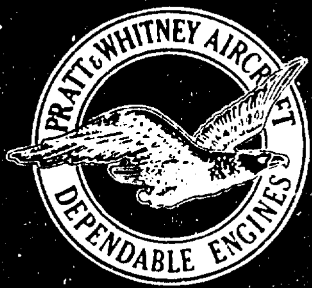
UNCLASSIFIED

AD NUMBER
AD378368
CLASSIFICATION CHANGES
TO: unclassified
FROM: confidential
LIMITATION CHANGES
TO: Approved for public release, distribution unlimited
FROM: Distribution: Further dissemination only as directed by Federal Aviation Agency, Washington, DC 20553, Sep 1966, or higher DoD authority.
AUTHORITY
FAA ltr, 10 Oct 1972; FAA ltr, 10 Oct 1972

THIS PAGE IS UNCLASSIFIED

AD No. 378368
DDC FILE COPY



Pratt & Whitney Aircraft
FLORIDA RESEARCH AND DEVELOPMENT CENTER

UA

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

All distribution of this document is controlled. In addition to security requirements which apply to this document and must be met, it may be further distributed by the holder <u>only</u> with specific prior approval of:

Director of Supersonic Transport Development
Federal Aviation Agency
Washington, D. C. 20553

The distribution of this report is limited because it contains technology identifiable with items excluded from export by the Department of State (U. S. Export Control Act of 1949, as amended).

contract - pro forma [illegible]

⑭ PWA-FP-66-100-Vol-3G

CONFIDENTIAL

PWA FP 66-100
SEPTEMBER 1966
C28-6C 2360. H

15

~~(UNCLASSIFIED TITLE)~~

⑥

ENGINE PROPOSAL
FOR PHASE III OF THE
SUPERSONIC TRANSPORT DEVELOPMENT PROGRAM,

VOLUME III.

TECHNICAL/ENGINE.

REPORT G.

⑤

GROWTH POTENTIAL (U).

⑪ Sep66

⑫ 50p.

([redacted])

PREPARED FOR
FEDERAL AVIATION AGENCY
OFFICE OF SUPERSONIC TRANSPORT DEVELOPMENT
WASHINGTON, D. C.

DDC
JAN 20 1967

⑮ FA-SS-66-8

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18 U. S. C., SECTIONS 793 AND 794. ITS TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

B

Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION
FLORIDA RESEARCH AND DEVELOPMENT CENTER

(401355)

DECLASSIFIED AFTER 12 YEARS. DOD DIR 5200.10

CONFIDENTIAL

FAA SECURITY CONTROL
NO. 67216

Printed in the United States of America

PAGES NOT FILMED ARE BLANK.

CONTENTS

REPORT G
GROWTH

SECTION I
INTRODUCTION

The JTF17 series engine can be developed to produce 15% more sea level takeoff and transonic thrust with a 4% decrease in Mach 2.7 cruise TSFC within 5 to 6 years after introduction into commercial service. It can be developed to cruise efficiently at a flight Mach Number of 3 or greater when airframe technology and airline service economics warrant. The twin spool, duct heating turbofan cycle and particular design features of the JTF17 engine permit exploitation of component improvements and modifications to attain these goals with a minimum of redesign and development effort. Lower noise is inherent in the design of the JTF17. Further noise reductions will result from increased thrust to permit higher climb rates. Increased knowledge of sound generation characteristics of exhaust jets and fan blading and of attenuation characteristics of the reverser-suppressor and sound absorbent duct liners will lead to significant quieting during the growth period.

The material on the growth potential of the JTF17 is presented in the following sequence:

Objectives - benefits to the SST operation

Goals - specific numerical levels of performance, life, and specific weight

Component Growth - presentation of growth of the major components of the engine as they could contribute to improvements in performance, life, and specific weight.

Plan for Engine Growth - presentation of potential specific combinations of growth features of the components which are compatible on the basis of cycle matching and timing to provide advanced models of the JTF17 engine capable of higher takeoff and transonic thrust, lower supersonic cruise TSFC, reduced noise, higher Mach number, longer life, reduced specific weight, improved tolerance to inlet distortion, lower smoke generation and utilization of lower cost fuel.

SECTION II
OBJECTIVES

Engine growth objectives are related to the improvement of overall economic attractiveness of the airplane. More specifically, efforts are aimed at the traditional airplane growth demands and reduction in noise.

Objectives include:

1. Increased sea level and transonic thrust (with reduced specific weight) to accommodate airplane weight increase
2. Decreased fuel consumption for increased range and payload
3. Increased component life and engine overhaul time for reduced overall operating cost
4. Increased operating envelope, specifically to higher Mach number, for improved economic benefits
5. Reduced noise level at takeoff and approach conditions
6. Lower cost fuel.

SECTION III
GOALS

The minimum goals for the continued development of the JTF17 series engine for each of the objectives within 5 to 6 years after introduction to commercial service are:

1. Performance - Sea level takeoff and transonic thrust - up 15%
   - Mach 2.7 cruise TSFC - down 4%
   - Noise at constant thrust - down 3PNdb at takeoff and 7PNdb on approach
   - Flight envelope increase - expanded to Mach 3+
2. Engine Life - Equivalent TBO - increased to 4600 hours
3. Specific Weight - Sea level takeoff and transonic - down 10%

SECTION IV
COMPONENT GROWTH

A. GENERAL

The improved component characteristics which will be the basis of future growth of the JTF17 engine must come from a combination of engine development effort and advanced component technology programs. The need for support of both of these areas has been historically recognized by the management of P&WA. Today, the scope of pertinent research and development includes programs at Pratt & Whitney Aircraft in East Hartford, the Florida Research and Development Center, the UAC Research Laboratories, and at specialized vendor research activities throughout the country. Technical reviews in each component field are held regularly to advance and coordinate this work. As a result of JTF17 engine design characteristics and of advanced technology programs which are underway now, component growth is most clearly indicated in the areas discussed below.

B. COMPRESSOR

1. JTF17 Engine

The dual rotor design of the JTF17 provides inherent versatility in compressor growth trade-off possibilities compared to a single rotor engine. For example, speed changes can be made on either rotor independently. Blading which will provide improved stage loading in the high compressor can be traded off for reduced weight by reducing high rotor speed, without affecting the low turbine or fan performance. An additional degree of freedom is also provided by the fan. The relationship between fan pressure ratio, bypass ratio, duct augmentation, turbine work, etc., can be matched to give the best overall performance based on individual component capabilities.

The design specific flow and average stage pressure ratio of both the fan and high compressor of the JTF17 are shown in figures 1, 2, 3, and 4 in relation to the state-of-the art. The specific flow of both the fan (41.2 lb/ft^2 sec) and the high compressor (37 lb/ft^2 sec) can be seen to be lower than that of previous production engines. The stage pressure ratios of both the fan and compressor are slightly higher than that of previous production engines. Figure 2 shows the stage pressure ratio of the first fan stage in comparison with single stage pressure ratios obtained experimentally. As can be seen, both Government and FRDC research stages have achieved considerably higher loadings. The high spool stage pressure ratio is plotted in figure 4, compared with previous P&WA production engines to show the logical progression to this design value.

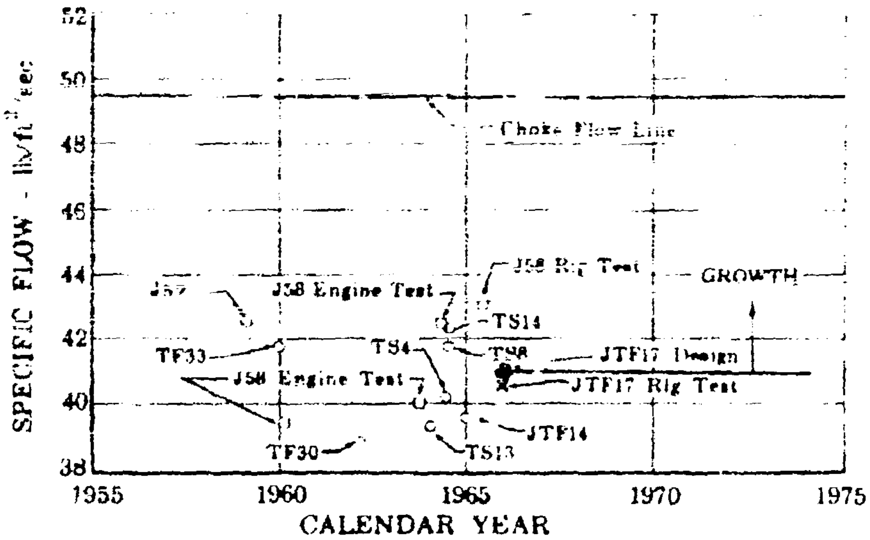


Figure 1. Fan Specific Flow Growth

FD 17055
GIV

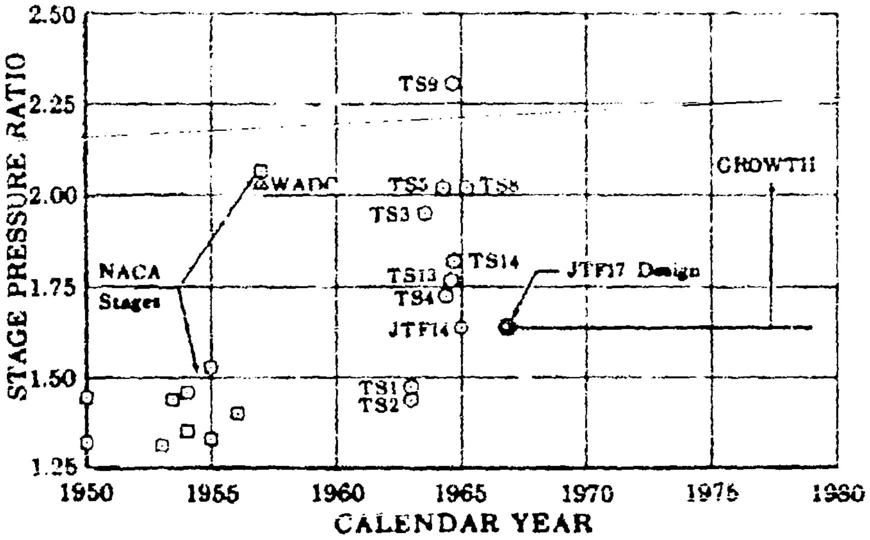


Figure 2. Fan Pressure Ratio Growth

FD 17056
GIV

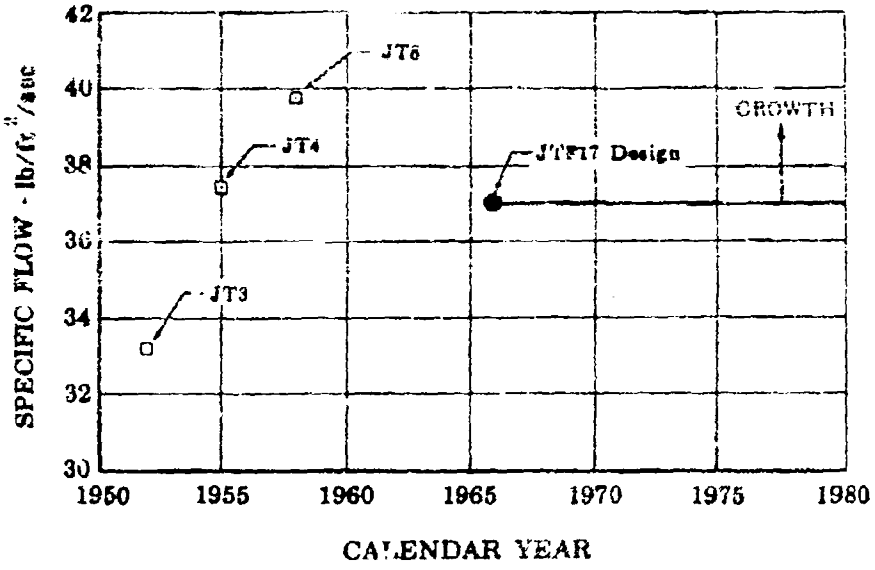


Figure 3. High Compressor Specific Flow Growth

FD 17057
GIV

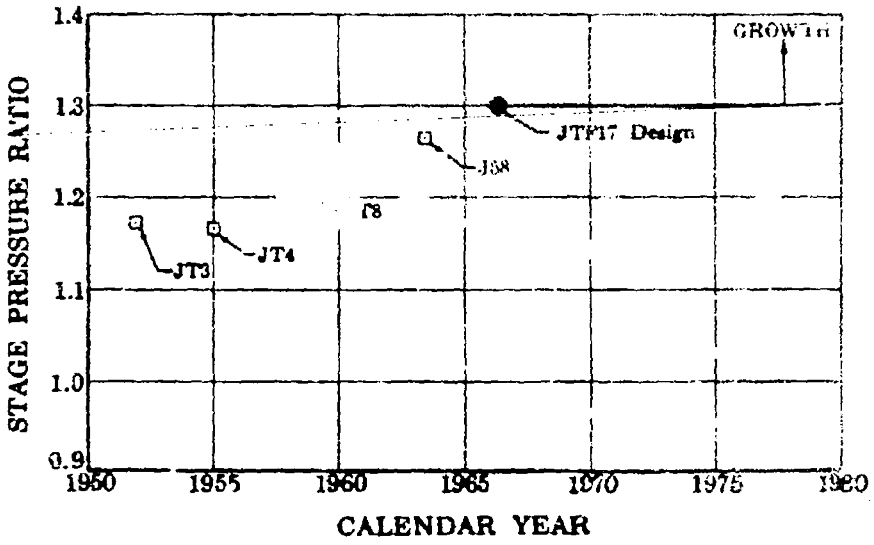


Figure 4. High Compressor Pressure Ratio Growth

FD 17058
GIV

2. Advanced Compressor Technology Investigations

Pratt & Whitney Aircraft's advanced compressor technology relies heavily upon experimental design limits and development data that have been generated through more than 500,000 hours of cascade and rotating machinery testing. Working jointly with the UAC Research Laboratories, systematic test data from more than 100,000 performance tests have been compiled and correlated for cascades of NACA four-digit and 65-series airfoils as well as double circular arc sections and several special blade designs for high Mach number applications. Since its inception more than 20 years ago, this effort has been responsible for continued compressor growth, as illustrated in figure 5. The blocks in this figure represent the reduction in compressor size achieved through growth, even though each new compressor has had to operate over an increasingly wide operating range. As indicated below, the advanced technology effort responsible for this growth is increasing. Compressor research programs currently underway at P&WA that are being performed on JTF17 type blading and are particularly pertinent to SST engine growth are discussed briefly in the following paragraphs.

