in the rotor to the design diameter, the grits are exposed 0.01 to 0.02 cm (0.004 to 0.008 in) by an acid etch.

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4.0 Engine Test Program

Two JT9D experimental engines were used to evaluate the sprayed ceramic seal system - each with its own test program. Both engine test programs were used to evaluate the same ceramic seal designed for the JT9D. Both programs were also designed to: 1) provide an initial transient acceleration condition to produce a blade tip rub to define the rub capability of the system, and 2) evaluate seal durability by at least a 1000 cycle endurance test.

There were differences as well as similarities in the two engine tests in order to maximize useful design information and reduce unncessary duplication.

The similarities and differences of each of the tests are highlighted in Table I. Each of the tests is described separately and in detail in the following sections.

Table I

Sprayed Ceramic Seal Engine Test Summary

	FAA Type Cyclic Endurance Test	Accelerated Endurance
Number of Cycles	1000	1825
Running Time (hrs)	157.7	440.4
Hot Time (hrs)	35	50
Average engine exhaust temperature °C (°F)	657 (1215)	660 (1220)
Maximum gas path temperature at seals °C (°F)	1593+ (2900+)	1648+ (3000+)
Number of Seal Segments	48	45
Number of Proposed Design	30	30
Number and Type of Other Segments	18 - Earlier design	15 - 2x length
Additional Test Objectives	Evaluate up to 3500 Cycles on Ceramic	Evaluate Potential of Larger Segments
Number of Abrasive Tip Blades	27	34

4.1 FAA Type Cyclic Endurance Test

A JT9D engine (X-491) was used to perform a blade/seal rub test and a 150 hour - 1000 cycle endurance test conducted with FAA cognizance for potential service use of the sprayed ceramic seal system in the JT9D by the airlines.

Forty eight (48) sprayed ceramic seal segments were installed. Figure 7 shows a typical turbine module assembly. Thirty (30) of the 48 seal segments were of the proposed design and formed the lower half of the seal stage where a blade seal rub was anticipated. Figure 8 shows a closeup of three of these segments installed in the turbine case. The upper half of the seal stage was composed of 18 segments of an earlier design. Figure 9 shows typical pre-test conditions of two of the 18 segments as installed in the case.

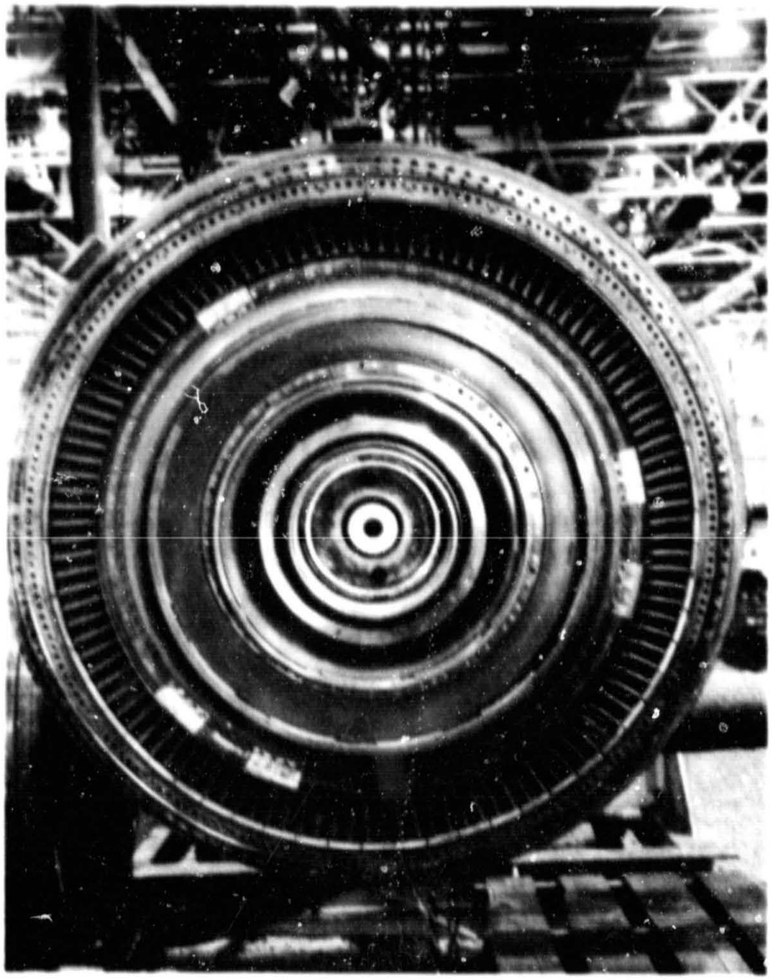

Figure 7 Typical Turbine Module Assembly

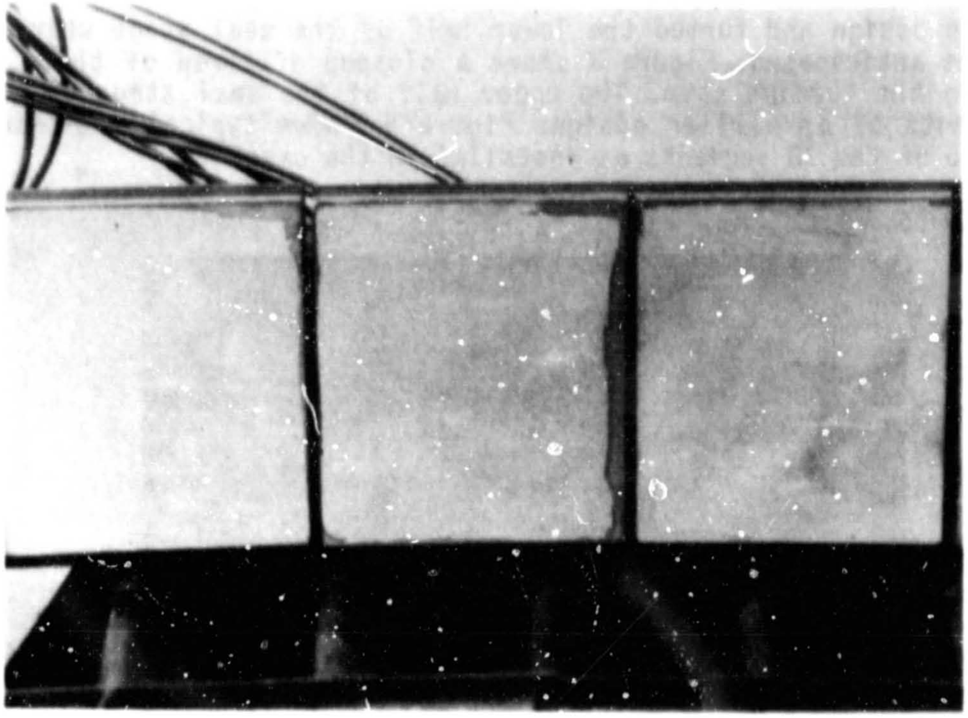

Figure 8 Closeup of Three Typical Sprayed Ceramic Seal Segments Installed in Turbine Case

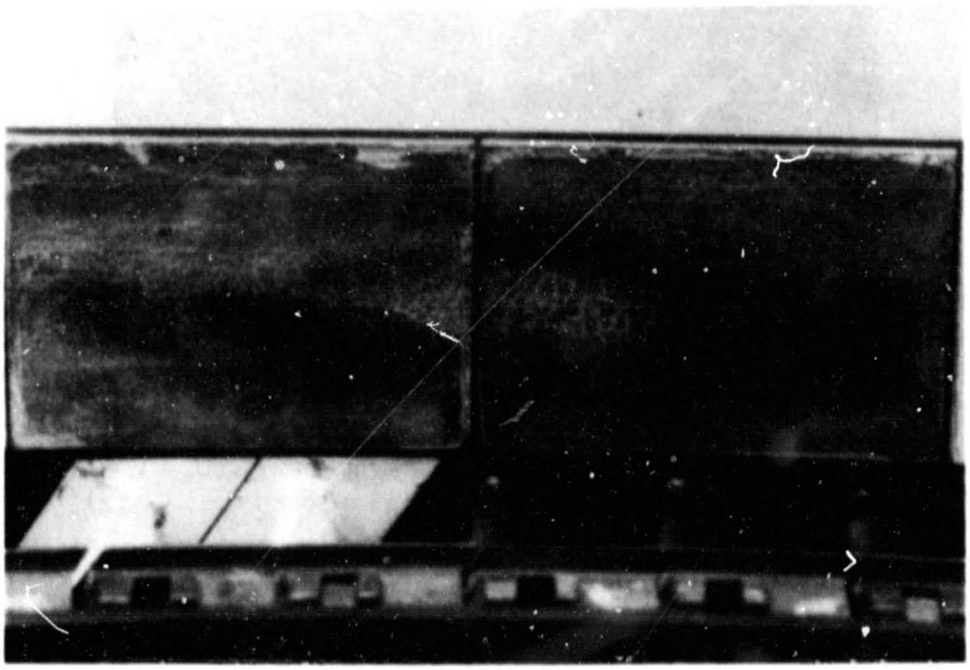

Figure 9 Two of Eighteen Sprayed Ceramic Seal Segments of an Earlier Design with Previous Engine Test Time

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After assembly the seals were ground in the case, Figure 10, to provide desired blade/seal clearance, and subsequently disassembled for cleaning and inspection. Two segments of the JT9D design were observed to have laminar cracks as shown in Figure 11 and were replaced. Experimentation with spare seal segments produced similar cracks indicating the reason to be mechanical loading resulting from assembly and not a basic deficiency in the system.

