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Results of NASA's Energy Efficient Engine Program

Carl C. Ciepluch*
NASA Lewis Research Center, Cleveland, Ohio
Donald Y. Davis†
General Electric Company, Evandale, Ohio
and
David E. Gray‡
Pratt & Whitney, East Hartford, Connecticut

The major activity undertaken in the NASA Energy Efficient Engine Program has been completed. This paper reports on the progress made toward achieving the program goal of developing advanced technology to significantly reduce fuel consumption and operating costs of future subsonic transport-type propulsion systems. An additional goal was that the advanced concepts be compatible with future environmental regulations. Along with the results obtained, a brief overview of the design details of both the General Electric and Pratt & Whitney energy efficient engines and the overall program scope are presented. Overall, this program has been highly successful; the technology developed during its course is, and will continue to be, effectively employed in both current and future advance transport aircraft engine designs.

Introduction

THE sudden energy crisis in 1973 raised fuel conservation to an issue of paramount importance to the U.S. economy. The aviation industry, which is a relatively heavy user of petroleum-based fuels, was significantly affected by the subsequent increase in fuel costs. Between 1973 and 1975, the price of aircraft jet fuel tripled. Recently, fuel costs have been about six times higher than the precrisis level of the 1970s.

Accordingly, NASA initiated the Energy Efficient Engine (E^3) project in the mid-1970s as one of several major activities under the NASA Aircraft Energy Efficiency (ACEE) program[1] aimed at substantially improving aircraft fuel efficiency. To make the fuel savings technology viable for commercial and military transport aircraft, it also was important to consider overall economic and environmental effects. The E^3 project goals, which took into account fuel savings and economic and environmental improvements, were 1) to reduce specific fuel consumption (SFC) by 12%; 2) to reduce SFC performance deterioration by 50%; 3) to reduce direct operating costs by 5%; 4) to meet FAA noise regulations; and 5) to meet EPA proposed emissions standards. The fuel and economic improvements are relative to high-bypass-ratio turbofan engine (P&W JT9D-7A & GE CF6-50C) in use in widebody aircraft in the mid to late 1970s.

Initial Studies

Prior to initiating the E^3 project, Pratt & Whitney (P&W) and General Electric (GE) were contracted to study advanced propulsion systems for subsonic aircraft. Boeing, Lockheed, and McDonnell Douglas provided significant guidance for these studies,[2-7] which examined turbofan engine size, cycle, and advanced component technologies in addition to various types of unconventional engine concepts such as geared fans, regenerators, and advanced turboprops. Eastern and Pan American airlines were also contracted to review the overall benefits of, and assess, the engine concepts and advanced technologies proposed for evaluation in the E^3 project from an airline user's point of view. The output of this total effort was the definition of flight propulsion systems (FPS) by both P&W and GE. These engine definitions would be a guide for the technology to be developed in the E^3 project and would be representative of the fully developed potential of this technology.

General Electric

The General Electric E^3 FPS configuration and major components are illustrated in Fig. 1. The engine is sized for approximately 36,000 lb of takeoff thrust. An aggressive cycle was employed for improving engine efficiency. The cycle and performance characteristics as compared to the reference CF6-50C engine for the maximum cruise condition at 0.8 Mach number and 35,000-ft altitude are shown in Table 1.

The engine has two corotating spools supported by a total of five bearings in two main frames that form the basis of the GE E^3 configuration. The accessory package is located inside the core cowl. This contributes to the slender, low-drag nacelle lines. Bulk-absorber-type acoustic treatment is used in the inlet and the inner and outer walls of the fan duct, and aft of the low-pressure turbine at the end of the core flow passage. The nacelle includes a fan-stream thrust reverser totally encased in the outer structure with no actuation links in the fan bypass stream.

The fan has a single stage consisting of solid titanium blades, incorporating a midspan shroud located at approximately 55% span near the trailing edge to minimize aerodynamic losses. A composite frame is featured wherein the vanes are integrated with the support struts to minimize the number of airfoils, reducing fan-frame weight and cost.

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*Project Manager for Aerospace Plane.

†Advanced Demonstrator Engine Systems.

‡Design Model Man, Propulsion-Fan Project.

The integral vane-frame design requires that the vane/struts be large enough to provide adequate support, but few enough in number to avoid excessive blockage. This results in about an equal number of blades and vanes. The axial spacing between vanes and blades is increased to about two blade chord widths to provide a reduction in source noise. The inlet is cantilevered from the fan frame and is independent of the fan casing which, as a result, is not subject to any flight loads. This allows tighter clearances in the fan and provides subsequent performance increase. A quarter-stage island booster is placed behind the fan to give automatic core flow matching; it also acts as a foreign object separator, throwing dirt and other particles outward and back into the bypass stream away from the engine core.

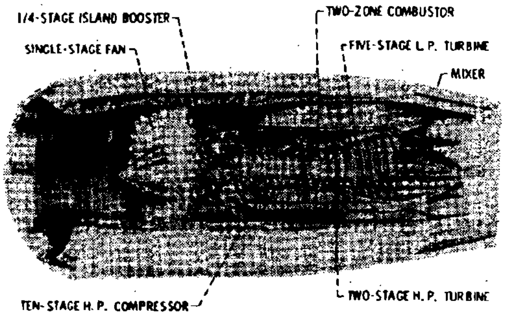


Fig. 1 General Electric energy efficient engine.

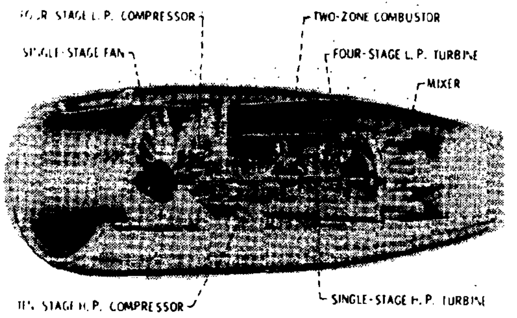


Fig. 2 Pratt & Whitney energy efficient engine.

Table 1 Comparison of cycle and performance characteristics for GE CF6-60C and GE E^3 FPS

	GE CF6-50C	GE E^3 FPS
Bypass ratio	4.3	6.9
Fan pressure ratio	1.73	1.61
Overall pressure ratio	30.1	36.1
Compressor pressure ratio	12.5	22.6
Turbine rotor inlet temp., °F		
Hot day takeoff	2400	2450
Maximum cruise	2080	2170
SFC	Reference	−14.2%

Table 2 Comparison of cycle and performance characteristics for P&W JT9D-7A and P&W E^3 FPS

	P&W JT9D-7A[a]	P&W E^3 FPS[a]
Bypass ratio	5.1	6.6
Fan pressure ratio	1.58	1.71
Overall pressure ratio	25.4	37.3
Compressor pressure ratio	10	14
Turbine rotor inlet temp., °F		
Hot day takeoff	2285	2480
Maximum cruise	1990	2190
SFC	Reference	−15.1%

[a] Parameters at 35,000-ft altitude, Mach 0.8, maximum cruise power setting.

