CF6 PERFORMANCE IMPROVEMENT

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SUMMARY

Potential CF6 engine performance improvements directed at reduced fuel consumption have been identified and screened relative to airline acceptability. The screening process was developed to provide evaluations of fuel savings and economic factors including return on investment and direct operating cost. In addition, assessments of development risk and production potential were made. Based on a ranking involving these factors, several promising concepts have been selected for full-scale development.

INTRODUCTION

The expanding national energy demand is outpacing domestic supply and is causing an increased U.S. dependence on foreign oil plus rising fuel prices. These events are significantly impacting the U.S. economy including both public and private sectors. A major user of petroleum products is the U.S. transportation system; the U.S. Government, with the support of private industry, has initiated programs directed at both the supply and demand aspects of the transportation problem for both the long and short range. With regard to the aviation industry, a promising short range approach to reduced fuel usage is improvement in the fuel efficiency of current aircraft engines. An evaluation of this approach has indicated that up to five percent reduction in fuel consumption, through both improved engine performance plus improved performance retention, may be possible starting in the early 1980's. To this end, the National Aeronautics and Space Administration is sponsoring programs directed at achieving the above goal.

The CF6 series of engines, developed by General Electric, includes the CF6-6 engine which powers the Douglas DC-10-10 aircraft and the CF6-50 engine (Figure 1) that powers the Boeing 747-200, Douglas DC-10-30, and Airbus Industrie A300 aircraft. These high bypass turbofan engines, at the time of their initial development, offered significant fuel savings over preceding engines. Subsequently, airline operational experience and technology advancements have indicated that further reductions in fuel consumption are possible. This paper presents the results to date of the NASA-sponsored CF6 Performance Improvement Program that is directed at these further reductions.

PROGRAM STRUCTURE

The CF6 Performance Improvement Program consists of the following three technical efforts:

- Feasibility analysis
- Development and evaluation - ground test
- In-service and flight testing

The Feasibility Analysis involves the identification of performance improvement and retention concepts, the development of an analytical screening procedure, evaluation and ranking of the concepts, and preparation of technology development plans and proposals for subsequent development. The second and third efforts are to provide for this subsequent development of the selected concepts prior to introduction into commercial airline service. Figure 2 traces the flow of a concept through this process.

Implementation of this program involves a complex series of interfaces as illustrated in Figure 3. General Electric placed subcontracts with Boeing and Douglas to provide for aircraft system evaluation and the economic analyses. They, in turn, have American and United Airlines as consultants to provide support for the economic evaluation as well as to comment on airline acceptance of the improvement concepts. In addition, Eastern and Pan American Airlines are functioning as NASA technical consultants under contract to NASA. This arrangement provides participation by all elements from the producer through the user and gives high assurance relative to the overall concept acceptability and the ultimate production introduction of selected concepts.

ANALYTICAL SCREENING PROCEDURE

An analytical screening procedure was developed to provide an evaluation and ranking of each concept relative to four criteria:

- Fuel savings
- Economic impact/airline acceptability
- Development risk
- Production potential

This analytical procedure is shown schematically in Figure 4. The first step in the process was the preliminary design of promising concepts by General Electric. The preliminary design proceeded to the point where the required engine impact data could be estimated. These data consisted of manufacturing costs and subsequent prices, weight changes, performance (thrust and SFC) at seven key aircraft mission points, maintenance data including material and labor, retrofit capability, and other impacts including noise and aircraft system power management. These data were submitted to Boeing and Douglas for evaluation in their respective aircraft. This evaluation included the determination of reduction in fuel consumption for three mission profiles which were based on data supplied by American and United Airlines. Figure 5 shows a typical mission profile. In lieu of a complete route analysis, three representative missions were selected for each aircraft to determine potential airline fuel savings achieved with each engine improvement. Current airline usage for the study aircraft was determined from the August 1976 Official Airline Guide. Departures for each airplane were distributed by stage length. Then this distribution of total departures was divided into three equally weighted groups, and the average stage lengths of each group were selected as the three representative missions (Figure 6). Preliminary aircraft design studies to assess any required aircraft changes were performed, and the resulting data were combined with the General Electric inputs and "flown" in the standard missions to determine improvements in aircraft system impacts for each stage length. Data from this effort included airplane performance changes (range, payload, block fuel, field length, and climb performance), operating empty weight, maintenance cost changes, prices, and other impacts. These data plus engine maintenance costs then were used to determine incremental direct operating costs (DOC), return on investment (ROI), and payback periods. The economic data for each concept were determined for the three stage lengths, three fuel prices, and all applicable aircraft and retrofit options as appropriate. These data then were submitted to United and American for evaluation. The final step consisted of evaluation of the foregoing data in terms of total impact and ranking of concepts considering airline comments plus technical and other risks, production potential, and other factors provided by General Electric and the other contributors as appropriate.

ECONOMIC ANALYSIS

The first step in the determination of the economic impact involved the calculation of the incremental net yearly savings which included aircraft fuel, insurance and maintenance costs, and the cash outlay which included the engine and aircraft modification costs, additional spares inventory, and installation costs. The payback period is simply the initial cash outlay divided by the net yearly savings.

The return on investment (ROI) is the discount rate at which the net present value of future cash inflows equals the initial cash outlay. This is depicted in the following equation:

$$\sum_{N=1}^{\text{Useful Life}} \frac{\text{Cash In}}{(1 + \text{ROI})^{N}} = \text{Cash Out} \qquad (1)$$

Significant features of this approach include the following:

- Based on cash flow of engine modification and annual savings
- Recognizes time value of money

- Relatable to any airlines cost of capital to show how much such a modification is above or below the "hurdle rate"

- Cash flow is in constant dollars to assure consistent comparison of different modifications

- Effect of inflation is contained in airline ROI "hurdle rate"

All ROI data were determined on a before-tax basis; however, before- and after-tax relationships were calculated for basic assumptions of depreciation and tax rate to permit evaluation on an after-tax basis.