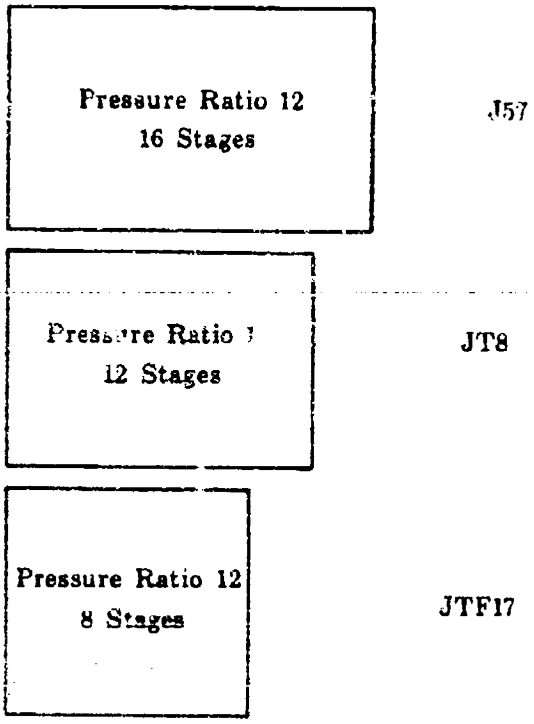


Figure 5. Improved Compressor Envelope and Stage Loading FD 13832A GIV

a. Slotted Blading

Slotted airfoil concepts, such as that shown in figure 6, that provide suction surface boundary layer control and off-design lift improvement for operational aircraft have been applied with an encouraging degree of success to JTF17 type compressor stages. Analytical and experimental effort associated with the J58, JT8D, and TF30 advanced development programs involving slotted vanes and rotor blades indicated a potential for slotted blading to reduce profile loss at high loading levels and to increase operating range. In addition to continued in-house effort to explore this potential in two-dimensional cascade and full-scale engine compressor rigs, P&WA is currently working on a systematic evaluation of slotted vanes and rotor blades under NASA Contract NAS3-7603.

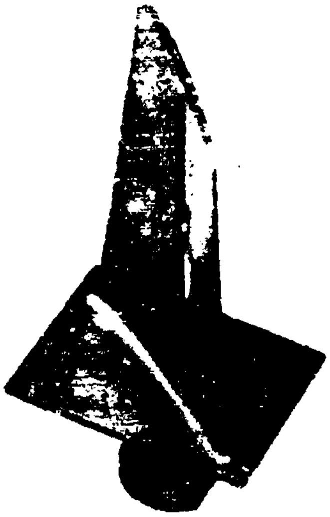


Figure 6. Slotted Rotor Blade

FE 61294
GIV

An annular cascade investigation of slotted stator vanes was conducted to evaluate slot geometry parameters and slot location to establish preliminary slot design criteria for rotating rig blading. A typical cascade assembly is shown in figure 7. The best slot configuration resulted in a loss coefficient reduction from about 0.07 to 0.012, nearly a factor of six improvement. This is illustrated in figure 8 by the comparison of wake total pressure profiles for an unslotted and slotted stator.

The single stage rotating rig part of the NASA program involves tests of three slotted rotor configurations and three stator configurations. To date, two slotted rotor configurations and one slotted stator configuration have been tested in the FRDC compressor research facility and rig shown in figure 9.

Loading level (D-factor), deviation, and loss coefficient at 10, 50, and 90 percent span location (root, mean, and tip) for a slotted rotor configuration having a design tip diffusion factor of 0.46 are presented in figures 10, 11, and 12. A direct comparison is made in these figures with the test results of the same blade design without a slot. A nominal

Loss coefficient reduction of 50 percent can be seen. Loading level (D-factor) and deviation at the same incidence angle are not appreciably affected by the slot; however, the decrease in loss permits operation over a larger incidence range which can be used to advantage in one or more of several ways: (1) increased surge margin, (2) increased distortion tolerance, (3) increased loading level, and (4) increased efficiency.

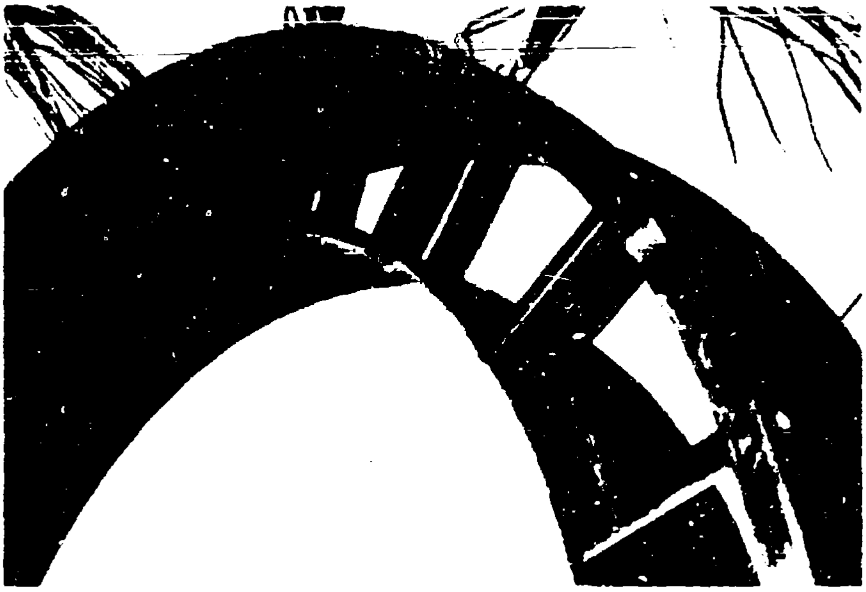


Figure 7. Cascade Compressor Rig FE 53351 GIV

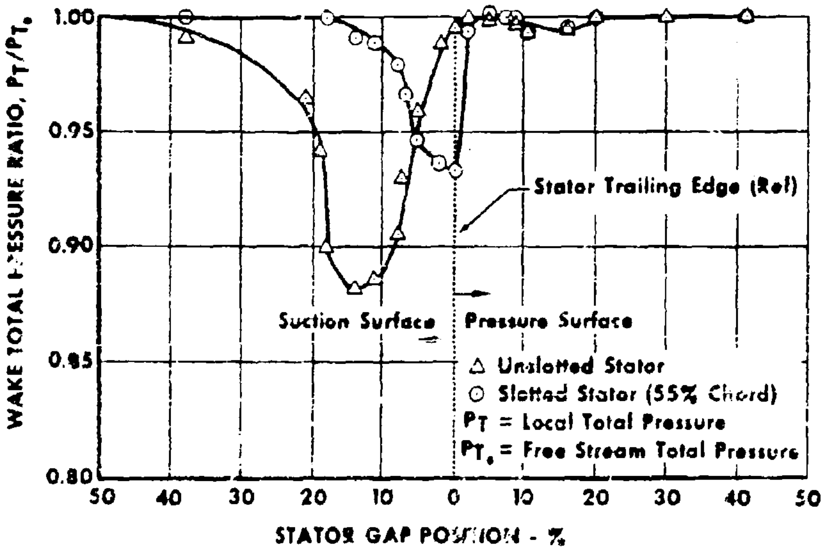


Figure 8. Stator Wake Comparison FD 13399A GIV

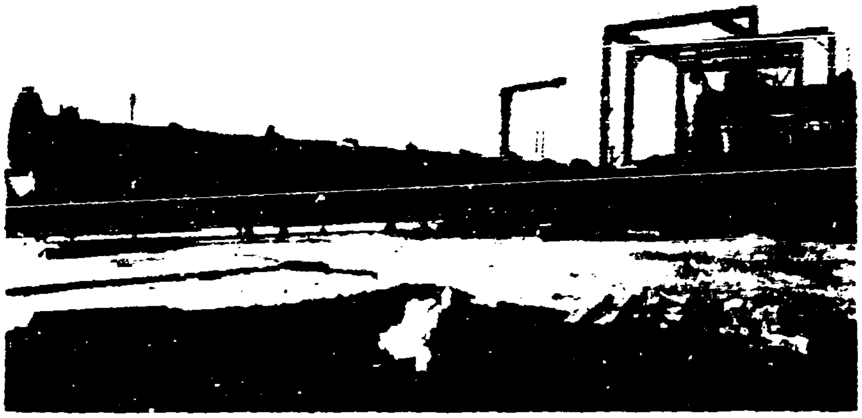


Figure 9. Compressor Research Facility GS 1270 GIV

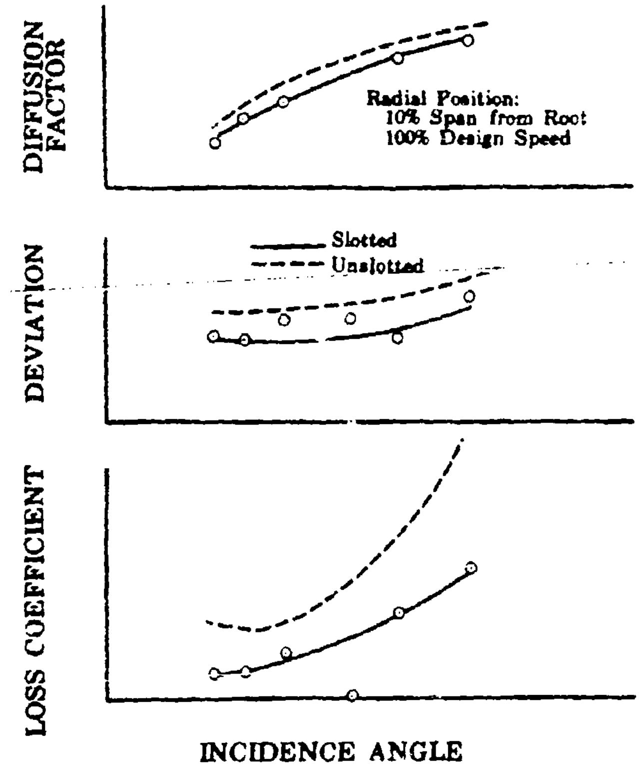


Figure 10. Slotted Rotor Test Results - 10% Span FD 17059 GIV

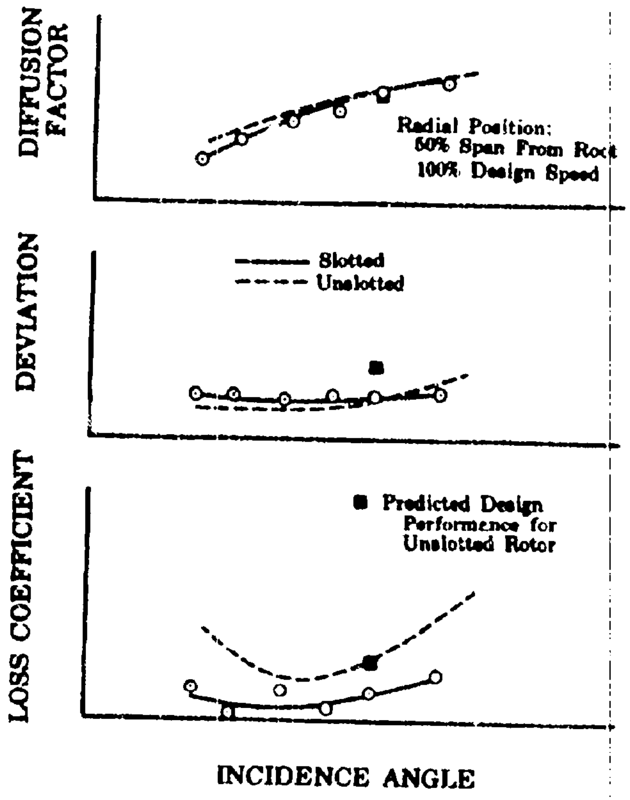


Figure 11. Slotted Rotor Test Results - 50% Span FD 17060 GIV

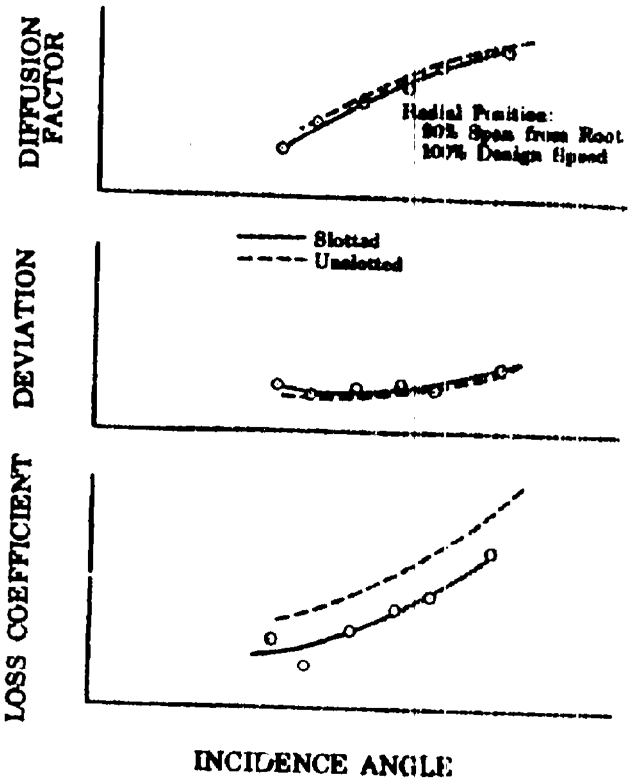


Figure 12. Slotted Rotor Test Results - 90% Span FD 17061 GIV

Similar test results with a slotted stator configuration having a design hub D-factor of 0.60 (39-degree camber) are shown in figures 13, 14, and 15. In these figures, a comparison is made with an unslotted stator designed with a hub D-factor of 0.52 (30-degree camber). The more highly loaded slotted stator had a lower loss than the unslotted stator, and the measured D-factor level for the slotted stator is higher than the design value.