The compressor is a major area of innovation, aimed at achieving a pressure ratio of 23:1 in only 10 stages by utilizing highly loaded, low-aspect-ratio, rugged airfoils. It has four variable vane stages and a variable inlet guide vane. Active clearance control is employed on the last five stages to achieve tight running clearances by controlling cooler front stage bleed air as it passes over the outer surface of the aft inner casing. Climb and particularly cruise performance increase as a result. The shorter compressor is stiffer than conventional compressors and, therefore, less subject to performance deterioration.

The double-annular combustor is designed for low emissions and is an outgrowth of the NASA Experimental Clean Combustor Program. A segmented or "shingled" liner is utilized to provide increased life and low maintenance while the split duct diffuser divides the flow for the two concentric burning zones, permitting a very short combustor length. In the GE E^3 combustor, a threefold increase in burner life is expected due to the segmented design, which reduces the thermal stresses during rapid heating and cooling cycles.

The high-pressure turbine is a two-stage design which incorporates active clearance control by allowing fan air to impinge on the turbine case. This two-stage turbine is cooled by means of compressor-discharge and interstage air for the vanes and blades, respectively. Major design features are the substantially extended life obtained through use of advanced directionally solidified airfoil material, a ceramic shroud over the first-stage rotor, advanced-powder metallurgy disks, and the elimination of bolt holes in the disks. Cooling air requirements have also been reduced through the use of the advanced higher-temperature turbine materials.

The low-pressure turbine has five uncooled stages, which incorporate aerodynamic advances, and is acoustically tuned to reduce noise. Higher performance is achieved by reducing pressure losses, improving the aerodynamic design, using active clearance control, and incorporating a short transition duct between the turbines.

The hot core engine stream is mixed with the cooler fan bypass stream prior to the engine exhaust by means of a 12-chute mixer. A full-authority, digital electronic control (FADEC) coordinates all engine variables. FADEC incorporates a "failure indication and corrective action" (FICA) strategy which provides for continued normal engine operation, even with the loss of one or more key input parameters. Further details of the GE E^3 can be found in Ref. 8.

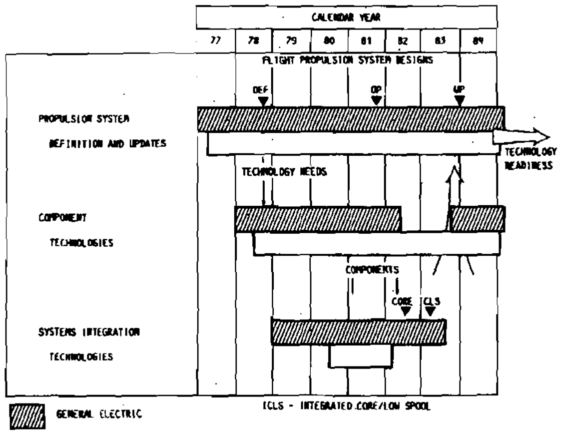


Fig. 3 Program schedule.

Pratt & Whitney

The Pratt & Whitney's E^3 FPS, shown in Fig. 2, is also sized for approximately 36,000 lb of takeoff thrust. A substantially higher pressure ratio and bypass ratio cycle than for the reference JT9D-7A engine was chosen to improve performance as shown in Table 2. In the program, the counter-rotating, two-spool engine is a five-bearing design with two main support frames and two main bearing compartments. An advanced, low-drag, single-nozzle nacelle system is used to accommodate the fan and core exhaust mixer. A low-loss acoustic liner is used in the inlet and exhaust ducts to attenuate noise emanating from the fan and the core. A fan-stream thrust reverser with directive cascades is housed within the nacelle contours.

Two fan design approaches were included in the program. The first was a single-stage, shroudless, hollow blade design; the second was a single-stage, shrouded, solid blade design. The former was a more advanced, higher-performance design, the technology for which may not be completely developed during the course of the E^3 program. The latter was a nearer-term approach, which was carried as an alternate for the higher-risk shroudless, hollow blade concept. The unshrouded fan contains 24 hollow blades. The shrouded fan rotor consists of 36 solid blades with each blade having an aft part span shroud to provide the necessary stability and durabilty requirements. The fan rotors are acoustically matched to the duct exit guide vanes by spacing the blades and vanes apart by three blade chord lengths.

The compressor intermediate case supports the fan case, and along with the low- and high-pressure spool rotors, forms the flow path from the low-pressure compressor to the high-pressure compressor inlet, and transfers engine loads to the mount system. In addition, the intermediate case contains the provisions and plumbing for the rotors and accessory drive shafts and gears. The case includes an inner ring which forms the outer diameter wall of the front bearing compartment and the inner diameter flow-path transition wall between the low- and high-pressure compressors. Ten main structural struts extend radially outward to the outer fan case to form the fan exit struts. Nineteen additional nonstructural fan exit guide vanes are bolted between the inner and outer fan walls. A center casing, which forms the outer diameter core flow-path wall and fan inner diameter wall, is welded to the struts. This casing transfers engine loads to the mount system ring attached to the back side of the struts.

The compressor section, designed for lightweight, reduced-cost, improved performance retention, is configured as two short, stiff, drum rotor low- and high-pressure sections. The high-pressure compressor is designed to produce a 14:1 pressure ratio in 10 stages for maximum efficiency. Advanced "controlled diffusion" airfoils with elliptical leading edges, variable stator vanes in the front four stages, and actively controlled clearance in the rear six stages of the compressor using fan air are included to increase performance.

The design included wide chord blades for reduced airfoil count, advanced construction techniques, such as electron-beam-welded front drum, hot-isostatic-pressed single-piece rear drum, brazed rear stator shrouds, and full-loop rear case and advanced materials. Collectively, these features resulted in a calculated reduction of 38% in weight. There was also an estimated reduction in initial and maintenance costs of 33 and 32%, respectively, when compared to the JT-9D compressor, which is about the same size.