HIGH POTENTIAL CONCEPTS

In the intial concept identification phase, 62 improvement ideas were identified. Initial screening based on qualitative engineering judgement reduced this list to 23 items which then were subjected to the screening process defined above. Some of the more promising concepts, that illustrate the extent and type of improvements studied, are presented below.

Improved Fan

This improvement concept involves the aerodynamic redesign of the current CF6 fan blade principally in the area of the midspan shroud. This shroud, which is dictated by vibratory stress requirements, results in performance losses. The redesign involves repositioning the shroud (see Figure 7) in such a manner as to minimize the aerodynamic losses. Coupled with this change is a change in the fan operating line to shift the fan cruise operating point to a region of higher efficiency. This is accomplished through a modest increase in fan exhaust nozzle area. Another item also included in this overall improvement concept is the reduction in fan-blade-to-casing clearance. The addition of a stiffener ring (see Figure 8) to the case was found to change system vibratory response such that the clearances could be reduced without undesirable vibratory interaction between the rotor and the stator.

The net result of the above items is a predicted 1.8% reduction in specific fuel consumption (SFC) for the CF6-50 and a 1.6% reduction for the

CF6-6 engines. A modest engine weight increase of 13 kilograms is required. One other favorable effect is a maintenance cost reduction (lower DOC) resulting from the lower turbine gas temperatures that accompany the improved engine performance. The thrust setting parameter of the CF6 engines is fan speed. Because the speed-airflow characteristics of the new fan are different from the current fan, changes to aircraft power management procedures are required.

The predicted aircraft fuel savings and economic data for this and the following concepts are presented in a later section.

New Front Mount

The CF6 engine thrust loads are transferred to the aircraft pylon through a mount located at the junction of the fan frame and the top front end of the high pressure compressor case. Because of the displacement of this mount, relative to the centerline of the engine, a bending moment is induced in the engine and is reacted through radial force vectors at the front and rear mounts. This bending moment results in local inward deflections of the compressor case at the top 12-o'clock position. This deflection then establishes the maximum rotor blade tip diameter for each rotor stage that can be produced without rotor-casing rubs. Analysis and static load tests indicated that the modification of the front mount through the addition of tangential links (Figure 9) would better distribute the loads and reduce the local deflection to levels more closely approaching the deflection produced from simple beam bending without the local 12-o'clock distortion (see Figure 10). This reduction in deflection then permits increases in rotor blade diameters with a net reduction in clearance and a commensurate improvement in compressor efficiency and engine sfc reduction of approximately 0.3%.

Improved High Pressure Turbine

The core of the CF6-6 engine was initially developed over ten years ago for the USAF TF39 engine which powers the C5. There have been subsequent technology advancements especially in the high pressure turbine. Figure 11 presents a proposed new turbine for the CF6-6 engine that is predicted to provide a sfc reduction of up to 1.3%, improved performance retention and reliability, and a significant reduction in maintenance cost.

The key features of this turbine include single-shank HPT blades that have optimized cooling both initially and after long-time operation, revised exit swirl to better match the orientation of the frame located downstream of the turbine, improved rotor/stator casing clearance match, and other aerodynamic and cooling system refinements. Because of the reduction in direct operating cost, this concept is predicted to be very attractive even for an attrition retrofit into current in-service engines.

Short Core Exhaust

There currently are two core exhaust systems in operational service on the CF6: (1) a combination core engine reverser/nozzle system and (2) a simple nozzle having the same flow path contour but no reverser capability. Parametric nacelle model testing, conducted by General Electric and Douglas, indicates that installed CF6-50 engine performance could be improved through a recontour of the core nacelle aft of the fan exhaust and a shortening of the core engine exhaust system. The flow path contours for the proposed new exhaust are compared to the current system in Figure 12. Improved nozzle performance is accrued through reduced internal and external skin friction drag and reduced wing/nacelle interference drag. This is predicted to result in a sfc reduction of one to three percent depending on the final reduction in interference drag.

High Pressure Turbine Roundness and Clearance Control

Clearance control in all the turbomachinery components is required for minimum fuel consumption, the high pressure turbine being the most critical component. The problem of clearance control/retention is compounded because of the significant thermal growths that accompany the high temperature of the turbine components. The improvement concept described herein (See Figure 13) is directed at achieving an improved thermal response of the stator system such that reduced rotor/stator clearances can be maintained during engine steady-state cruise operation while still permitting full engine transient operability. Also included in this item are improvements in the turbine midframe located aft of the turbine. This strutted frame serves as the aft engine mount as well as being the aft bearing support for the high pressure rotor. Mount loads plus nonuniform start temperatures cause asymmetric radial deflections that are transmitted to the turbine stator. These deflections result in the increased turbine clearances relative to the ideal case of a perfectly round stator system. The proposed improvements would further isolate the stator shrouds from the local frame deflections and would also produce a better radial growth match between the frame struts to improve roundness. The net result would permit an overall decrease in turbine clearance with an increase in efficiency and a decrease in engine sfc of approximately 0.3% for new engines and a retention improvement of an additional 0.3%.

Active Turbine Thermal Response

This improvement concept is intended to achieve further high pressure turbine clearance reduction at cruise power settings. Generally, the minimum clearance between the rotor blades and stator occurs at the high engine power settings; however, the clearance increases for the lower cruise power condition because of reduced disk centrifugal growth and rotor/stator thermal growth differences. Passive techniques involving improved rotor/stator growth matching can provide clearance reduction, but there are limitations.

One potential solution is to provide variable source/temperature cooling air to the turbine stator that is controlled as a function of engine power setting. Thus lower temperature air can be supplied at cruise to reduce the stator temperature effecting a clearance reduction. This concept (Figure 14) is predicted to produce a cruise sfc reduction of approximately 0.4%.

Cabin Air Recirculation

One means of reducing engine fuel consumption is the lowering of the power or bleed air extractions required for operation of the aircraft. Currently, the cabin air environmental system on the DC-10 provides air direct to the cabin area. By adding a recirculation system involving filters and fans (Figure 15), the fresh air required from the refrigeration packs can be reduced by about 40% while still maintaining adequate passenger comfort. This results in a potential engine sfc reduction of approximately 0.7%.

