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16. Abstract

The NASA-sponsored Engine Component Improvement - Performance Improvement Program at Pratt & Whitney Aircraft advanced the state-of-the-art of thermal barrier coatings and ceramic seal systems, demonstrated the practicality of an advanced turbine clearance control system and an advanced fan design in the JT9D engine, and demonstrated the advantages of modern cooling, sealing, and aerodynamic designs in the high-pressure turbine and compressor of the JT8D engine. Several of these improvements are already in airline service in JT8D and JT9D engines, and others will enter service soon in advanced models of these engines. In addition, the technology advances are being transferred to completely new engine configurations, the PW2037 engine and the NASA-sponsored Energy Efficient Engine.

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SECTION 1.0

SUMMARY

The NASA-sponsored Engine Component Improvement, Performance Improvement Program* at Pratt & Whitney Aircraft advanced the state-of-the-art of thermal barrier coatings and ceramic seal systems, demonstrated the practicality of an advanced turbine clearance control system and an advanced fan design in the JT9D engine, and demonstrated the advantages of modern cooling, sealing and aerodynamic designs in the high pressure turbine and compressor of the JT8D engine. Several of these improvements are already in airline service in JT8D and JT9D engines and others will enter soon in advanced models of these engines. In addition, the technology advances are being transferred to completely new engine configurations, the PW2037 and the NASA-sponsored Energy Efficient Engine.

* This work was conducted by Pratt & Whitney Aircraft for the National Aeronautics and Space Administration under Contract NAS3-20620. This contract was managed by the Lewis Research Center.

SECTION 2.0

INTRODUCTION

The NASA sponsored Aircraft Energy Efficiency (ACEE) Program is directed at reducing 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 Pratt & Whitney Aircraft Performance Improvement (PI) effort is the portion of the ECI Program with the objective of reducing the fuel consumption of existing models of the JT8D and JT9D engines by designing, developing and demonstrating component improvement concepts.

The concepts addressed by the ECI-PI hardware program were selected from 27 candidate concepts evaluated under a Feasibility Analysis (Ref 1) conducted at the beginning of the program in 1977. The Feasibility Analysis, which was conducted in cooperation with the Boeing and Douglas aircraft companies and American, United and Trans World Airlines, assessed the airline acceptability, the probability of introduction into production in the 1980 to 1982 time period, and the retrofit potential of each candidate concept. The top ranking concepts were selected by NASA for the hardware efforts that culminated in the following improvements:

- Technology advancement of thermal barrier coatings for turbine vane platforms
- Technology advancement of abradable ceramic outer air seals for unshrouded turbine blades
- Refinement and demonstration of a JT9D active turbine clearance control system with increased effectiveness
- Refinement and demonstration of a JT9D single-shroud fan with advanced aerodynamics
- Design and demonstration of a modern cooled turbine blade and outer air seal for the JT8D engine
- Design and demonstration of abradable tip rubstrips and aerodynamic refinements in the JT8D high pressure compressor

These improvements are described and their current and future applications are discussed in the following sections of this document.

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SECTION 3.0

DISCUSSION

Thermal Barrier Coating (Ref 2)

The thermal barrier coating concept applies a ceramic coating to the JT9D first stage turbine vane platforms, allowing reduction of the cooling airflow required in this area (Figure 1). This concept is envisioned as a first step toward the eventual use of thermal barrier coatings on the entire vane and on the turbine blades, allowing further reductions in cooling air requirements.

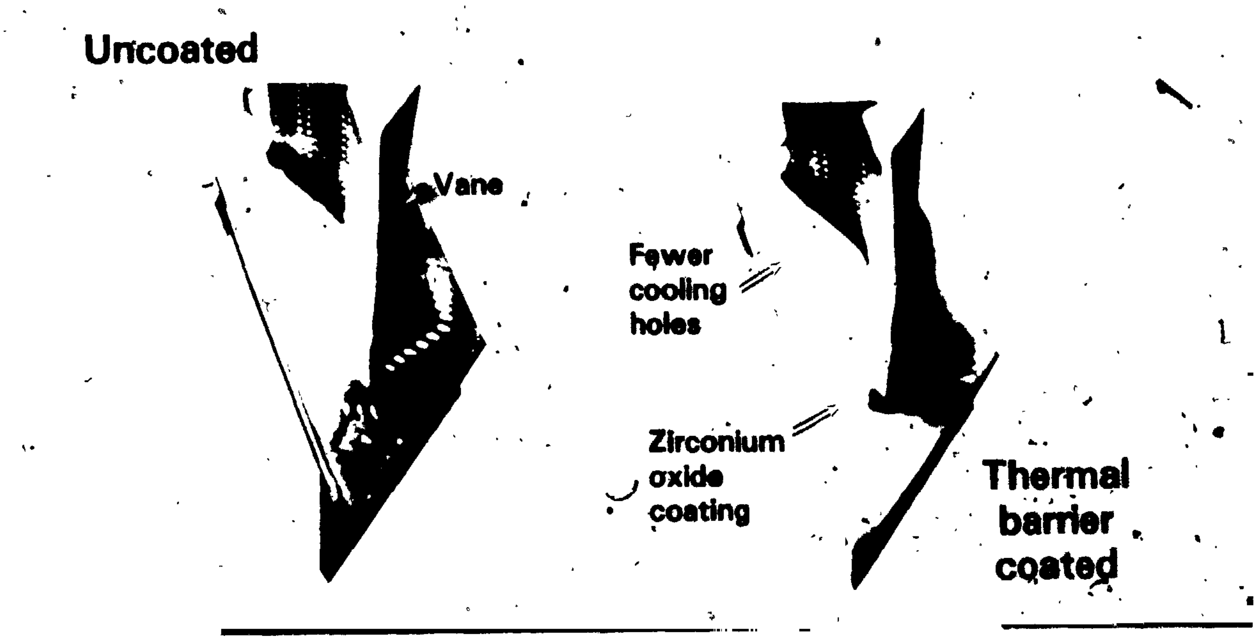

Figure 1 Thermal Barrier Coating. Used on turbine vane platforms, it allows reduction of cooling air flow.