The two-zone combustor was designed to meet both the low- and high-power EPA-proposed emissions standards. The zones were axially aligned as primary and secondary combustion regions. To meet an 8000-h life requirement, the combustor liner was designed as a segmented structure to allow unrestrained axial and circumferential thermal expansion. A unique cooling system was designed in which compressor discharge air first convectively cools the back faces of the liner segments, then reverses direction and film-cools the combustor side of the segments.

The P&W E^3 high-pressure turbine is a transonic, single-stage design aimed at lowering initial and maintenance costs while efficiently meeting the large power requirements of the high-pressure compressor. The turbine utilizes active clearance control to reduce blade tip clearances at critical operating conditions. The disk was designed with a second-generation powder/metal/nickel alloy for substantially higher strength and life. Airfoils are a second-generation single-crystal nickel alloy with a temperature capability of +100° F over B-1900 alloy. A ceramic outer air seal is used over the rotor. The 24 vanes require only 6.41% of core engine inlet flow for cooling, while the 54 blades utilize only 2.75%. The vanes have three internal cavities for crossflow impingement cooling augmented by a cooling film from leading-edge showerhead holes. The blades have a multipass internal configuration. Internal trip strips promote turbulence to increase heat-transfer effectiveness. Other design features contributing to efficiency improvement include contoured vane endwalls, a large gas-path annulus combined with high rotor speed, high reaction levels, and transonic airfoils with thin trailing edges.

The low-pressure turbine has four stages. The design includes advanced aerodynamic blading concepts, high-temperature materials to eliminate cooling, active clearance control, and counter-rotation relative to the high-pressure turbine to minimize gas turning required by the transition duct struts. The hot low-pressure turbine exhaust gases are mixed with the fan discharge air in an 18-lobe mixer before being discharged through a common nozzle. A dual-channel, full-authority electronic control is used to schedule fuel flow, variable geometry stator vanes, and stability air bleeds. Fault detection and self-correction systems are utilized to provide continued normal engine operation in the event of a control malfunction. Further information on the P&W E^3 can be found in Ref. 9.

Overall Study Impact

As noted above, it was projected that the GE and P&W E^3 FPS's would be capable of producing specific fuel consumption reductions for the maximum cruise condition in the 14-15% range. This exceeded the E^3 project goal of a 12% reduction. Projections of emissions levels and noise levels for both FPS's also indicated that they would meet the environmental goals. Calculations of typical transport aircraft fuel usage using the FPS's revealed that block fuel savings in the range of 18% could be obtained for a nominal 3000-n.mi. mission,[6,7] and this represents substantial potential savings for airline operators. To further illustrate the potential fuel savings, the total fuel consumption of domestic carriers is reduced by approximately 100 million gal per year for each percentage point reduction in fuel consumption. On the average, about half of this savings is a result of improvements in component efficiencies and the remaining half is due to the advanced cycle, mixer nozzle, and nacelle aero refinements. The cycle advances include the higher bypass ratios for improved propulsion efficiency and the higher cycle pressure ratios and turbine temperatures for increased thermal efficiency. Attainment of these fuel savings, along with estimated engine weights, was projected to produce direct operating cost savings of between 5 and 10% for three- and four-engine transcontinental aircraft. Thus, if the fuel savings is attained, the 5% direct operating cost reduction goal should be exceeded.

Program Description

The overall schedule for the E^3 project is shown in Fig. 3. The initial studies reported on in the previous section defined the flight propulsion systems and were conducted in 1977; the major technology development activity at GE and P&W began in 1978. The initial studies were updated periodically as the technology development progressed. These studies identified the advanced technologies needed for each engine component, which were then incorporated into the various engine components and evaluated in bench, subcomponent and, in most cases, full-scale component tests. As a final verification of the technology, the original plan was that the advanced engine components were to be evaluated in a real engine environment through both core (compressor, combustor, and turbine) and ICLS (integrated core/low-spool, or core plus low-spool) tests. However, as a result of program budget reductions, the planned P&W core and ICLS tests were deleted from the program in 1982 and replaced with less costly additional component technology efforts. The GE core and ICLS tests were completed. At the conclusion of the component and systems integration technology efforts, it was then possible to assess the viability of the advanced technologies and the performance levels that could be attained in the flight propulsion systems.

E^3 Technology Advancements

The accomplishments of the program, including both the component technology development and systems integration efforts, are presented in this section for each of the engine designs.

General Electric

During the six-year program, all major advanced technology engine components were rig-tested prior to engine test. Over 2000 h of component rig testing were accumulated. Highlights of this effort follow.

Fan

A full-scale fan component test provided data on fan efficiency, stall margin, and blade vibratory responses. Eighty-two test hours were completed, including 14 intentional stalls. Stall margin was 2-4% over the 16% goal for the takeoff condition. Blade vibratory responses were low; 21% of design limit under normal operation and 50% during stall. Standard day efficiencies measured are shown in Table 3.

High-Pressure Compressor

Several hundred test hours were completed on three builds of the GE high-pressure compressor. These tests optimized aerodynamic design and variable geometry and included 230 intentional stalls for thorough performance and stall mapping. Takeoff stall margin was measured to be 21% with an efficiency of 0.849 at 35,000 ft, Mach 0.8, and maximum cruise. Airfoil vibratory responses were well within limits under all operating conditions, including stall.

Table 3 Standard day efficiencies

	35,000 ft, $M = 0.8$ Maximum cruise	Sea level static Takeoff
Fan bypass	0.892	0.893
Fan hub	0.895	0.898

Combustor

Both sector and full-annular, full-scale combustor rig testing of well over 300 h was completed. A circumferentially averaged temperature profile entering the turbine rotor during simulated high-power operation of

$$0.125\,(T_{\text{circ. avg. at a given radius}} - T_{\text{comb. inlet}})/T_{\text{comb. outlet}} - T_{\text{comb. inlet}})$$

was demonstrated. Goals for emissions of smoke, carbon monoxide (CO), and unburned hydrocarbons (H_xC_y) were bettered. While the challenging goal for oxides of nitrogen (NOx) was not achieved, the NOx levels attained were well within the more recently proposed EPA requirements. Transitioning from single- to dual-annular combustion was successfully demonstrated.

High-Pressure Turbine

Annular cascade and two-stage warm-air turbine rig testing involving well over 300 test hours was completed. All cooling flows were simulated during the high-pressure turbine rig tests, demonstrating an efficiency of 0.925 at standard day, 35,000 ft, Mach 0.8, maximum cruise. This efficiency is based on ideal turbine work that does not include the penalty associated with cooling flows.