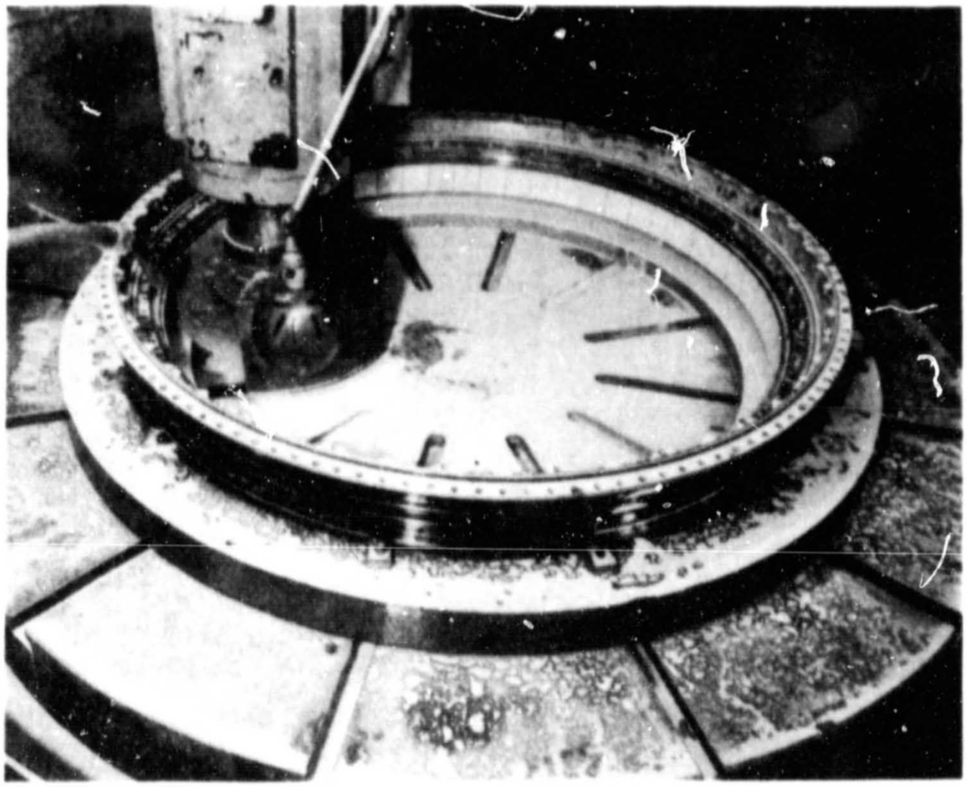

Figure 10 Ceramic Seals were Ground in the Case to Final Diameter

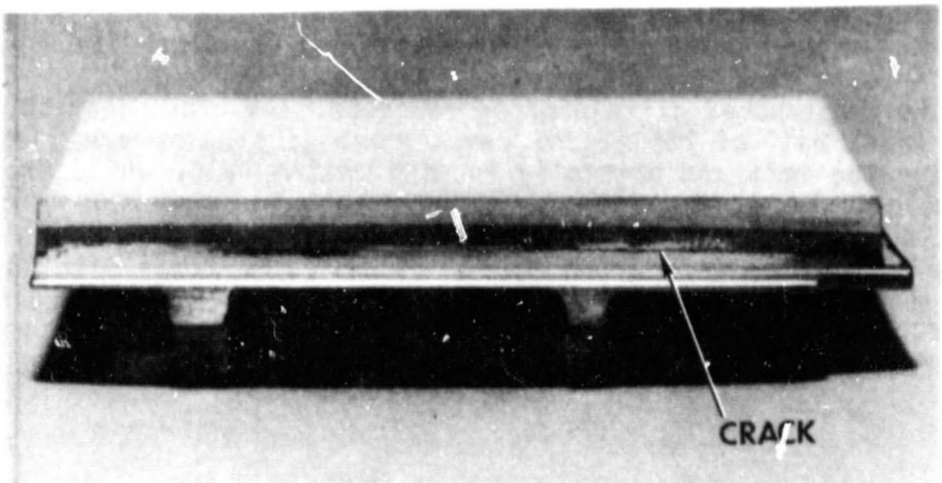

Figure 11 Laminar Cracks Occurred During Assembly

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Twenty seven (27) abrasive tip blades, out of a stage total of 116, were used in this test. The abrasive tip blades were ground in the rotor to a radius of 0.038 cm (0.015 in) to 0.051 cm (0.020 in) longer than the non-tipped blades. This was done to prevent the non-tipped blades from participating in the rub and thereby compromising the rub capability of the abrasive tip blade. Typical pre-test conditions of the abrasive tip is pictured in Figure 12.

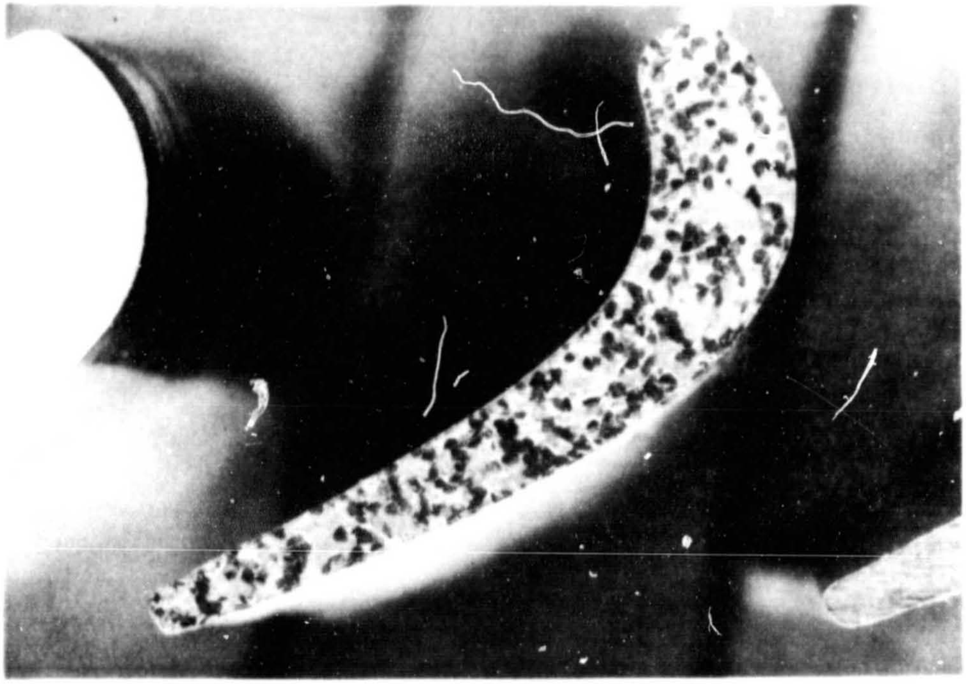

Figure 12 Typical Pre-Test Condition of the Abrasive Tip

4.1.1 Test Stand Description

The engine was installed in a sea-level engine test stand. This stand is a gas turbine engine test facility designed to test large high by-pass ratio turbofan and turbojet development engines at static sea level conditions.

The stand is constructed of reinforced concrete. The cross-section of the air inlet and front half of the engine compartment is square; the middle portion has a square top half and partially rounded bottom half, while the rear section of the cell has both a circular top and bottom. Noise reduction is accomplished at the inlet by means of 36 percent sound stream insulation and in the exhaust by passing the air around a series of turns lined with 10.2 cm (4.0 in) thick sound absorbing panels. Secondary air for engine cooling is admitted to the cell through a 21 sq m (225 sq ft) roof opening, the inlet duct of which is treated in the same manner as the exhaust.

The test engine is mounted from a flexure supported overhead thrust measurement platform; the thrust being measured by means of a strain gage load cell located on the platform centerline. Provisions are also incorporated in the system for a calibration load cell train located concentrically with the primary load cell.

The controls and instrumentation necessary to operate the test engine and monitor selected performance parameters are located in an adjacent control room. Continual visual observation of the engine is possible through a window in the test cell wall.

4.1.2 Test Program

The initial portion of the test program was designed to provide a blade seal interaction. As shown in Figure 13, an initial vane calibration schedule was conducted up to 177928 N (40000 lbs) of thrust. After return to idle the engine was "snapped" to takeoff power to provide the anticipated rub. A stepped deceleration to idle, stepped calibration to takeoff and a snap deceleration to idle followed. Less than ten (10) minutes was spent at any operating condition. A maximum corrected thrust of 247320 N (55600 lbs) was attained at the takeoff condition.

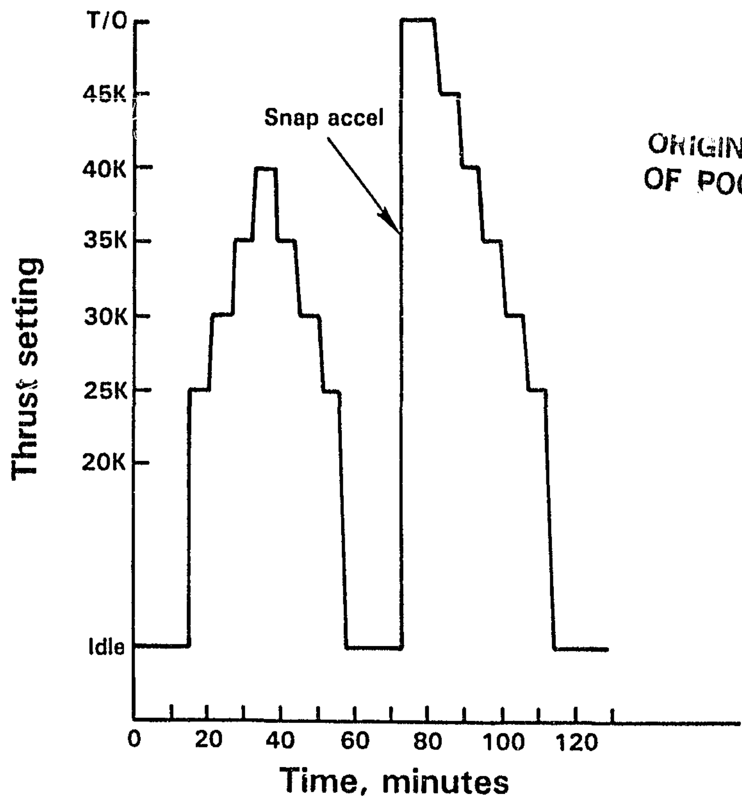

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Figure 13 Engine Rub Test Condition

Upon completion of this phase of the program, the turbine module was removed from the engine in the test stand as shown in Figure 14. The seals and blades were inspected.

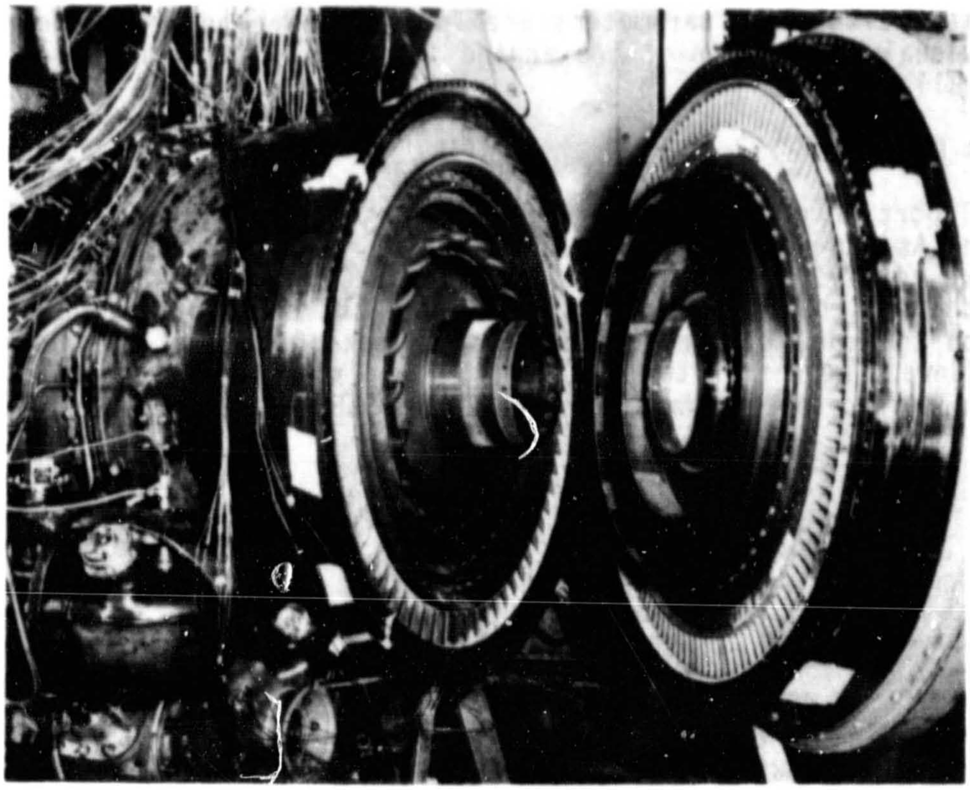

Figure 14 Turbine Module Removed from Engine in Test Stand

Ten of the seals were rubbed by the blades to a maximum rub depth of 0.020 cm (0.008 in). A sketch of the rub path and location is shown in Figure 15. Figures 16 and 17 are photographs of the rub path showing a clean groove with no metal transfer from the blades. Inspection of the seals in the turbine module revealed that only eight (8) seal segments had minor laminar cracks at the leading edge and only one (1) was visible without magnification. Inspection of the blades, limited because of the lack of disassembly, indicated little, if any, smearing or wear of the blade tips.