ECONOMIC ANALYSIS RESULTS

An example of the economic analysis is provided by Table 1, which shows the improved fan annual savings, ROI, and payback period for each aircraft at the three stage lengths and median fuel price. ROI and payback data also are included for both attrition and campaign retrofit replacement as well as new engines. It readily can be observed that the fan improvement concept is very attractive for both new engine and attrition replacement introduction. Retrofit with full scrappage of replaced parts only appears attractive for the longer stage lengths. Table 2 presents a summary of the sfc savings, and Table 3 presents the economic analyses for the concepts described above under the median conditions of stage length and fuel price.

CONCEPT COMPARISON

Figure 16 shows one of the comparisons used in concept ranking, in addition to tabulations similar to Table 2. In this comparison, yearly aircraft fuel savings versus payback period for the median range and fuel price was depicted. The improved fan, which has been identified, has the highest yearly fuel savings. Also identified are the other concepts described earlier. The shaded region shows the range of savings for the Douglas DC-10-10 and the longer-range Boeing 747-200. In addition to the quantitative economic and fuel saving comparisons, the concepts also were ranked on the basis of development risk. Finally (using General Electric market forecasts, service introduction, and retrofit estimates), total fuel savings for the 1980-1990 time period were predicted.

TECHNOLOGY DEVELOPMENT

The foregoing constitutes the Feasibility Analysis. The next step in the Performance Improvement Program is that of development and evaluation of the most promising concepts. The improved fan has been selected by NASA for development. The fan development program, which is typical of other concepts, includes engineering, component tests, and full-scale engine noise, performance endurance, and crosswind stress testing. These programs are designed to provide the technical confidence needed prior to the certification and production introduction phases.

CONCLUDING REMARKS

The Feasibility Analysis program has been very effective in the identification and evaluation of high potential improvement concepts. Further, the Feasibility Analysis has suggested additional improvements beyond those evaluated under this program.

NASA participation in the development of performance improvement concepts has served as a catalyst for the initiation of General Electric performance improvement programs and is resulting in the accelerated development of concepts with a higher probability of ultimate airline service introduction. The concepts scheduled for development programs initiated to date plus those being evaluated are expected to produce a very measurable and worthwhile fuel savings in the 1980's and beyond.

TABLE 1
Fan Economic Analysis Data
Median Fuel Price

Aircraft	Stage Length km	St. Mi.	ΔDOC* Dollars	ROI/Payback %/Years New	Attrition	Campaign
B747-200	772	480	-14,800	74/1.4	36/2.4	—
	3459	2150	-24,800	123/0.8	67/1.5	0/7.0
	6194	3850	-49,100	244/0.4	136/0.7	21/3.5
DC-10-10	634	400	-16,200	46/2.2	25/3.2	—
	1689	1050	-23,400	67/1.5	42/2.2	—
	3701	2300	-26,400	75/1.3	48/1.9	—
DC-10-30	805	500	-16,900	48/2.1	27/3.0	—
	2735	1700	-29,600	85/1.2	55/1.7	1/6.7
	6275	3900	-57,400	164/0.6	112/0.9	23/3.4

* 1977 Dollars

* Fuel Price DC-10-10, B747-200 — $.12/liter ($.45/Gallon); DC-10-30 — $.15/liter ($.55/Gallon)

TABLE 2
High Potential Concepts
SFC Improvements

Item	Potential ΔSFC @ Cruise — % CF6-6	CF6-50
Improved Fan	-1.6	-1.8
Short Core Exhaust	—	-1.0 to -3.0
Improved HPT	-1.3	—
New Front Mount	-0.3	-0.3
HPT Roundness/ Clearance Control	—	-0.3
Active HPT Thermal Response	-0.4	-0.4
Cabin Air Recirculation	-0.7	-0.7

TABLE 3
Economic Analysis Comparison
High Potential Concepts
Median Stage Length and Fuel Price

	ROI %*	Payback Years*
Improved Fan	67/85/123	1.5/1.2/0.8
Short core Exhaust	-/-/-	-/-/-
Improved HPT	600/-/-	0.2/-/-
New Front Mount	165/201/166	0.6/0.5/0/6
HPT Roundness/ Clearance Control	-/145/111	-/0.7/0.9
Active HPT Thermal Response	10/21/-	7.7/4.4/-
Cabin Air Recirculation	64/87/-	1.6/1.2/-

*DC-10-10/DC - 10-30/747-200

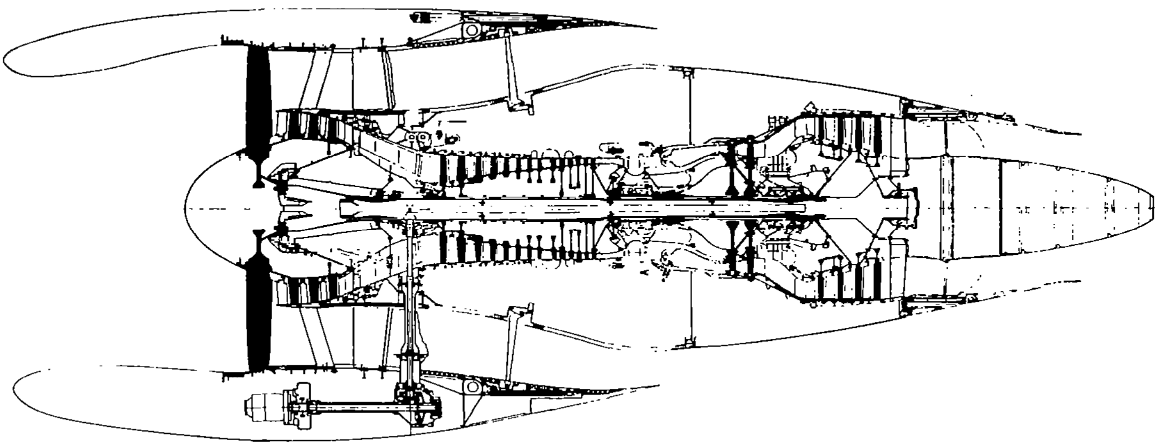

Figure 1.- CF6-50 engine cross section.