Low-Pressure Turbine

Scale model rig tests of both a two-stage warm air turbine and a full five-stage warm air turbine totaled 374 test hours. A standard day, 35,000 ft, Mach 0.8, maximum cruise efficiency of 0.915 was demonstrated.

Nacelle and Mixer

Substantial model tests of various E^3 nacelles and mixers were conducted at NASA Langley. The results of these tests guided the nacelle and mixer designs later incorporated into the ICLS turbofan test vehicle.

Control System

Prior to both the core engine testing and the ICLS engine testing, the complete engine control system was thoroughly

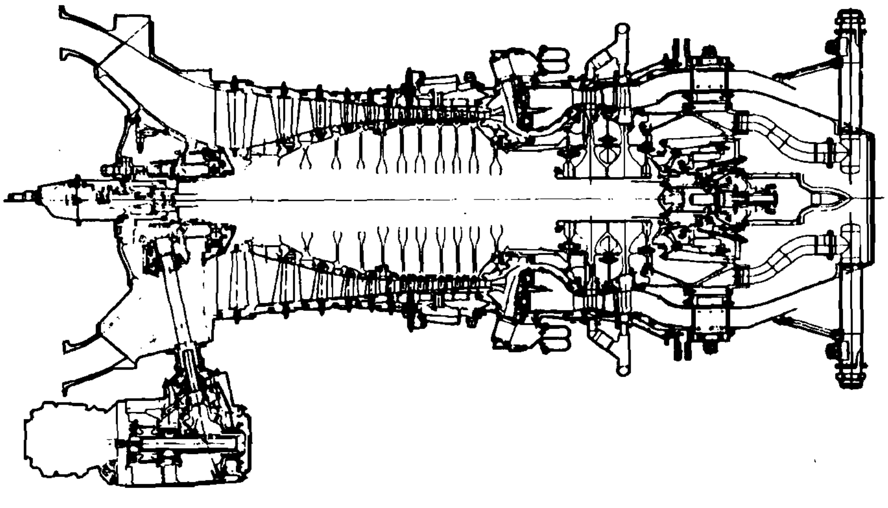


Fig. 4 General Electric core engine.

evaluated in a rig configuration. All controls and accessories were "powered up" and placed under FADEC control for evaluation of accuracy and repeatability of each variable. The control system later operated flawlessly during both core and ICLS testing.

Core Tests

The E^3 core, consisting of the high-pressure compressor, combustor, and high-pressure turbine, was assembled and tested to evaluate the overall core engine system prior to integration into the ICLS (turbofan) test vehicle. The core vehicle is illustrated in cross section in Fig. 4. Figure 5 shows the core engine prepared for test cell installation. Determination of overall system and individual component performance were the test objectives. The E^3 core test was quite successful; the scheduled 80-h test was completed in under 45 h with all test objectives accomplished. Over 1400 sensors provided more than 1 million parametric readings, which were fed into an automated data system for rapid analysis. Tests conducted included seal level and Ram inlet mechanical checkout, HPC stator optimization, active clearance control evaluation, windmilling characteristics, starting optimization, operating line migrations, and transient evaluations.

The ICLS 100% standard day physical rotor speed was exceeded and a compressor discharge pressure of over 302 psia at 100.4% corrected rotor speed was reached. There were no aeromechanical problems over the range of operation. Rotor dynamics were no problem. The engine starts were routinely accomplished in about 44 s with no bleed and no stalls. Active clearance controls were effective in achieving higher high-pressure compressor and high-pressure turbine test efficiencies: Measured increases in efficiency when the design clearance control flow was used were 0.6 and 1.2 points, respectively.

Overall performance was better than predicted. High-pressure compressor efficiency was up 0.8% relative to rig test results because of additional aerodynamic adjustments incorporated after rig test completion. High-pressure test efficiency was very close to that predicted based on rig tests. Transitioning the combustor from single- to dual-annular burning and back was accomplished without problems. Combustor emissions and smoke results were low, as shown in Tables 4 and 5.

ICLS Tests

The core engine, fan, low-pressure turbine, mixer, and nacelle were combined into the ICLS turbofan test vehicle and installed in an outdoor test facility at GE's Peebles, Ohio, test site. The test vehicle is illustrated in Figs. 6 and 7.

The ICLS test was the final verification of the component and system designs previously tested and now incorporated into a full-scale turbofan propulsion package. All aspects of the E^3 propulsion package were evaluated: mechanical and aeromechanical characteristics and integrity, performance, acoustics, engine control, rapid accelerations and decelerations, and starting. No aeromechanical or mechanical problems were found over the full engine operating range, up to the maximum thrust achieved: 37,415 lb.

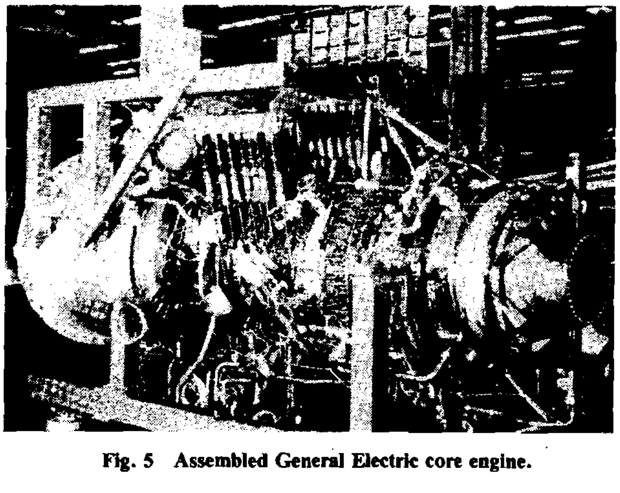


Fig. 5 Assembled General Electric core engine.

The measured sea level static takeoff SFC is shown in Fig. 8. These measured data were taken with the engine in full research test configuration—heavily instrumented, real inlet and exhaust, nonoptimized flow function matching, and overlimits nacelle leakage (nonflight design). An SFC of 0.326 at 36,500 lb of thrust was achieved, representing the lowest SFC ever demonstrated for a high-bypass-ratio turbofan engine. Analytically correcting the data in Fig. 8 for instrumentation removal, ideal inlet, and reduced nacelle leakage for a flight design and rematching flow functions would improve the measured SFC by several percentage points.

Starting was accomplished in 45 s. There were no stalls and bleed was not used. The control system operated flawlessly. Bursts from 10-90% thrust were made in 5s with no turbine temperature overshoot. All overrides held, FICA control strategy was demonstrated, and accurate variable stator and speed control were demonstrated, as was FADEC control of clearances.

Fan performance paralleled that of the fan rig test with stresses and efficiencies being very close to those of the rig test. Core performance was also very close to that demonstrated during the core vehicle test.