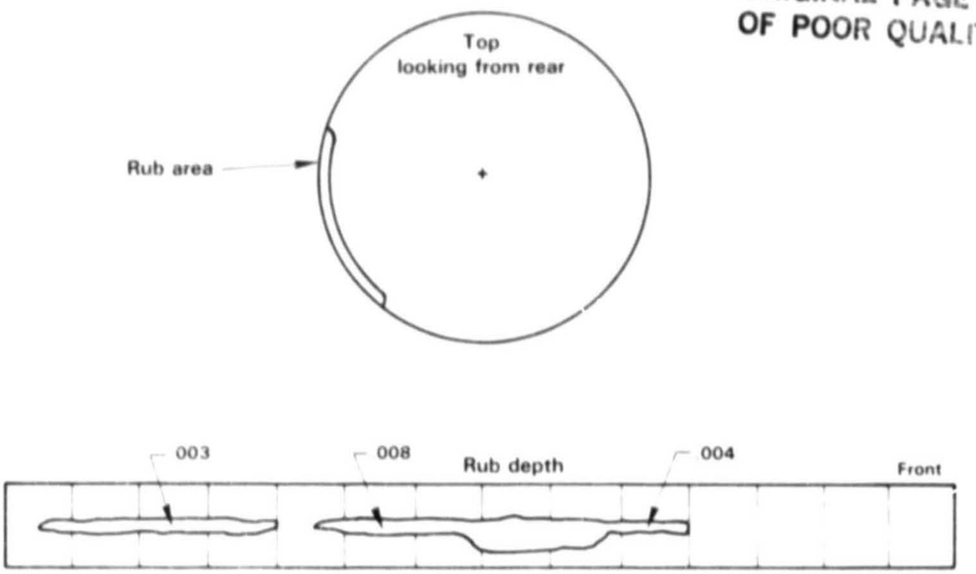

Figure 15 Ten Ceramic Seal Segments were Rubbed up to a Depth of 0.02 cm (0.008 in)

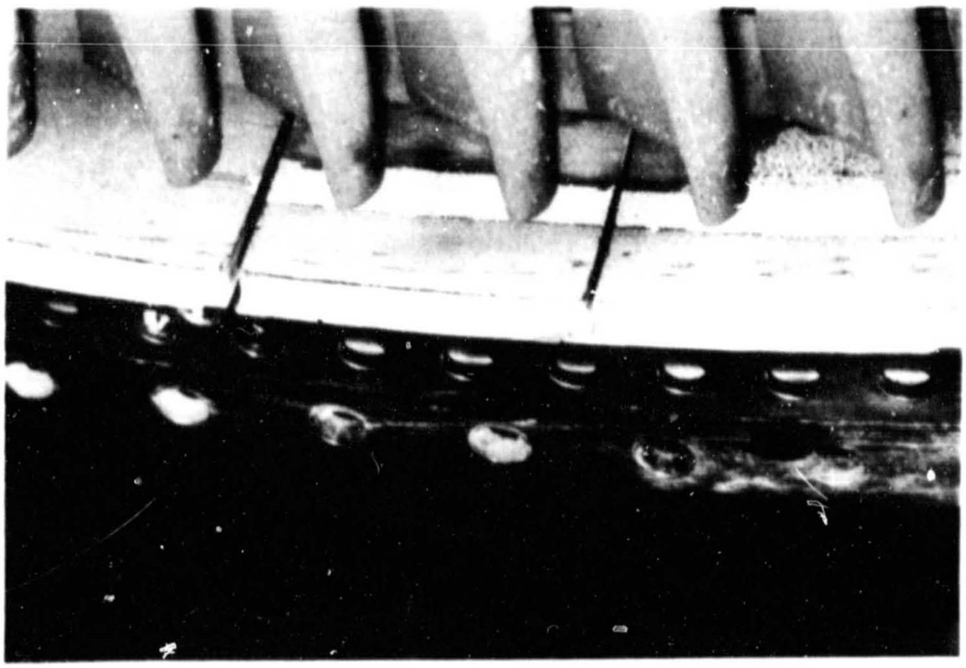

Figure 16 Photograph of Rub Path Showing Clean Groove with No Metal Transfer from the Bl·des

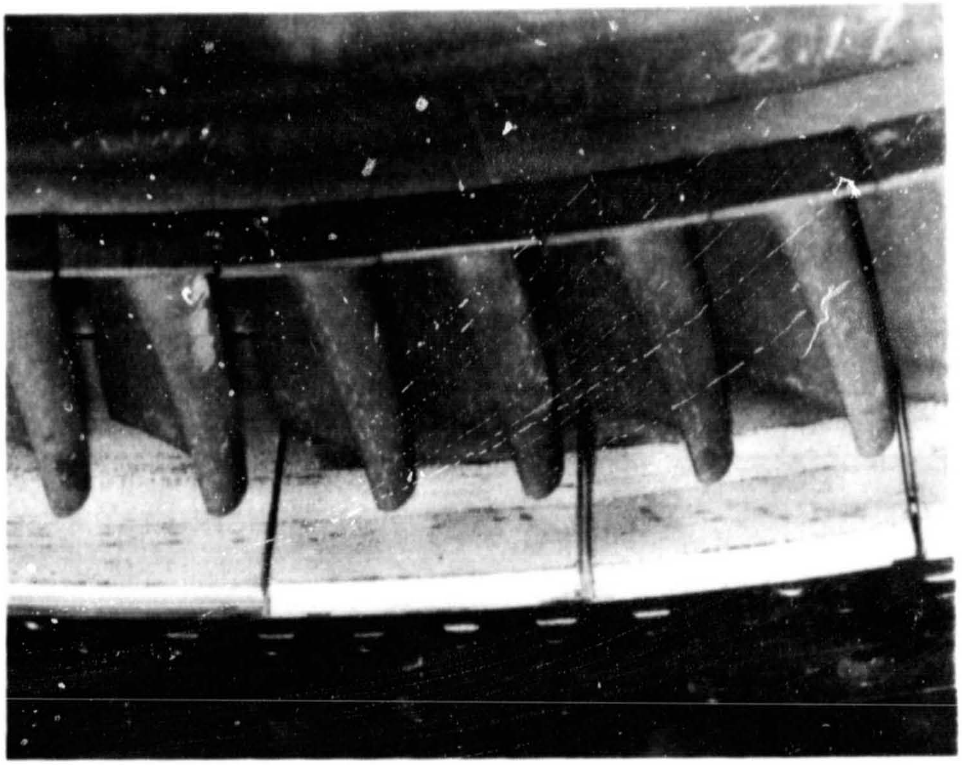

Figure 17 Photograph of Rub Path Showing Clean Groove with No Metal Transfer from the Blades

The rub performance, that is, the capability of the blades to preferentially groove the seal, is measured by a volume wear ratio (VWR) which is the ratio of volume of seal material removed to the blade tip volume wear. A volume wear ratio of 120 was calculated, assuming an average abrasive tip blade wear of 0.0013 cm (0.0005 in) for this rub test, considerably above the design goal of 10.

The engine was reassembled, returned to test and completed 1000 low cycle fatigue endurance cycles to the schedule shown in Figure 18. Maximum takeoff power attained was 244651 N (55000 lbs) of thrust. An average engine exhaust gas temperature of 657°C (1215°F) was recorded. The 1000 cycles provided a total time at takeoff conditions of approximately 36 hours with a total engine running time of 150 hours.

Engine testing was completed on November 4, 1981.

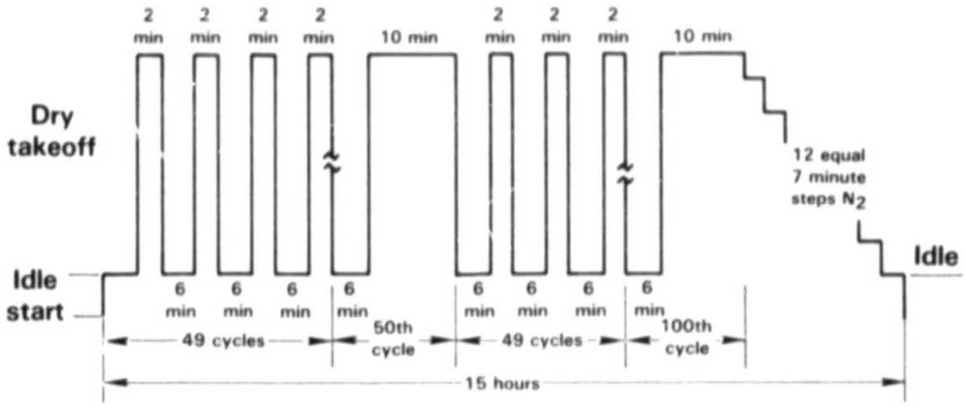

Figure 18 FAA Type Cyclic Endurance Program

Figure 19 shows the turbine assembly removed from the engine. All proposed design seal segments were intact and in good condition. Only five (5) segments showed minor spalling and location of material removed was generally outside the blade path location thereby not contributing to performance deterioration. The generally good structural appearance of the seals is shown in Figure 20. The largest spall in the blade path location is shown in Figure 21. This spall is at the location of a radial step with the seal edge being closest to the blade diameter. Blade movement was from right to left in Figure 21 and it is expected that blade contact on that edge of the seal may have contributed to that spall. Inspection also revealed radial and laminar micro-cracks but little evidence of connection between the two types of cracks that would contribute to material spalling.