The thermal barrier coating evaluated is zirconia, plasma sprayed over a thin oxidation protection coating on the platforms of the vane casting. The challenge was to enable the coating to accommodate the differential thermal expansion of the zirconia versus the metal casting, which had previously resulted in early spalling of such coatings. This was accomplished by optimizing the particle size of the zirconia powder, the type and amount of stabilizer material mixed with the zirconia, the distance from the plasma spray gun to the work, and the prestress in the coating at room temperature. The program resulted in a spectacular improvement in the spalling resistance of the coating on test specimens in a rig which simulated the thermal cycles encountered in the engine (see Figure 2). Based on the substantial improvement demonstrated in the rig, the program proceeded to engine endurance tests with high confidence of success.

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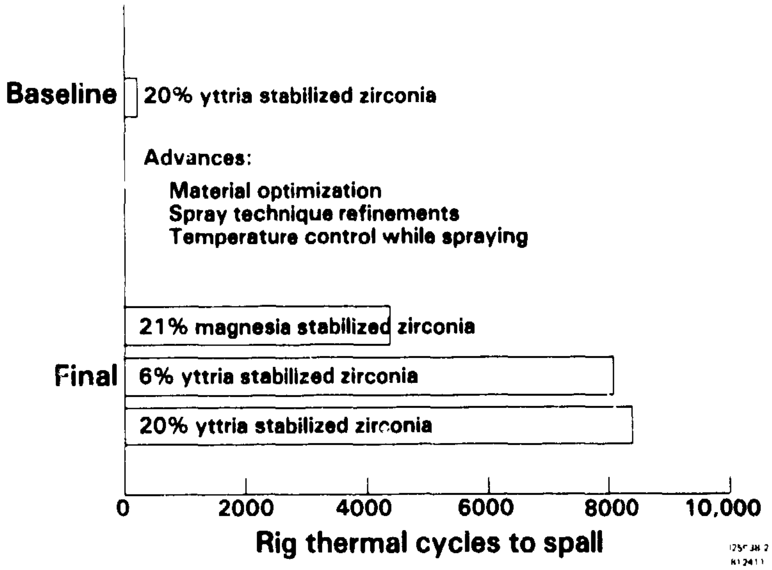

Figure 2 Thermal Barrier Coating Refinement Results. Durability was increased by a factor of 40.

A prototype cooling system for the coated vane platforms was designed using impingement and convective cooling principles instead of the film cooling system used on the JT9D bill-of-material vanes. This modification improves engine cycle efficiency by reducing cooling air requirements, and turbine efficiency by eliminating the cooling air film from the flowpath, resulting in an estimated specific fuel consumption advantage of 0.2%. The prototype system included all of the performance related features that would be desireable in a production configuration, but was compromised from the fabrication standpoint by the requirement to use existing vane castings.

High pressure turbine vanes incorporating the prototype cooling system and the three improved coatings identified on Figure 2 were subjected to 1500 cycles of accelerated endurance testing in a JT9D-7Q engine. The condition of typical vanes after the test is shown in Figure 3.

Figure 3 Typical Vane After Engine Tests. Thermal barrier coating (on platforms) is in good condition after 1500 cycles of engine endurance testing.

The JT9D-59/70/7Q engine series was selected as the testbed for the thermal barrier coated vanes at the beginning of the program in 1978 when this was the most advanced JT9D series. The concept has been considered for production application in this series and in the JT9D-7 series, but there are no current plans to complete development for these series. Instead, the concept is being developed for the JT9D-7R4G and H models, which are now the most advanced and highest rated engines in the JT9D family. The first of these models will enter airline service in mid-1983. The thermal barrier coating and cooling technology has been applied to the vane platforms of the PW2037, which is well along in its development program and will enter airline service in 1985. The technology has also been applied to the first stage turbine vane platforms of the NASA sponsored Energy Efficient Engine, which is intended for airline service starting about 1990. These applications are summarized on Figure 4.

Ceramic Outer Air Seal (Ref 3 and 4)

The ceramic outer air seal concept combines abradable ceramic outer air seals with abrasive tipped blades in the unshrouded high pressure turbine stages of the JT9D engine (see Figure 5). This system allows operation with tighter blade tip clearances, improving turbine efficiency and reducing engine specific fuel consumption by an estimated 0.3%. The insulative property of the ceramic also allows the use of less critical material for the metal shoes and perhaps reduced cooling airflow.

JT9D	Applicability	Tested	Bill-of-material	Airline service starting
-7A thru -7J	Similar design	Yes	No	–
-59/-70/-7Q	Direct	$\boxed{\text{Yes}}$	No	–
-7R4/-7R4H	Similar design	Yes	Yes	Mid 1983
PW2037	Technology	Yes	Yes	Early 1985
EEE	Technology	No	Yes	Approx. 1990

☐ = ECI program test

Figure 4 Applications of ECI Thermal Barrier Coatings. The refined thermal barrier coatings have potential application to a wide variety of current and future engines.