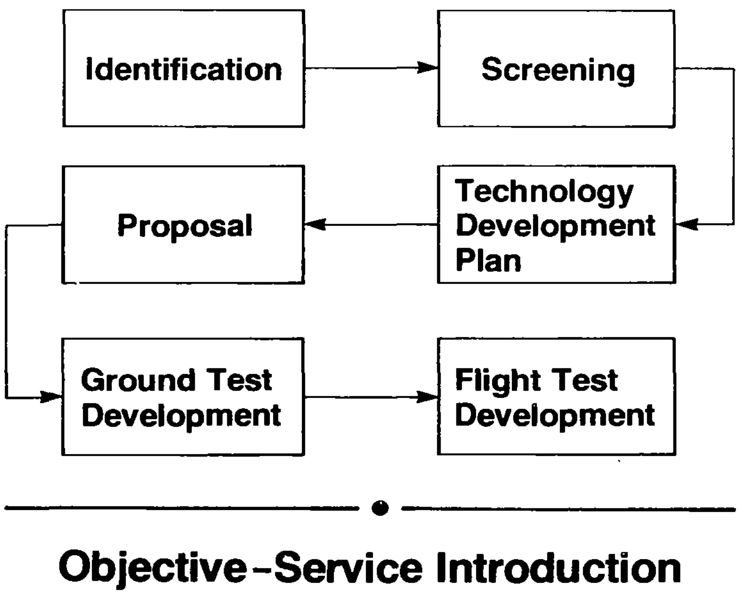

Figure 2.- Concept flow chart.

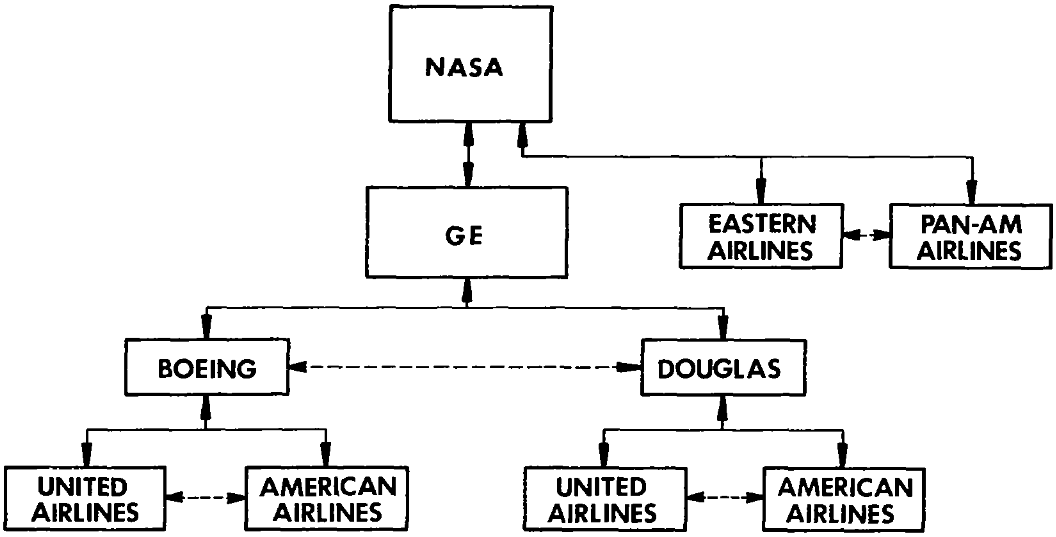

Figure 3.- CF6 jet engine performance improvement program channels of interface.

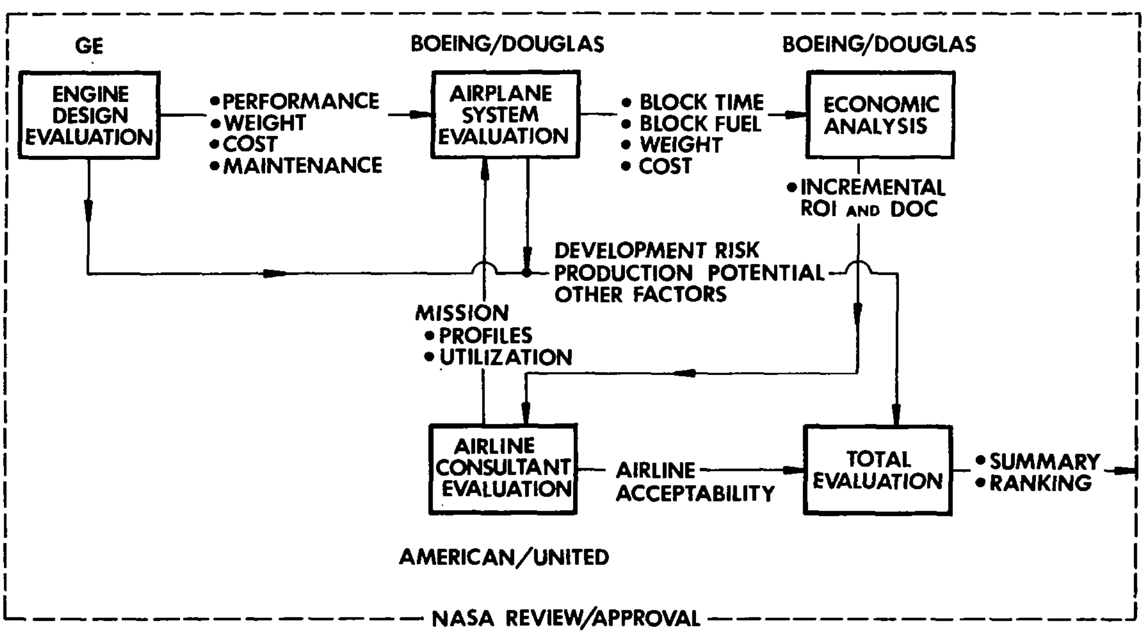

Figure 4.- Analytical procedure.

