ENERGY EFFICIENT ENGINE PRELIMINARY DESIGN AND INTEGRATION STUDIES

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SUMMARY

A NASA sponsored study to determine the characteristics and system benefits of an Energy Efficient Engine (E^3) suitable for use on advanced subsonic transport aircraft has been completed. Relative to a current CF6-50C engine, the following benefits were estimated.

- 14.4% reduction in installed cruise Specific Fuel Consumption
- A reduction in Direct Operating Cost of more than 5%

The advanced technology E^3 system would also permit:

- Compliance with FAR 36 (1977) noise limits
- Compliance with 1981 EPA Emission Standards

The above was accomplished with an engine design that meets all anticipated commercial standards.

INTRODUCTION

With the advent of fuel shortages in the fall of 1973 and a general public realization that fossil fuel sources for our economy are not only limited but subject to disruption came pressure to find ways to conserve and extend our fuel supplies. One response to the problem has been an effort to plan and develop new transport aircraft that would provide the level of fuel economics over current aircraft that wide bodied high bypass turbofan aircraft provided over the earlier narrow body pure jet aircraft.

To provide impetus and technology base, NASA began to sponsor studies of advanced engines that would conserve fuel yet be economically attractive to airline users. Several of these studies performed by General

Electric are summarized in References 1 and 2. Out of these studies came general configuration and cycle choices for an advanced technology direct drive turbofan engine that showed promise of an approximate 10% reduction in SFC (Specific Fuel Consumption) compared to a current CF6-50C engine.

In conjunction with the above studies, NASA also funded studies to determine the potential value of various advanced material technologies such as ceramics, directionally solidified turbine blade alloys and high temperature, high strength turbine disk alloys. To provide a basis of comparison the studies (Reference 3 and 4) employed benefit analyses based on an advanced airframe-engine system with SFC, DOC (Direct Operating Cost), ROI (Return on Investment) and other merit factors derived. From these materials studies came the recognition of the importance of the newer turbine blade materials, lightweight composites and ceramics in fuel efficient engines.

The Energy Efficient Engine (E^3) studies sponsored by NASA under contract NAS3-20627 and beginning in December of 1976 were the culmination of these advanced engine studies to define and study advanced technology engines suitable for advanced subsonic transport aircraft that could be certified in the late 1980's and early 1990's.

E^3 STUDY GOALS

NASA defined some important goals for this study. They were as follows:

- A 12% reduction in installed SFC relative to a current high bypass engine installed on an advanced subsonic transport plane at maximum cruise power.
- A 5% reduction in DOC.
- Ability to meet FAR 36 (1969) - 10 EPNdB (Effective Perceived Noise Decibels) level.
- Ability to meet 1981 EPA emissions standards.
- Engine growth should not compromise the above goals.

ABBREVIATIONS

App	Approach
DOC	Direct Operating Cost
E^3	Energy Efficient Engine
ECCP	Experimental Clean Combustor Program
EGV	Exit Guide Vane
F_n	Thrust
FOD	Foreign Object Damage
FPS	Flight Propulsion System
GE	General Electric
LCC	Lockheed Company of California
M	Mach Number
MCD	McDonnell/Douglas Company
NA	Not available
PAX	Number of Passengers
P/P	Pressure Ratio
ROI	Return on Investment
SFC	Specific Fuel Consumption
SL	Side Line
SLS	Sea Level Static
SLTO	Sea Level Take-Off
TBC	The Boeing Company
T/O	Take-Off
TOGW	Take-Off Gross Weight
W_f	Fuel Burned

STUDY METHODS

It was necessary to select a reference engine for comparison purposes for the study. General Electric selected the CF6-50C as the comparison engine since it was the most advanced General Electric high bypass ratio turbofan in current wide spread commercial service. In addition, its performance, cost, and excellent thrust to weight ratio provided a challenging goal.

The study was conducted by performing a mission system benefit analysis of candidate engines installed on projected advanced aircraft systems thought to be typical of the late 1980's and early 1990's. Subcontracts were let to The Boeing Company, the Lockheed Company of California and the McDonnell/Douglas Company to provide aircraft/engine mission evaluations. There were also internal aircraft-engine evaluations of the candidate engines. Both a domestic and intercontinental mission were evaluated.

The studies were performed with rubberized engines and aircraft with each company defining its own advanced aircraft-engine systems. For all the studies, the mission and payloads were fixed while airframe characteristics and engine sizes were altered to reflect differences in engine performance. Properly scaled CF6-50C engines were used on comparable advanced technology aircraft to provide a comparison with the advanced aircraft engine system.

From these studies, direct comparisons of DOC, TOGW (Take-Off Gross Weight), W_f (fuel burned) and other important merit factors were carried out. Noise estimates were also made and other aspects of aircraft engine integration were investigated, especially by the sub-contractors.

STUDY RESULTS

The early portions of the study were concerned with evaluating direct and geared engines with both separate and mixed flow exhaust configurations to determine what advanced engines and installations could best meet the NASA goals. Earlier studies had used a cruise condition of .8 M at 10,668 m (35,000 feet) as the reference performance point and this was continued for the internal General Electric studies. From this reference performance point, selection of fan pressure ratio had been in a range of

1.65 to 1.75 and an overall engine pressure ratio of 38 to 1 was retained from the STEDLEC and USTEDLEC studies (Reference 1 and 2).

Four advanced engines were defined for this portion of the study and their descriptions are given in Table 1 along with that of the reference CF6-50C engine. The engine sizing point was the maximum climb thrust condition at 10,668 m (35,000 feet) altitude and .8 M since this was the probable limiting power condition for the advanced aircraft/engine systems studied.