The low-pressure turbine, in a full-scale test for the first time, performed very close to prediction. Mechanical integrity was excellent over the full range of operation, with blade vibratory stresses never exceeding 25% of limits. All temperatures were within limits and close to predictions. Active clearance control was effective.

Mixer performance was better than predicted, achieving a mixing effectiveness of 78% at 0.64% pressure loss for a 2.4% SFC improvement at the standard day, 35,000 ft, Mach 0.8 maximum cruise condition. Figure 9 shows the analytically projected aircraft noise levels of E^3-powered aircraft, based on engine acoustic measurements, compared to measurements made on existing aircraft. As can be seen, two- and three-engine E^3-powered aircraft meet the FAA requirements with at least a 2-dB margin.

Altitude performance projections of the E^3 ICLS sea level static data were made using data from component tests covering a range of altitude, corrected speeds, Reynolds numbers, etc. This projection indicated that the 35,000-ft, Mach 0.8, standard day, uninstalled maximum cruise SFC would be 0.55, producing a SFC reduction 1.5 percentage points greater than the program goal of a 12% decrease in SFC.

In summary, the GE program produced the following results relative to the original goals of the program. In terms

Table 4 Combustor emission results vs goals

	Emission index in g/k of fuel		
	CO	H_xC_y	NO_x
Required to meet goal	20.75 at idle	2.75 at idle	17.50 at T/O
Measured (Corrected to turbofan cycle)	19.13	1.45	20.1

Table 5 Smoke results vs goals

	SAE smoke number	
Combustor inlet temp., °F	Goal	Measured
370	20	2.2
425	20	2.1
700	20	0.6

of fuel savings, results from component and ICLS (full engine) tests indicate that the fuel savings goal of 12% was exceeded with experimental hardware. Fully developed engines based on E^3 technology would show even greater fuel savings. Attainment of the fuel savings goal along with the flight propulsion system weight estimates also indicate that the goal of a 5% reduction in direct operating costs should be met when applied to various transport aircraft. In terms of environmental program goals, projection of ICLS ground test noise measurements to flight conditions shows that all FAA noise requirements could be attained with at least several dB margin for both two- and three-engine aircraft. Also, emissions measurements indicate that all the original EPA goals were met except for NOx. However, the NOx levels attained are lower than the more recently proposed EPA requirements.

Pratt & Whitney

Pratt & Whitney's Energy Efficient Engine Program approached the challenge of reducing engine fuel usage and operating costs by undertaking an intensive development of component technologies. The technology demonstration plan addressed verification of new fuel saving technologies for modern aircraft engines into the late 1980s. Effort focused on the main sections of the engine, with particular emphasis on the fan and core engine components.

Well over 4000 h of testing was completed in a number of component technology efforts. The following presents some of the highlights and accomplishments of the NASA/Pratt & Whitney E^3 Program.

Fan

Seale model rig tests, featuring a rotor bladed with solid titanium shroudless airfoils, were conducted to enhance development of hollow blade aerostructural analysis and design methodology. In these tests, 270 test hours were completed, including 28 intentional surges. Results showed dynamic stresses to be well within acceptable levels at all speeds. Vibratory stresses were low and comparable to those of shrouded blades. Testing corroborated shroudless blade untwist and tip gap predictions, permitting accurate aerodynamic definition of tip gap and tip stagger angle. When the shroudless blade model test data were compared to model test data from a high-performance shrouded blade, the

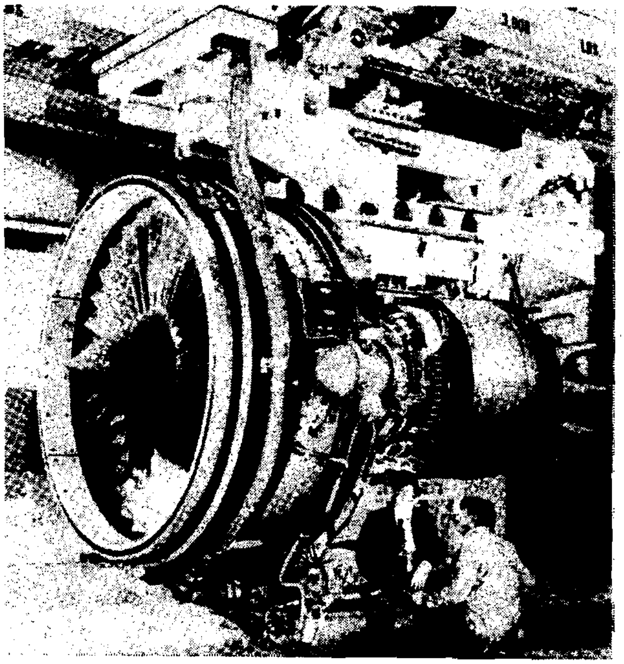


Fig. 6 General Electric energy efficient engine.

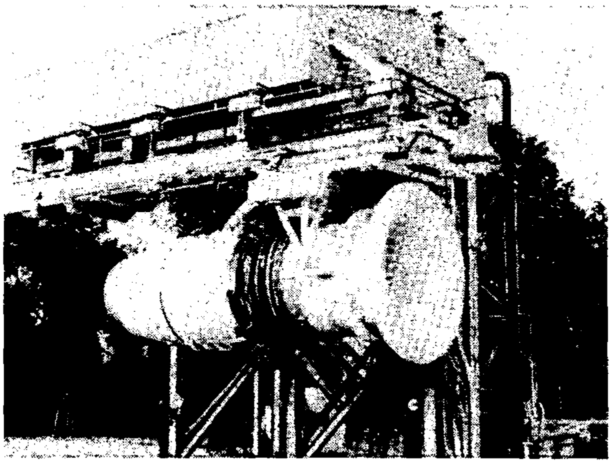


Fig. 7 General Electric energy efficient engine ready for test.

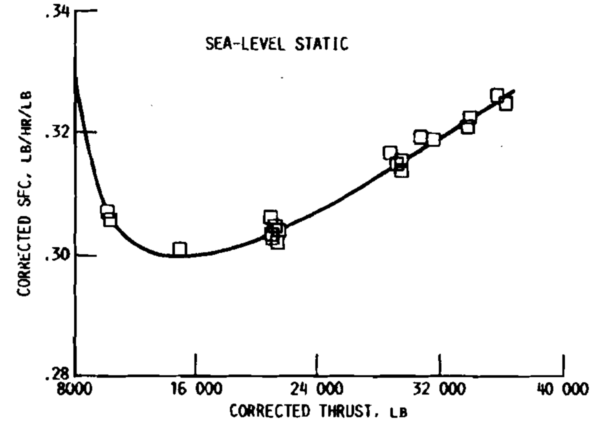


Fig. 8 Measured General Electric energy efficient engine specific fuel consumption.