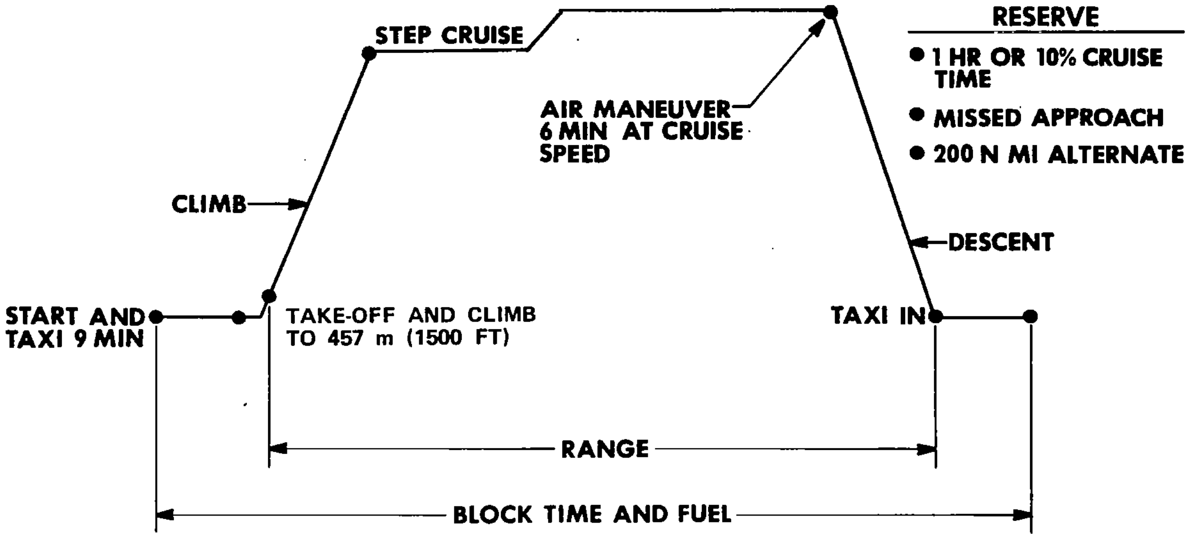

Figure 5.- Mission profile.

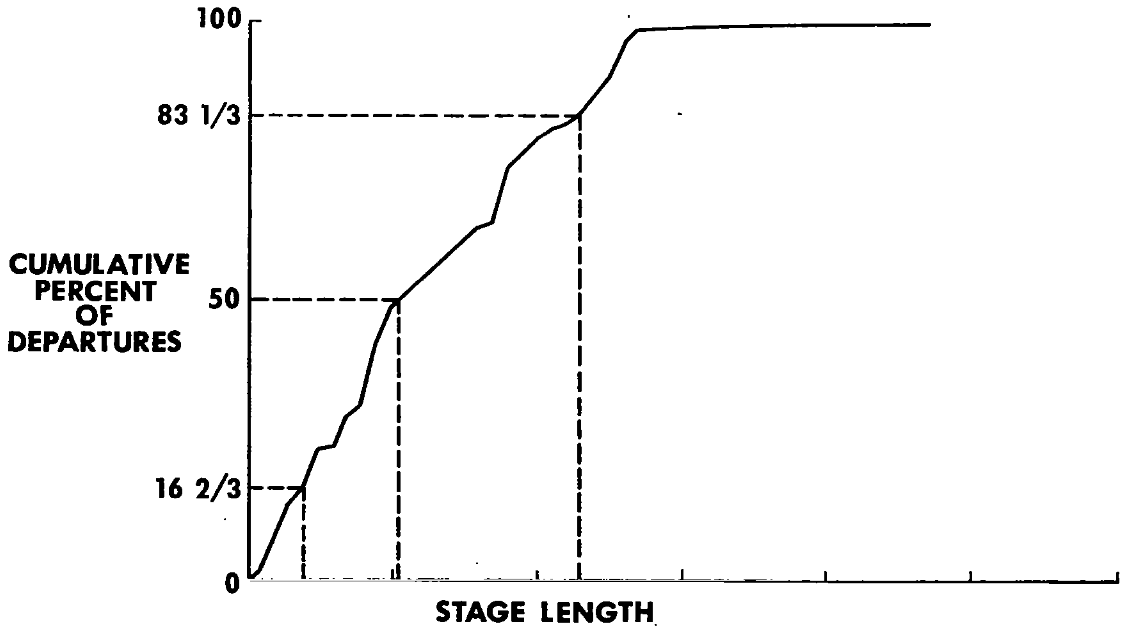

Figure 6.- Aircraft departures.

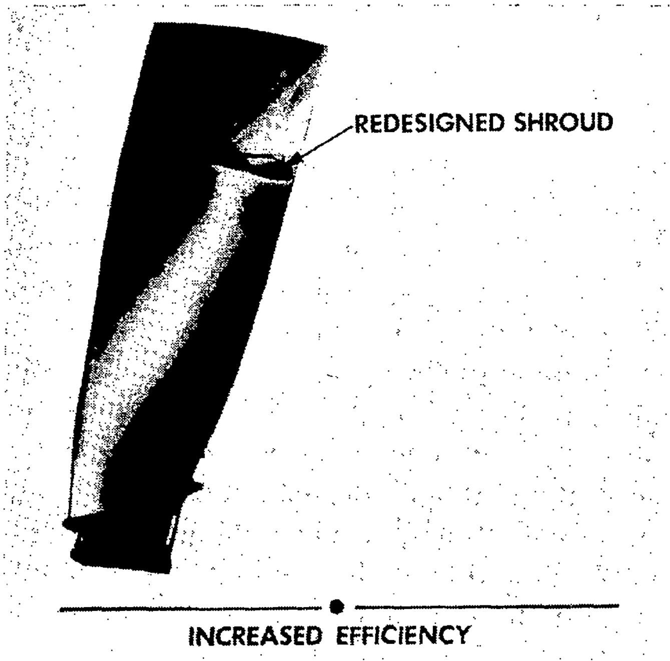

Figure 7.- New fan blade.

