

## N O T I C E

THIS DOCUMENT HAS BEEN REPRODUCED FROM  
MICROFICHE. ALTHOUGH IT IS RECOGNIZED THAT  
CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED  
IN THE INTEREST OF MAKING AVAILABLE AS MUCH  
INFORMATION AS POSSIBLE

(NASA-TN-79304) ENGINE COMPONENT  
IMPROVEMENT PROGRAM: PERFORMANCE  
IMPROVEMENT (NASA) 17 p HC A02/NF A01

**CSCL 21E**

Unclass  
46205

**G3/07**

**John E. McAulay**  
**Lewis Research Center**  
**Cleveland, Ohio**



Prepared for the  
Eighteenth Aerospace Sciences Meeting  
sponsored by the American Institute of Aeronautics  
and Astronautics  
Pasadena, California, January 14-16, 1980

## ENGINE COMPONENT IMPROVEMENT PROGRAM - PERFORMANCE IMPROVEMENT

by John E. McAulay\*  
NASA Lewis Research Center  
Cleveland, Ohio

### Abstract

The Engine Component Improvement (ECI) Program is NASA sponsored and is specifically directed at reducing the fuel consumption of commercial aircraft in the near-term. As part of the ECI program, a Performance Improvement (PI) effort aimed at developing fuel saving and retention components for new production and retrofit of JT9D, JT8D, and CF6 engines is underway. This paper reviews the manner in which the PI concepts were selected for development and summarizes the current status of each of the 16 NASA selected concepts.

### Introduction

In 1975-1976 the Aircraft Energy Efficient (ACEE) Program was formulated and begun under NASA sponsorship. As part of this program technological advances were initiated specifically aimed at improving the fuel efficiency of the JT8D, JT9D, and CF6 turbofan engines. This effort, called the Engine Component Improvement (ECI) Program, has been divided into two parts: Engine Diagnostics and Performance Improvement. The Engine Diagnostics part of the program consists of analysis and test of the JT9D and CF6 engines to isolate and quantify the causes of performance deterioration with time. The use of these data is expected to reduce the fuel consumption of current engines about 1 percent and also aid in the design of future engines.

The Performance Improvement (PI) part of the program, which is the subject of this paper, is directed at developing fuel saving and retention components for new production and retrofit of JT9D, JT8D, and CF6 engines which are shown in Fig. 1. In an attempt to insure that the fuel saving and retention components are technically sound and economically acceptable to the air transport industry, the Performance Improvement (PI) effort started with a Feasibility Study by the manufacturers of the JT8D, JT9D, and CF6 engines.<sup>1,2</sup> The study objectives were to develop a cost/benefit methodology for screening and evaluating the PI concepts, identify promising concepts, and then, carry out a screening assessment using the cost/benefit method and technical and economic data collected or derived as a part of the study.

The results of the Feasibility Study were then used to aid in selection of PI concepts which NASA funded. Of the 16 concepts funded, development of 9 have been completed.

This paper reviews the manner in which the PI concepts were selected for development and summarizes the current status of each of the 16 NASA-selected concepts.

### Feasibility Study

In order to make the Feasibility Study accurate and reflect the real world, it was desirable to obtain as wide a range of industry participation as possible. The chart shown in Fig. 2 illustrates the Feasibility Study participants and their relationship to each other. Each box on the chart represents a contributing organization. Those connected with solid lines were prime participants, while those connected with a dashed line served in a consulting and/or advisory role. Of particular note is the independent and direct consulting role of Eastern and Pan American to NASA, and the differences in the Pratt & Whitney Aircraft and the General Electric team structure. Pratt & Whitney cooperated with Trans World Airlines (TWA) in establishing a cost/benefit methodology and in performing the economic analysis of the PI concepts. Thus, TWA provided the route structure, fleet composition, and extensive experience necessary to provide practical viewpoints and realistic economic evaluations of the PI concepts. For General Electric, United and American provided aid to Douglas and Boeing so that they could perform the necessary analysis to simulate airline usage.

Once these Pratt & Whitney and General Electric teams had established their cost/benefit methods, the engine manufacturers identified potential performance improvement concepts. Some additional engine related PI concepts were added by the airframe manufacturers. Initially, the total list of JT8D and JT9D concepts numbered 95 while the CF6 concepts totaled 58. Preliminary screening reduced the number of JT9D concepts to 18, JT8D concepts to 11 and CF6 concepts to 29. The primary reasons for concept rejection at this point in the study were developmental cost beyond program scope, fuel savings too small to measure or verify, very high development risk, and development time longer than program guidelines (i.e., introduce to production by 1980-82).

Following the reduction of the PI concepts to a more manageable number, a detailed screening procedure was initiated on these remaining concepts. A summary of this screening procedure is shown in Fig. 3. The upper left-hand box enumerates the Engine Factors which provide input for the screening process. Included are specific fuel consumption (SFC), weight, price, maintenance cost, retrofit potential, and technical risk. This information was then transmitted to the airframe company which determines what effect the modified engine will have on the aircraft. This includes an evaluation by the structures, weights, noise, propulsion, and aerodynamics groups. The results of this evaluation were used to determine the effect on airplane per-

\*Head, Performance Improvement Section, NASA Lewis Research Center.

formance, weight, and price. Once these data were available, a typical airline route structure and fleet composition was used to arrive at a fuel savings. This, in conjunction with economic assumptions (i.e., cost/benefit methodology) such as engine life, market sales projections, depreciation, taxes, fuel price, and airline hurdle rate (i.e., cost of capital), was used to establish the economic viability of the PI concepts being investigated.

The primary factors NASA used in selecting PI concepts for funding, are given in the lower boxes of Fig. 3. These factors were fuel savings, airplane economic acceptability, as defined by payback period, ROI, etc., development time and risk, and NASA development cost. The fuel savings potential was, of course, enhanced if the PI concept had retrofit potential.

Using these criteria, NASA selected 16 concepts to develop with NASA funding. These PI concepts are listed on Fig. 4, along with the engine application, the fuel savings potential in terms of cruise SFC reduction and cumulative liters (gallons) of fuel saved through the year 2005, and the payback period. At the time the study was made, fuel prices of 40 cents per gallon were typical. Present prices are nearer 65 cents per gallon, an increase of over 60 percent. This fuel cost effect would substantially reduce the payback periods given on the figure.

#### Performance Improvement Concepts

A schematic of the current and improved JT8D high pressure turbine (HPT) outer air seal is shown in Fig. 5. The current blade discharges all of the cooling air at the blade tip and because of this and other considerations has a large blade tip clearance with attendant high leakage. In the revised scheme most of the cooling air discharge is relocated to the suction side of the blade by plugging and drilling the current blade. This allows the addition of another knife edge seal on the blade tip and the extension of the honeycomb seal material to the trailing edge of the existing spoiler, thus reducing the seal leakage. This reduced leakage was estimated to reduce cruise SFC by 0.5 percent. This development effort has been successfully completed and back-to-back engine altitude tests have exhibited a SFC reduction of 0.6 percent.<sup>3</sup>

The JT8D high pressure turbine root discharge blade (see fig. 6) uses a two pass cooling system with improved cooling effectiveness. The new blade design requires a new casting; therefore, updated materials, improved airfoil shape, and reduced trailing edge thickness are incorporated. When compared to the improved JT8D HPT outer air seal configuration (fig. 5), there is a reduction in cooling air required, an elimination of the momentum loss due to the discharge of cooling air on the suction side of the blade, and reduced blade contour losses. It is estimated that the root discharge blade will provide 0.9 percent reduction in fuel consumption beyond the improved high pressure turbine outer air-seal configuration. At the present time, the concept design is complete, much of the test hardware is available, baseline testing of the bill-of-material configuration is complete, and testing of the root discharge configuration is being initiated.