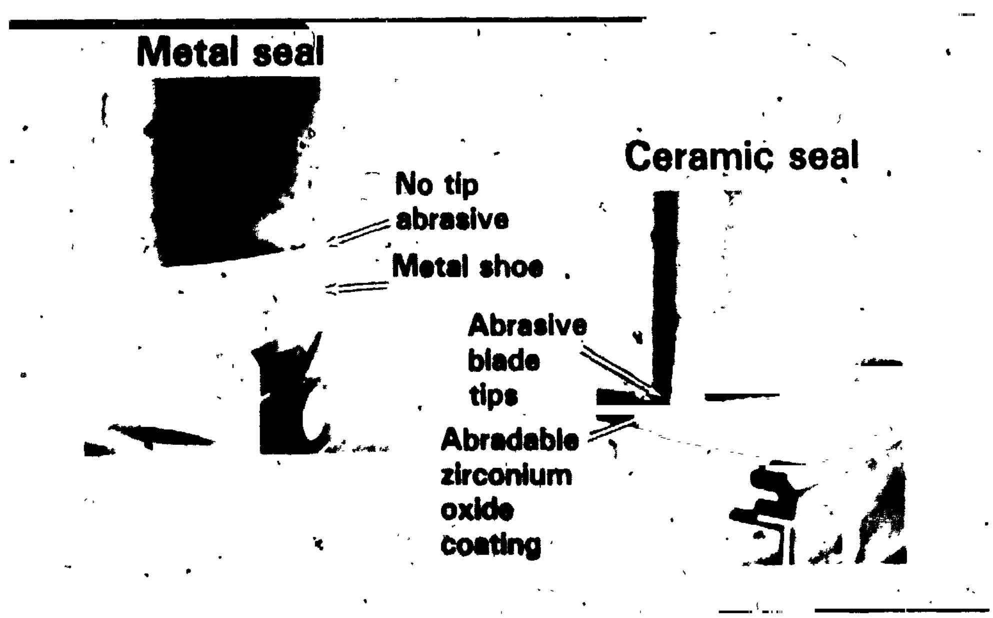

Figure 5 Ceramic Outer Air Seal. This system, applied to unshrouded turbine stages, allows operation with reduced blade tip clearances.

The abradable surface is porous zirconia applied over graded layers of dense zirconia with increasing percentages of CoCrAlY in the lower layers. The graded layers serve to ease the thermal expansion mismatch between the zirconia and the metal backing shoe. All of these layers, plus a thin bond coat of NiCrAl on the backing shoe surface, are plasma sprayed.

The seal system refinement effort under the ECI program reduced the thermal stresses and improved the structural properties in the graded zirconia layers by optimizing the spray gun operating parameters, increasing the accuracy of the spray process instrumentation and controls, and optimizing the structure. The process of the refinement effort was evaluated primarily by rig tests which subjected multi-layer specimens to increasingly severe thermal shocks until a crack could be detected under 60X magnification. The amount of improvement in thermal shock tolerance accomplished during the program is shown on Figure 6. Since earlier engine testing had shown the baseline ceramic seal system to be marginally acceptable, the amount of improvement shown in the rig test was very encouraging.

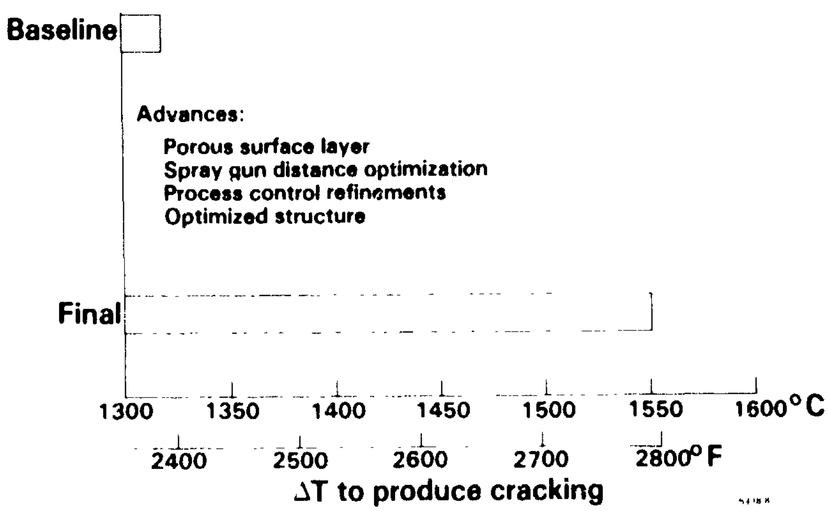

Figure 6 Results of Ceramic Seal System Refinement Effort. Thermal shock tolerance was improved by 230°C (415°F).

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Two full engine sets of ceramic seals incorporating the refinements were subjected to endurance tests in JT9D-7J and JT9D-7R4 engines. The parts shown in Figure 7 completed a 1000 cycle accelerated engine endurance test preceded by an intentional rub created by operating the engine through a severe transient cycle.

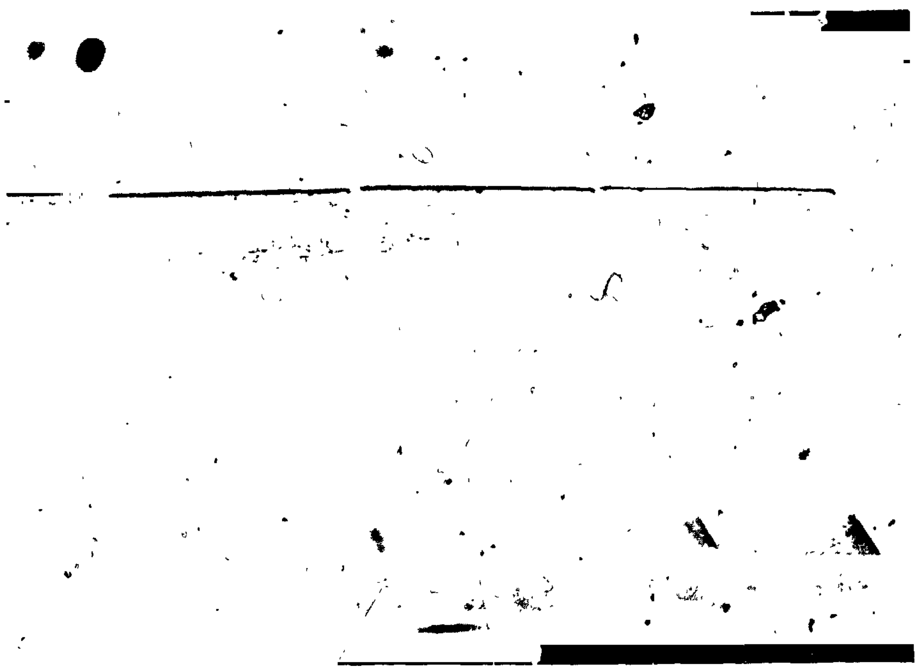

Figure 7 Typical Ceramic Seals after Engine Test. Parts are in good condition after intentional rub and 1000 cycle engine endurance test.