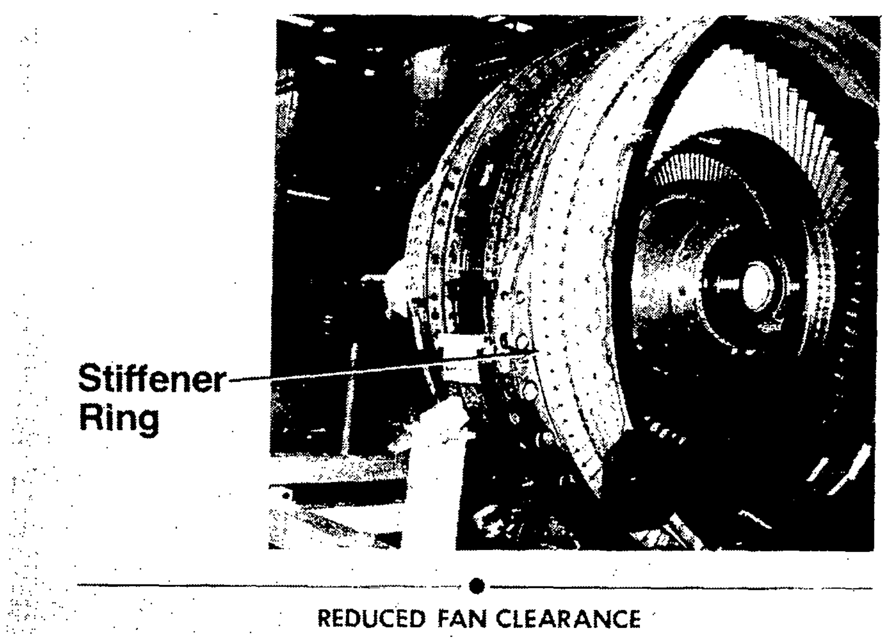

Figure 8.- Fan case stiffener.

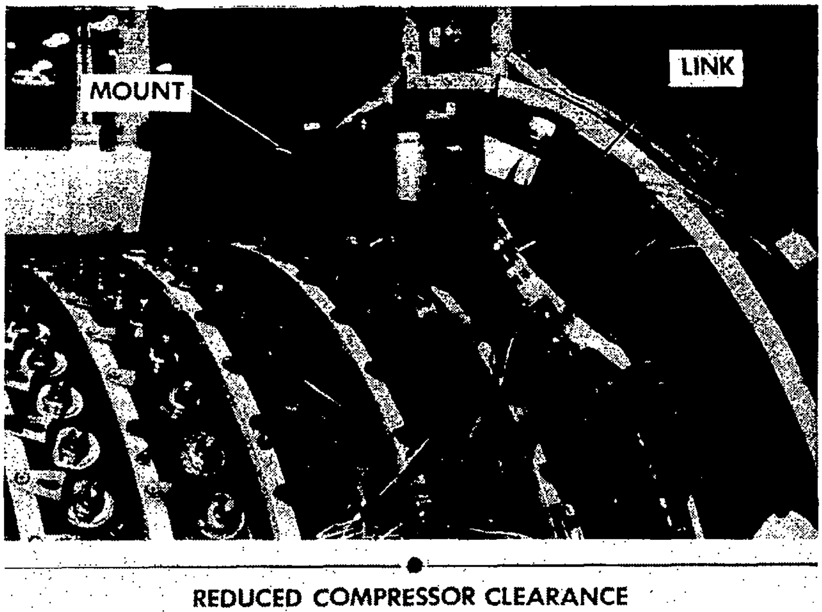

Figure 9.- New front mount.

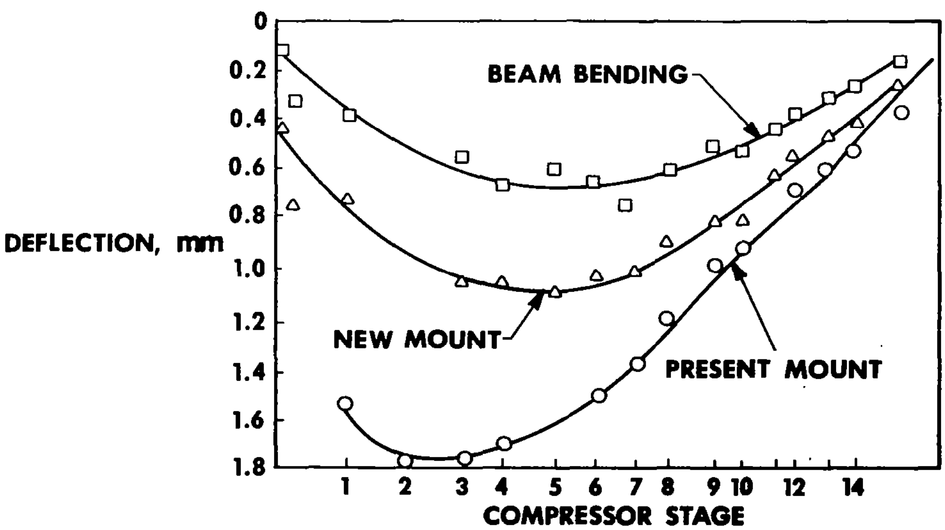

Figure 10.- Mount radial deflection comparison.
12 o'clock position; take-off/rotation.