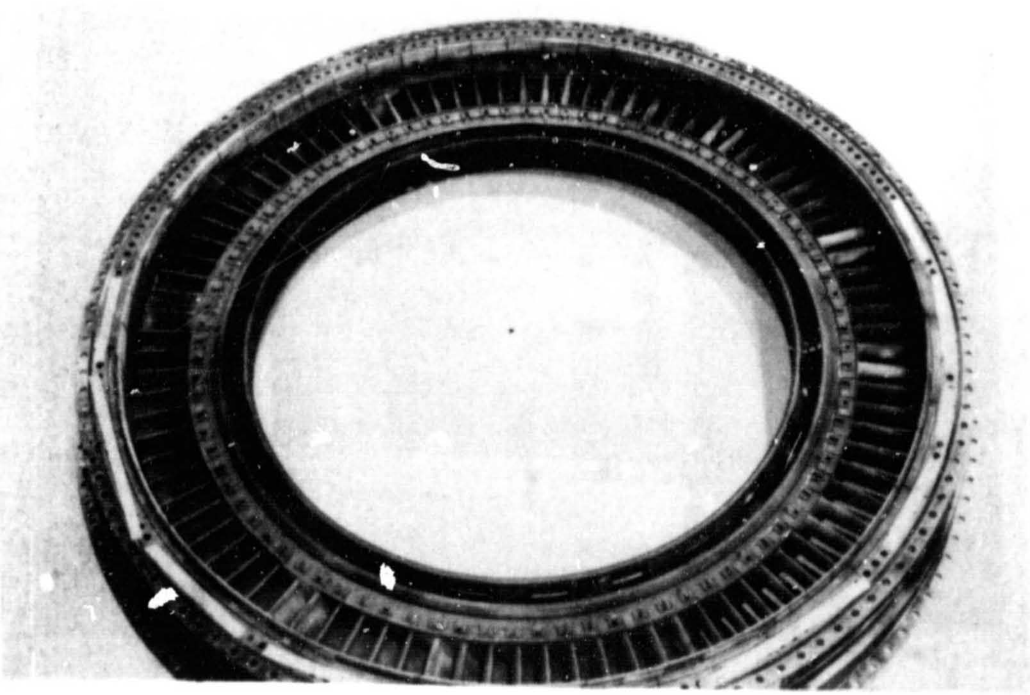

Figure 19 Turbine Assembly Removed from the Engine

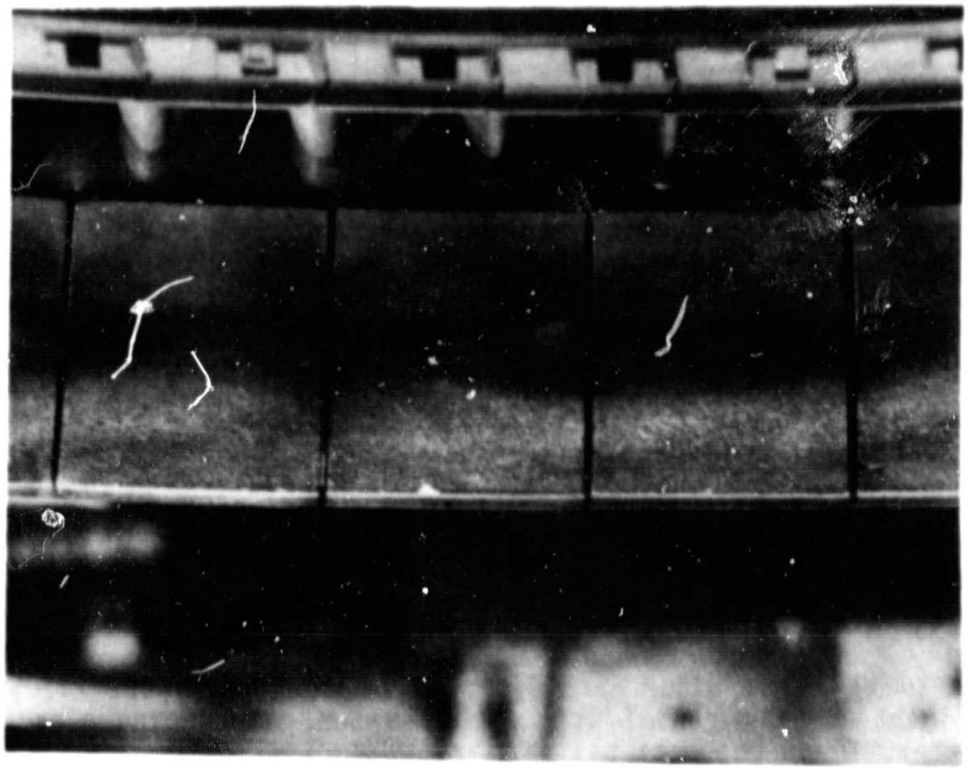

Figure 20 Sprayed Ceramic Seals Successfully Completed FAA Type Cyclic Endurance Test Without Adverse Effects

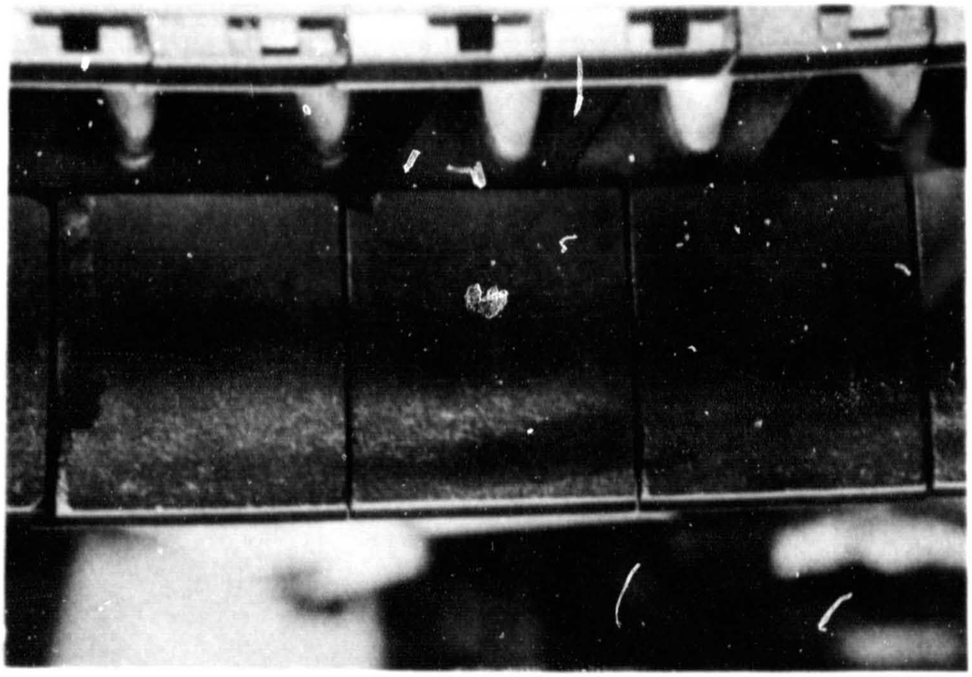

Figure 21 The Largest of Five Spalls

An additional rub, shown completely in Figure 22 resulted during the endurance program. It is expected that this rub was generated by slow thermal growth interaction and by excessive unbalance. As shown in Figure 23, this rub was in essentially the same location as the earlier rub generated during the acceleration transient.

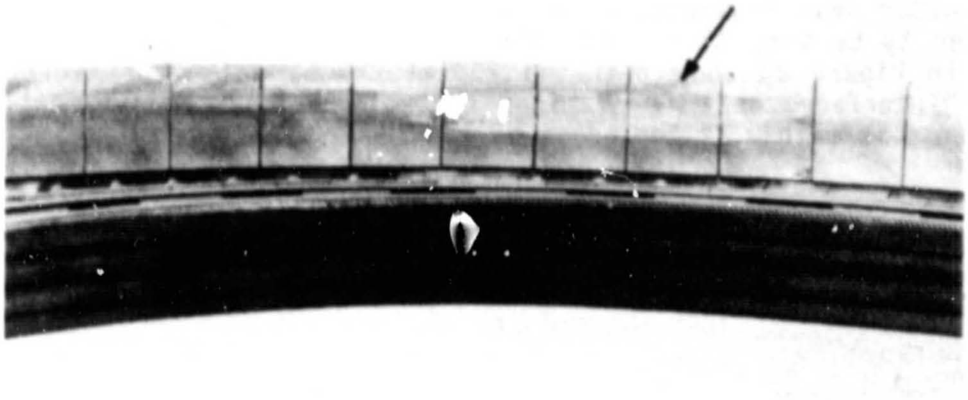

Figure 22 Additional Rub Resulting During the Endurance Program

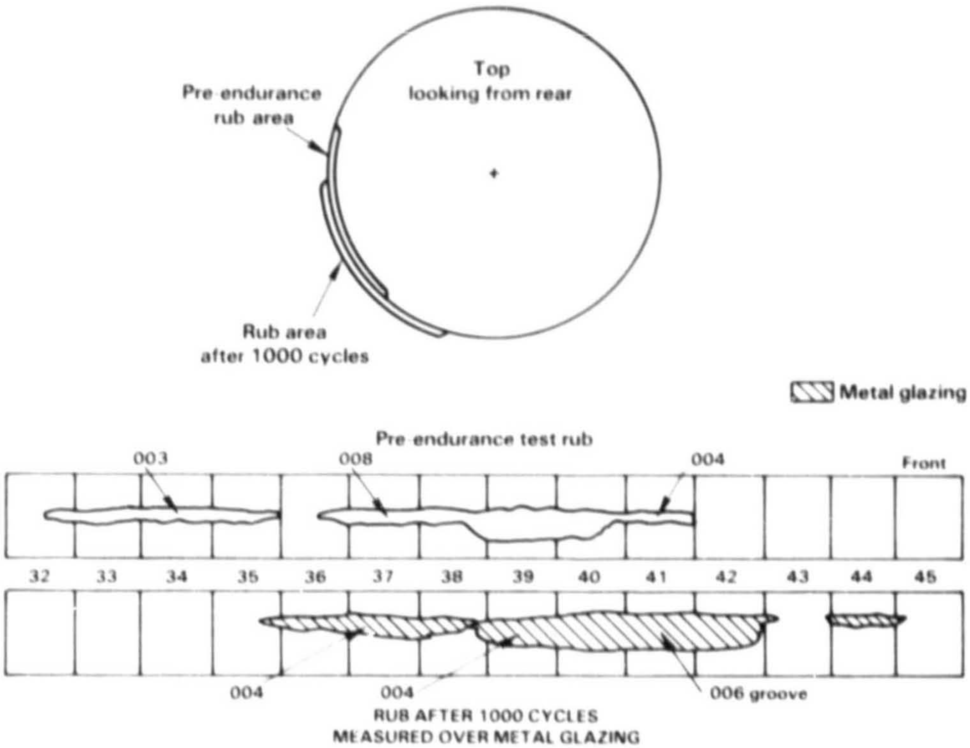

Figure 23 Rub During Endurance Testing is in the Same Location but Produced Glazing

Metallographic inspection of one of the seal segments was sectioned to investigate the thickness of blade material deposited on the seal and the nature and relationship of radial and laminar cracks. Figure 24 is a closeup photograph of the seal sectioned and shows the cuts made and the seal planes inspected metallographically. Figure 25 is a picture of plane A and shows the rub path. Blade material transfer in this location was similar in appearance to that on other seal segments. Metallographic examination, Figure 25, showed this transfer to be very thin, less than 0.005 cm (0.002 in). Examination of the cracks in Figure 26 show that the radial cracks extend primarily to the 85/15 layer interface. Very few laminar cracks were observed indicating that this occurrence is mainly at the edges of the segment.

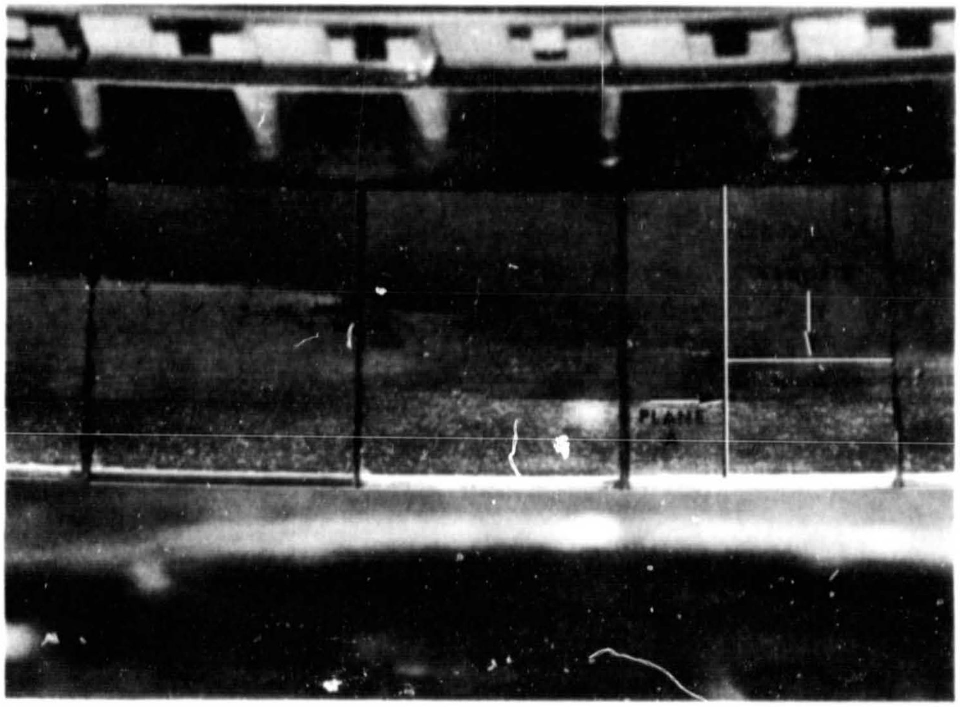

Figure 24 Closeup Photograph of Seal Sectioned Showing Metallographic Inspection Locations