Application of the demonstrated ceramic seal system is being considered for advanced models of the JT9D-7R4 series. Technology from the demonstrated system has been applied in the first two stages of the PW2037 turbine and in the first stage of the Energy Efficient Engine turbine. These applications are summarized on Figure 8.

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JT9D	Applicability	Tested	Bill-of material	Airline service starting
-7A thru -7J	Direct	Yes	No	–
-59/-70/-7Q	Similar design	No	No	–
-7R4	Direct	Yes	Under evaluation	
PW2037	Technology	Yes	Yes	Early 1985
EEE	Technology	No	Yes	Approx. 1990

☐ = ECI program test

Figure 8 Application of ECI Ceramic Outer Air Seal. The ceramic outer air seal has application to several current and future engines.

Turbine Clearance Control (Ref 5)

A few JT9D-59/70 engines were delivered before October, 1978 with the active turbine clearance control system shown in the left illustration of Figure 9. The improved system shown in the right illustration of Figure 9 was optimized and demonstrated under the ECI program.

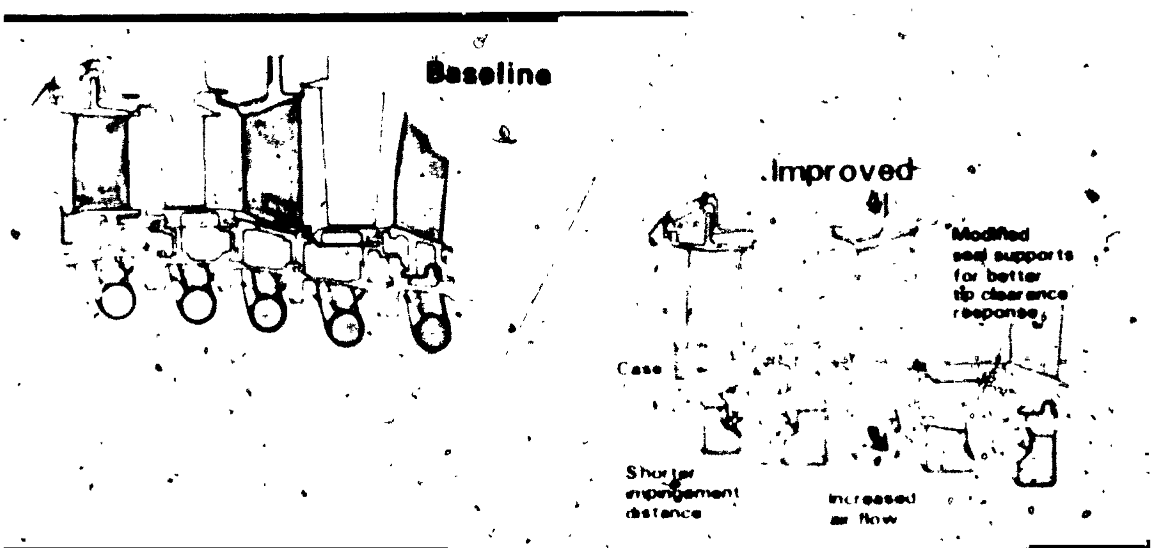

Figure 9 Turbine Clearance Control. Active control allows blade tip clearances to be closed during stabilized cruise conditions, opened during takeoff and climb.

The effect of both systems on specific fuel consumption is shown on Figure 10. The improved system reduces specific fuel consumption 1.4% when it is activated under cruise operating conditions, compared to a 0.7% reduction with the earlier system. The advantage of the improved system is the result of increased flow capacity, better targeting of the impingement jets and reduced stiffness of the turbine structural parts. The performance effects were demonstrated in the Pratt & Whitney Aircraft altitude test facility where the complete engine was operated under realistic altitude cruise conditions.

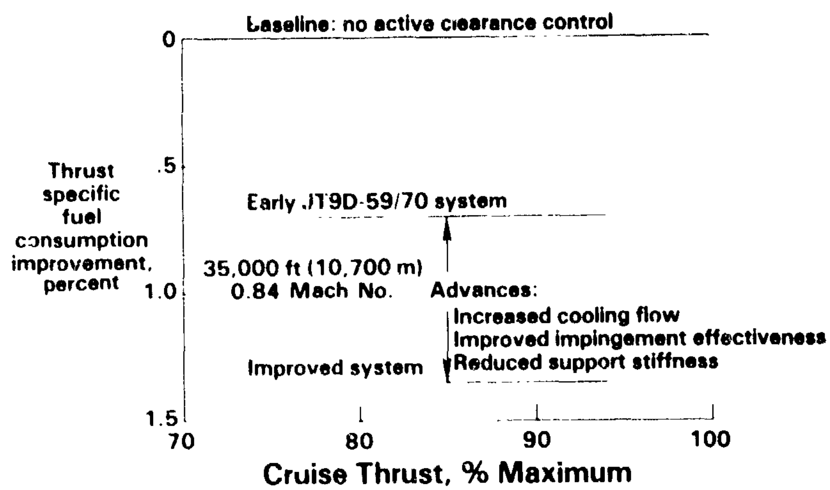

Figure 10 Results of Turbine Clearance Control Improvement Effort. Turbine clearance improves cruise TSFC by 0.7%.

Figure 11 shows the improved clearance control system installed on a JT9D-59 engine. It has been standard equipment on all JT9D-59, 7C and 7Q engines delivered since October, 1978, and several of the older engines have been retrofitted. A system based on the same principles is standard equipment on the JT9D-7R4 series of engines, which will enter airline service in mid-1982 in the Boeing 767. A system that incorporates some of the principles of the ECI system has been available on JT9D-7 series engines produced since 1978. The impingement cooling technology from the ECI program has been applied in designing the turbine clearance control systems for the PW2037. The Energy Efficient Engine uses an active clearance control system, but it operates on a different principle. These applications are summarized on Figure 12.