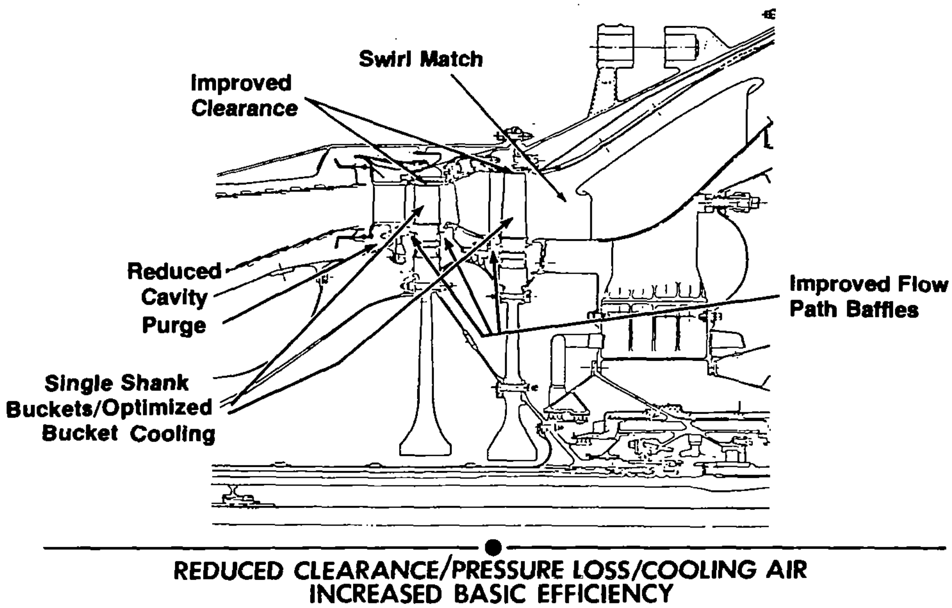

Figure 11.- Improved high pressure turbine design.

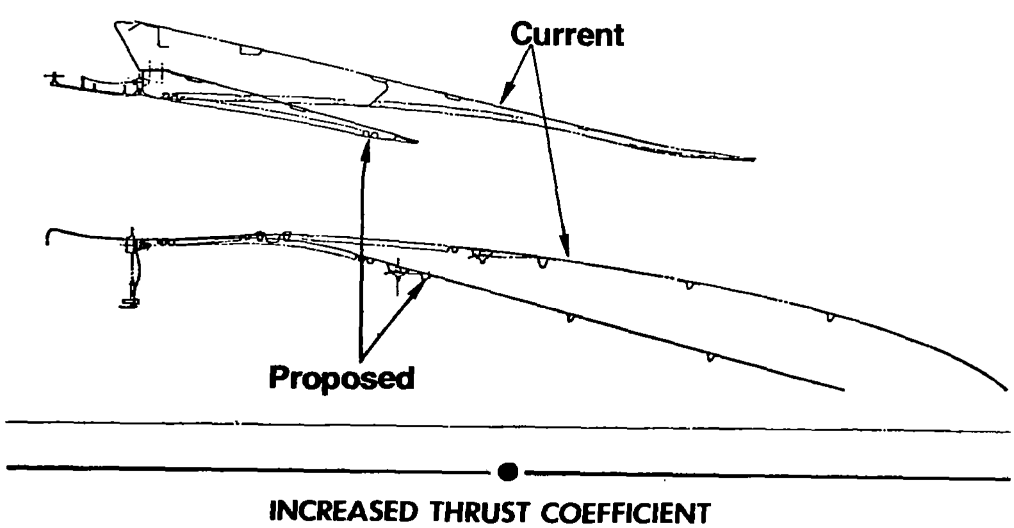

Figure 12.- Flow path contours for short core nozzle.

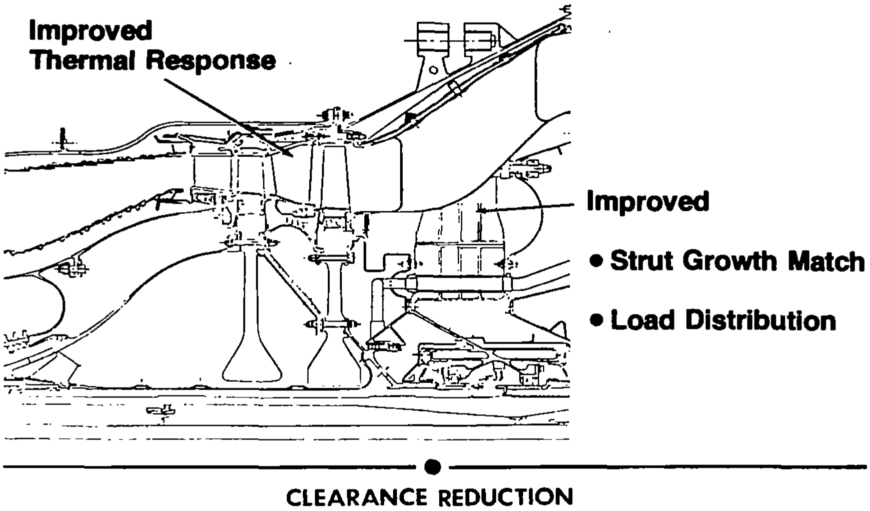

Figure 13.- High pressure turbine roundness and clearance control.