The effect of reduced blading losses on overall compressor efficiency is readily apparent. Applied to the JTF17 high compressor (six stages), slotted rotor and stator blading that provide the level of loss reduction as measured thus far under the NASA contract program would increase overall adiabatic efficiency a total of 6%. Slotted stators alone would increase efficiency approximately 3%.

Investigations of slot fabrication techniques and the effect of slots on blade stress limits are being performed concurrently with the aerodynamic evaluation of slotted blading. The desired slot geometries have been successfully machined into rotor and stator blading using the Electric Discharge Machining process and simple fixtures. Vibration and fatigue life test results show very little effect of slots on bending and torsion vibration frequencies, and essentially no loss in strength due to slots. Stress measurements obtained in rotating rig tests at blade tip velocities on the order of 1000 ft/sec corroborate the bench test results.

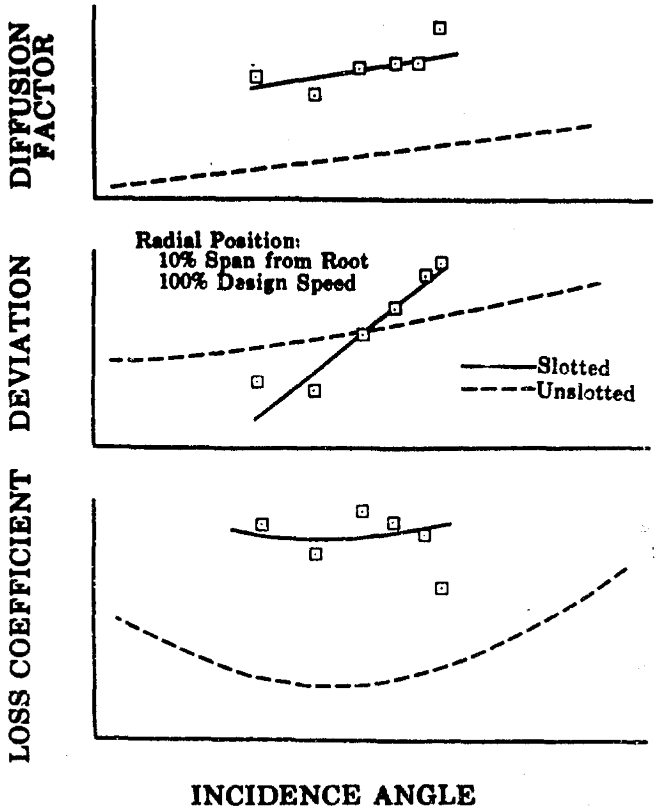


Figure 13. Slotted Stator Test Results - 10% Span

FD 17062
GIV

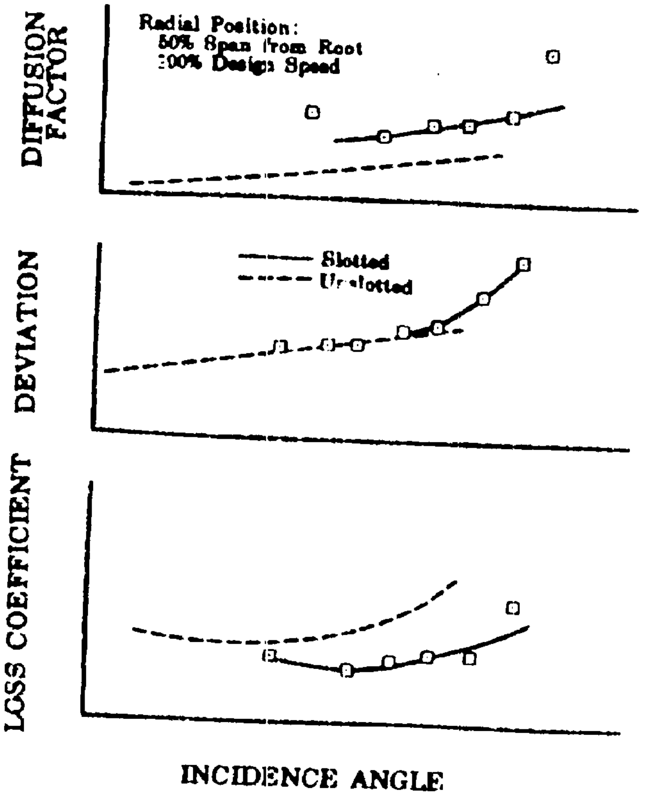


Figure 14. Slotted Stator Test Results - FD 17063
50% Span
GIV

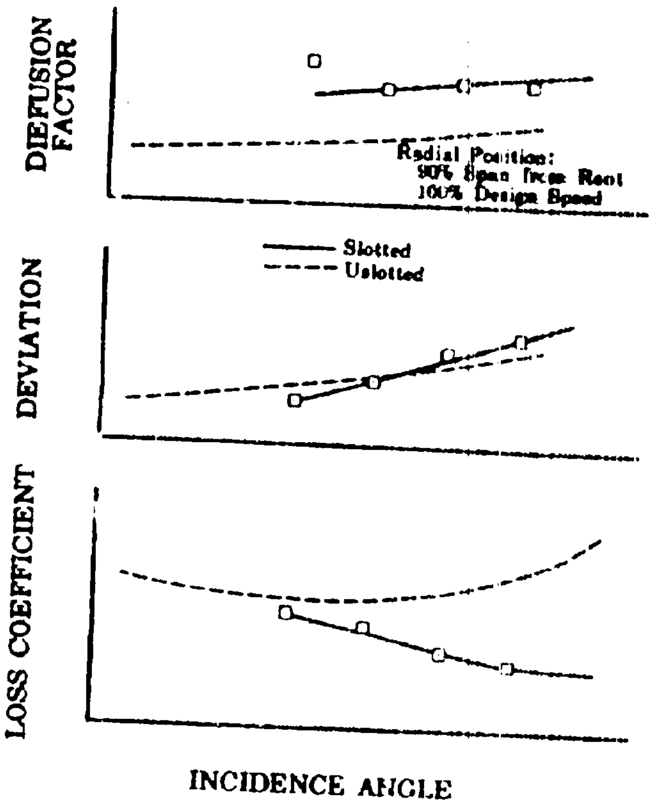


Figure 15. Slotted Stator Test Results - FD 17064
90% Span
GIV

b. End-Wall Loss Investigation

It has been recognized from advanced compressor stage development work that as loading levels are pushed higher for blading designed on the basis of two-dimensional cascade blade element data, three-dimensional flow effects in the end-wall regions (particularly near the rotor root section) become predominant and cause a departure from cascade deviation and loss correlations. An investigation of end-wall losses in a single-stage rotating rig was initiated to extend the axial flow compressor design system to higher loading levels. The results of this program provided the necessary modification of two-dimensional cascade deviation, incidence, and loss near the end walls, as illustrated in figure 16, to permit the design of stable stages at the desired loading levels of the growth versions of the JTF17 high compressor. Results of this effort, applied preliminarily in the form of the stator end bends under the Phase II-C compressor development program, have met with a high degree of success. Design revisions, which may either overcome the end-wall loss effect or which may take advantage of the high mid-channel flow distribution, are currently under investigation.

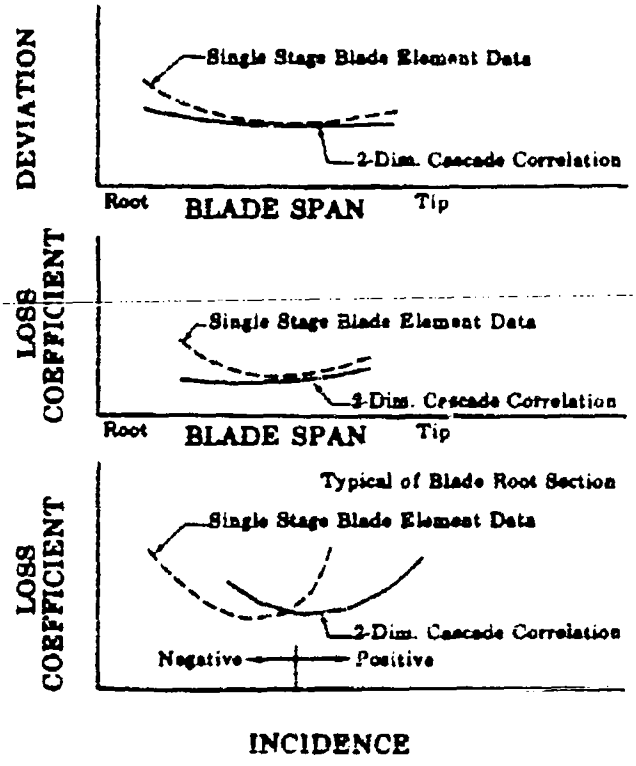
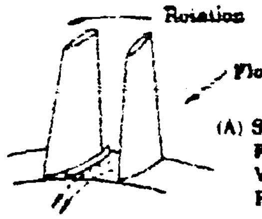


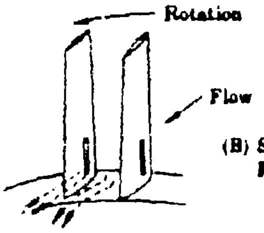
Figure 16. Mod 7F Two-Dimensional Cascade Data Correlation

FD 17065
GIV

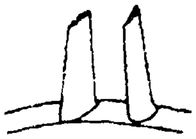
The end-wall loss investigation is part of continuing research at FRDC to improve compressor design technology. This program includes investigation of the interdependence between blade loading, blade span, and chord. Exploratory investigations are also being conducted with end-wall "flow-fixing" devices, such as secondary flow fences, slots in short-chord blading, wall fillets, etc.; figure 17 shows some of these devices.



(A) Short-Span Secondary Flow Fences Applied to Reduce Vortex Curl-Up at Rotor Root and Stator Root and Tip



(B) Slots to Energize End-Wall Flow Defect Region



(C) End-Wall Fillets (Based on Successful Application to High-Aspect Ratio Airplane Wings)

Figure 17. Secondary Flow Fixing Devices FD 17066 GIV

c. Variable Geometry Research Program

Another area of advanced compressor research involves the evaluation of variable geometry concepts as a means of extending stable and efficient operation over wider ranges of compressor inlet conditions. A program to accomplish this is being performed under NASA Contract NAS3-7604. One variable geometry inlet guide vane with a slot and two variable geometry stators, one having a slot in a fixed forward section and a flapped rear section, and the other having flapped forward and rear sections, will be tested. The blading and flow conditions are representative of a high Mach number compressor first stage. Figure 18 shows the test configuration midspan sections for design speed (SLTO) and 70 percent design speed (cruise) conditions for the inlet guide vane and slotted stator. The variable camber inlet guide vane concept was evolved from work performed at P&WA. The double-hinge arrangement permits more aerodynamically clean geometry than a single flap configuration would permit at the extreme operating conditions. The slot in the rear section of the guide vane is expected to extend the range of low-loss turning.

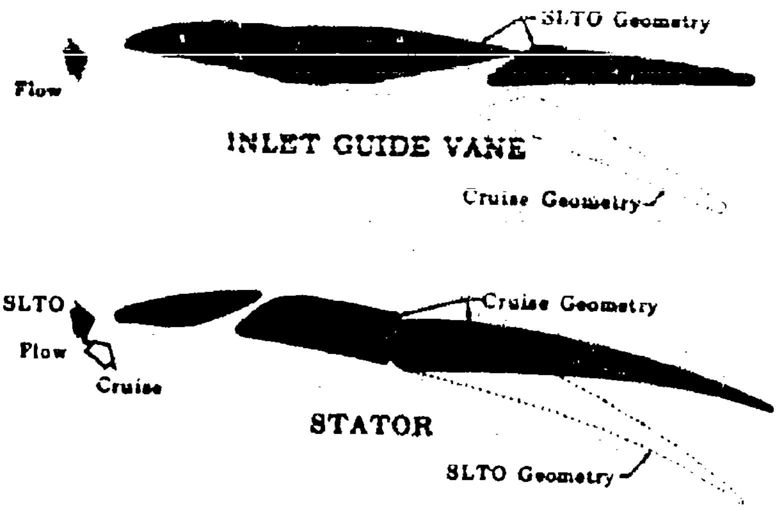


Figure 18. Variable Geometry Slot Concepts FD 17067
CIV

The slot in the forward section of the stator configuration is designed to prevent flow separation at high incidence cruise conditions. Annular cascade results have indicated the effectiveness of this slot application, as shown in figure 19. Wake loss coefficient was reduced 20 percent, and turning was increased 3 degrees. Flow separation, observed at about 50 percent chord without a slot, was completely eliminated with a slot. Inclusion of this performance with the wide variation of geometry that is possible with the double hinged or flapped concepts holds promise of a substantial increase in the effectiveness of the inlet stages of high Mach number compressors.