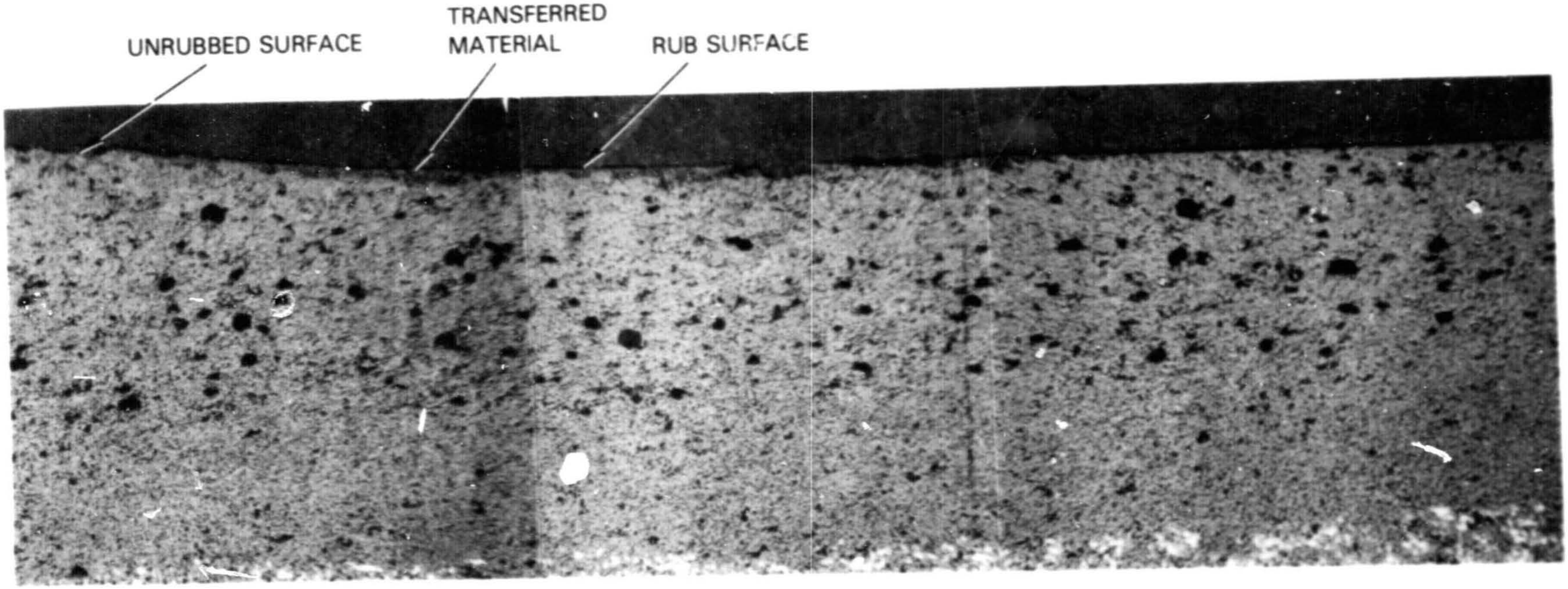

Figure 25   Plane A of Figure 24 Showing Rub Path and Thinness of Transferred Material

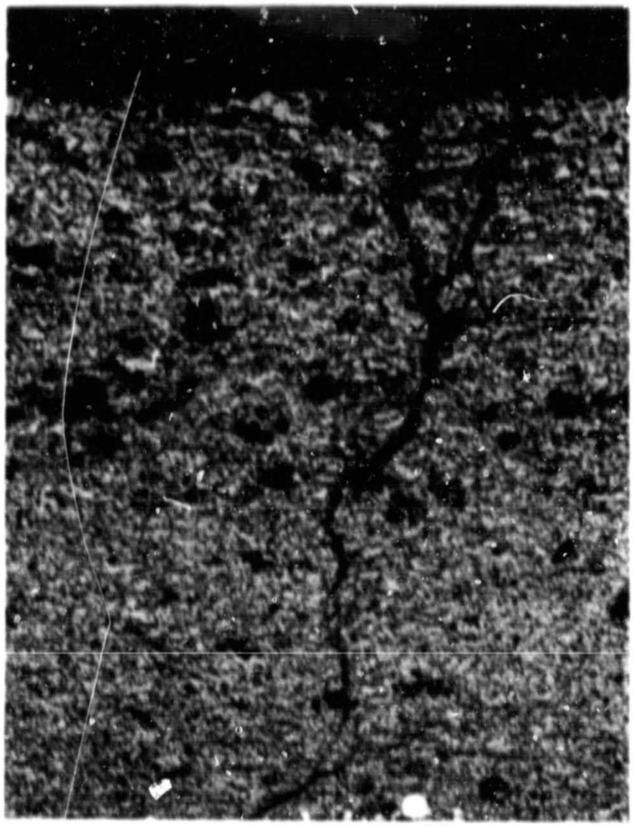

Figure 26 Metallography of Plane B of Figure 24 Showing Radial Cracks Extend to the 85/15 Layer

Inspection and measurement of the 27 abrasive tip blades revealed that all had worn an average of 0.043 cm (0.017 in). Inspection of non-tip treated blades which were machined shorter than the abrasive tip blades substantiated that wear, in that some of them had also worn slightly. A photograph of a typical abrasive tip blade after engine test is shown in Figure 27. Metallography shown in Figure 28 shows good structural integrity but the efficiency of the abrasive tip was lost because the smearing metal matrix filled the cavities between the grits.

The rub interaction resulting from the endurance test, a result of slow thermal growth and unbalance caused by loss of a second-stage blade, resulted in mainly blade wear as evidenced by blade and seal inspection.

The occurance and results of this second rub does not compromise the potential performance benefit of the ceramic seal system because of the off-design engine operating condition involved. The initial rub test demostrated efficient seal grooving would occur at acceleration transient rub conditions.

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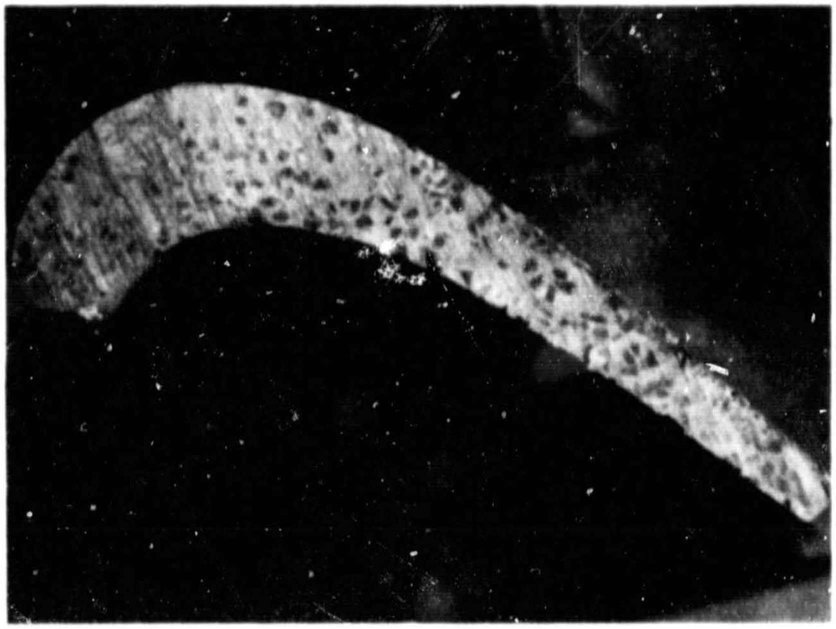

Figure 27 Photograph of Typical Abrasive Tip Blade After Engine Test

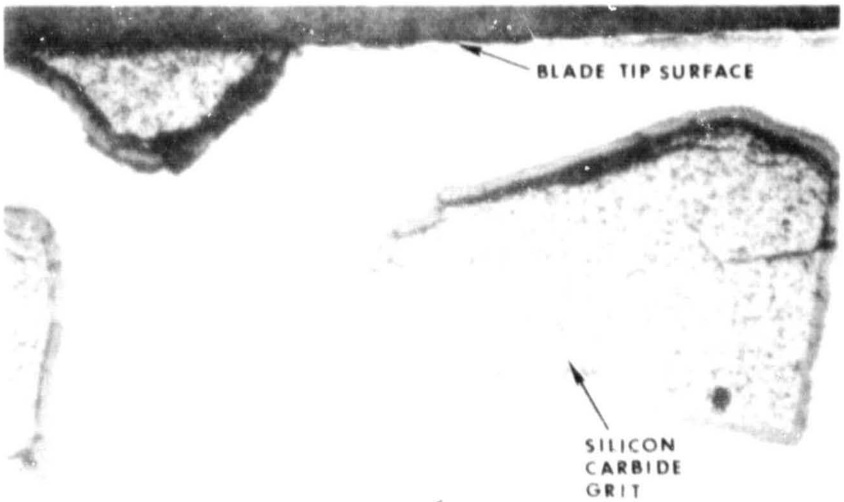

Figure 28 Metallography Showing Good Structural Integrity of the Abrasive Tip

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4.2 Accelerated Engine Endurance Test

A second JT9D experimental engine (X-567) was also used to conduct a blade/seal rub interaction test and cyclic endurance evaluation of the ceramic seal. The approach taken for the rub portion of the test was the same as for the first test; that is, an acceleration transient was conducted early in the program to provide a relatively fast interaction. The turbine module was removed soon after to inspect the effect of the rub. The endurance portion of the test, however, was different from the first engine test and, in fact, much more severe. The purpose of this endurance program, described later in this section, was to evaluate seal durability in the most extreme engine operating conditions to better assess degradation modes of the seals and other engine components.

Forty five (45) sprayed ceramic seal segments were installed in the first turbine stage of the engine. Thirty (30) of the seal segments were of the improved design and were positioned in the lower 180° of the seal stage. The other half, the top of the seal, was composed of 15 segments twice as long. Two views of the seal assembly are shown in Figure 29 illustrating the comparative size of the two seal segments. The evaluation of the longer seal segments was undertaken to determine if potential cost savings associated with the longer segments would be compromised by reduction in rub performance and/or durability. Because of manufacturing and assembly variations ZrO_2 thickness on these seals averaged approximately 0.102 cm (0.040 in), about 0.089 cm (0.035 in) less than the design objective.

Abrasive tip caps were bonded to 34 turbine blades. These blades were ground to be approximately 0.025 cm (0.010 in) longer than those without tip treatment. A typical blade tip is shown in Figure 30. The blades were installed in the rotor, Figure 31, and mated with the seal assembly to comprise the turbine module for this test as shown in Figure 32.