The JT8D trenched-tip high-pressure compressor (HPC) configuration is shown in Fig. 7. The use of abradable rub strips through the high pressure compressor permits running with tighter tip clearances. A sprayed Nichrome-polyester abradable appears most promising based on cost, erosion, and abradability considerations. The compressor outer case is also trenched so that the blade tip at cruise can run line-on-line with the outer flow path. In addition, rim seals have been added along the inner flow path to reduce inter-stage cavity recirculation, thereby improving stall margin. It is estimated that this blade-case configuration will provide a 2 percent improvement in compressor efficiency which corresponds to a 0.9 percent reduction in cruise SFC.

Currently, bill-of-material compressor rig tests have been completed, and the trenched-tip configuration is being readied for test. These rig tests will then be followed by an engine demonstration.

The current and modified DC-9 thrust reverser stang is shown in Fig. 8. The thrust reverser hinge assembly in the current configuration reduces the base area with a more complete fairing. The new fairing is made of Kevlar/PMR-15, an advanced composite material which will tolerate the 500° F environment created by the engine exhaust gas while providing improved fatigue strength over the current aluminum fairing. The development effort on the reverser stang is complete. Included in this effort were several flight tests to determine the drag reduction. The initial tests incorporated static pressure measurements on the fairing as well as a tuft survey. These first tests dictated a modification to the fairing contour. The latter flight tests relied on an extensive tuft survey to detect the local flow conditions. From these results a drag (or SFC) reduction at cruise was calculated to be 1.2 percent. A 1 year in-service evaluation of the reverser stang fairing is just being initiated.

The improved JT9D-7 fan concept is shown in Fig. 9. Fan performance is improved by elimination of one of the part span shrouds and by incorporation of improved fan blade aerodynamics (i.e., multiple circular arc airfoils). The fan blade chord is increased (reduced aspect ratio) in order to avoid blade flutter and to provide satisfactory foreign object damage characteristics. In addition, the reduced number of fan blades permits, because of acoustic considerations, a reduction in the number of fan exit guide vanes with an attendant performance improvement. Initial estimates were that the improved fan would reduce the cruise SFC by 1.3 percent.

Initial ground and flight testing of this improved fan verified its performance and stability expectations. However, the requirement for a somewhat different fan for the JT9D engine model for the Boeing 767 airplane led to halting development of this improved fan. Nevertheless, the increase in the data base from testing of the improved fan is directly applicable and is being used in the fan development program for the JT9D-7R4 fan for the B-767.

Figure 10 shows the improved JT9D-59/70 high pressure turbine active clearance control. The JT9D-59/70 high pressure turbine is encircled by perforated pipes which spray fan air on the turbine



case. The air supply is turned off during takeoff, climb, and landing when the engine is subjected to the most severe thermal and structural loads. Since the case is hotter with the air turned off, thermal expansion of the case and seal supports provides larger clearances between the turbine blade tips and the seals. The cooling air is turned on during cruise and the shrinkage of the case and seal tightens the tip clearance, improving turbine efficiency. The improved system incorporates increased coolant air supply and an improved distribution system which results in a reduced striking distance for the impinging jets. These improvements will give a greater reduction in outer air seal diameter at cruise and therefore a greater improvement in cruise SFC. The predicted improvement in cruise fuel consumption was 0.9 percent beyond that achieved with the current active clearance control system. Development of this concept has been completed with a demonstrated reduction in SFC of 0.65 percent, less than that predicted. The reason for this deficiency is the actual blade tip clearance available for closure was less than the original estimates.<sup>4</sup>

Zirconia ceramic coating of the JT9D first-stage nozzle guide vane endwalls (fig. 11) provides a thermal barrier or insulating effect which allows a reduction in cooling air and thus a predicted SFC reduction of 0.2 percent. Further development may allow thermal barrier application to vanes and blades in the future with additional reductions in the fuel consumption.

Up to the present time, considerable effort has been expended on the investigation of various coating chemistries and the development of coating application techniques. For example, temperature control of the metallic substrate during the application of a plasma-sprayed coating has provided a 50 percent improvement in coating durability during burner rig tests. The first exposure of several thermal barrier coatings to an engine environment in this program is planned in the near future.

The JT9D ceramic high pressure turbine outer air seal concept is shown in Fig. 12. The combination of a ceramic outer air seal and an abrasive blade tip provides a considerable improvement in abrasability relative to current shroud/blade material combinations. This permits use of tighter tip clearances. Also the ceramic shroud material acts as an insulator thereby reducing cooling air requirements. A potential cruise SFC improvement of 0.4% is estimated for this concept. Currently material property and spray parameter tests are being conducted to develop a seal composition suited for severe engine endurance tests. Previous developmental effort has already yielded a seal configuration that has successfully been tested in an engine environment over a short period of time.

An improved fan package for the CF6 engine is pictured in Fig. 13. The two most significant features of the fan package are the blade aerodynamic design and the fan case stiffener. The improved fan design has a single part span shroud which has been moved rearward on the blade. In addition, the blade camber has been increased by a small amount and the distribution of camber modified to move the throat passage forward. Thus, the part span shroud blockage has been shifted downstream of the blade passage throat with an attendant reduction of aerodynamic losses.

The thickness distribution of the new fan blade is the same as the current production design in a chordwise and spanwise direction. The platform and shank of the new blade are very similar to the production blade. The dovetail is identical so that the two designs are completely interchangeable in the same fan disk in sets. Both fan blades are common to both CF6-6 and CF6-50 engines. The new fan blade has the same maintainability features as the current production blade, such as individual replacement on wing. A change in the fan disk platform is required because of a small change in the hub flowpath. Otherwise, all interfaces are unchanged.

The fan case stiffener has been designed to raise the critical interaction frequencies of the fan and the fan case above the maximum operating fan speed. This permits the fan blade tip clearances to be reduced which leads to an increase in fan efficiency.

The development of the improved fan package has been completed and the predicted performance gain, a reduction of cruise SFC of 1.8 percent, has been demonstrated with no increase in noise or loss in stability.<sup>5</sup>

A short core exhaust nozzle system for the CF6-50 engine is schematically shown in Fig. 14. This concept involves replacing the current core engine reverser/exhaust nozzle system with a reduced length exhaust system. The short core exhaust results in reduced diameter fan flow lines aft of the fan reverser and necessitates recountouring the engine core cowl as well as the core nozzle. Theoretical and model tests indicated a potential for a 1.0 percent reduction in cruise SFC because of reduced internal nozzle pressure losses. In addition, a significant reduction in engine weight was predicted. Development of this concept has been successfully completed with engine tests exhibiting an 0.9 percent SFC improvement, no increase in engine noise, and 1000 flight cycles of endurance testing without any signs of distress.<sup>6</sup>

A new front mount for the CF6 engine is shown in Fig. 15. This redesigned mount effectively reduces the point loading in the compressor casing by applying the engine thrust reaction at two points +30 degrees from the top vertical centerline, thus the case distortion is reduced allowing the compressor blade tip clearances to be decreased. It was estimated that the decreased clearances would reduce the cruise SFC 0.3 percent. Development of the new front mount, which included fatigue analysis, materials testing and deflection/distortion and cyclic endurance tests, has been completed. These results demonstrate that the mechanical aspects of the new mount are satisfactory and that the decreased clearances in the compressor should produce a 0.1 percent reduction in SFC and a substantial increase in compressor stall margin.<sup>7</sup> The reason that the SFC reduction is only 0.1 percent and not 0.3 percent is that testing and analysis conducted during the program has shown that the compressor blade clearance closure potential is less than originally estimated.