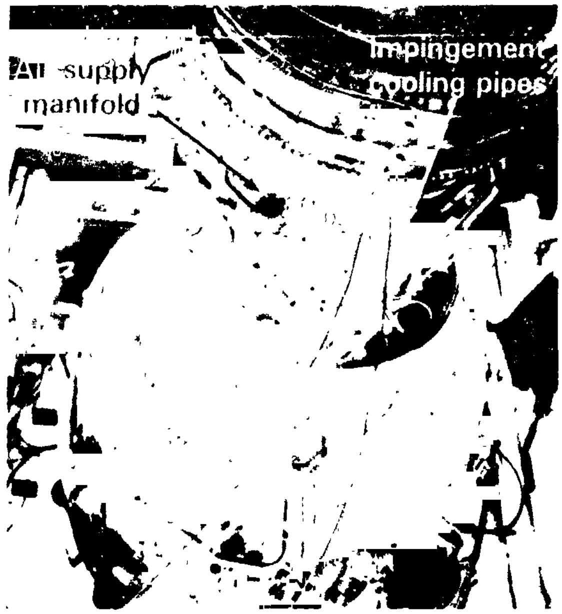

Figure 11 JT9D-59 engine with improved turbine clearance control. All JT9D-59, 70, and 7Q engines delivered since October 1978 have this system.

JT9D	Applicability	Tested	Bill-of-material	Airline service starting
-7A thru -7J	Similar features	Yes	Yes	Late 1978
-59/-70/-7Q	Direct	$\boxed{\text{Yes}}$	Yes	Late 1978
-7R4	Similar design	Yes	Yes	Mid 1982
PW2037	Technology	Yes	Yes	Early 1985
EEE	*	-	-	Approx 1990

*Uses different type of clearance control

☐ = ECI program test

Figure 12 Applications of ECI Turbine Clearance Control. In addition to current production engines, turbine clearance control is applicable to advanced engines.

Single Shroud Fan (Ref 6)

The JT9D-3A/7 fan was designed in 1966 with an unusually short blade chord in the interest of weight saving. Structural considerations related to the short chord dictated two part span shrouds, as shown in Figure 13. A new fan design, with blade chord increased sufficiently to allow the use of a single part span shroud, was optimized and demonstrated under the ECI program. The weight effect of the increased chord is minimized by reducing the number of blades and by using a hollow disk.

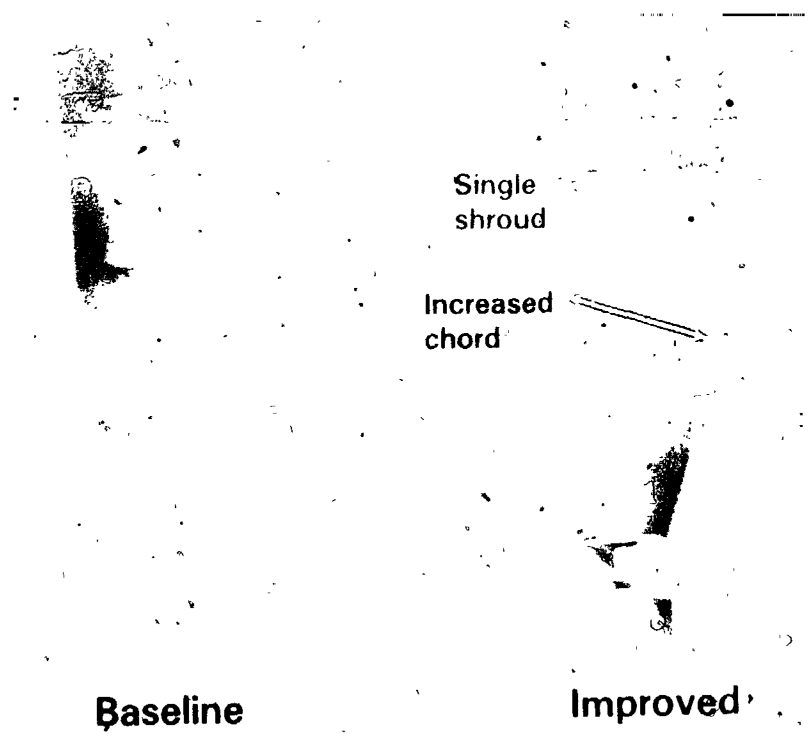

Figure 13 Single Shroud Fan. Original JT9D fan has short blade chord and two part-span shrouds for low engine weight.

A JT9D-7 engine equipped with the single shroud fan demonstrated a specific fuel consumption improvement of 1.0 to 1.3% at typical cruise conditions (see Figure 14) when tested in the Pratt & Whitney Aircraft altitude test facility. This improvement is the result of eliminating the losses associated with one set of part span shrouds, incorporating modern aerodynamic design technology in the blade airfoils and reducing blockage losses in the fan exit guide vanes.

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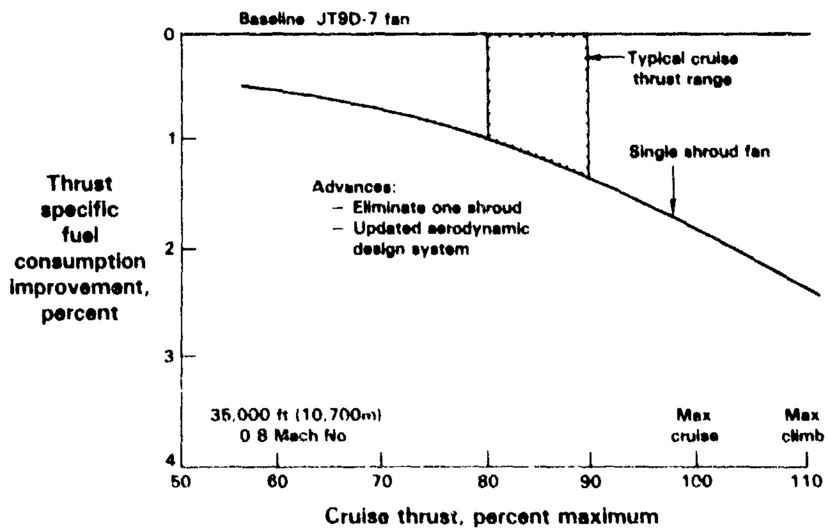

Figure 14 Results of Single Shroud Fan Effort. The single shroud fan improves cruise TSFC by 1 - 1.3%.