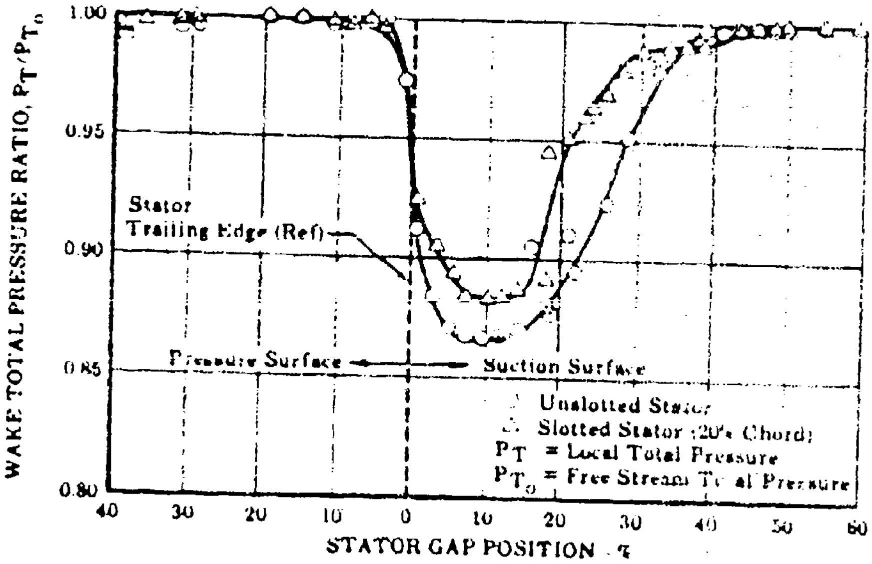


Figure 19. Slotted Stator Wake Comparison FD 14112A
CIV

d. Mechanical Design Considerations for Aerodynamic Performance

Improvements in fan stage blade element performance can be applied to reduce blade solidity and thus reduce blade weight for a given stage efficiency and pressure ratio level. The reduction in blade weight can be traded for increased annulus area (lower hub/tip ratio) for a given rotor speed, which in turn provides increased engine airflow. This can be accomplished within the area presently available in the JTF17 fan case design. Improvements in structural efficiency through use of higher-strength alloys will permit size and weight reduction in blade attachment and rotor disk design. Improvement in this direction can also be applied to reduce hub/tip ratio and increase airflow.

Continuing programs of aeroelastic research for advanced compressor blading and compressor disk designs have contributed to the development of new blade and disk damping techniques and higher strength-to-weight ratio stages.

3. Compressor Growth Contribution

Gains from increases in airflow, efficiency, pressure ratio, and stage loading can be incorporated in the JTF17 to increase thrust, improve TSFC, reduce noise, and decrease weight. Increases in specific flow with commensurate increased pressure ratio at constant efficiency will increase takeoff and transonic thrust in direct proportion. Each 1% increase in fan and compressor efficiency would add approximately 0.45% increase in takeoff and transonic thrust and represent approximately 0.30% decrease in cruise TSFC for approximately a 360-lb increase in payload.

C. COMBUSTORS

1. JTF17 Engine

The combustion systems of the JTF17 are based on previous advanced technology work which has resulted in a new combustor concept which has been called "ram-induction." It has enabled the attainment of even temperature distributions at high temperatures with aircraft inlet distortion, conventional fuels, and low pressure loss, in substantially less length than conventional multi-nozzle combustor designs. Compared with current production engines, both the primary combustor and duct heater of the JTF17 represent significant advancements to the state-of-the-art. However, in perspective with the continuing advanced technology programs on this concept, it is evident that substantial potential growth is indicated.

2. Advanced Ram-Induction Burner Investigations

a. JTF17 Advanced Development

The JTF17 ram-induction burner program is supported by advanced research in rigs which include (1) a water table, (2) a water tunnel, (3) a straight 70° primary burner sector, (4) a straight duct heater sector, (5) a curved 120° primary burner sector, and (6) a curved 30° high pressure primary burner sector. Two research primary burner diffuser rigs are being designed, and the development program has utilized both full-scale duct heater and full-scale primary combustor rigs. These supporting rigs have been used for both development testing and for investigation of advanced concepts with indicated growth potential. Figure 20 shows a novel lightweight duct heater design which is being investigated and has shown promising performance. Figure 21 is a reduced-scoop main combustor sector which is also being evaluated for specific weight improvement. Although this effort has not yet resulted in designs suitable for use in the engine, it has been a partial basis for the Government-supported research programs described below. Altogether, these investigations provide strong evidence that the ram-induction burner concept, as currently designed to meet the requirements of the JTF17, has not reached the limit of its growth in performance, size, or durability.

b. Short Main Combustor

Under NASA Contract NAS3-7905, two ram-induction burner concepts, which have as an objective the reduction of the JTF17 primary combustor to 12 inches of burning length, are being experimentally investigated. These two concepts are shown in figure 22 in relation to the JTF17 primary combustor and a conventional multinozzle can-annular combustor. Figures 23 and 24 are photographs of the actual combustors. The goal of the contract effort is to conduct a 40-hour endurance test on one of the combustors under environmental conditions that are appreciably more severe than those imposed on the JTF17 combustor during cruise.

The volumetric heat release rates of both short main combustors are almost double that of the JTF17 primary combustor. Successful evolution of either concept holds promise for appreciable increase in temperature rise and decrease in weight and cost.

c. Advanced Vaporizing Combustors

Vaporizing type combustors capable of operation with less expensive fuels than current aviation kerosene are included in the advanced combustor research and development efforts at P&WA. The successful evolution of this concept makes it quite attractive for growth versions of the engine by permitting the use of lower cost fuels.

Figure 25 is a cutaway photograph of a vaporizing primary combustor. Proper mixing of air and fuel, (as in a carburetor) permits the fuel to enter the combustion chamber as a combustible mixture without leaving deposits in the vaporizing passages. This principle has been combined with ram-induction air admission to provide one of the two concepts considered to be feasible for the short main combustor contract objectives, and is currently under test. Tests are being conducted to document the relations between fuel-air ratio, pressure, temperature, mass flow velocity, and tube length to avoid either coking deposits or chemical reaction to various types of fuel. The results of this effort should provide an alternate combustor design for growth versions of the engine which can be operated with low quality, inexpensive fuels.

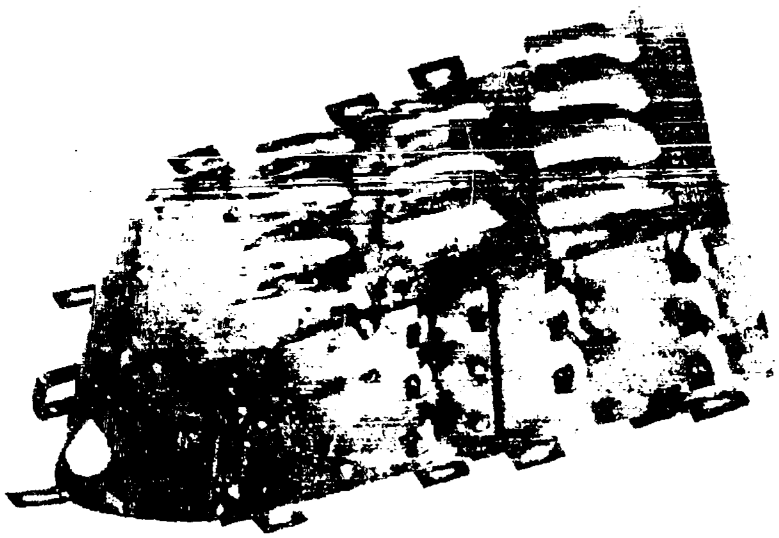


Figure 20. Lightweight Scoop Ram-Induction Burner FE 57227 GIV

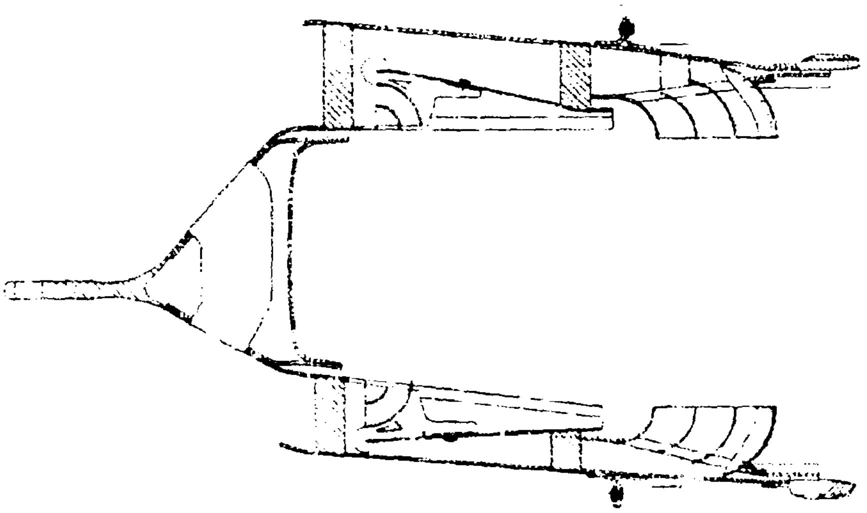


Figure 21. Reduced Scoop Combustor FD 17068 GIV

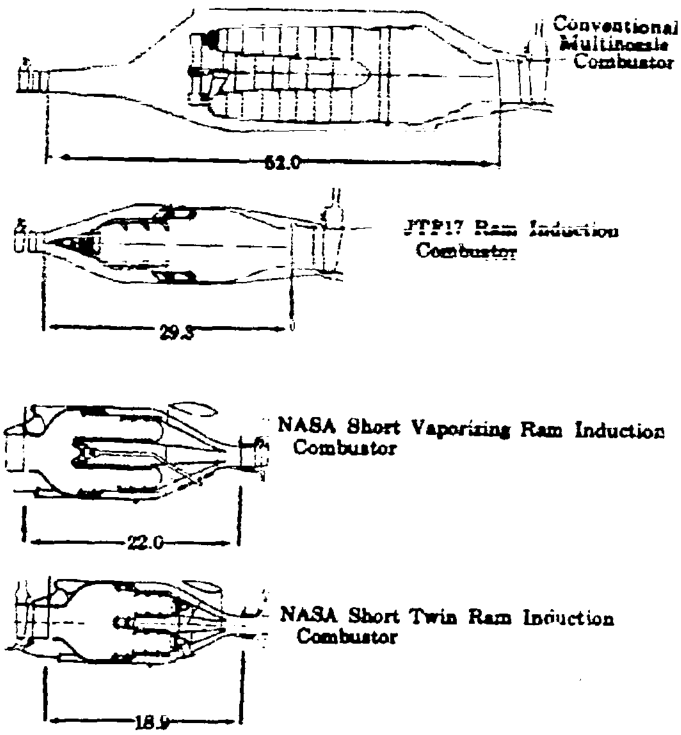


Figure 22. Combustor Size Comparison

FD 11063
GIV

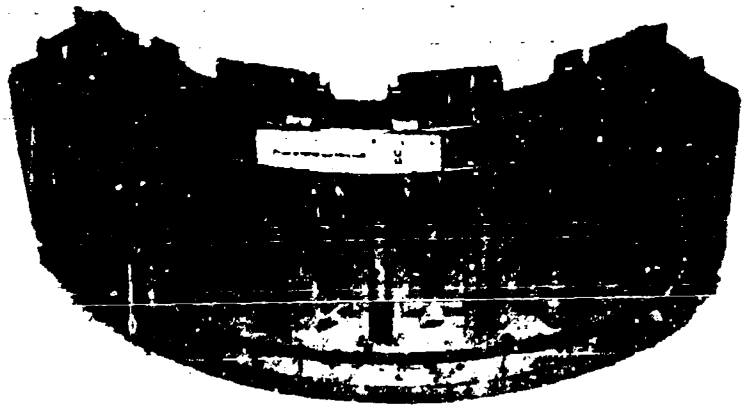


Figure 23. Twin Ram-Induction Combustor

FE 57838
GIV

Figure 24. Vaporizing Ram-Induction Combustor

GS 1282
GIV

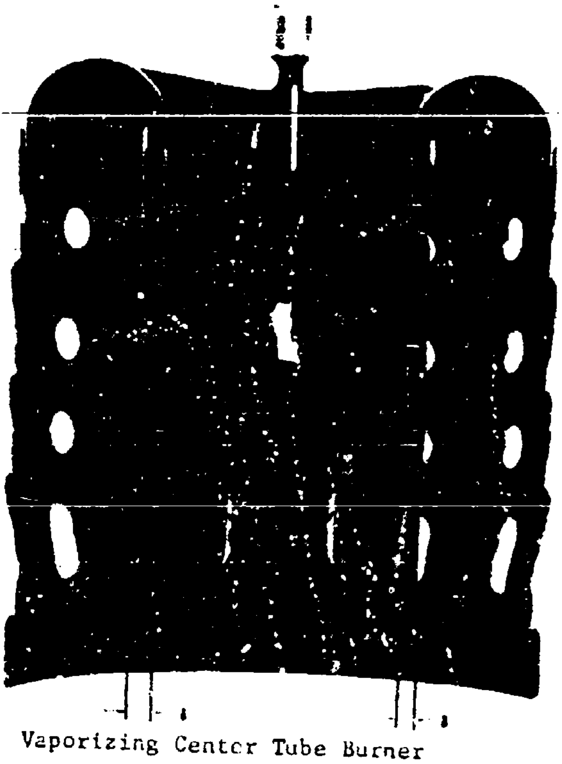


Figure 25. Vaporizing Center Tube Burner

FD 8293
GIV

d. Full Annular Duct Heater

Experimental investigation of the ram-induction duct heater is being conducted under NASA Contract NAS3-7907 in addition to the major effort being carried out in support of the JTF17. The primary goal of the NASA contract is to evaluate the durability of the duct heater by subjecting it to a 250-hour cyclic endurance test prior to the time that such a test could be expected to be conducted under the engine development schedule. The operating range required of the duct heater is also somewhat greater than that which must presently be met by the engine duct heater. Figure 26 is a cross section of the duct heater designed to meet the NASA requirements. Figure 27 is a photograph of the NASA duct heater assembled prior to its installation in the Lewis Research Center test facility where the test program is being conducted. This advanced component testing adds to the technical base from which the advanced JTF17 engines must come.

e. Full Annular Main Combustor

Similar to the duct heater, an early evaluation of a ram-induction main combustor durability (500-hour cyclic endurance) is scheduled to be conducted under NASA Contract NAS3-9403. This effort will also add to the background which must be built up in order to support engine growth developments.