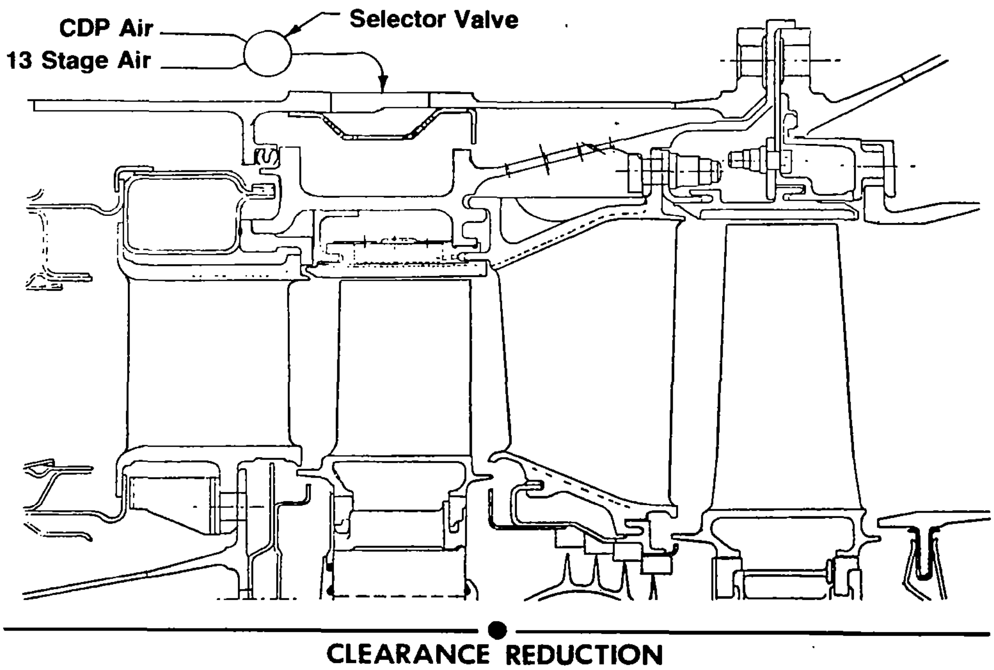

Figure 14.- Active thermal response variable cooling air.

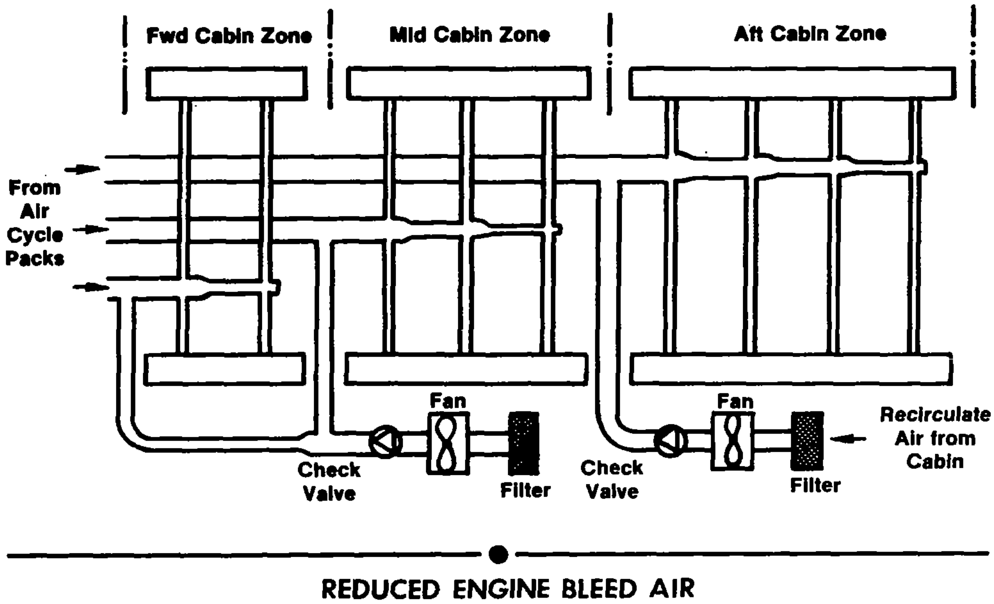

Figure 15.- Cabin air recirculation system.

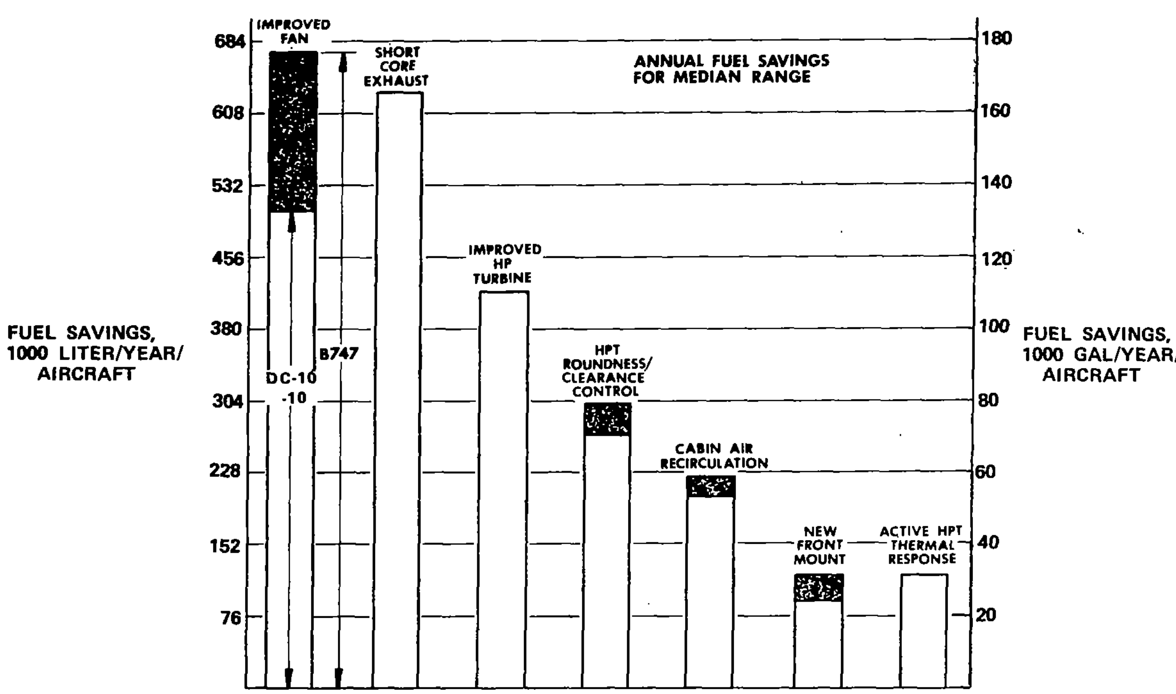

Figure 16.- Concept comparison.