A schematic drawing depicting the main features of an improved CF6-6, high pressure turbine is presented in Fig. 16. Included in the improved turbine are: (1) single shank turbine blades in the first and second stages, (2) reduced turbine exit

swirl which lowers the turbine mid-frame pressure losses, (3) improved cooling techniques thereby reducing the cooling flow requirements, (4) aerodynamic refinements such as increase solidity and smoother blade surface finish, and (5) mechanical and cooling improvements of the shroud to allow reduced blade tip clearances. The predicted SFC reduction resulting from this performance improvement concept is 1.3 percent for new engines and 1.6 percent after 3000 hours of operation. Development of the improved turbine is complete. Data from recent back-to-back engine performance tests are being analyzed.

Three interrelated PI concepts which involve improved control of CF-6 turbine clearances are schematically illustrated in Figs. 17 to 19. Figure 17 shows the main features of the high pressure turbine roundness control (i.e., passive clearance control). The primary features of this concept are an improved mechanical design including such considerations as mass and mass distribution of supporting structure, insulating or shielding the supporting structure from the influence of cavity air recirculation, and selection of materials which provide thermal growth rates more compatible with the turbine rotor structure. The anticipated reduction in SFC of this concept is 0.4 percent for new engines and 0.8 percent at 3000 hours.

Figure 18 shows the high pressure turbine (HPT) active clearance control PI concept. Cooling air from the fan aft duct, which is directed to impinge at appropriate high pressure turbine shroud supports, is controlled to provide a minimum allowable turbine tip clearance at cruise. The reduced SFC value predicted for the HPT active clearance control concept is 0.3 percent for new engines and 0.6 percent at 3000 hours.

The low pressure turbine (LPT) active clearance control system is schematically illustrated in Fig. 19. Fan air which is continuously used to cool the LPT shroud supports is augmented with additional fan air at cruise to permit a reduction in blade tip clearance at cruise. The predicted SFC reduction using this system is 0.3 percent.

All of the three turbine concepts are currently in the design and hardware procurement stages. Development of the HPT Roundness Control and LPT Active Clearance Control is scheduled for 1980. Development of the HPT Active Clearance Control is scheduled through 1981.

A schematic diagram of the improved DC-10 cabin air circulation system is presented in Fig. 20. A recirculation system has been added to the existing circulation system in order to reduce the engine bleed air required. The primary components of the recirculation system are a fan, filter, and appropriate ducting and controls. The predicted value of SFC improvement accompanying the engine bleed reduction is 0.7 percent. The cabin air recirculation system has been installed on an American Airlines DC-10 and an in-service evaluation due for completion in August 1980 is underway.

The data presented in Fig. 21 summarizes the fuel saving results for those performance concepts for which development is now complete. Inspection of these results show that although there are differences between the predicted and achieved SFC reductions in several cases, the overall comparison on balance is quite good. The projected cumulative

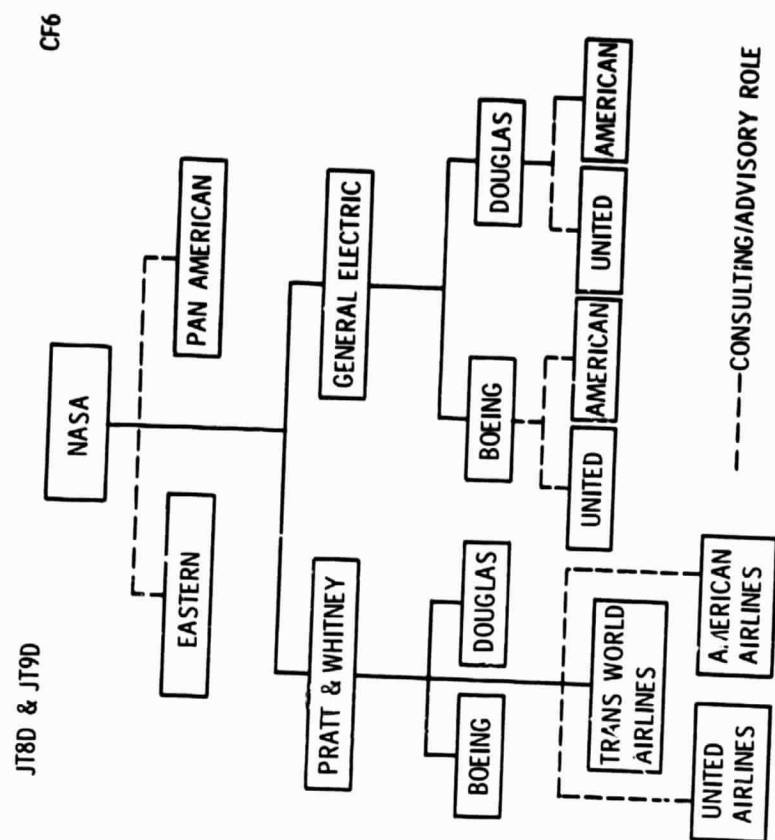
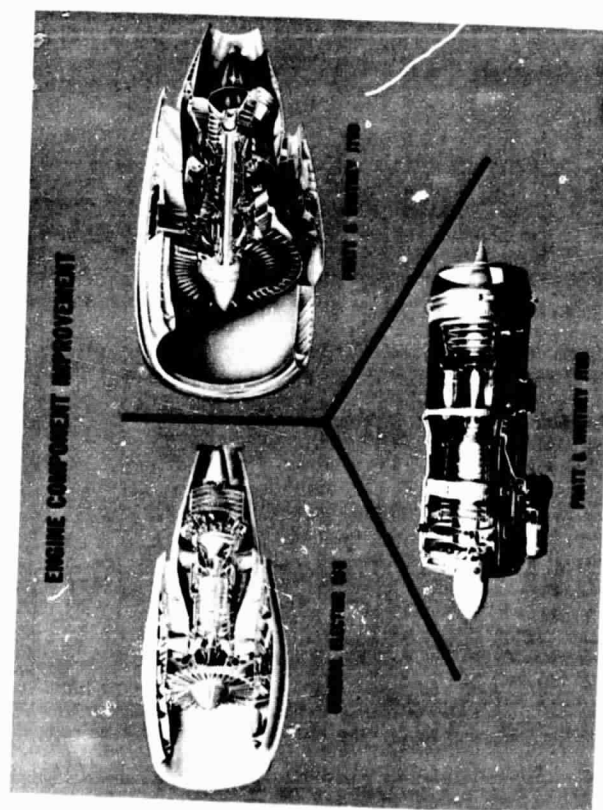
fuel saved is a function not only of the SFC reduction but the number of engines affected by any specific performance improvement concept. Thus, in the case of the JT8D HPT Improved Outer Air Seal, the added number of affected engines anticipated after concept development increased the fuel saved more than that reflected in the SFC variation.