3. Combustor Growth Contribution

The inherent high combustion efficiency and low pressure loss of the JTF17 ram-induction primary combustor preclude significant growth in these parameters; however, the development of combustors outlined above will permit higher temperature rise to match increased turbine temperature capabilities, and shorter length to reduce specific weight. Duct heater growth from the advanced development of this component will contribute to improve subsonic cruise TSFC at the rate of 0.35% for each 1% reduction in pressure loss and 0.70% lower cruise TSFC for each 1% increase in combustion efficiency (equal to approximately 1400 pounds payload increase).

One of the objectives of the development of the JTF17 ram-induction combustor and growth versions will be to produce less smoke than current commercial engines. This will have the dual benefit of reducing turbine airfoil erosion and eliminating a source of air pollution in the vicinity of airports and overhaul facilities. Inherently the ram-induction burner of the JTF17 designed for high temperature rise will produce less smoke than current engines as shown in table 1. The goal will be to maintain less than 20 at all significant power levels.

The ability to operate the main combustor and the duct heater on less expensive fuels will make a proportionate decrease in direct operating cost. The ram-induction type main combustor lends itself to exploiting this advantage and the similarity of the ram-induction duct heater, unlike an afterburner, assures that principles learned on the main combustor can be applied directly to the augmentor.

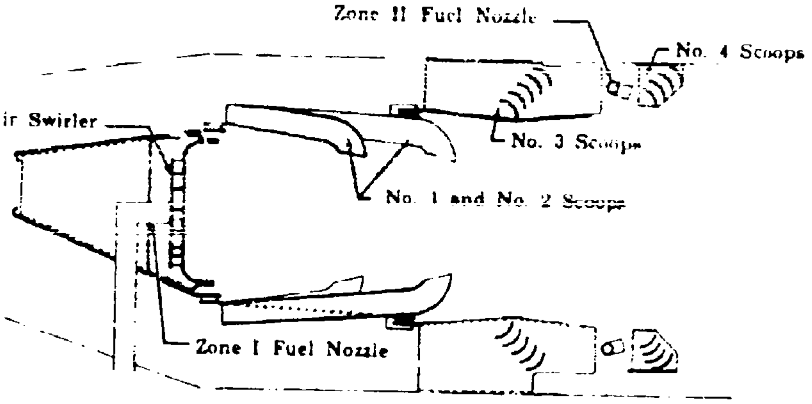


Figure 26. NASA Duct Heater

FD 13591A
GIV

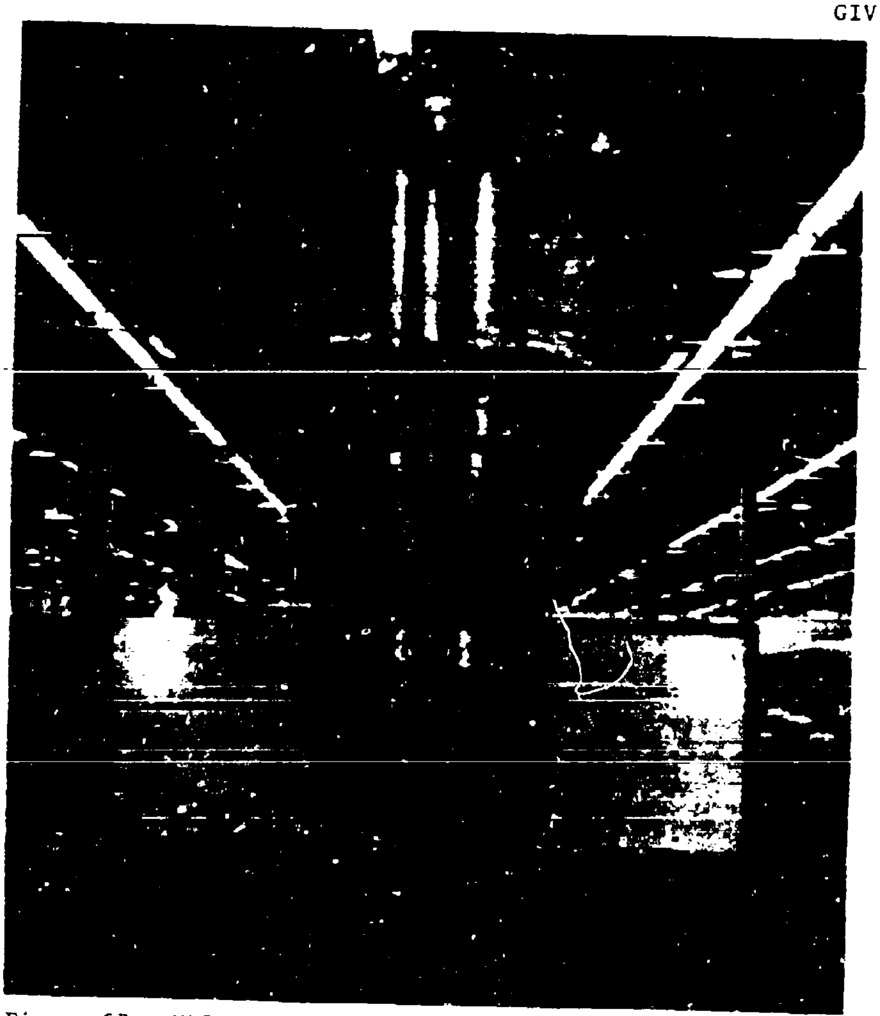


Figure 27. NASA Duct Burner Rig

FE 57726
GIV

TABLE I. SMOKE DENSITY AT SEA LEVEL TAKE-OFF

Engine	Smoke Density*
J57	50
J79	46
JT8D	45
JT3D	39
JT12	23
JTF17	16

*(100-Reflectivity as measured by Von Brand smoke meter)

D. TURBINE

1. JTF17

As in the compressor and fan sections, the dual rotor design of the JTF17 provides inherent versatility in the selection of growth possibilities as compared to a single rotor engine. A wide choice of rotor speeds, rotor work splits, and stage temperature levels is possible, permitting optimum use of growth developments.

The current JTF17 turbine design incorporates the concept of controlled vortex flow. This has permitted a lower design velocity ratio with a consequent reduction of rotor speed and savings in weight. However, as the initial application to a turbofan engine, it has been conservatively integrated into the overall turbine design. Further improvements in the application of the controlled vortex concept to turbine design can be expected and exploited in the JTF17 to give weight reduction, improved efficiency, or increased work.

a. Blades and Vanes

The design blade and vane metal temperatures of the JTF17 have been set below the strength capability of the materials currently specified because of erosion, corrosion and/or sulfidation limits. PWA 658 is specified for the turbine blades. Columnar grain PWA 664 will be fully developed by the time the engine is introduced into commercial service. As now available, PWA 664 has the strength capability to be operated 75°F above the JTF17 design temperature. The TD nickel in the first-stage vanes is also not being pushed to its limit.

b. Disks

Pratt & Whitney Aircraft has also evolved casting techniques, forging processes, and heat treatments for two different alloy systems, the IN-100/SM-200 type, and the UX-1500 type. These advanced fabrication capabilities should lead to turbine disks produced in the near future which have a 50°F or more operating temperature advantage over Astroloy, the material now specified for turbine disks in the JTF17 engine. Such an increase of temperature capability is compatible with a 300°F increase in turbine operating temperature.

Astroloy in turn possesses a significant advantage in high temperature strength capability over Waspaloy, which has been specified for the JTF17 turbine cases. Pratt & Whitney Aircraft has developed Astroloy sheet and methods of utilizing it for welded and fabricated assemblies. This technology, combined with the forging procedure developed for making large rings for the J58 engine, gives P&WA the capability of producing Astroloy turbine cases whenever the other components of the turbine are ready for temperature upgrading.

Although no sheet has been made from UX-1500 or IN-100, the technology developed in the forging of disks from these alloys can be applied to produce sheet. There is an excellent possibility that sheet from these alloys would have elevated temperature strength superior to Astroloy. The possibility of using IN-100 sheet is especially intriguing from the standpoint of its lower density (0.280 lb/in^3), compared to that of Astroloy (0.288 lb/in^3) and Waspaloy (0.297 lb/in^3).

These improved materials with higher temperature capability than currently developed alloys will provide growth for the JTF17 in flight Mach number to 3 or higher.

2. Advanced Turbine Technology

Technology directed at increasing turbine inlet temperatures has received major emphasis in research and development effort at P&WA during the past few years. The J58 engine in the SR-71 aircraft has accumulated extensive high temperature flight operation. The JT4 high spool turbine development rig described in Report F of Volume III, has completed a 200-hour endurance test at 2500°F, and extensive rig tests have been conducted at temperature levels up to 3000°F.

a. Cooling Effectiveness

Although systematic investigation of film and transpiration cooling is continuing, convective cooling of turbine airfoils has been emphasized because of the inherent structural integrity and resistance to foreign object damage so provided. Furthermore, gas path flow disturbances are minimized by this method compared to film or transpiration cooling. Significant progress has been made in developing analytical and experimental techniques to improve current turbine designs and to provide the tools for advancing the state-of-the-art. Advanced cooling concepts for turbine airfoils have been evolved and tested at temperatures considerably above current engine practice. This effort is directly applicable to the advanced turbine technology requirements of providing growth potential for the JTF17 engine. The wafer vane concept, which provides for a large internal heat transfer surface area and permits almost unlimited design flexibility, is illustrated in figure 28. Advanced manufacturing techniques are also being investigated to provide higher cooling performance for turbine blades and vanes. Among the more advanced research efforts is an attempt to cast a turbine blade with small cooling passages similar to the wafer vane. Ceramic wafers are being molded and stacked together to form the casting core.

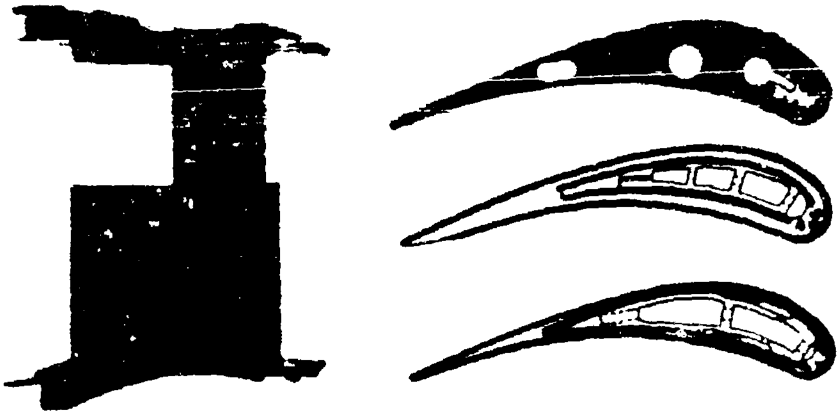


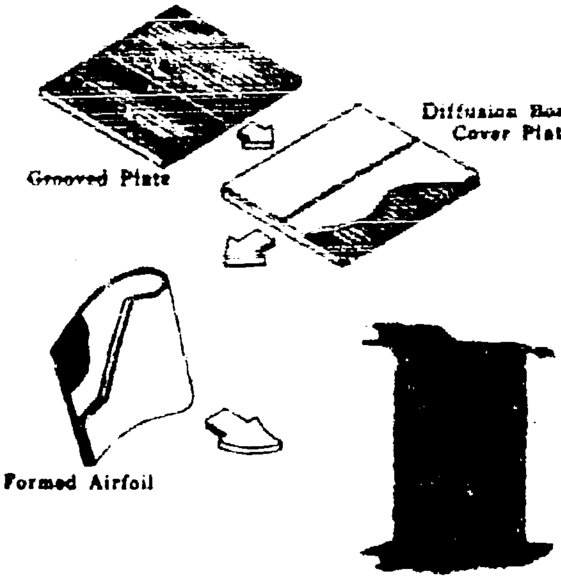
Figure 28. Wafer Vane Configurations

CS 1709A
GIV

Significant advance in the state-of-the-art of diffusion bonding has also been achieved. The diffusion-bonded thermal shield configuration (figure 29) was also conceived to provide effective heat exchanger characteristics in a solid structure. It has been successfully tested at gas stream temperatures up to 3000°F as has the wafer vane shown in figure 30, with the chordwise metal temperature profile plotted. As a result of research programs in environments substantially more severe than those required of the JTF17 engine, turbine cooling capability has been evolved which will meet higher temperature limits required for overall growth of the engine.

b. High Temperature Materials

Until the advent of aircooled turbine airfoils the increase in turbine inlet temperature was paced by advances in metallurgy to develop high strength, high temperature materials. Although air cooling has reached a high degree of sophistication and additional refinements can be made, further improvements in high temperature materials can benefit the engine growth directly by permitting reduction of airflow to improve overall turbine efficiency or to increase the turbine inlet temperature without an increase in cooling airflow. Projected materials such as PWA 1409 (Monocrystalloy MAR-M-200) will have improved high temperature strength properties. As superior protective systems are evolved from the advanced coating and cladding programs in progress, described in detail in Report F of Volume III, turbine metal temperature can be raised by more than 200°F.