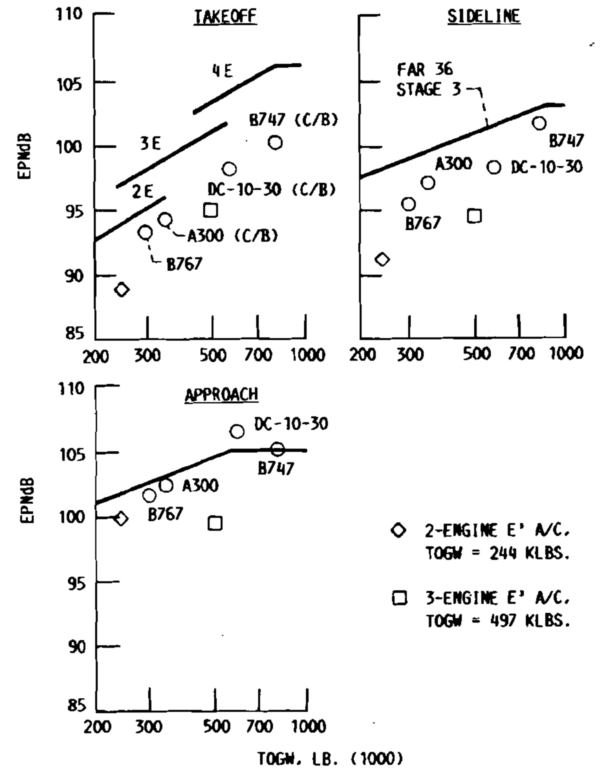
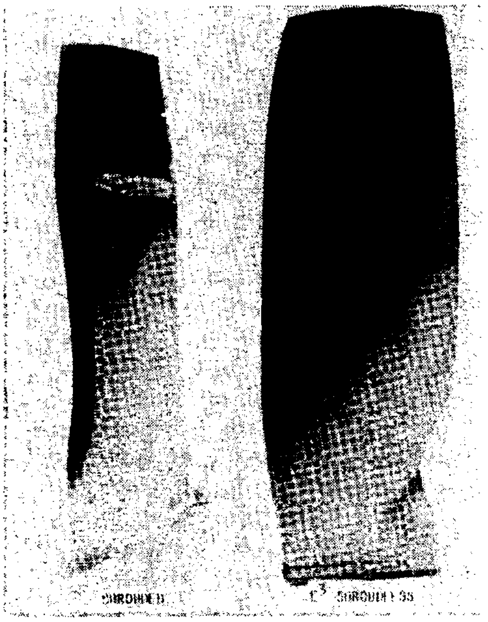


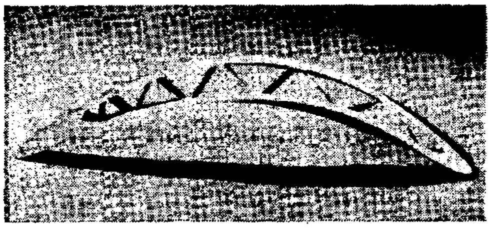
Fig. 9 Comparison of aircraft noise levels.

shroudless configuration was two percentage points higher in efficiency (Fig. 10c), of which 1.5 percentage points are attributed to shroud removal. This efficiency gain exceeded the 1.5 percentage point goal established for the scale model fan. During the test program, over 300 million velocity signals were measured and recorded using laser Doppler velocimetry (LDV) to document discrete flow velocities between blade elements and in the downstream wakes. These data were used to define intrablade shock positions as well as to calculate work, flowfield losses, blockage, and static pressure.

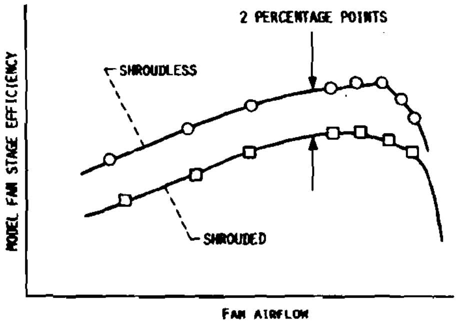
Evaluation of several approaches to fabricating hollow fan blades was also conducted. Thirteen full-scale blades were fabricated and structural integrity tests were conducted on blade specimens representing two superplastic forming/diffusion bonding (SPF/DB) construction techniques investigated in the program. Figures 10a and 10b illustrate the three-piece SPF/DB construction technique. These tests identified elements in the fabrication process that will require further development. Photoelastic modeling was successfully utilized to document stress distributions in candidate blade/disk attachment schemes. These test data will provide a sound data base for future applications.



a) Full-scale blades.



b) Cross section of 3-piece SPF/DB blades.



c) Aerodynamic performance.

Fig. 10 Results of shroudless, hollow fan technology.

Compressor

Efficiency and performance potential of the P&W high-pressure compressor were demonstrated during an extensive component test program comprising two builds. Over 1800 data points were acquired and 87 surges were accumulated during 538 h of testing. Compressor operation was excellent. Measured vibratory responses were within acceptable limits. A stator vane schedule was developed that provided the correct speed, airflow, and pressure relationships; this yielded an adjusted adiabatic efficiency of 85.7% at the aerodynamic design point compared to a goal of 86.5% after the two rig tests. A compressor performance map is shown in Fig. 11. A significant highlight of this test program was the successful demonstration of the feasibility of using LDV as a non-flow-intrusive method for measuring flow angle and velocity in the front, mid, and rear stages. Typical results are illustrated in Fig. 12. Quantifying these two parameters provided comprehensive insight into aerodynamic blockage, which is one of the primary controlling parameters in compressor aerodynamic design.

Combustor

Combustor testing was conducted in both sector and full-annular, full-scale rigs. Sector rig testing comprised 26 rig

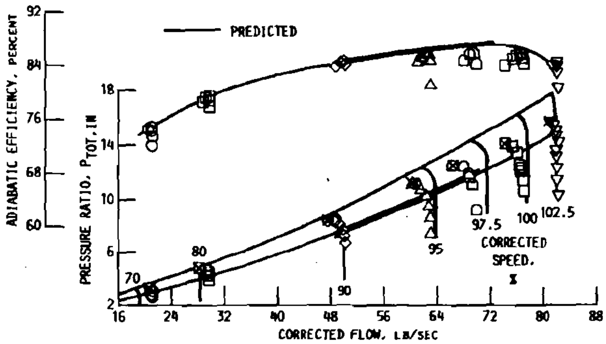


Fig. 11 Pratt & Whitney high-pressure compressor performance.