### Conclusion

The Performance Improvement Program sponsored by NASA has already provided significant potential for reductions in the fuel consumed by the commercial air transport fleet. Additional fuel savings potential are expected by PI concepts still under development.

### References

1. Gaffin, W. O., and Webb, D. E., "JT8D and JT9D Jet Engine Performance Improvement Program - Task 1, Feasibility Analysis," Pratt and Whitney Aircraft Group, East Hartford, Conn., PWA-5518-38, Apr. 1979. (NASA CR-159449)
2. Fasching, W. A., "CF6 Jet Engine Performance Improvement Program - Task 1, Feasibility Analysis," General Electric Co., Cincinnati, Ohio, R79AEG295, Mar. 1979. (NAEA CR-159450)
3. Gaffin, W. O., "JT8D Revised High-Pressure Turbine Cooling and Outer Air Seal Program," Pratt and Whitney Aircraft Group, East Hartford, Conn., PWA-5515-77, Mar. 1979. (NASA CR-159551)
4. Gaffin, W. O., "JT9D-70/59 Improved High Pressure Turbine Active Clearance Control System," Pratt and Whitney Aircraft Group, East Hartford, Conn., PWA-5515-87C, June 1979. (NASA CR-159661)
5. Fasching, W. A., "CF6 Jet Engine Performance Improvement - New Fan," NASA CR-159699, Dec. 1979.
6. Fasching, W. A., "CF6 Jet Engine Performance Improvement Program - Short Core Exhaust Nozzle Performance Improvement Concept," General Electric Co., Cincinnati, Ohio, Sep. 1979. (NASA CR-159564)
7. Fasching, W. A., "CF6 Jet Engine Performance Improvement - New Front Mount," NASA CR-159639, Oct. 1979.



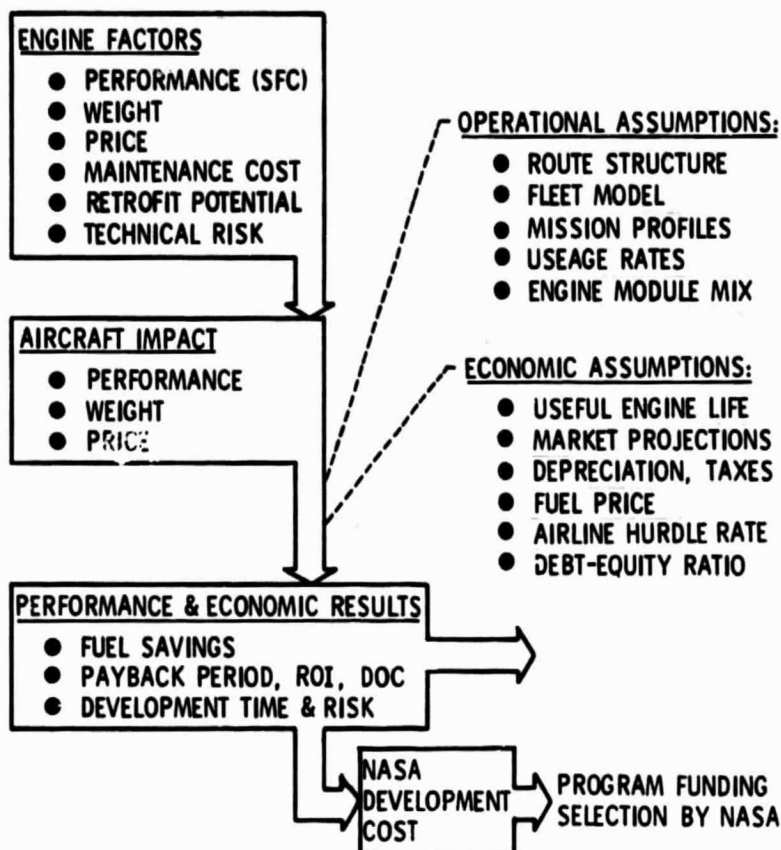


Figure 3. - Procedure and factors involved in screening of performance improvement concepts.

CONCEPT	SFC REDUCTION AT CRUISE - %	CUMULATIVE FUEL SAVED THROUGH 2005		PAY BACK PERIOD, yr*	
		10 <sup>6</sup> LITERS	10 <sup>6</sup> gal	NEW BUY	ATTRITION RETROFIT
<b>P&amp;VA JT8D</b>					
IMPROVED HPT OUTER AIR SEAL	0.5	341	90	3.9	>5
HPT ROOT DISCHARGE BLADE	0.9	980	259	0	0
TRENCHED HPC BLADE TIP	0.9	2229	589	1.2	N/A
DC-9 NACELLE DRAG REDUCTION	0.5	322	85	0.7	0.7
<b>P&amp;VA JT9D</b>					
3.8 ASPECT RATIO FAN	1.3	2725	720	0.9	N/A
HPT ACTIVE CLEARANCE CONTROL	0.9	1771	468	1.0	>5
HPT VANE THERMAL BARRIER COATING	0.2	980	259	0	0
HPT CERAMIC OUTER AIR SEAL	0.4	1953	516	0.3	0.4
<b>GE CF6</b>					
IMPROVED FAN	1.8	3997	1056	1.3	2.0
SHORT CORE EXHAUST NOZZLE	1.0	1730	457	0	N/A
NEW FRONT MOUNT	0.3	800	211	0.6	N/A
IMPROVED HP TURBINE	1.3-1.6	1120	296	0.2	N/A
HPT ROUNDNESS/CLEARANCE	0.4-0.8	1506	398	0.8	N/A
HPT ACTIVE CLEARANCE CONTROL	0.3-0.6	916	242	4.4	N/A
LPT ACTIVE CLEARANCE CONTROL	0.3	348	92	4.1	N/A
DC-10 REDUCED ENGINE BLEED	0.7	3028	800	1.0	1.0

\*BASED ON AVERAGE FUEL PRICES OF 40¢/gal. N/A - NOT APPLICABLE

Figure 4. - Performance improvement concepts selected for NASA/ECI funding.