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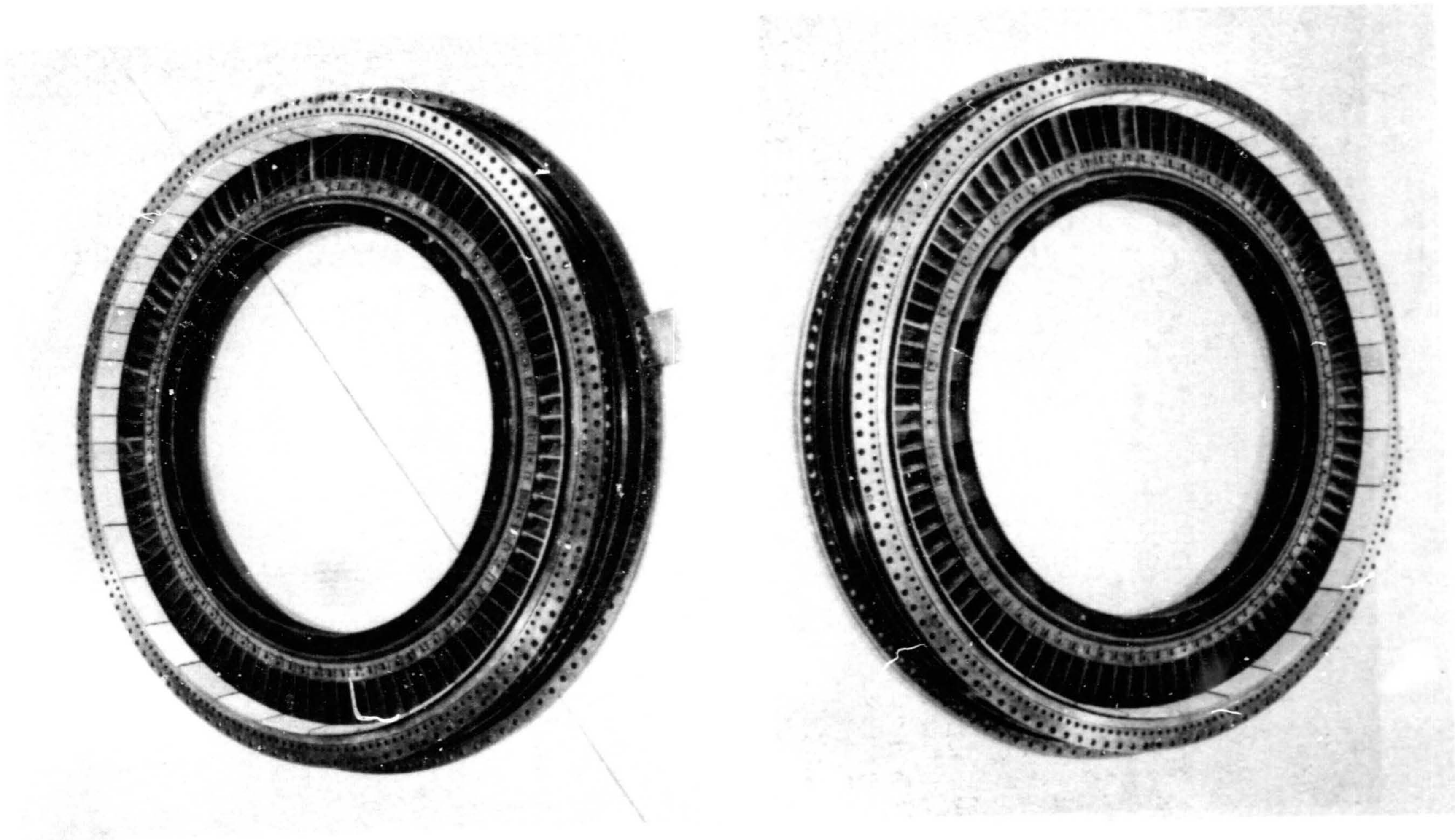

Figure 29 Two Seal Segment Sizes Were Tested to Evaluate the Effect of Length on Durability

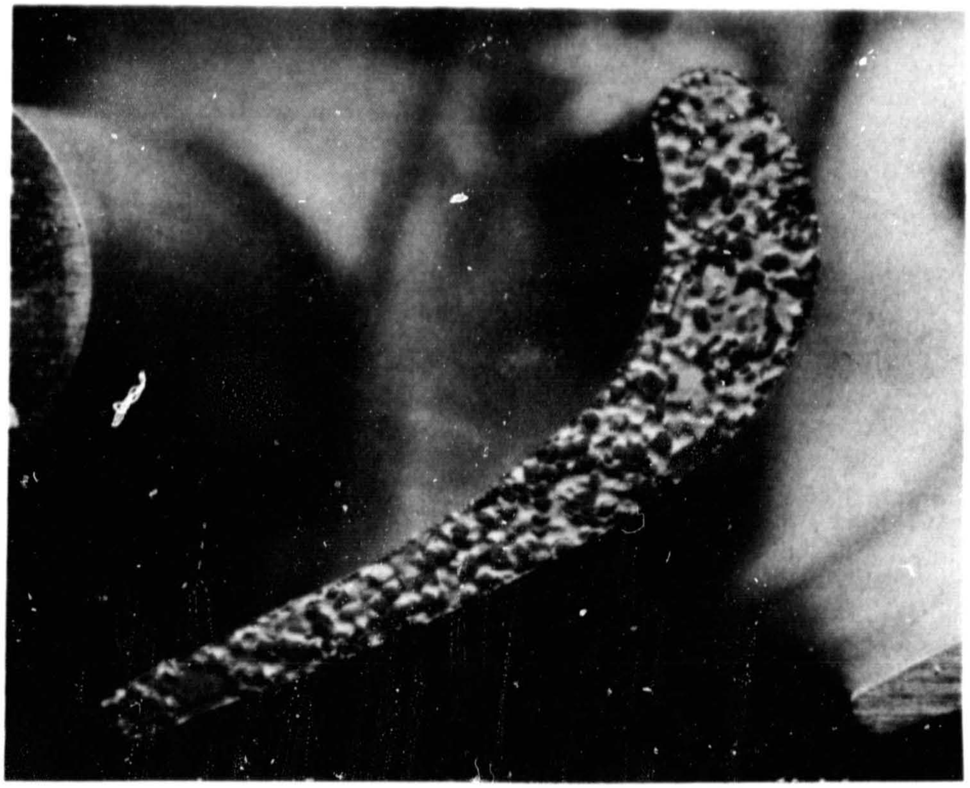

Figure 30 Typical Blade Tip

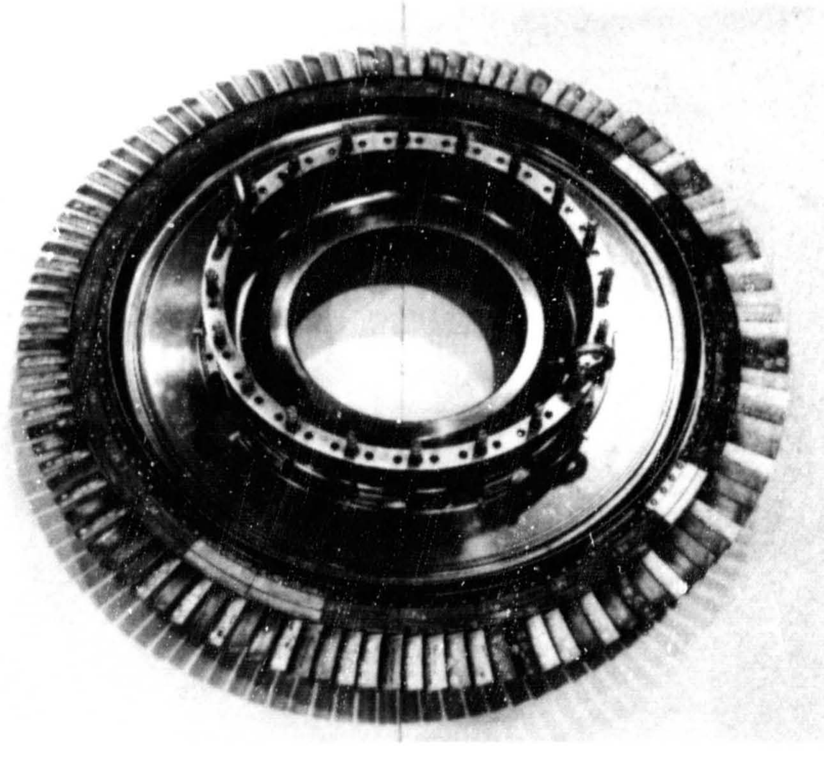

Figure 31 Rotor Assembly Ready for Installation

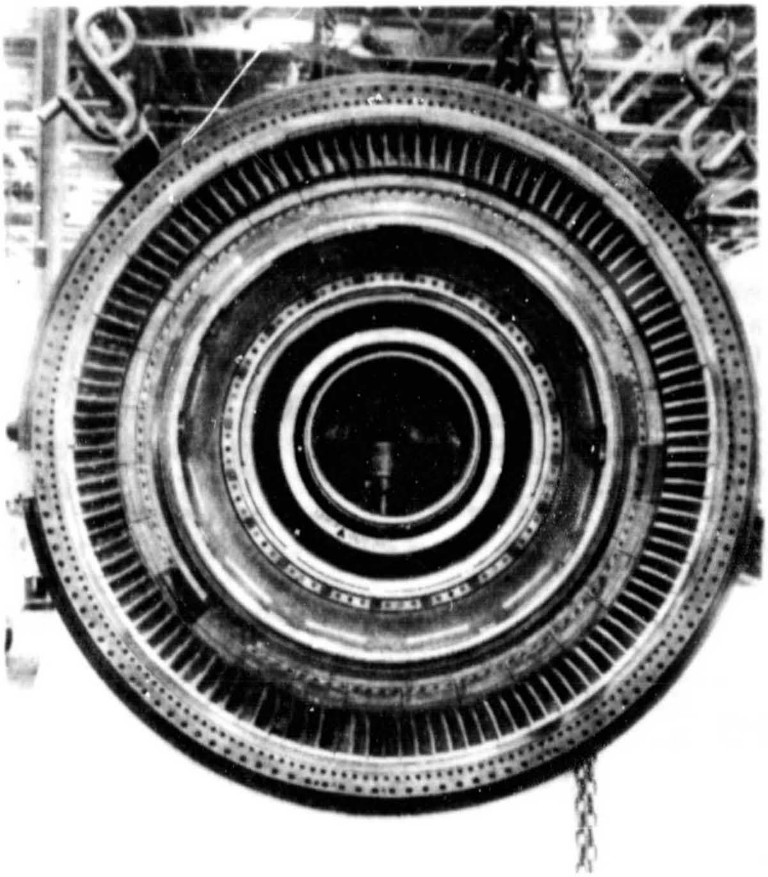

Figure 32 Turbine Module Prior to Test

4.2.1 Test Stand Description

The stand is constructed of reinforced concrete. The air inlet, test cell compartment, secondary air inlet, and the exhaust outlet have a square cross-section. Atmospheric air is admitted at one end of the test cell through a horizontal full area inlet, and exhausted upward at the opposite end. Noise reduction is accomplished at the inlet by means of 42 percent sound stream insulation and in the exhaust by passing the air through thirty-nine 97 cm (38 in) inner diameter 6 m (20 ft) length vertical perforated corten steel tubes covered with 14 mesh monel glass cloth. The area between the tubes is packed with fiberglass to absorb the sound energy. Secondary air for engine cooling is admitted to the cell through a 31 sq m (330 sq ft) roof opening, the inlet duct of which is composed of 50 percent open area splitters for sound attenuation.

The test engine is mounted from a flexure supported overhead thrust measurement platform; the thrust being measured by means of a strain gage load cell located on the platform centerline. Provisions are also incorporated in the system for a calibration load cell train located concentrically with the primary load cell.

The controls and instrumentation necessary to operate the test engine and monitor selected performance parameters are located in an adjacent control room. Continual visual observation of the engine is possible through a window in the test cell wall.

4.2.2 Test Program

After an initial vane calibration program and turbine exhaust case strain gage program, a series of three (3) hot accelerations were conducted to provide a blade seal rub interaction. Maximum thrust operation resulted in an average engine exhaust gas temperature of 660°C (1220°F).

The turbine assembly was removed from the engine and the blades and seals inspected in the assembly. Nine (9) of the seals were rubbed to a maximum depth of 0.036 cm (0.014 in) as shown in Figure 33. The rub path was clean with no evidence of blade material transfer. Inspection revealed that blade tips were generally unaffected with grits still exposed. Although inspection of the blade tips in the assembly was difficult, by using a mirror it was determined that only 16 of the 34 blades had interacted with the ceramic seals. Based on the assumption that those 16 blades had worn an average of 0.0013 cm (0.0005 in), a volume wear ratio of 225 was calculated which is significantly greater than the design goal of 10.