* Trademark

Figure 29. Thermal-Shield* Vane (* Trademark) FE 17071
CIV

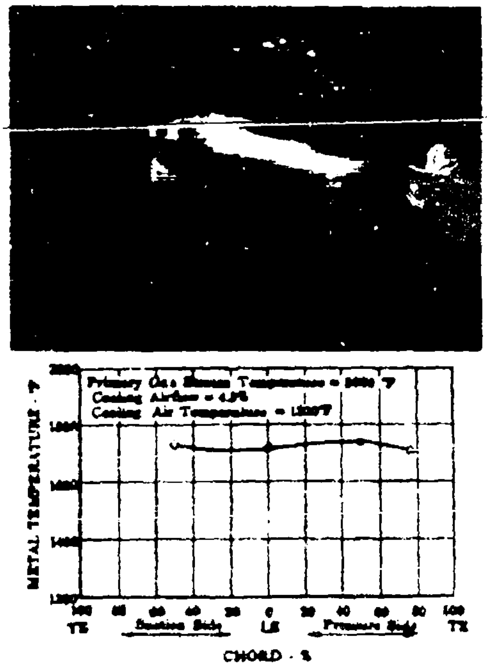


Figure 30. 3000°F Wafer Vane Test Results FD 17072
CIV

c. Aerodynamic Performance

Turbine aerodynamic efficiency is affected by many factors including airfoil geometry, orientation with respect to the primary gas stream, and method of discharging cooling air. One of the test rigs being used to investigate the effects of these factors on airfoil profile losses is the annular cascade rig shown in figure 31. Data from vane tests with various trailing edge thicknesses and cooling air discharge slot sizes has shown that the profile losses associated with this method of discharge can be minimized by proper selection of blade geometry and airflow parameters. (See figure 32.) These data demonstrate that controlled introduction of turbine airfoil cooling air through a slot in the trailing edge will minimize aerodynamic losses by reducing the "base drag". Further refinements of such methods will effectively increase the turbine efficiency of air-cooled parts while maintaining the ruggedness of thick trailing edges. Figure 33 shows reduction of aerodynamic loss at higher cooling air flows for a wafer vane design. This curve demonstrates that when the cooling effectiveness increase obtainable with this design with increased airflow is desirable for the engine cycle, the additional cooling flow can be reintroduced into the turbine flow stream with minimum loss. Rotating and cascade testing will be continued to provide the design criteria necessary for JTF17 growth through improved turbine performance.

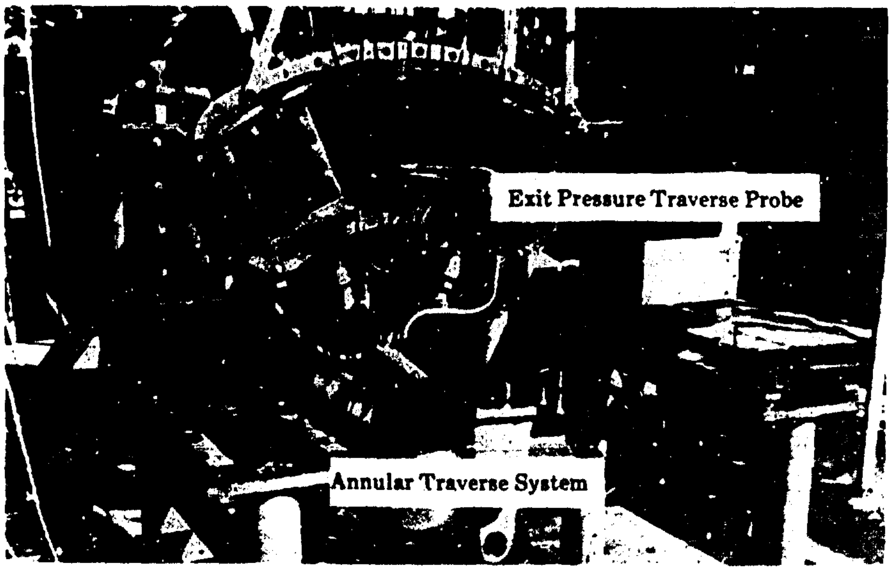


Figure 31. Turbine Annular Cascade Rig

FD 14497
GIV

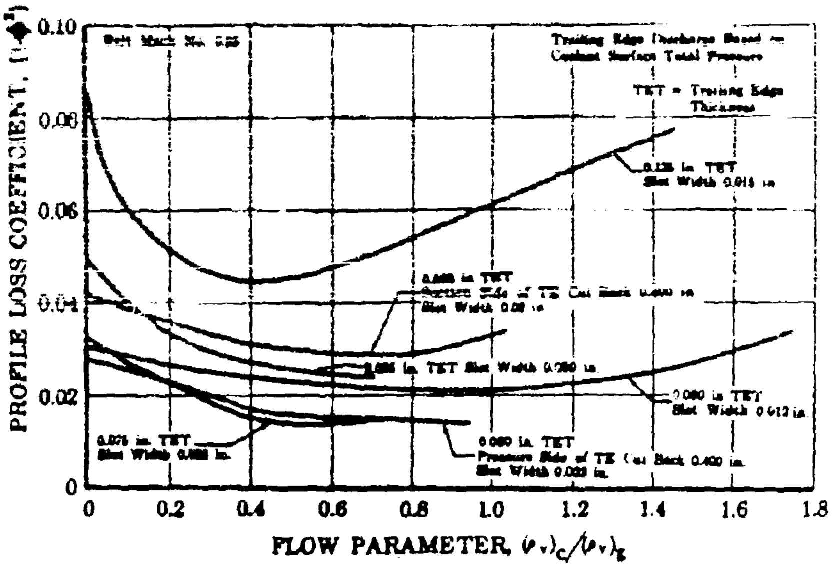


Figure 32. First Turbine Vane Profile Loss Coefficient FD 17073 GIV

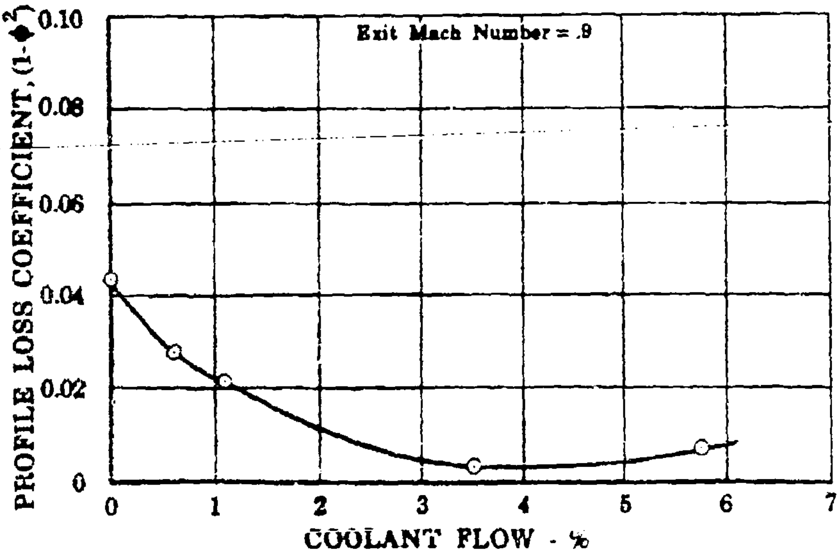


Figure 33. Wafer Vane vs Flow Parameter Profile Loss Coefficient vs Coolant Fl w Rate FD 17555 GIV

d. Thermal Fatigue

As turbine inlet temperatures are increased, thermal fatigue becomes an increasingly important mode of turbine failure since thermal fatigue life is affected by both the cyclic temperature range and the thermal gradient through the metal. Pratt & Whitney Aircraft has developed analytical methods of predicting thermal fatigue based on realistic thermal shock testing of standard specimens and airfoil parts. The thermal shock cascade rig shown in figure 34 at the Florida Research and Development Center cycles main stream airflow, main stream fuel flow, and cooling airflow to simulate engine thermal stress conditions. A typical thermal cycle is shown in figure 35. Experimental data from this unit will provide verification of analytical life predictions and lead to growth in the thermal shock resistance of advanced vane and blade designs.

3. Turbine Growth Contribution

The most ~~immediate requirement for increased growth in airline service~~ will be to increase hot section inspection (HSI) on engine heavy maintenance (EHM) periods and extend time between overhaul (TBO) as rapidly as safety and economics warrant. These have historically been paced by the life of turbine parts. Therefore, growth in the form of improved coatings to extend the present life limiting variable, sulfidation and erosion-corrosion, will be of utmost importance and receive the most development effort. Past history also indicates a turbine inlet temperature increase of approximately 40°F per year. Improved coatings with 75°F higher temperature capability will immediately permit increasing the overhaul life to the full 1% creep life of PWA 658 to 10,000 hours. PWA 664 with a compatible coating would permit increasing the turbine inlet temperature by 50°F. Further materials improvements and/or cooling effectiveness, with no turbine efficiency penalty, will directly result in increased turbine inlet temperature. An increase of 100°F can be translated into 2.2% additional thrust and 1.2% reduction of TSFC by rematching the current JTF17. The same increase applied to increasing bypass ratio will yield 12% increase in takeoff and transonic thrust and a cruise TSFC reduction of 2%.

Figure 34. Thermal Shock Cascade Rig FE 61108 GIV

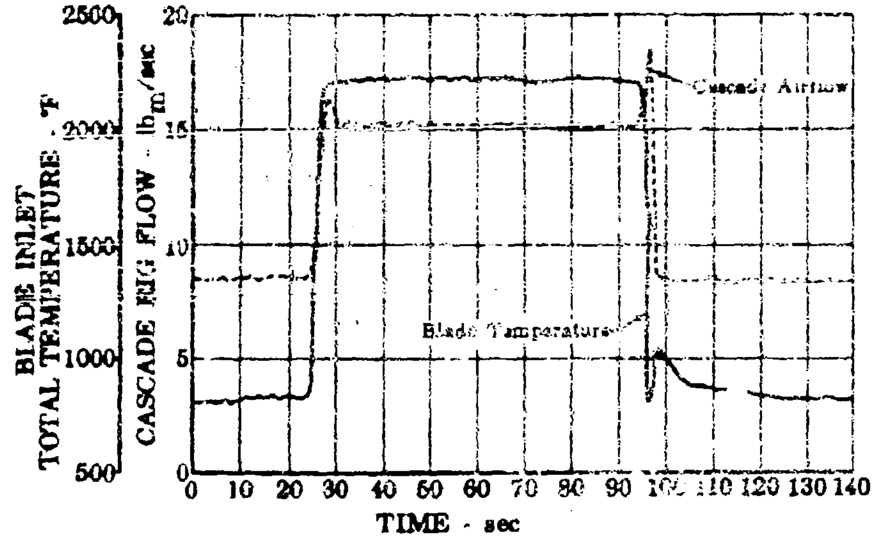


Figure 35. Thermal Shock Rig Cycle FD 17074 GIV

4. Exhaust System

Improvements in exhaust nozzle technology are expected to play a dominant role in determining advancements in propulsion for the next generation of aircraft since changes as small as 0.1% will increase payload approximately 500 pounds. The trend of increased exhaust system performance is shown in figure 36.

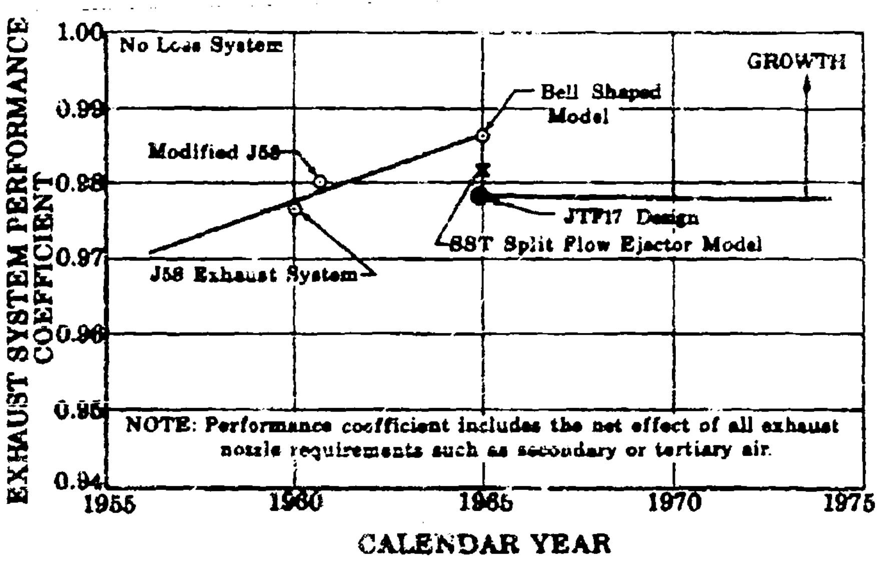


Figure 36. Exhaust System Performance Design Point Operation - Cruise FD 17075 GIV

To provide the turbopropulsion exhaust nozzle technology needed to meet such future propulsion requirements, the Air Force Systems Command, in June 1965 selected Pratt & Whitney Aircraft to conduct a three-year "Exploratory Research Program for Turbopropulsion Exhaust Systems" (Contract AF 33(615)-3128). Technological fall-out from this work obtained by direct interchange of data on a day-to-day basis and regular reports is expected to contribute appreciably to the growth potential of the JTF17.

The above are in addition to specific items of growth delineated in the exhaust nozzle and reverser-suppressor performance and design sections of this proposal (Section E of Report A and Sections E and F of Report B, Volume III). Examples of growth potential cited in those sections are:

1. Use of a split-flow nozzle, as shown in figure 37, to provide higher supersonic cruise performance levels through better utilization of pressures available in the secondary flow is shown in figure 38.
2. Use of titanium actuators for the reverser-suppressor clamshells and variable-area duct nozzles to reduce weight.
3. Providing higher reverse thrust by changing materials for the clamshell support structure.
4. Providing reverse thrust more quickly by modifying the clamshell control system to permit a null-thrust mode of operation.