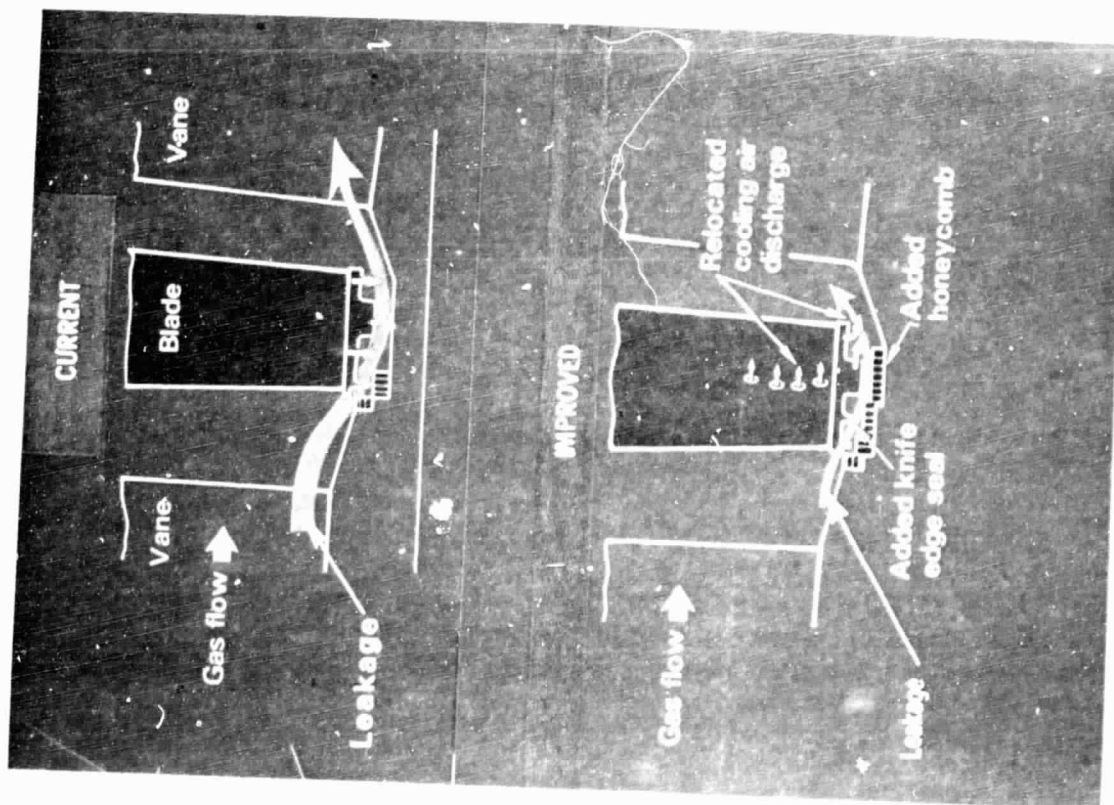


Figure 5. - JT8D high pressure turbine outer air seal.

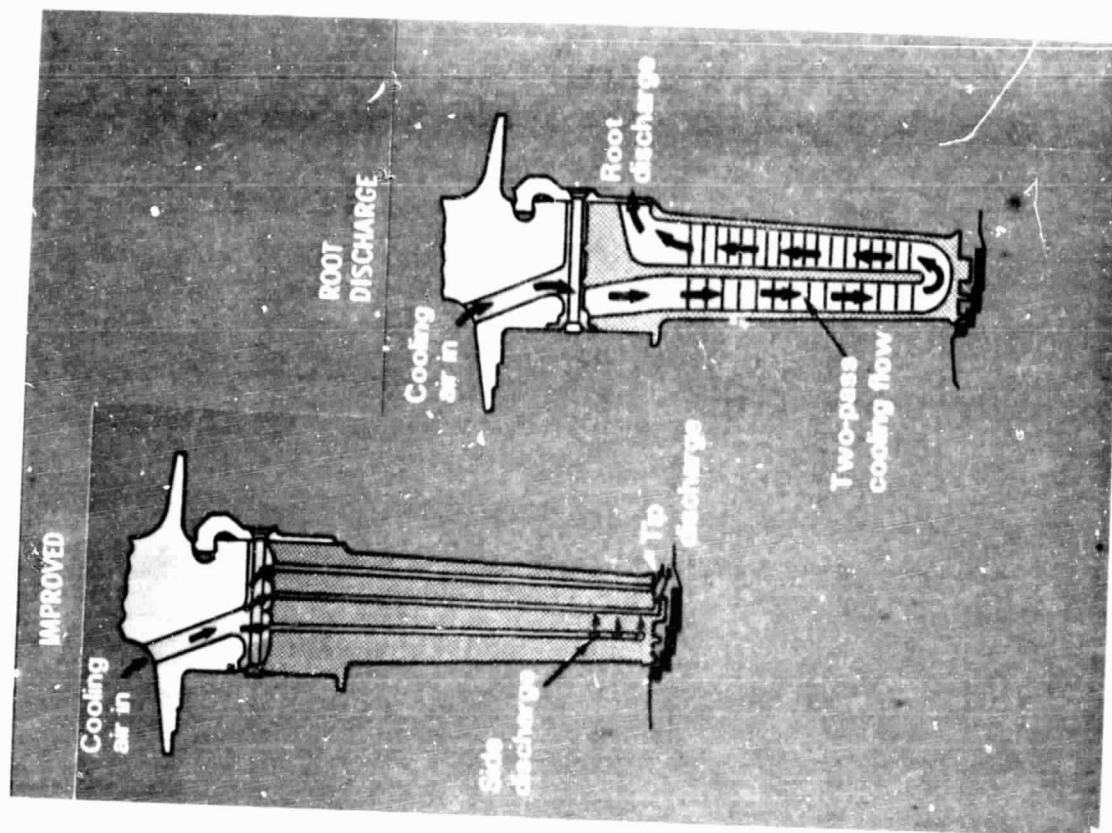


Figure 6. - JT8D high pressure turbine blade cooling schemes.

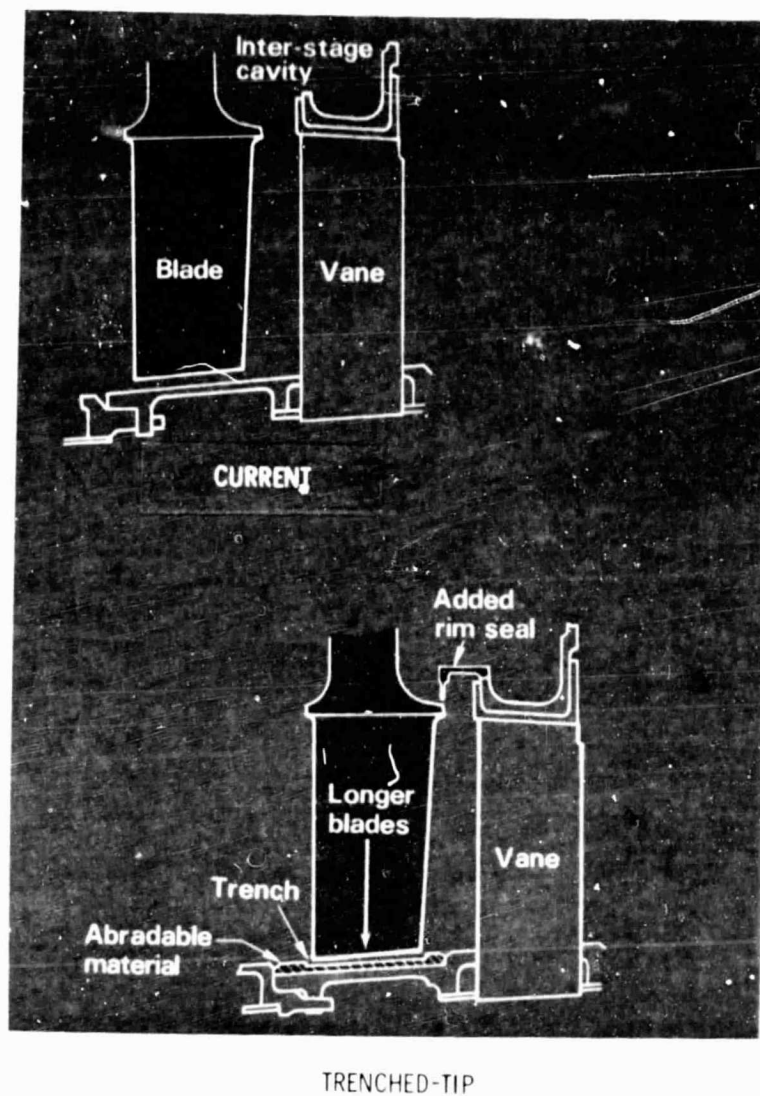


Figure 7. - IT8D high pressure compressor stage.