Other engine tests, including flight testing on the Pratt & Whitney Aircraft B-52 testbed shown on Figure 15, were conducted under the ECI program. These tests showed the noise, stability and operational characteristics of the single shroud fan to be equal to or better than the two shroud fan.

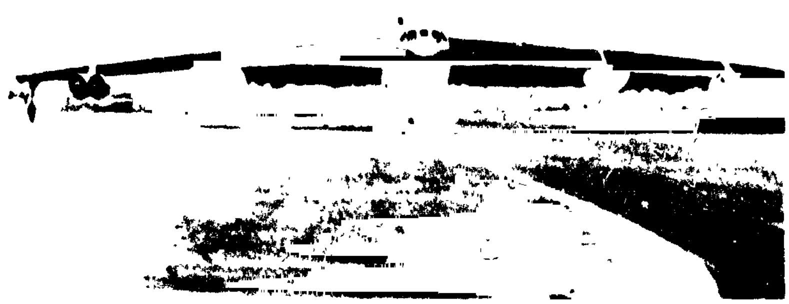

Figure 15 B52 Flying Testbed. Flight tests of single shroud fan showed stability and operational characteristics equal to or better than the two shroud fan.

Development of this particular single shroud fan, which fits only JT9D-3A and -7 engines, was discontinued because of increasing airline interest in the JT9D-7R4 engine series. A similar single shroud fan, but with bigger diameter and different flowpath shape, has been developed for the JT9D-7R4 engine series based on the technology of the ECI fan. The JT9D-7R4 fan system can be adapted to the JT9D-59/70/7Q engine series, but development of this combination has not started.

The PW2037 and Energy Efficient Engine fans differ from the JT9D fans in their physical dimensions and performance requirements, but the aerodynamic and structural technology of the ECI fan was applied in their design. These applications are summarized on Figure 16.

JT9D	Applicability	Tested	Bill-of-material	Airline service starting
-7A thru -7J	Direct	Yes	No	–
-59/-70/-7Q	Technology	No	No	–
-7R4	Technology	Yes	Yes	Mid 1982
PW2037	Technology	Yes	Yes	Early 1985
EEE	Technology	No	Yes	Approx. 1990

☐ = ECI program test

Figure 16 Applications of ECI Single Shroud Fan. The single shroud fan is planned for used in advanced engines.

JT8D Turbine (Ref 7)

The JT8D-15, 17 and 17R engines have a simple, single pass cooling system for the first stage turbine blades with the cooling air discharging from the blade tips, as shown on Figure 17. This arrangement requires that the blade tip sealing be concentrated near the forward edge of the shroud to allow the cooling air to escape.

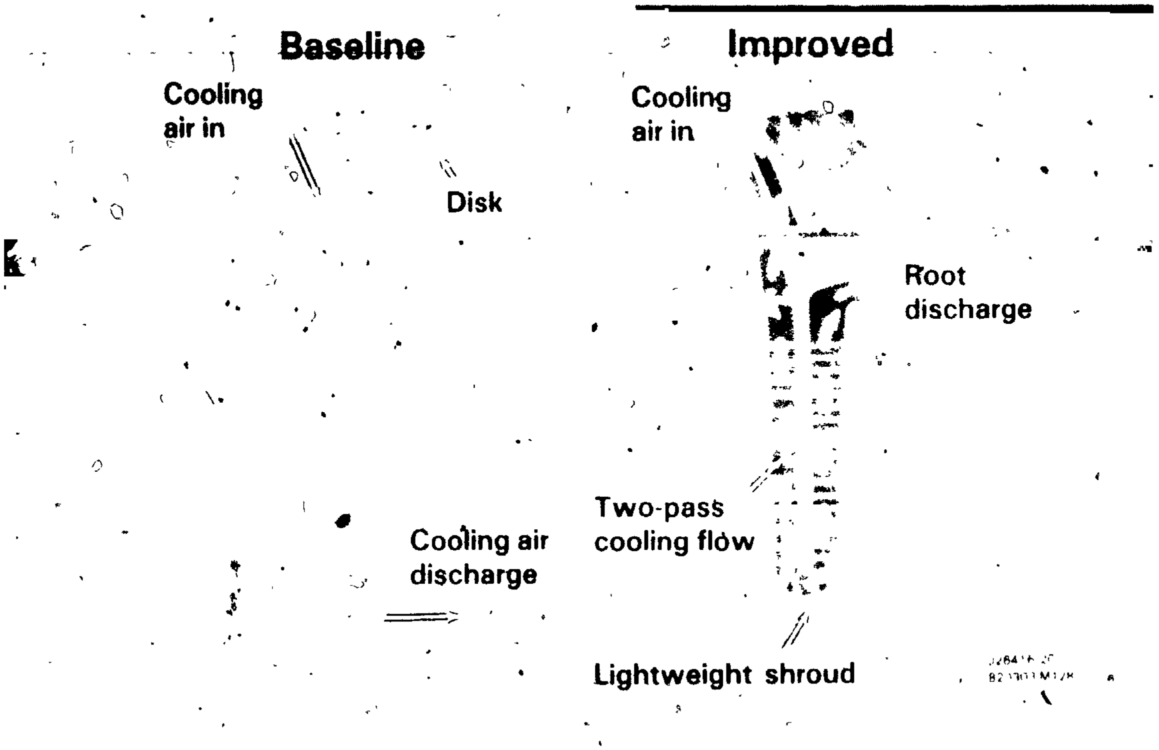

Figure 17 JT8D High Pressure Turbine. Original JT8D cooled turbine blade and seal were improved using proven technology.