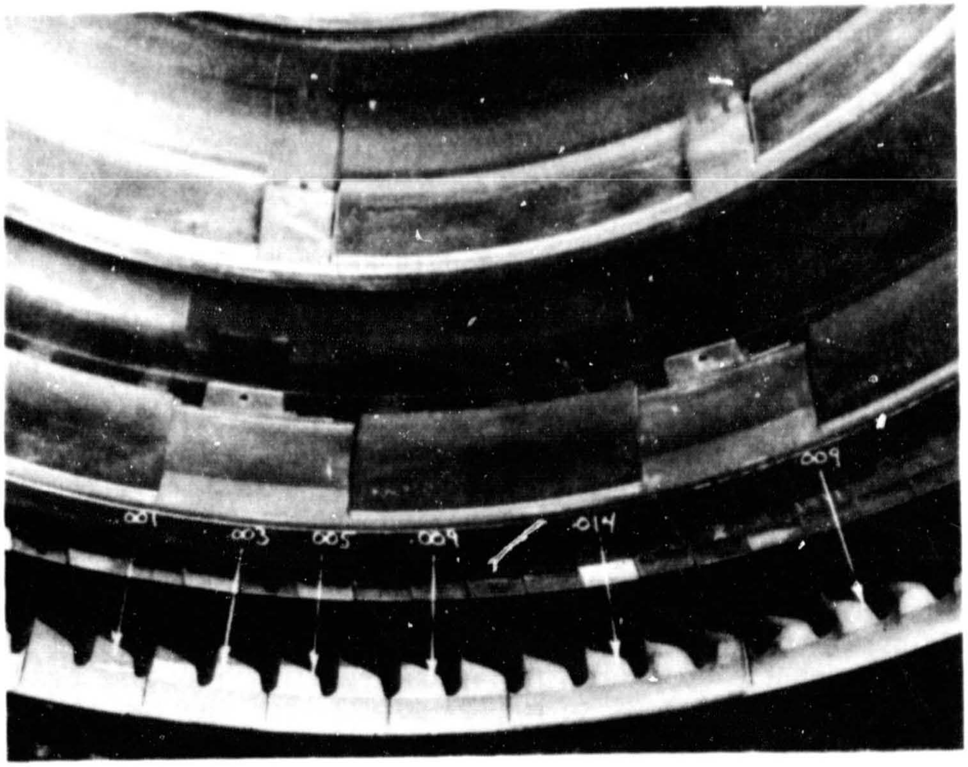

Figure 33 Nine Ceramic Seal Segments Were Rubbed to a Maximum Depth of 0.036 cm (0.014 in)

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The seals were further inspected and were found to have radial cracks to varying degrees, the most noticeable of which can be seen on the segment shown in Figure 34. Inspection of the leading edge of each of the segments revealed that only two (2) segments had laminar cracks.

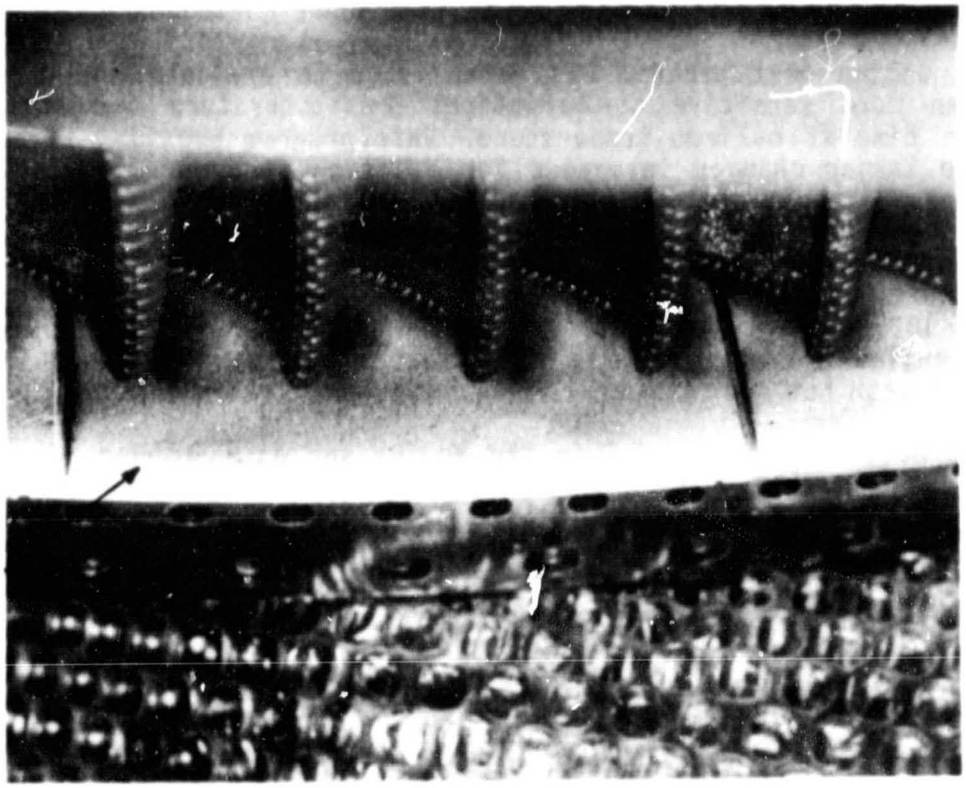

Figure 34 Seal Segment with Most Noticeable of the Radial Cracks

The turbine was reassembled and the engine was returned to test to run the cyclic endurance program defined in Figure 35. This endurance program shown in Figure 35 differs from that used in the earlier engine test.

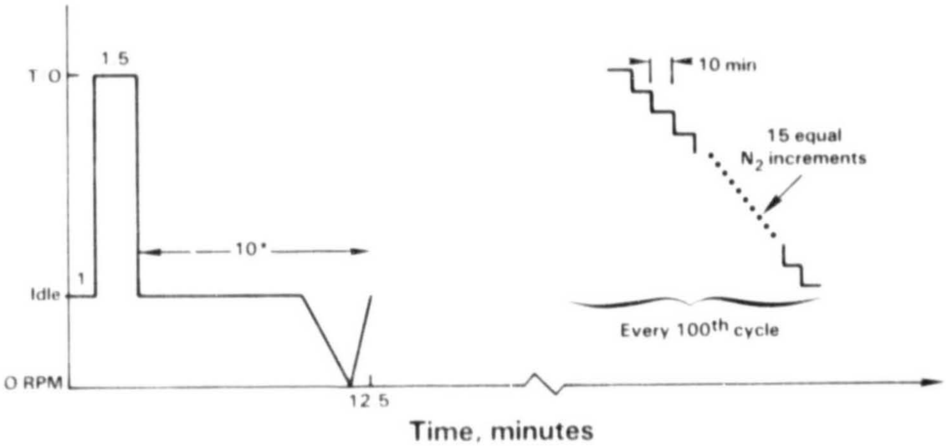

Figure 35 Cyclic Endurance Program for the Second Engine Test

The initial test program, Figure 18, was established to satisfy FAA requirements for field service use of time at maximum power and provided for 2 minutes at full power for each cycle. This type of program, with relatively high time per cycle at maximum power, is particularly beneficial for evaluating durability of cooled turbine airfoils. The temperature at any given location in the engine ranges from that at idle to maximum power during each cycle.

The second engine test program was established to evaluate engine component modification more sensitive to variations in temperature and rotor speeds rather than time at maximum temperature. This program provides higher strain rate due to larger changes in speeds for rotating parts and greater temperature changes for thin section parts. A comparison of the two programs will show that for 1000 cycles, time at maximum power would be 36 hours and 27 hours respectively.

A total of 1825 engine cycles were conducted with over 1600 cycles conducted at severe engine operating conditions. These seals saw in excess of 1648°C (3000°F) gas path hot spot temperatures for approximately 50 hours.

The turbine module was removed from the engine and disassembled. The seal assembly is shown in Figure 36 and reveals, by the second vane burn-through in the two o'clock location, the severity of the operating conditions.

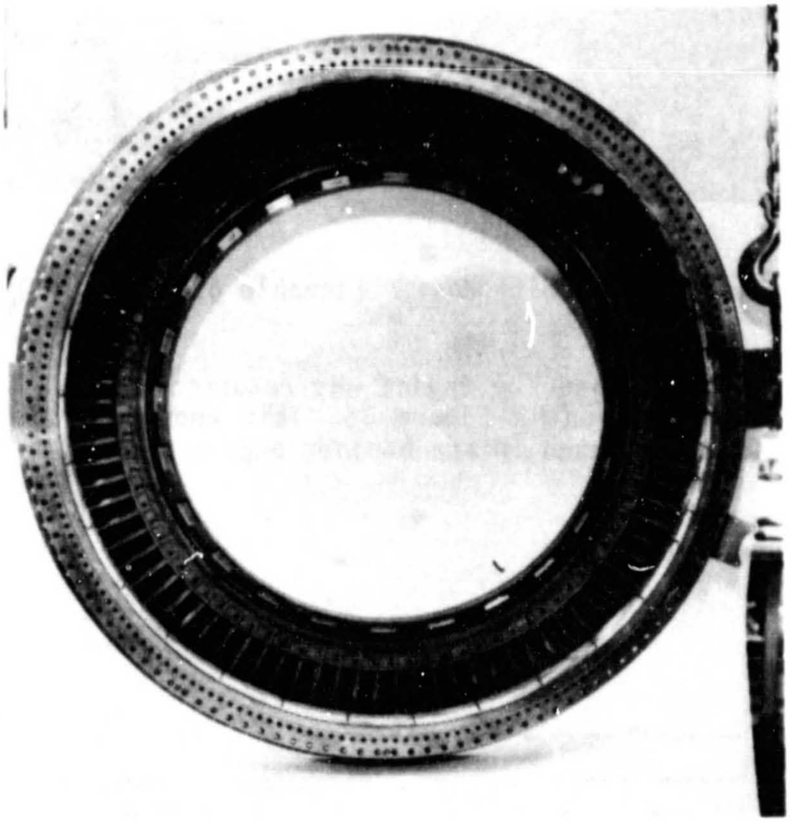

Figure 36 Seal Assembly Revealing Severity of the Test Program

The seal segments were removed from the module and inspected. Seal spalls were documented by sketching each of the seals as shown in Figure 37. Spalling of the seal area immediately under the blade path was surveyed and measured to determine the effect of the engine operating conditions on performance degradation. It was determined that only 20 percent of the seal surface area under the blade path was spalled. A closeup of one of the locations is shown in Figure 38. Although certainly not desirable, estimates indicate that the spalling was approximately equivalent to only 0.025 cm (0.010 in) in clearance increase. The significance of the decrease in engine performance associated with that 0.025 cm (0.010 in) clearance increase is reduced when considering the relative condition of other engine components such as the combustor, vanes and blades. In addition, the ceramic thickness of the seal segments tested in this engine was less than the design objective. Less ceramic means less insulation and therefore a higher temperature at the first intermediate layer (85/15). It is reasonable to assume that greater oxidation of the CoCrAlY in this layer occurred and, as a result, strains, greater than expected in the design configuration, contributed to the spalled conditions.

Inspection of the blades revealed typical conditions associated with time at high temperature. Blade tips, those tipped and those without revealed oxidation and cracking. Generally, the tipped blades showed more radial cracks but less oxidation attack. A picture of a typical abrasive tipped blade after the test is shown in Figure 39.