Figure 8. - DC-9 thrust reverser stung.

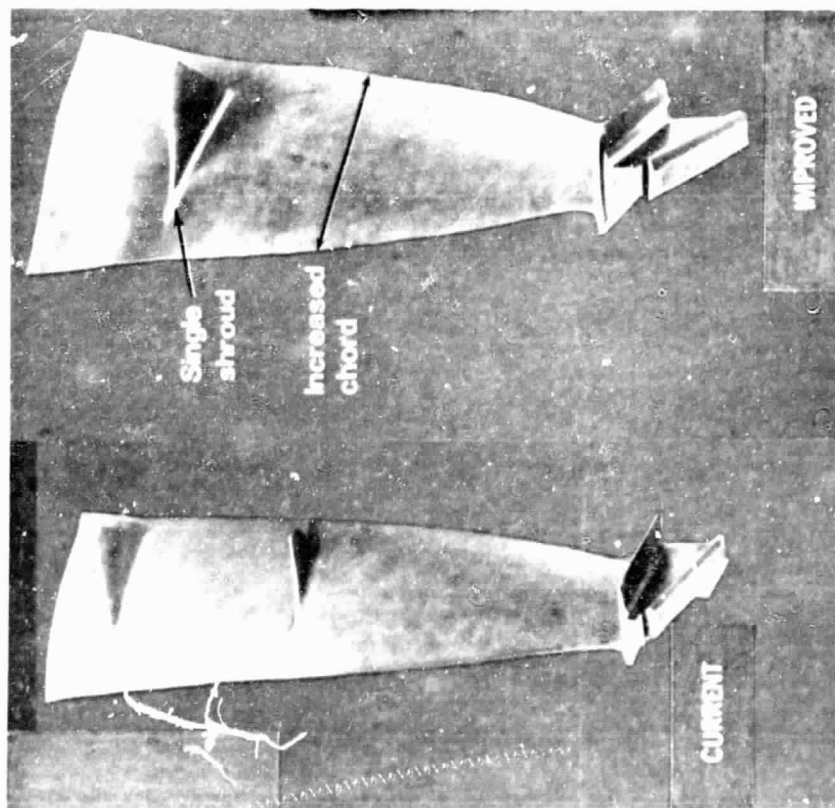


Figure 9. - JT9D-7 fan blade.

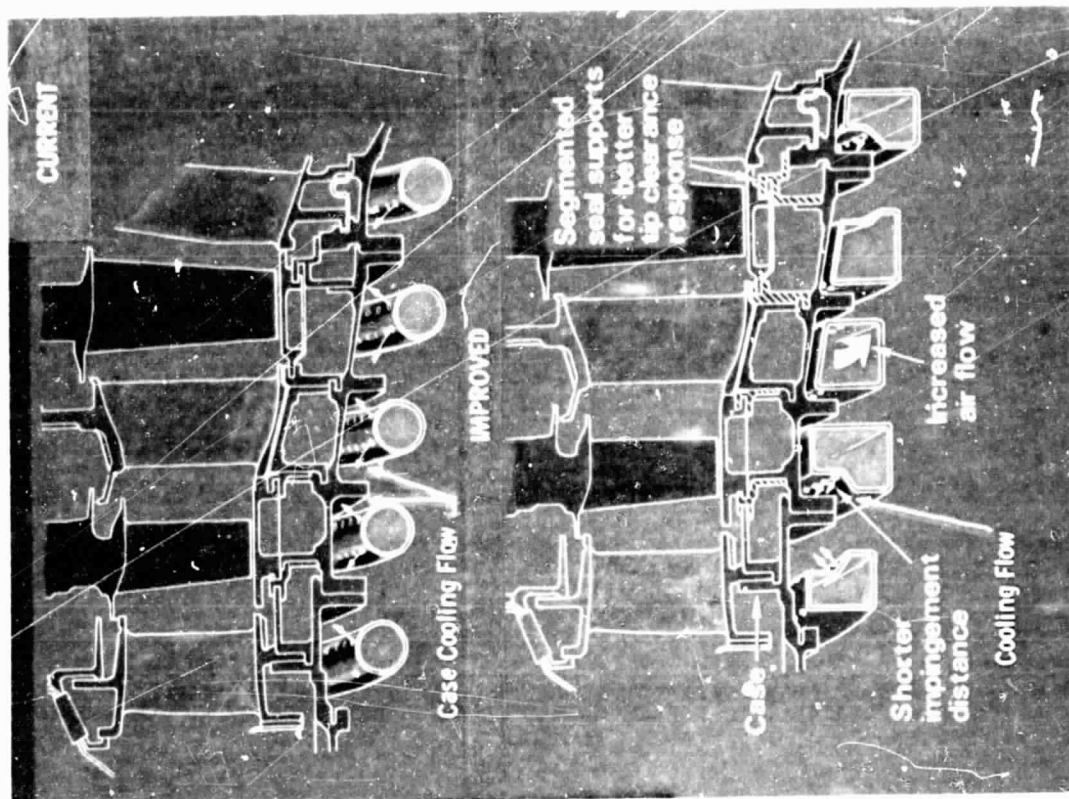


Figure 10. - JT9D-59/70 high pressure turbine active clearance control system.

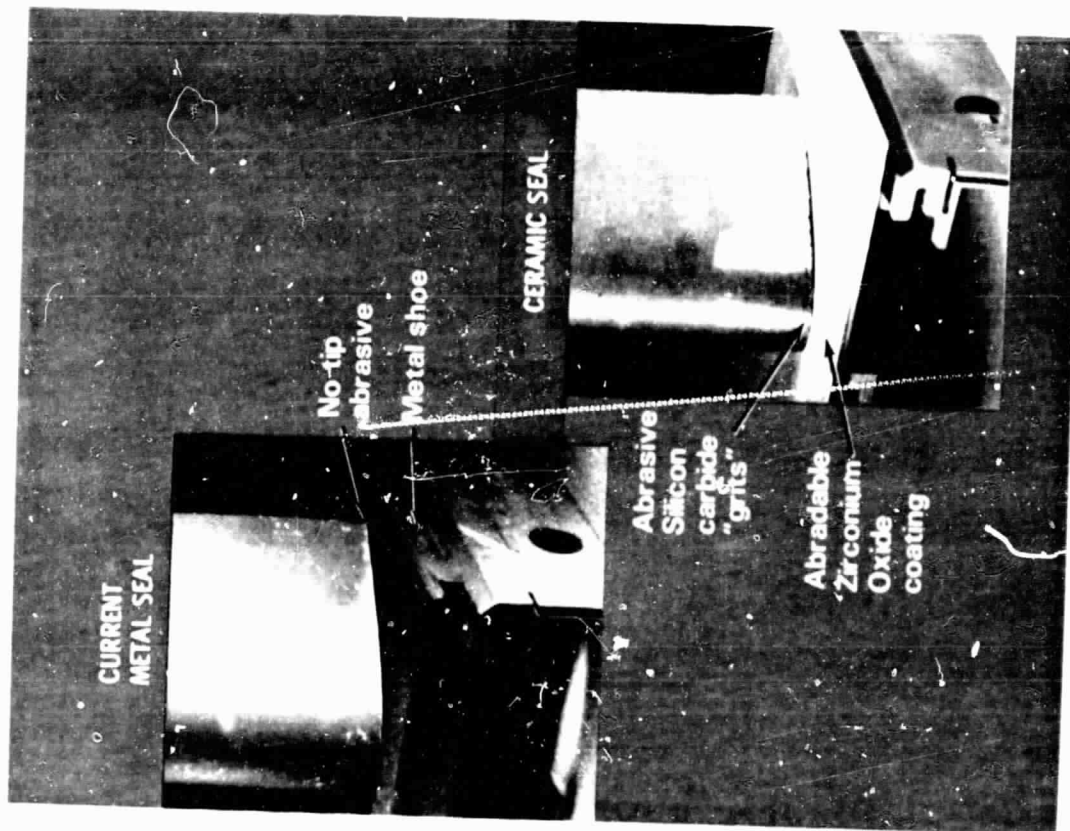


Figure 12. - JT9D high pressure turbine outer air seal.