Under the ECI program, a new blade and outer air seal combination (see Figure 17) was designed and tested, based on two pass blade cooling technology that had been applied successfully in JT9D second stage turbine blades. The new blade was designed to accommodate an optional overlay coating for improved sulfidation protection and the blade material was changed from B-1900 to Mar-M-247 for improved castability and creep resistance. The new outer air seal uses stepped honeycomb lands mating with wide surfaces without knife edges on the blade shrouds (see Figure 18).

The blade cooling and sealing improvements were combined with aerodynamic refinements in the blades and second stage vanes, sealing improvements in the first stage vanes and better control of secondary airflow around the outer air seal to form the high pressure turbine performance improvement package.

This package was engine tested at both sea level and altitude cruise conditions under the ECI program. The demonstrated improvement in specific fuel consumption of 1.8 to 2.4% at typical cruise conditions is shown on Figure 19. At sea level static, takeoff power conditions the package demonstrated specific fuel consumption and exhaust gas temperature improvements of 1.9% and 18°C, respectively.

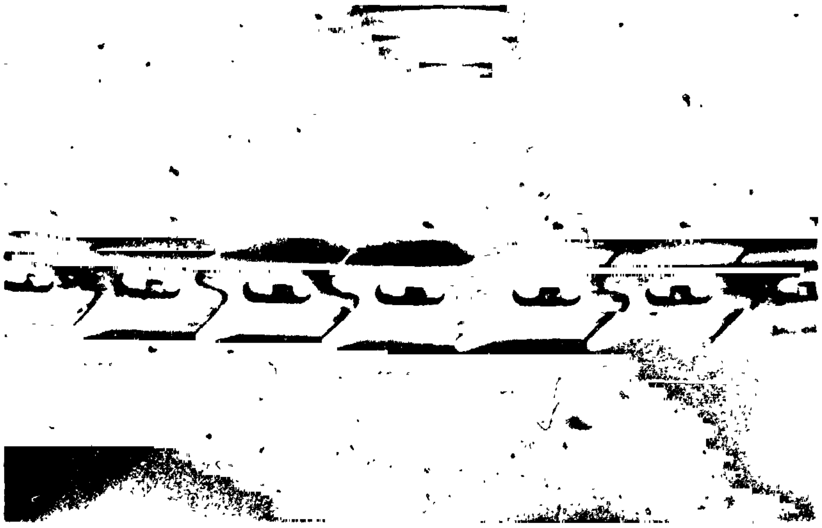

Figure 18 New JT8D cooled turbine blade. The blade tip shroud, which has no knife edges, is sealed by stepped honeycomb lands.

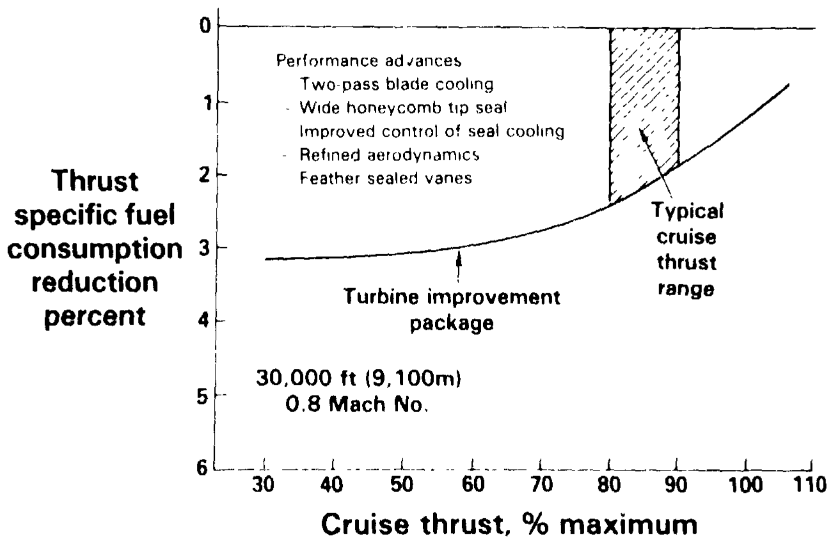

Figure 19 Results of JT8D High Pressure Turbine Improvement Effort. The improvement package improves cruise TSFC by 1.8%.

The high pressure turbine improvement package is applicable to all models of the JT8D engine that use a cooled turbine. The package is included in the original bill-of-material for the JT8D-217 engine, which started airline service in August, 1981 in Douglas DC-9-80 airplanes. With some aerodynamic improvements, it is the largest single contributor to a 5.5% specific fuel consumption improvement package that is bill-of-material in the JT8D-15A, 17A, and 17AR engine models, which will start airline service in late 1982 in the Boeing 727 and 737. The 5.5% improvement package will also be available in late 1982 as a retrofit kit for existing JT8D-15, 17 and 17R engine models in Boeing 727 and 737 and Douglas DC-9 airplanes. These applications are summarized on Figure 20.

JT8D	Applicability	Tested	Bill-of-material	Airline service starting
-15/-17/-17R	Direct *	$\boxed{\text{Yes}}$	Retrofit	Late 1982
-15A/-17A/-17AR	Direct *	Yes	Yes	Fall 1982
-217	Direct	Yes	Yes	August 1981

*With added aerodynamic improvements

$\boxed{}$ = ECI program test

Figure 20 Applications of ECI JT8D High Pressure Turbine. The high pressure turbine package is planned for use in the JT8D family of engines.