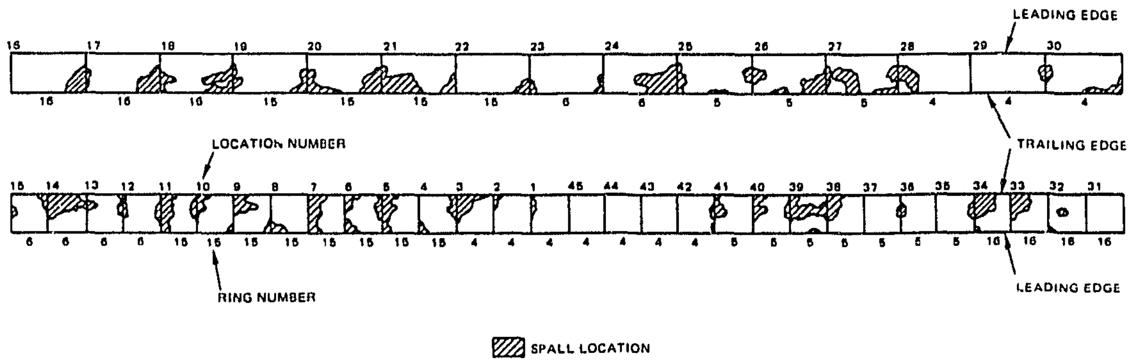

Figure 37 JT9D Sprayed Ceramic Seal Segments Spall Locations After 1825 Extreme Engine Cycles

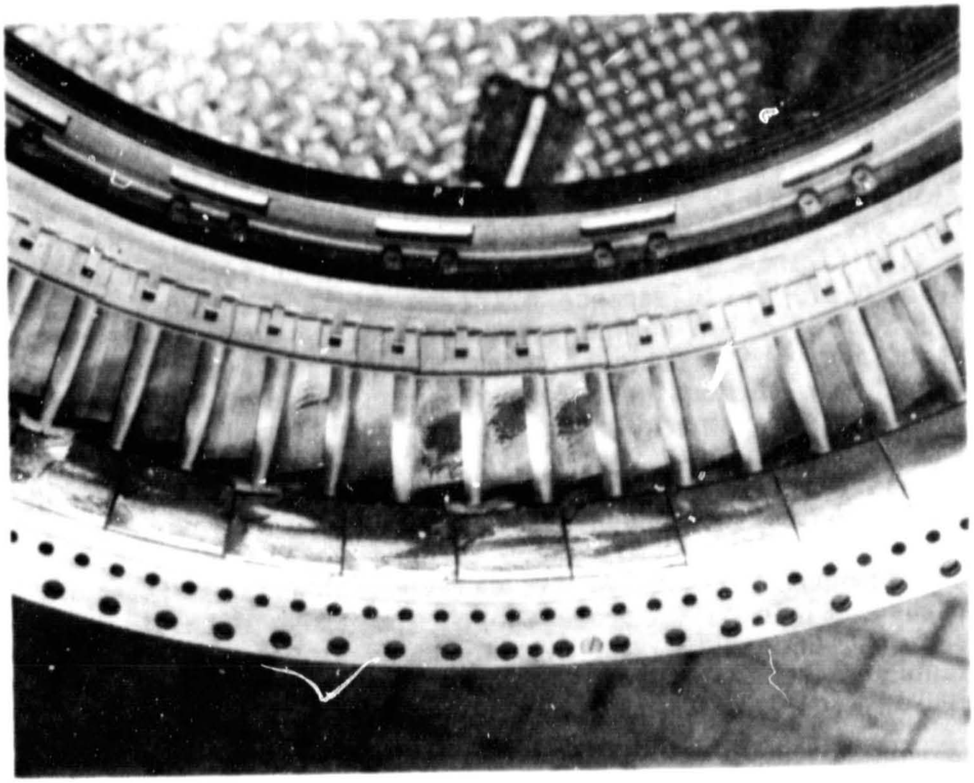

Figure 38 Closeup of One of the Spalled Locations

Figure 39 Picture of Typical Abrasive Tipped Blade After Test

4.3 Summary of Results

The programmed rub tests of both engines produced clean rub grooves in the ceramic seal with essentially no blade material transfer. Because of the relatively new processes used in the fabrication of abrasive blade tips, sufficient abrasive tip caps could not be obtained to provide 100 percent tipped blades in time to meet the engine test schedule. As a result, abrasive tip caps were installed on a small percentage, roughly 25 percent, of the blades of each of the engines.

Inspection of the abrasive tip blades revealed that even though comparatively few of them were in each rotor, all of them did not participate in the interaction. It is projected therefore, had clearances in these engines been tighter, to provide a greater interaction, the seals would have been grooved to a greater depth without wearing the abrasive tip blades to a point where they would have lost all of their rub efficiency.

Even with this comparatively small number of blades participating in the interaction volume wear ratios of 120 and 225 resulted from the two engine tests. These volume wear ratios were considerably greater than the design goal of 10 required, as an indication of abradability sufficient to accomodate eccentric rubs without rotor wear and allow reduction of engine clearances.

The two engine tests added three significant data points which proved invaluable in the assessment of the potential durability of the ceramic seal system in airline service. The first was the 1000 cycle test at representative JT9D engine conditions. The ceramic seals completed this test with minimal indication of distress.

Seals in the second test completed 1825 cycles at severe operating conditions resulting in seal spalling. This spalling would have contributed to engine performance deterioration but, based on measurements obtained, would not have deteriorated sufficiently to negate the performance benefit attributable to the ceramic seal system. These three data points indicate the potential of the sprayed ceramic seal system to attain 5000 hours of engine operation in the field.

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5.0 Energy Impact

The fuel saving potential of the ceramic outer air seal system was estimated in the ECI-PI Feasibility Analysis (Reference 1) based on performance, airline acceptability, and engine market projections available in 1977. This estimate has been updated to reflect the results of the subject program and a revision of the initial availability date. The original and updated estimates are shown side-by-side in Tables II and III for convenient comparison.

The good abradability characteristics demonstrated with the improved system (volume wear ratio greater than 100) verifies that the 0.025 cm (0.010 in) turbine blade tip clearance reduction and the engine specific fuel consumption improvements (see Table II) assumed in 1977 can be achieved. These results plus the durability and safety aspects of the system demonstrated in the engine test program provide strong encouragement for airline acceptability.

The 1977 analysis showed excellent airline acceptability, with payback periods ranging from 0.3 to 0.7 years, as shown on Table IV, compared to an acceptability limit of 5 years (see Reference 1). It is inappropriate to update the acceptablility evaluation at this time because the development of production equipment and processes is continuing in an effort to minimize the implementation cost of the ceramic seal system. However, because of the large acceptability margin in the 1977 evaluation and the expected benefits of the production development effort, it is reasonable to assume that the ceramic seal system will be acceptable to the airlines. For the updated fuel saving estimate shown on Table III, it was assumed that the system would be acceptable to the airlines in all JT9D models, including retrofit to all existing JT9D engines.

Table II

Potential Fuel Savings Evaluation
(World Fleet of JT9D Powered Aircraft)

	1977 Estimate	Current Estimate*
Start of service date	January 1982	January 1984
Fuel saving, percent	0.4	0.4
Number of engines affected:		
New buy	1620	1070
Retrofit	2530	3000
Total	4150	4070
Cumulative fuel saved	3.8×10^6 liters (10^6 gal)	3.8×10^6 liters (10^6 gal)
New buy	1120 liters (296 gal)	712 liters (204 gal)
Retrofit	833 liters (220 gal)	946 liters (250 gal)
Total	1953 liters (516 gal)	1718 liters (454 gal)

* Assumes airline acceptability in all JT9D engines.

Table III

1977 Estimate Of Engine Effects (Per JT9D Engine)
Is Unaffected By Results Of This Program

TSFC improvement, %	
Takeoff	0.56
Climb	0.32
Average Cruise	0.32
Hold	0.70
EGT improvement, °C	
Takeoff	6
Climb	3
Weight change	0
Price change, $	+3400
Kit price (attrition), $	5000
Maintenance cost change, $/hr	
Materials	+0.70
Labor @ $30 per manhour	-2.54

Table IV

1977 Estimate* of Airline Costs (Per Aircraft)

Airplane Model	747-200		DC10-40	
Operating Costs Changes, $/Year	-7	-70/59	-70/59	
Fuel	-31,830.	-34,100.	-13,230.	
Maintenance	-33,600.	-33,700.	-18,940.	
Block Speed Effect	-200.	-200.	-500.	
Total	-65,630.	-68,000.	-32,670.	
Type of Investment	New Buy	Retrofit	New Buy	Retrofit
Required Airline Investment Changes, $	-7&-70/59	-7&-70/59	-70/59	-70/59
Installed Engines	+13,600	+20,000	+10,200	+15,000
Spare Engines	+3,710	+5,450	+2,350	+3,450
Spare Parts	+2,720	+4,000	+2,040	+3,000
Total	+20,030	+29,450	+14,590	+21,450
Payback Period, Years	0.3	0.4	0.4	0.7
DOC Change, %	-0.3		-0.2	

*Updated cost information is not available.

6.0 Conclusions and Recommendations

The objectives of the JT9D sprayed ceramic seal program to demonstrate, by engine test, performance improvement and durability capability, have been achieved successfully. Results of engine rub tests, which demonstrated that the Pratt & Whitney Aircraft sprayed ceramic seal system has the necessary abradability, indicates that JT9D turbine clearances can be reduced by at least 0.025 cm (0.010 in) and associated engine performance benefits obtained. Engine cyclic endurance testing for 1000 and 1825 cycles has indicated that the ceramic seal system has the potential for 5000 hours of engine operation.

Although, without question, additional experimental engine testing would be of some value, the success of this program has substantiated the advisability of taking the next step in incorporating the ceramic seal in commercial production engines. There was no indication in either test conducted under this program or others conducted by Pratt & Whitney Aircraft that the ceramic seals and/or abrasive tip blades could result in engine malfunction or significant damage. Field service evaluation by the airlines is a useful method of fully assessing the benefits, possible limitations, and durability of the sprayed ceramic seal system and is recommended.

This program has satisfied a major prerequisite of field service evaluation by successfully completing engine endurance testing under FAA cognizance.

An effectively monitored field service evaluation will provide:

1) definition of performance benefits during engine "green-run" testing and user operation. The "green-run" test is the engine acceptance test conducted on each production engine before delivery to the customer.

2) demonstration of the erosion resistance and other durability characteristics of the ceramic seal system under actual operational and environmental conditions.

3) by utilizing a variation in the number of abrasive tip blades in the field service engines, "green-run" tests will provide additional data which will allow optimization of the number of blades to be tipped.

4) with data from 1, 2 and 3, the advisability of incorporating minor modifications of the seal system to optimize the abradability/durability trade-off to be consistent with airline needs.

A field service program of from five to ten engines is recommended. The design effort required to produce a net-shape casting to reduce or eliminate all prespray machining should be accomplished prior to and for the fabrication of parts to be evaluated in the field.

The field service effort recommended will provide the final necessary data to produce performance, durability and cost optimized ceramic seal systems for commercial engines.

Further, the high additional risk of incorporating new design features in an already high development cost industry must be modified to facilitate incorporation of design features which are in the national interest. We believe that design features, such as ceramic seals, which improve engine performance and thereby reduce dependence on foreign oil are vital to our national interest and security. Therefore, Pratt & Whitney Aircraft recommends that the development of a life prediction model for application of ceramic seals to gas turbine engines be initiated.

Appendix A

Product Assurance

I. Introduction

The Product Assurance system provided for the establishment of quality requirements and determination of compliance with these requirements, from procurement of raw material 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 requirements of the JT9D Ceramic Outer Air Seal Program. A full production-type program requires inspection to the requirements indicated on the drawings and pertinent specifications. On experimental programs 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, when requested, were made available to designated Government Representatives for on-site review.

Standard Pratt & Whitney Aircraft Commercial Engineering 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

II. 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.

III. 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, highlighting overdue items.

IV. 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.

Rig 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.

V. 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 JT9D Ceramic Outer Air Seal Program. The significant stress areas of the modified parts were analyzed to ensure that their structural margins were equal to or better than those of the bill-of-material parts.

The safety activities at Pratt & Whitney Aircraft 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.

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