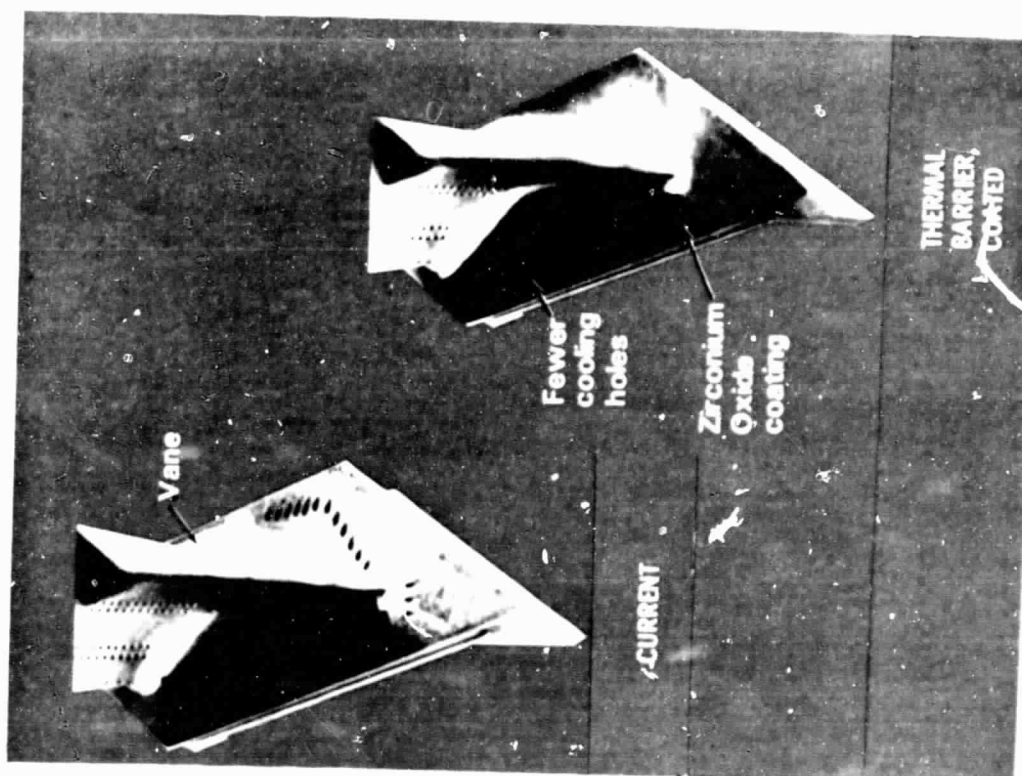


Figure 11. - JT9D high pressure turbine vane end wall.



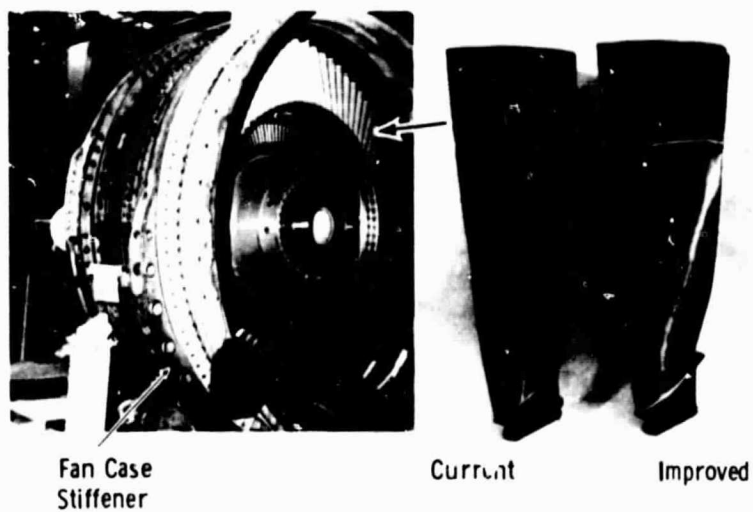


Figure 13. - CF6 fan.

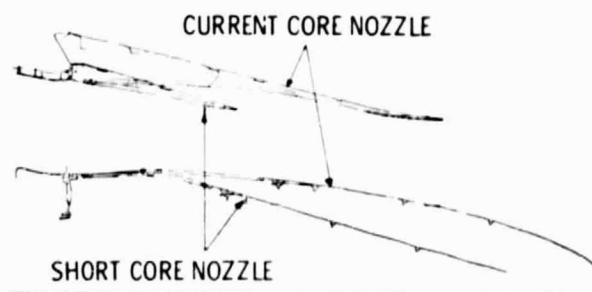


Figure 14. - CF6 core exhaust nozzle configurations.

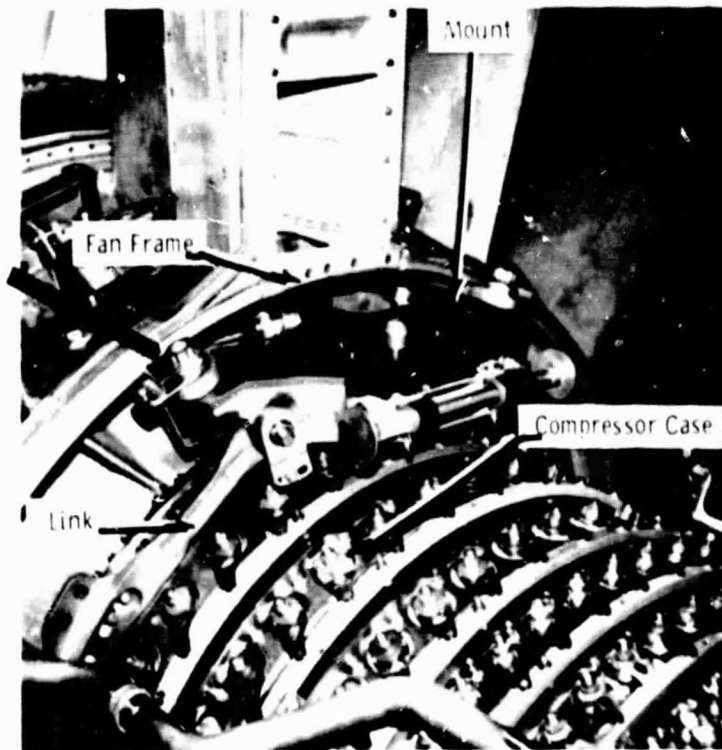


Figure 15. - New CF6 front mount.