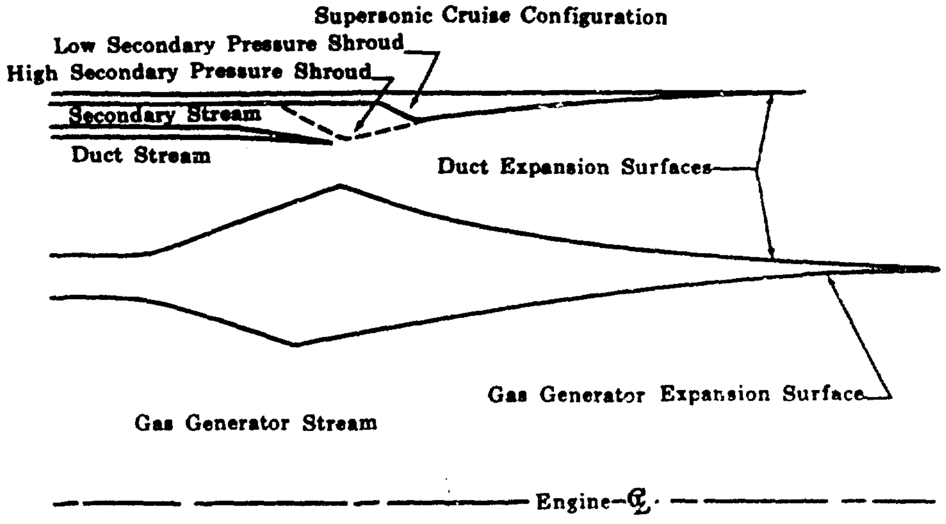


Figure 37. Split Flow Nozzle

FD 17133
GIV

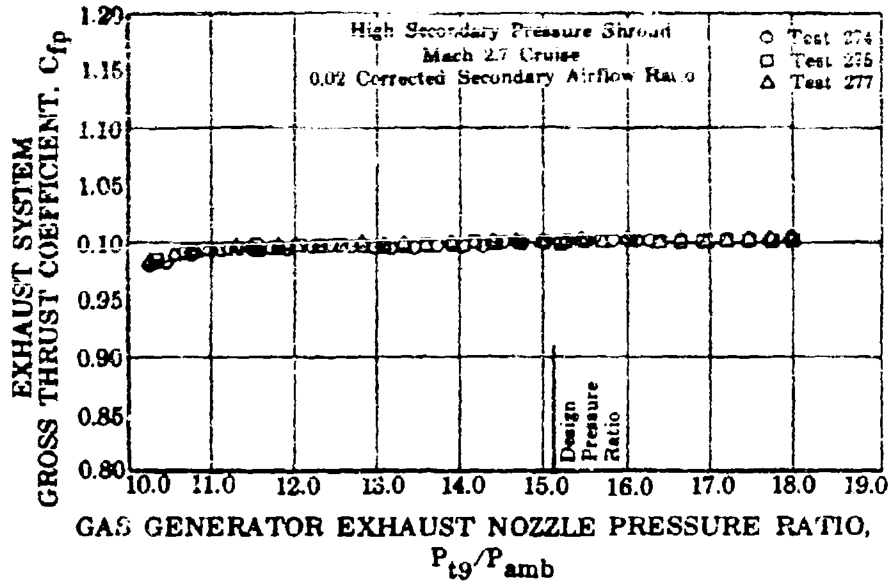


Figure 38. Split Flow Nozzle Performance FD 17076
GIV

5. Exhaust System Growth Contribution

The trade factor for the influence of improved performance of the exhaust system on overall SST performance is 4 times that of any other component. An increase of 0.5% in thrust minus drag coefficient would represent a 2500-pound increase in maximum payload. This order of improvement is projected for the JTF17 in 5 to 6 years after introduction to commercial service.

SECTION V
PLAN FOR ENGINE GROWTH

A. GENERAL

The selection of the duct heating turbofan over other engine cycles was strongly influenced by its ability to match the growth requirements of the supersonic transport. Historically, engine growth has been obtained through component improvements and turbine temperature increases. The JTF17 component and turbine temperature growth is illustrated herein. However, the duct heating turbofan has four additional growth dimensions: (1) the ability to change bypass ratio to increase transonic thrust at sea level and optimize TSFC at cruise; (2) the ability to increase cruise airflow by large increments without engine change or rotor speed change; (3) the ability to operate the aircraft economically over longer subsonic distances; and (4) the ability to increase the SST cruise Mach number and obtain the maximum range/payload improvement.

The aircraft requirements for engine growth cannot be precisely defined at this time. However, past experience and analysis indicate that improvements in SST economics will require increases in takeoff gross weight, time between engine overhaul, and cruise Mach number. The increase in takeoff gross weight provides a requirement for increased takeoff/transonic thrust, and reoptimization of the cruise thrust-TSFC relationship. To hold noise levels constant with increased takeoff gross weight, the noise-thrust relationship must also improve. It is also possible that adverse sonic-boom effects and political considerations may restrict more and more the supersonic operation of the aircraft, so that growth in the amount of subsonic flying may be required. Growth in cruise Mach number has been rare with subsonic jet transports; however, at supersonic conditions the drag function improves with Mach number and our analysis indicates that growth in this parameter should be expected.

Cruise TSFC is directly reflected in range/payload and economics.

The predicted growth of the JTF17 engine is described for each of these requirements.

B. SEA LEVEL AND TRANSONIC THRUST INCREASE

Component improvements and increased turbine temperature are expected to provide thrust increases of 15% during the first six years of airline service. (See figure 39.) Even larger thrust increases are available from increases in bypass ratio. These changes require a larger fan and may require a new low turbine. However, the high spool, control, burner, etc., remain substantially unchanged. Bypass ratio changes may be accomplished by retrofit in a manner similar to the retrofit of JT3 engines to JT3D engines. Thrust improvements from increases in bypass ratio are shown in figure 40.

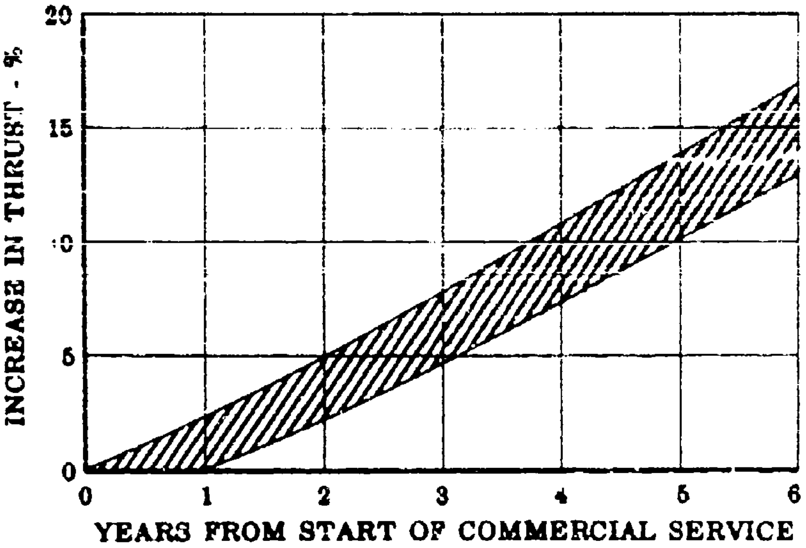


Figure 39. Growth-Component Development FD 17077 GIV

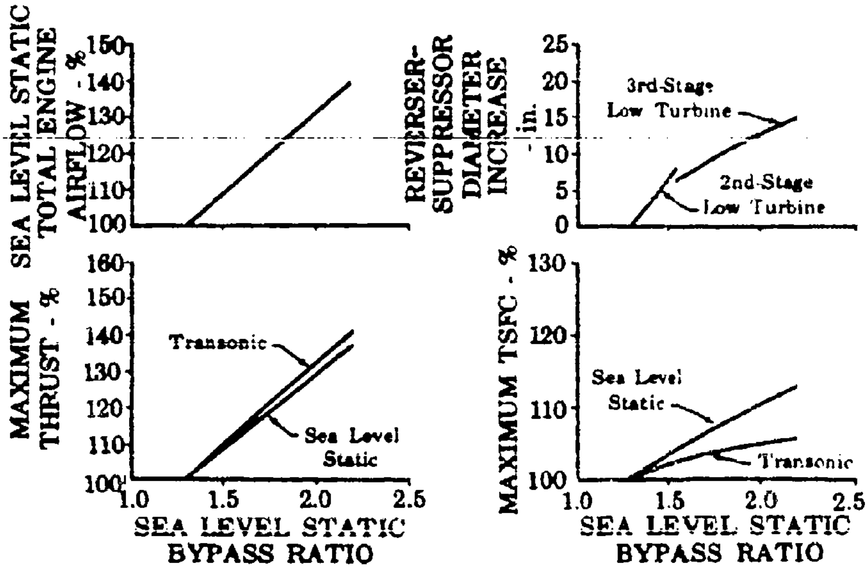


Figure 40. Growth-Bypass Ratio - Sea Level Static FD 17078 GIV

C. CRUISE TSFC

Cruise TSFC may be improved 4% by component development within the first six years of airline operation. (See figure 41.)

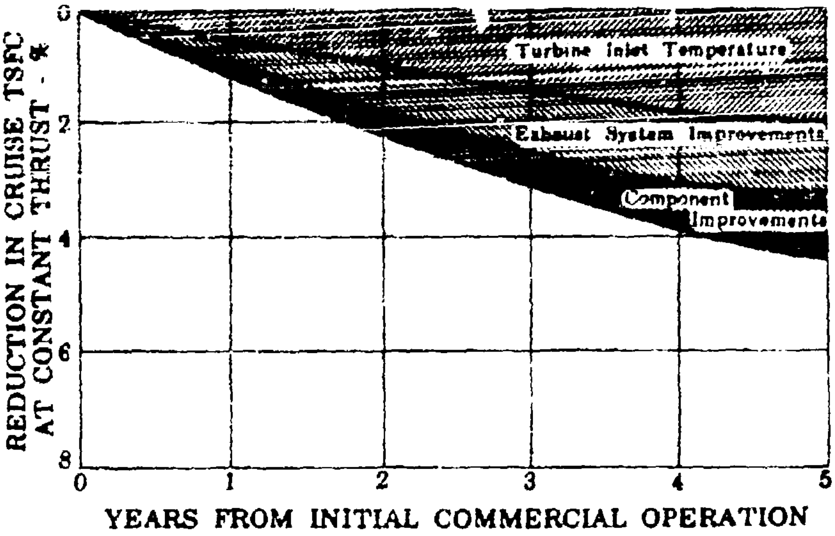


Figure 41. Growth-Cruise TSFC Reduction FD 17079 GIV

Bypass ratio changes relocate the minimum TSFC point as a function of thrust and may be employed to maintain the aircraft cruise thrust requirement near this minimum TSFC. Cruise bypass ratio may be varied either by changing the fan as described above or by changing to cruise airflow schedule. The turbofan has the capability of changing airflow at cruise in excess of 10% by merely replacing the cam in the fuel control which schedules the duct nozzle area. In this manner the JTF17 should be able to maintain optimum TSFC at cruise as gross weight increases.

Cruise TSFC can be matched to higher airframe gross weight coincident with increased SLTO thrust. Figure 42 indicates the effect of bypass ratio increase on TSFC thrust relationship. It can be seen that minimum TSFC occurs at higher thrust for the higher airflow engine. Thus, for operation above the minimum TSFC point, the cruise TSFC may be reduced by increasing airflow even though the minimum TSFC increases.

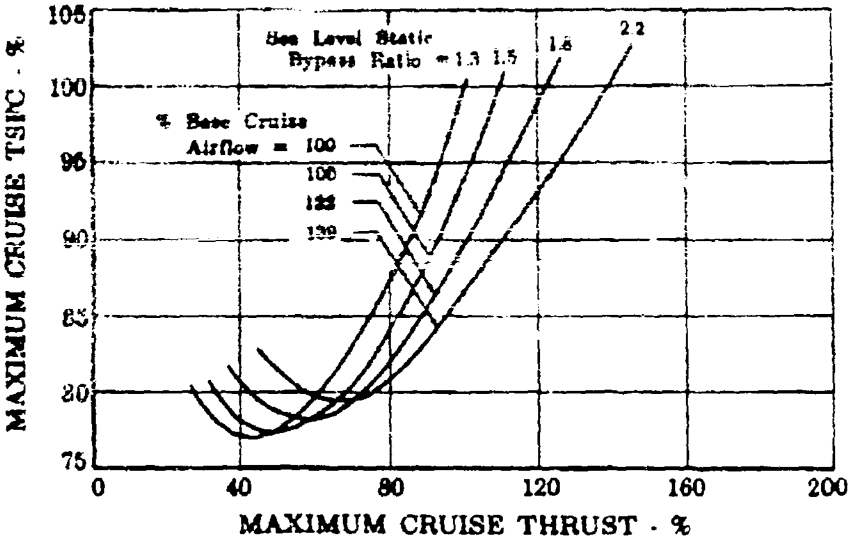


Figure 42. Growth-Bypass Ratio - Cruise FD 17080
GIV

D. INCREASED COMPONENT LIFE AND ENGINE TBO

All parts of the JTF17 are currently designed for a minimum of 10,000 hours TBO with minor repair, approximately 20,000 hours useful life for LCF limited disks and 50,000 hours useful life for creep limited cases, as explained in Section (Design). However, practical experience tells us that these parts lives can only be proved by day-in, day-out commercial operation. Parts life and resultant TBO increases come only as the result of learning in service how to most economically operate the SST, developing solutions to parts life problems unique to airline operation, and maintaining an aggressive engine development program. TBO beyond the 600-hour initial period will increase, with the approval of the FAA, at a rate set by engine condition sampling, in-flight shutdown rate and premature engine removal rate of the individual airline. By this approach it is expected that the JTF17 TBO growth will follow the pattern of previous P&WA commercial transport engines, which are shown in figure 43. The TBO growth projected for the JTF17 is shown in figure 44.

Component life and consequent engine TBO are functions of "most limited parts." It was pointed out that the development of coatings was the key to long turbine blade and vane life. High compressor disks are currently designed for 12,000 cycles by low cycle fatigue. Extended life for these parts will take the nature of material improvement and of reduced thermal gradients. Correction for wear and cracking depends on early recognition of the problem by accelerated engine development testing coupled with accurate, immediate reporting of data from the airlines and P&WA Service representatives as described in Volume IV, Report F, Section VI and action on such problems by aggressive development of repair procedures and/or engineering changes.