JT8D Compressor (Ref 8)

The JT8D high pressure compressor normally operates with relatively large clearances (about 0.050 in. on the average) over its blade tips. The resulting performance disadvantages have been accepted because service experience has shown that tighter clearances can result in blade tip rub against the metal outer shrouds (see Figure 21) under severe transient and maneuver conditions. Such rubs damage the blade tips and force more frequent blade replacement, increasing maintenance cost. The compressor designed and tested under the ECI program includes trenched abradable rubstrips for each blade row, allowing the blade lengths to be increased without risking blade damage. The abradable material is porous nickel-chromium, plasma sprayed into recesses in the modified outer shrouds (see Figure 21).

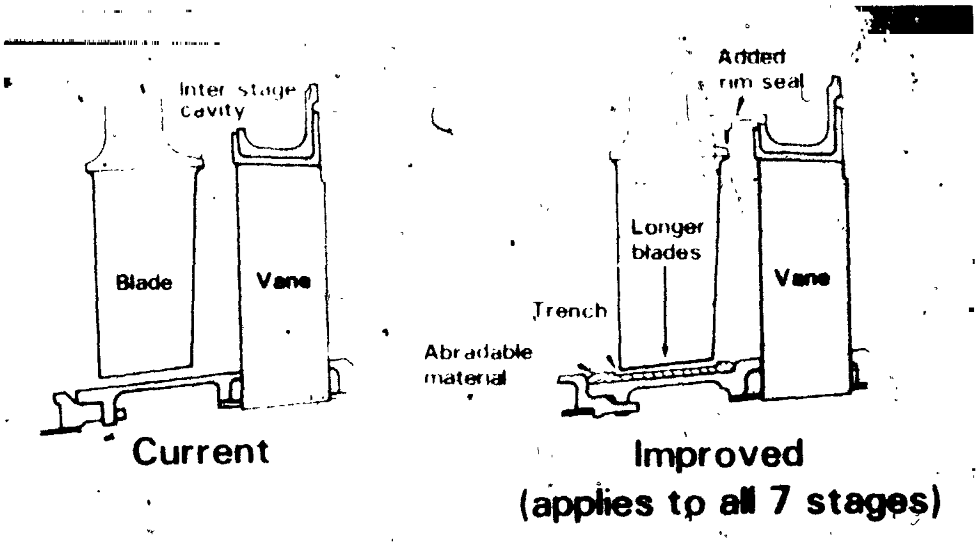

Figure 21 JT8D High Pressure Compressor. Original JT8D high pressure compressor was improved using advanced abradable material.

The JT8D high pressure compressor also has deep cavities on either side of the stator inner seals (see Figure 22), a result of the structural design of the rotor. These cavities were partially isolated from the flowpath in the modified compressor with simple extensions on the forward edge of the stator inner shrouds, as shown in Figure 21. The modified compressor also included manufacturing tolerance adjustments on the stator assemblies to minimize steps and bumps in the flowpath walls, and blade camber adjustments to compensate for the expected stability effects of reduced tip clearances.

Figure 22 JT8D High Pressure Compressor Cutaway. Deep inner seal cavities are the result of rotor structural arrangement.

The modified compressor was subjected to compressor rig and engine tests under the ECI program. It showed a 1% specific fuel consumption advantage over a wide power range in a sea level static engine test, as shown on Figure 23. It also showed a surge margin increase of 3 to 4%, implying that additional fuel consumption improvement is possible with aerodynamic fine tuning.

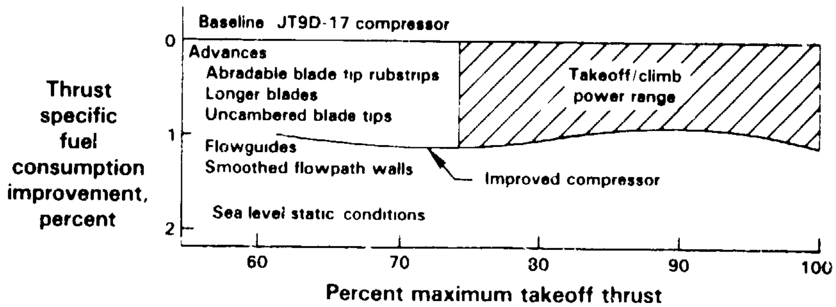

Figure 23 Results of JT8D High Pressure Compressor Improvement Effort. The modified compressor improves takeoff TSFC 1%.

These rig and engine tests also demonstrated the good abradability properties of the sprayed nickel-chromium rubstrip material (see Figure 24). Other engine tests have demonstrated its durability properties.

Figure 24 Typical Abradable Rubstrip after Engine Test. Plasma sprayed nickel-chromium rubstrips show good abradability properties.

The modified compressor will fit all models of the JT8D engine, including the new 200 series. However, current plans do not include completing its development because of the shift in airline interest from the JT8D toward advanced high bypass ratio replacement engines.

The sprayed abradable rubstrip technology which was developed during the program is being applied in the PW2037 and Energy Efficient Engine compressors. The applications are summarized on Figure 25.

JT8D	Applicability	Tested	Bill-of-material	Airline service starting
All models	Direct	In -17	No	–
PW2037	Technology	Yes	Yes	Early 1985
EEE	Technology	No	Yes	Approx. 1990

☐ = ECI program test

Figure 25 Applications of ECI JT8D High Pressure Compressor. This concept is planned for advanced engines.

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CONCLUSIONS

The NASA sponsored ECI program has resulted in significant improvements in current JT8D and JT9D engine models, and has made significant contributions toward improvements in all of the advanced commercial engine models under development at Pratt & Whitney Aircraft. These results are summarized on Figure 26.

	JT8D family			JT9D family			PW2037	EEE
Improvement	15/17/17R	15A/17A/17AR	217	7	59/70/7Q	7R4		
Thermal barrier coating						In	In	In
Ceramic outer airseal						*	In	In
Turbine clearance control				In	In	In	In	**
Single shroud fan						In	In	In
JT8D HP turbine	Option	In	In					
JT8D high pressure compressor							***	***

*Under evaluation
**Uses different type of clearance control
***Abradable material applied

Figure 26 ECI Applications Summary. The ECI Program has made significant contributions toward improvements in all of the advanced commercial engines.

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