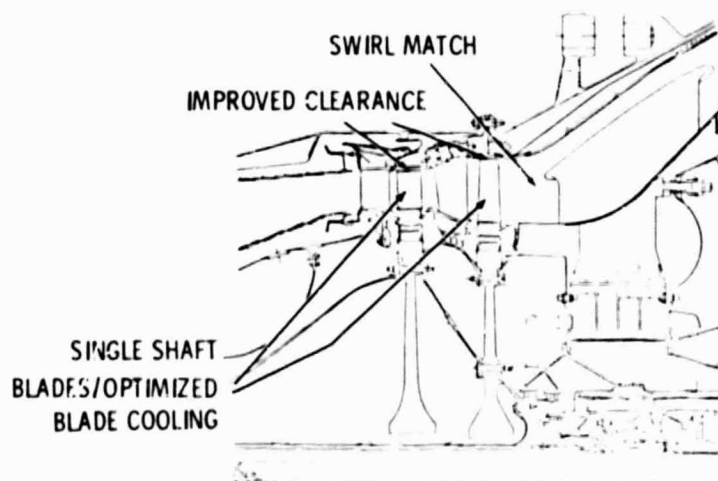
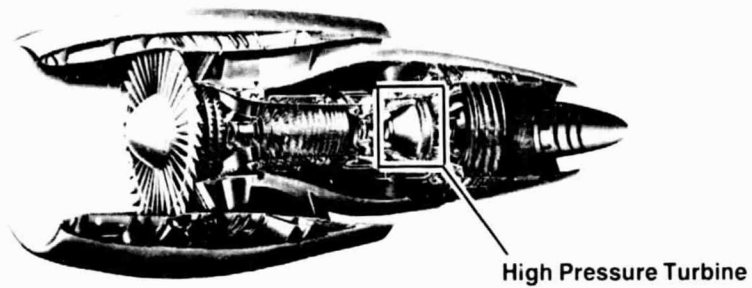


Figure 16. - Improved CF6-6 high pressure turbine.



- **Passive Rotor/Stator Thermal Matching**

- Materials
- Mechanical Design
- Cooling

Figure 17. - CF6 high pressure turbine roundness control.

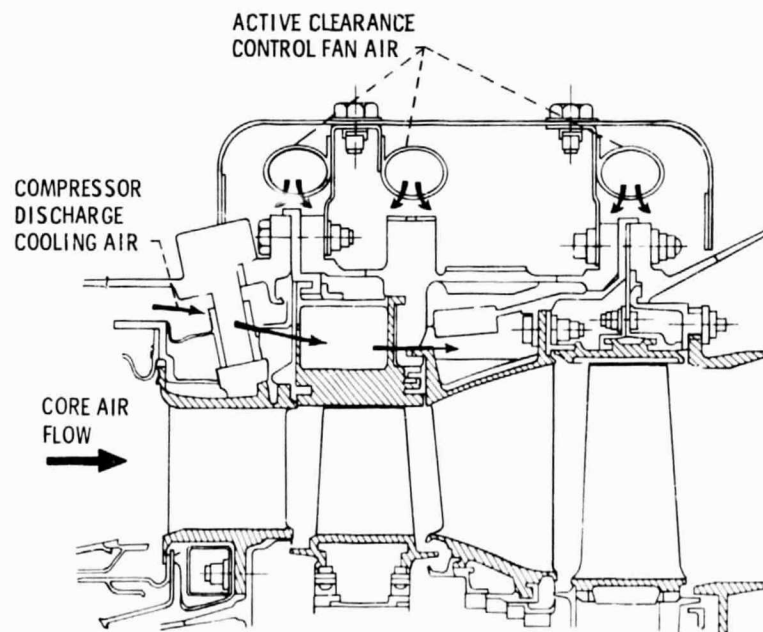


Figure 18. - CF6 high pressure turbine active clearance control system.

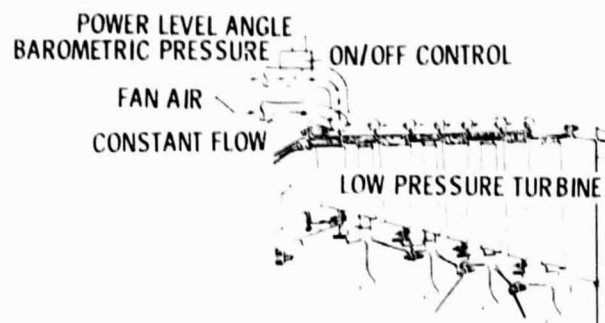


Figure 19. - Cr6 low pressure turbine active clearance control system.

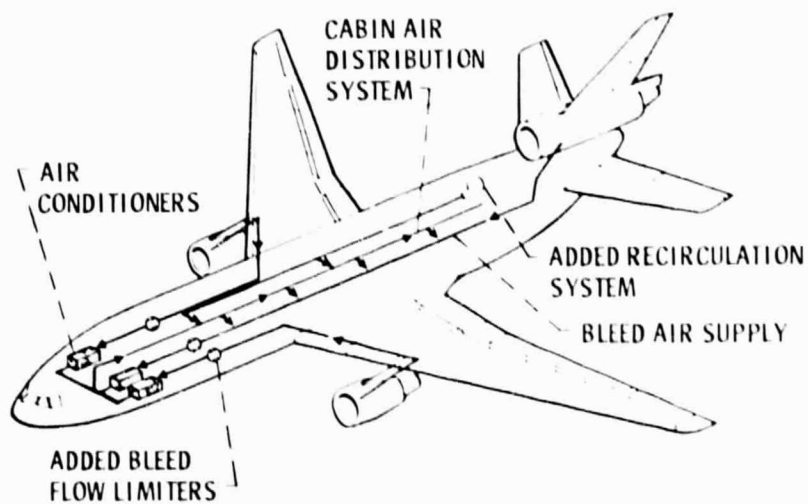


Figure 20. - DC-10 improved cabin air circulation system.



CONCEPT	SFC REDUCTION AT CRUISE - %		PROJECTED CUMULATIVE FUEL SAVED THROUGH 2005 (10 <sup>6</sup> LITERS)	
	PREDICTED	ACHIEVED	PRE-DEVEL.	POST-DEVEL.
JT8D HPT IMPROVED OUTER AIR SEAL	0.5	0.6	341	767
DC-9 NACELLE DRAG REDUCTION	0.5	1.2	322	773
JT9D 3.8 ASPECT RATIO FAN	1.3	1.3	2725	2725 <sup>o</sup>
JT9D HPT ACTIVE CLEARANCE CONTROL	0.4	0.65	1771	1279
CF6 IMPROVED FAN	1.7	1.7	3997	3997
CF6 SHORT CORE NOZZLE	1.0	0.9	1730	1594
CF6 NEW FRONT MOUNT	0.3	0.1	800	267
CF6 IMPROVED HP TURBINE	1.3	**	1120	**
DC-10 REDUCED ENGINE BLEED	0.7	0.7	3028	3028

<sup>o</sup> 3.8 ASPECT RATIO FAN NOT ENTERING PRODUCTION ON JT9D-7. TECHNOLOGY WILL BE USED ON JT9D-7R4 (SEE TEXT)

\*\* NOT AVAILABLE

Figure 21. - Fuel savings summary for those performance improvement concepts for which development is complete.