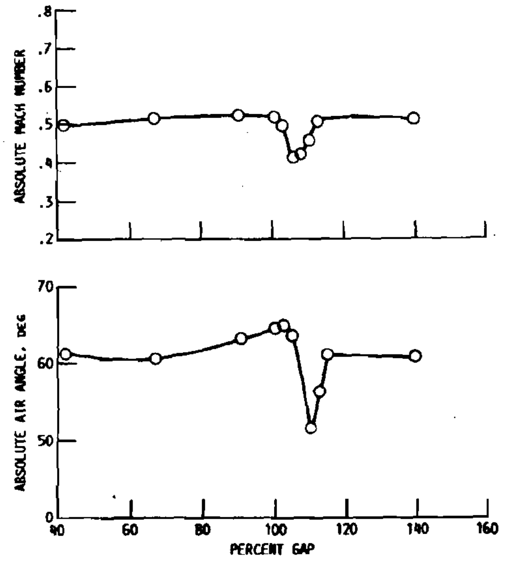
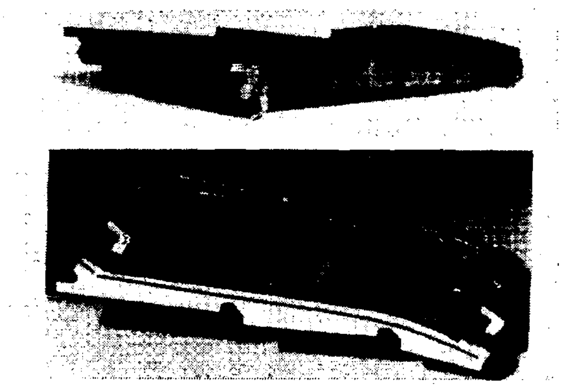
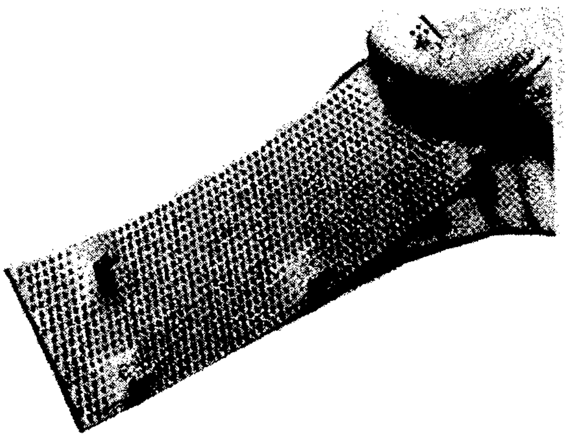


Fig. 12 Laser doppler velocimeter measurements behind ninth-stage stator (approximately midspan).

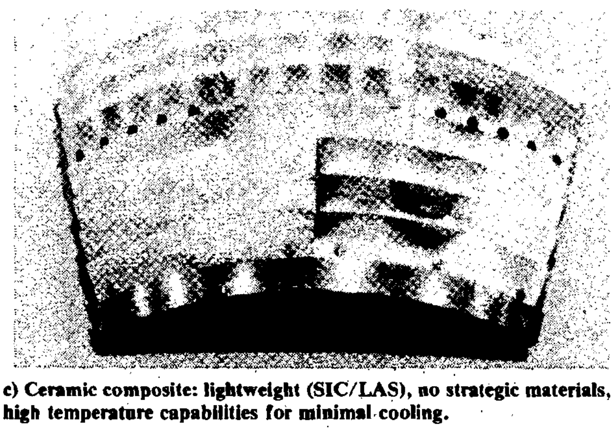
builds and 781 test hours. Full-annular rig testing comprised 27 test hours on one rig build with Counter Parallel Finwall® combustor liners. The sector rig tests were conducted to investigate diagnostically the structural integrity and performance associated with the combustor liner configurations shown in Fig. 13. Test results confirmed that significant improvements in combustor life can be achieved with cast metallic segments and improved cooling methods based on measured segment temperatures which were close to design levels. Ceramic composite materials were shown to have promise, but require further research and development. A pattern factor of 0.26 was demonstrated compared to an 0.37 goal. Pattern factor is defined as the maximum local outlet gas temperature minus combustor inlet temperature divided by average outlet temperature minus the inlet temperature. Goals for emissions of smoke, CO, and unburned hydrocarbons were comfortably exceeded. Demonstrated levels of NOx were slightly in excess of the stringent program goals, but well within recently proposed EPA requirements.



a) Counter Parallel Finwall®: turbine alloy materials, improved film and convective cooling, machined internal passages and edges.



b) Pin-fin improved convective cooling, as cast parts for minimal machining, approximates sheet-metal liner weights.



c) Ceramic composite: lightweight (SIC/LAS), no strategic materials, high temperature capabilities for minimal cooling.

Fig. 13 Combustor segment concepts investigated.

High-Pressure Turbine

Transonic blade and subsonic vane design benefits were demonstrated in both an uncooled rig test program comprising 710 h and a cooled-component rig test comprising 215 test hours. Annular vane cascade and full-stage tests were conducted in both rig programs. Stage reaction levels of 35 and 43% were investigated in the uncooled rig program and results showed the higher reaction level to improve stage efficiency. As shown in Fig. 14, these tests further confirmed the benefits of the additional technological advances incorporated into this unique single-stage design by exceeding the flight propulsion system efficiency goal.

Exhaust Mixer

A three-phase mixer model test program was conducted, using one-tenth scale mixer/tailpipe models. Aggressive goals were set—85% mixing efficiency, pressure losses approaching skin friction, and minimum mixer/tailpipe length. The parameters investigated included mixer lobe length, lobe number, mixer discharge plane orientation, lobe scalloping, duct stream penetration, tailpipe length, and residual swirl. These parameters were successively refined as each phase of the model test program progressed. Major conclusions from this program were 1) an 18-lobe configuration provides best overall performance; 2) inlet swirl produces large mixer losses; 3) scalloping of lobes provides significant mixing improvements; 4) pylon fairings can be integrated with the mixer with little loss; 5) longer mixers have lower internal loss; and 6) duct stream upstream lobe fairings (or hoods) improve performance. The aggressive mixing goal was nearly met and substantial progress was made toward achieving the specific fuel consumption goal, as indicated in Fig. 15.