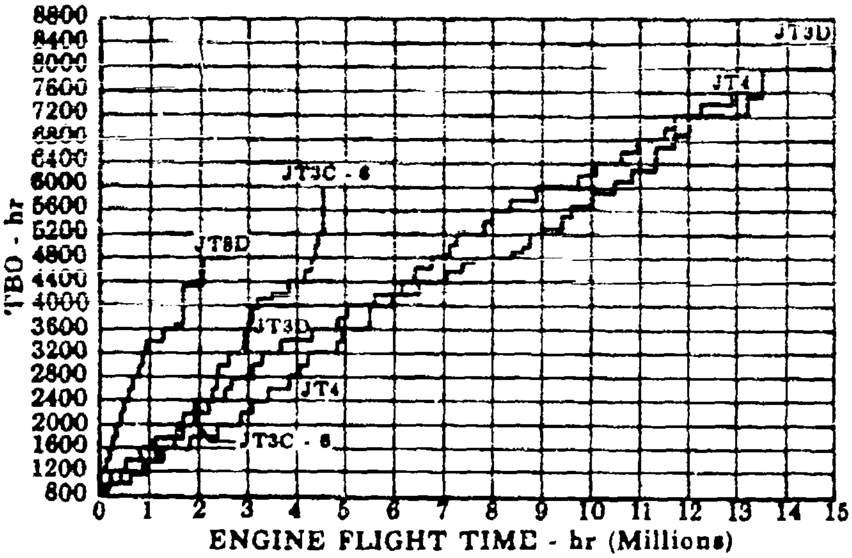


Figure 43. TBO Growth FD 17568
GIV

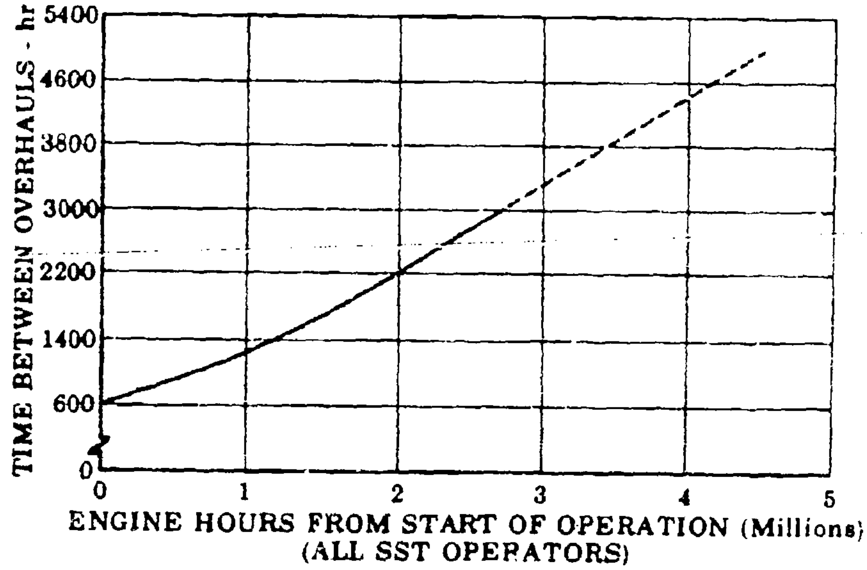


Figure 44. SST TBO Goals FD 17827
GIV

The Turbine Engine Reliability Program (TERP) allows the commercial airlines to operate turbojet engines in service without fixed TBO limits, during which time the engine reliability trends are being explored and evaluated as the engine ages in daily service operation.

The application of Pratt & Whitney Aircraft service data to the JTF17 design and development is described in detail in the JTF17 Reliability Program, Volume IV, Report F, Section II. Reliability growth functions for in-flight engine shutdowns and premature engine are also included in the plan.

The commercial airlines have long recognized that limited-life parts in turbojet engines have in the past played an all too dominant role toward the determination of fixed engine TBO's. Under the TERP maintenance concept, engines are scheduled into the Engine Heavy Maintenance (EHM) Shop for inspection, rework, repair, or replacement of these limited-life parts. The frequency of the scheduling of engines into the EHM Shop is predicated by a thorough study of parts-time reliability relationship. Engineering changes incorporated to improve parts life result in an increase in the EHM intervals. The EHM program as related to TERP allows the exploration of engine long-life parts on a far more rapid schedule while still maintaining a high degree of engine reliability. It is anticipated that the reliability of the JTF17 engine will be attained without the need of a fixed TBO limit. Studies related to the parts aging reliability aspects will determine the extent and frequency of line maintenance inspections as well as schedule engine removals for parts repair or replacement at EHM.

The end result of the TERP maintenance concept is that the EHM Program allows TBO's to develop far more rapidly while maintaining a high degree of reliability at a considerable reduction and saving in manhours and material costs.

The engine development program recognizes the dependency of the rapid acceleration of EHM intervals by concentrating on potentially life-limiting parts by means of an extensive Engine History Records system and a Reliability Program. Records of current subsonic commercial turbine engine transports show as much as a 2 to 1 variation in parts costs between engine makes, which is a direct result of an aggressive service organization and a responsive Engineering Development group. This background and the lessons learned by its application will be directly applied to the JTF17 and result in an accelerated improvement in parts life expectancy. The unitized construction and EHM concept of the JTF17 design, which will be developed and demonstrated on the JTF17 engine, lend themselves to the Turbine Engine Reliability Program.

E. INCREASED FLIGHT MACH NUMBER CAPABILITY

Mach number growth carries two basic consideration, airflow scheduling and structural design associated with increased compressor inlet temperature.

When considering engine growth it is important to keep in mind that the twin spool turbofan cycle high rotor operates like a fixed geometry turbojet with constant turbine inlet temperature during cruise. Thus, at any Mach number, changes to total airflow may be accomplished by changing the fan airflow only. Since, at the comparatively low pressure ratios associated with the fan corrected speed at high flight Mach number, constant rotor speed lines are essentially parallel to the locus of operating points obtained by varying duct jet area, a fairly large variation in airflow may be accomplished with little or no change to speed in either rotor.

These convenient methods of controlling airflow allow "hand tailoring" the airflow schedule to the installation for the best possible performance at each condition as described in Report B, Section III.

As cruise Mach number increases with the resulting increase in engine inlet temperature, the augmented turbofan operates more like a ramjet and the advantages become even more apparent. Most of the turbofan airflow is duct flow and, therefore, enters the duct heater combustion section at a low temperature. The combustor inlet temperature can increase considerably from this point without becoming so high that cycle efficiency suffers. Since, in a turbojet cycle, air enters both the primary and afterburner combustion section at a much higher temperature, growth in Mach number is considerably less attractive. The effect of Mach number growth on range for the JTF17 and a typical jet cycle is shown in figure 45.

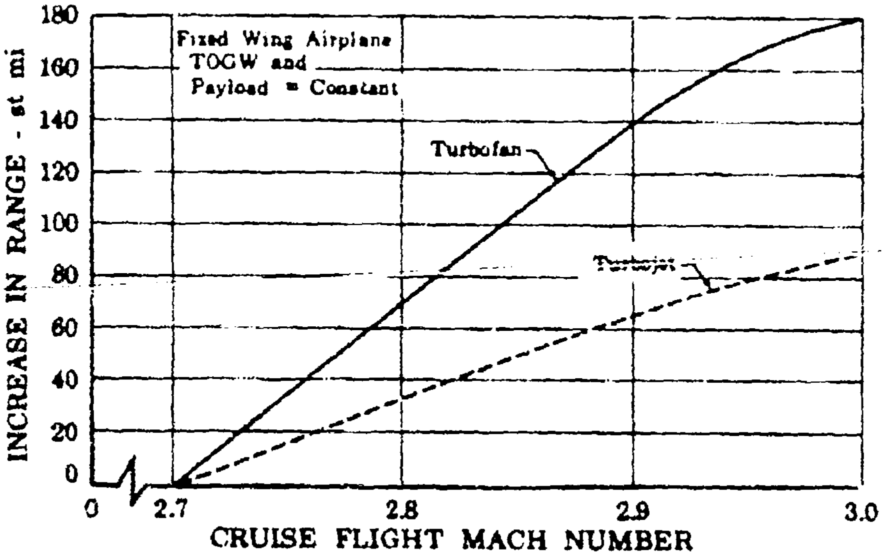


Figure 45. Cruise Mach Number Effect on Design Range FD 17082

Structural changes associated with increased Mach number to 3 and above depend heavily on the rotor speed schedule. Since the duct heating turbofan cycle does not require significant changes in rotor speed to attain efficient operation at higher Mach numbers, the design changes are primarily limited to improve high temperature materials in the front of the engine. The extensive background of the J58 development and flight at compressor inlet temperatures more than a hundred degrees in excess of those for Mach 3.0, give Pratt & Whitney Aircraft unique experience with very high strength-to-weight ratios, high temperature materials on a production basis. The J58 program required the recognition and solution to many problems not previously encountered in the compressor section of an engine. This knowledge has been applied to the JTF17 design and continued service exposure to such operation in the J58 will be applied to growth version of the JTF17 series engine.

Higher Mach number operation than that presently specified for the JTF17 engine will entail higher operating temperature conditions in the compressor which in turn will necessitate application and/or development of higher temperature titanium or the substitution of proven nickel base alloys. It is Pratt & Whitney Aircraft's objective to develop to the utmost the capabilities of the titanium alloys discussed above and in Volume III, Report F, Section II to avoid degrading the thrust-weight ratio of the engine as the flight Mach number capability is increased. The development of solid-solution dispersion strengthened titanium alloys could afford 1200°F capability. Nickel base alloys, Inco-718, Waspaloy, and Astroloy are proven performers and are available to provide the necessary capability. If the Inco 160 alloy comes up to expectations, it might become very attractive for introduction to an upgraded compressor for high Mach number engine operation.

F. NOISE REDUCTION

Growth in engine quieting will result from thrust growth as well as advances in attenuation techniques. The more promising possibilities are enumerated as follows:

1. Higher thrust will permit greater climb rate to reduce noise on takeoff
2. Research on the phenomenon of noise generation will open new possibilities of noise attenuation, both in fan and reverser-suppressor
3. Sound absorbing duct liners indicate promise. Felt metals and perforated sheet are among the possibilities currently being tested.

A prominent growth area is in the control of exhaust gas noise. Existing commercial jet engine suppression devices are inefficient in terms of both suppression gained and performance losses. The high exhaust gas velocities which will be generated by the engines required for the SST should allow improvements in the efficiency of these suppressors. However, it is also anticipated that large improvements will be gained at the low exhaust velocities required at airport approach and thrust cutback after takeoff. Methods of tertiary airflow control and nozzle designs to improve mixing will be investigated for this growth goal.

Extensive improvements in the control of fan noise are expected to result from improved application of acoustical liners located in the fan duct. This is expected to result from technical advancements in liner design techniques and materials, such as an analytical design method for nonresonant liner materials and improved structural properties of this material.

Application of the above attenuation devices in their fully developed form can be expected to increase fan noise attenuation above current levels (Report C, Section III,) by as much as 12 db. Improvement in jet noise suppression of 5 db is also expected at unaugmented power settings and of 3 db in the augmented power range.

Specific weight reductions developed into the engine will result directly in noise benefits. By providing an improved specific aircraft weight, higher altitudes will be achievable at takeoff with attendant reductions in perceived noise to an observer on the ground.

Research work is also expected to lead to a new generation of noise control devices. Both model and engine tests will be conducted to improve understanding of the noise generation process of exhaust gases and fan. This work will be conducted with Schlieren analysis of the interaction of ambient air with a high velocity exhaust stream and narrow frequency band analyses of the effect of fan design modifications. Fan duct discharge contours will be evaluated in detail to provide minimum pressure losses while retaining beneficial shapes for acoustical liners. It is anticipated that the application of the results of this effort will provide complete attenuation of fan noise as a significant contributor to total engine noise. Additional exhaust noise attenuations in the range of 4-6 PNdb are expected to result from this program.

G. REDUCTION OF SPECIFIC WEIGHT

Reduction of specific weight will accompany the thrust improvements described in Section V-A. This reduction will be accomplished by lightweight design features and material improvements as well as the component improvements. Some of the design improvements expected to result in lower weight are:

1. More advanced blade attachment designs
2. More effective use of cooling air
3. Shorter burners
4. Higher stage loading and subsequent rotor speed reduction
5. Lightweight fastening methods
6. Improved forging techniques for fewer flanges
7. Improved welding techniques for fewer mechanical joints.

As the JTF17 engine development program progresses, a sustained effort will be made by Pratt & Whitney Aircraft to substitute, where economically practicable, materials which will effect worthwhile reductions in engine weight. Materials presently under development which offer strength-weight advantage over specified materials include titanium alloys, intermediate temperature nickel base alloys, and high temperature nickel base alloys. In the case of titanium alloys, two compositions, IMI-679 and Ti-6Al-2Sn-4Zr-2Mo (Volume III, Report F, Section III) offer strength-to-weight advantage over Ti-8Al-1Mo-IV, which is specified quite extensively in the JTF17 for a fan disk, high compressor blades and vanes, and for fan duct and reverser-suppressor parts. Once the suitability of one or both of these development alloys can be definitively established, substitution of either, particularly the Ti-6Al-2Sn-4Zr-2Mo, should result in substantial weight saving.

Evaluation of the promising solid-solution dispersion strengthening system of titanium alloys discussed in Volume III, Report F, Section III, which have potential for use up to 1200°F is being diligently pursued because of the obvious gains that could be realized in the form of engine weight reduction through the substitution of such a titanium alloy for nickel base disks, blades, and vanes.

The intermediate temperature nickel base alloy, Inco-718, also is specified extensively in the JTF17 engine for welded and fabricated cases. Inco-160, an experimental alloy, based upon the preliminary data now available, offers opportunity for substantial weight reduction because of its outstanding strength-to-weight characteristics (Volume III, Report F, Section II). In addition to a possible substitution for Inco-718, it also might be attractive as a substitute for the specified Waspaloy compressor disks for weight saving. In the area of high temperature nickel base alloys, some weight reduction could be realized through the substitution of Astroloy for Waspaloy, and forged Inco-100 for Astroloy.

H. OPERATION WITH LOWER COST FUEL

Development of a main burner and duct heater to operate on lower cost fuel need not be timed by parallel developments of other components. Modified combustor sections could be incorporated in delivered engines as soon as substantiating engine testing supported the change. The benefits of reduced operating cost would then be immediately available to the airlines.