In summary, the results of the P&W component tests indicate that while some components exceeded the efficiency goals established for rig tests, others were modestly lower. Therefore, the overall fuel savings potential of the E^3 technology is expected to be very close to the 15% specific fuel consumption reduction originally estimated for a fully developed flight propulsion system. This would significantly exceed the program objective of a 12% improvement. Measurements of combustor emissions in a component test indicated that unburned HxCy, CO, and smoke levels were less than the program goals, while that for NOx was higher than the program goal. However, the measured NOx levels were much less than more recently proposed EPA requirements. Because of the very good component performance, the aircraft noise projections will not be materially affected; accordingly, the aircraft noise estimates made in the flight propulsion system studies would be unchanged. Finally, aircraft direct operating cost improvements of at least 5% are anticipated because of the very good performance obtained in component rig tests in conjunction with calculated engine weights based on component fabrication experience.

Concluding Remarks

The Energy Efficient Engine Program has demonstrated, through full engine and major component tests, the potential for significant improvements in the fuel economy of future aircraft propulsion systems. In addition, the environmental impact of engines based on this technology will be highly acceptable. Energy Efficient Engine component technology is currently being applied to a wide range of propulsion systems, and will continue to be used and provide economic dividends well into the 1990s.

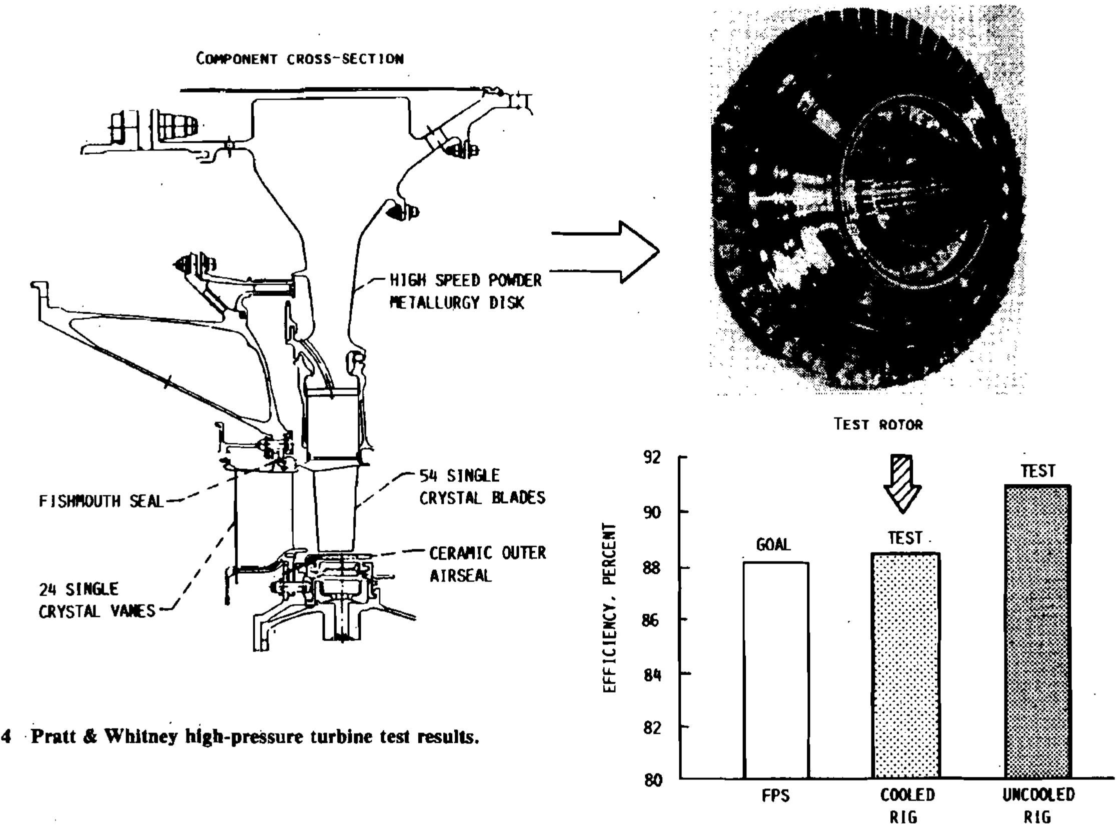


Fig. 14 Pratt & Whitney high-pressure turbine test results.

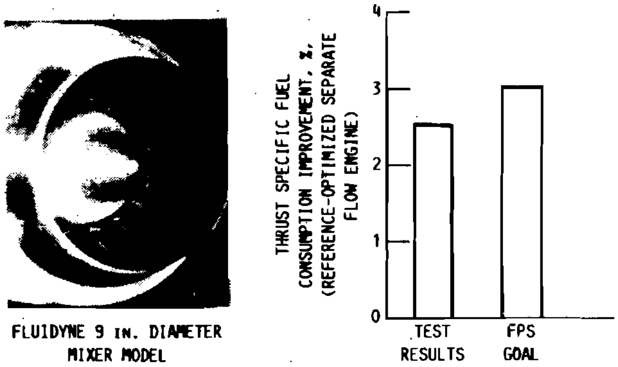


Fig. 15 Results of experimental mixer model research program.

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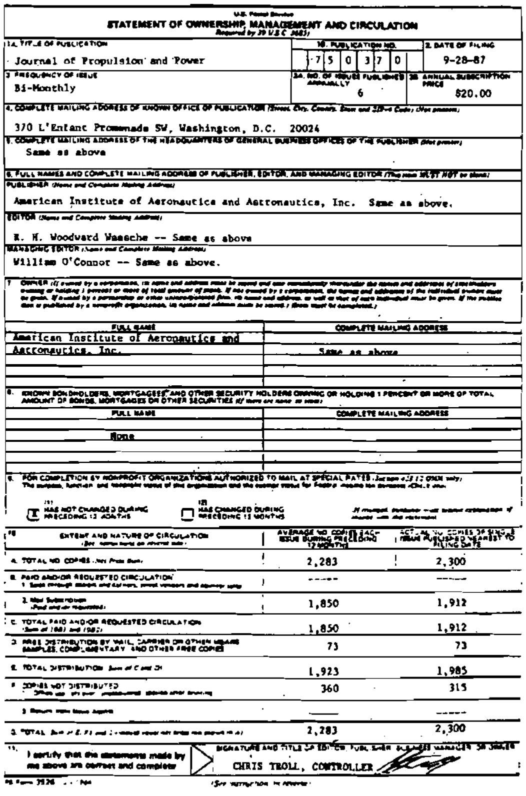

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