In making the comparison, each engine was configured to its best advantage while maintaining overall performance parameters constant such as fan and overall engine pressure ratio and turbine inlet rating temperatures. For instance, work extraction from the core stream was different for the separate and mixed flow engines to produce the best overall cycle performance. Evaluation of each engine on a General Electric advanced study aircraft produced the performance evaluation shown in Table 2. Higher bypass ratio and lower fan pressure ratios were employed on the geared engines to take better advantage of the benefits of gearing.

The separate flow configuration was 2 to 3% worse in SFC relative to the mixed flow exhaust engine on a consistent basis. Most of that difference was due to the mixer performance outweighing the advantage gained by a more highly extracted separate flow engine cycle. As a result, effort in the E^3 study was directed to further evaluation and definition of a geared and direct drive mixed flow engine. A summary of the engine comparisons including estimates of DOC, emissions, and growth potential and fuel usage is given in Table 3 for the mixed and separate flow engines.

For the second part of the E^3 study, General Electric and the airframe sub-contractors both evaluated a refined direct and geared engine (shown in Figure 1) installed on an advanced subsonic transport aircraft. From this part of the E^3 study was to come the recommendation of one engine cycle and configuration for a more intensive preliminary design definition.

For the mission evaluation, General Electric and each sub-contractor defined both a domestic and intercontinental advanced aircraft. A partial description of these aircraft and engines is provided in Table 4.

The two advanced technology engines were studied and compared with the current technology CF6-50C. As before, all engines were scaled to produce the same installed maximum climb thrust as the base line advanced technology direct drive engine.

Studies were performed to determine expected engine performance weight, costs and maintenance. From these, scaling information on thrust was provided to the sub-contractors to enable them to adjust the characteristics of the reference CF6-50C and advanced engines to the needs of their advanced aircraft. Performance characteristics of the advanced engines were calculated on a consistent installed cruise thrust basis for both the direct and geared engine with results given in Table 5. At the maximum cruise point, the direct and geared engine showed a 12.1% and 14.6% reduction in installed SFC, respectively, over the base CF6-50C engine. Figure 2 presents the economic benefits estimated for the direct drive advanced engine on a domestic and intercontinental aircraft by the sub-contractors and General Electric. For these evaluations, differences in engine cost and maintenance were not included due to the preliminary state of such estimates. It can be seen that both the Δ(Delta) DOC and ΔW_f estimates indicate that the advanced direct drive study engine would be a significant improvement over the reference CF6-50C.

Emission estimates were made for the direct and geared drive engine and their growth versions. When compared to the 1981 EPA Standards, only the NO_x emissions exceed the limit for all engines, except the design geared engine.

The benefits of the geared versus direct drive engine were determined using internal General Electric merit factor derivatives. For the domestic mission, uninstalled SFC of the geared engine was 2.5% better than the direct drive engine (relative to the CF6-50C), but the weight, cost and drag effects predominate such that the DOC was 1.3% higher and the fuel saving was only .9%.

A short summary of the results of this portion of the E^3 study is given in Table 6. Since the geared engine was estimated to only reduce fuel consumption by .9% while incurring a DOC penalty of 1.3%, the direct drive engine was recommended to NASA as the engine for further efforts in the preliminary design portion of the E^3 study.

NASA indicated that more SFC margin would be required for a direct drive engine to assure that the original 12% SFC reduction goal would be met. Therefore, further engine cycle and configuration optimization effort began to determine what changes could be made to improve the fuel consumption of the direct drive engine. Three additional engines were studied in some detail with small changes in fan pressure ratio and LP spool configuration only. Prior studies had indicated that the engine overall pressure ratio and turbine inlet temperatures were already well matched so these parameters were not varied (except for growth).

The three additional engines studied had the following characteristics. The first was a modification of the direct drive engine studied already but with the fan tip speed reduced and a short LP turbine transition duct to improve LP turbine efficiency. The other two engines were altered in configuration to permit a lower fan pressure ratio (and tip speed) but core supercharge was held constant with the use of a quarter stage booster. As with the improved engine, a short transition duct was employed to permit a higher LP turbine tip speed with a corresponding increase in efficiency.

Table 7 presents a comparison of the final advanced geared and direct drive study engines. On a comparable installed net thrust basis, the geared engine weighed over 480 kilograms more, burned 1.9% more fuel even with a small SFC advantage and was 2.1% higher in DOC than the advanced direct drive engine. For these reasons, the final direct drive configuration was retained for the remainder of the E^3 study.

As designed, the advanced technology study engine incorporated many advanced technology features in terms of configuration, component performance, material systems, performance retention, design features and environmental protection. Figures 3 through 8 show and illustrate many of these features and some of the reasons behind the choice of the very advanced 10 stage high compressor.

An estimate of the emissions performance of the advanced double annular combustor (see Figure 6) is presented in Table 8. It is believed that this combustor design can be developed to permit compliance with the 1981 EPA emission standards.

A comparison of several operating parameters for the final direct drive study engine and the reference CF6-50C is shown in Figure 9 for equivalent installed maximum climb thrust. At the maximum cruise measuring point, it is estimated that the advanced study engine would permit a 14.4% reduction in SFC compared to the reference CF6-50C. Table 9 shows an estimate of the source of SFC reduction. The largest improvements come from component improvements, cycle effects and the mixed exhaust system.

An updated benefit analysis was performed as previously described using a rubberized engine and aircraft with only the mission and payload fixed. Aircraft technology assumptions for the General Electric study aircraft are given in Table 10 while the merit factor derivatives that go with these advanced study aircraft are given in Table 11.

The revised airframe sub-contractor study results using the final study engine characteristics are shown in Table 12. Since price or maintenance effects were not included in these results, an estimate of these effects (as derived from the General Electric study aircraft) is included in Table 13. Even though some of the advanced technology and performance retention features resulted in an estimate of a higher relative initial engine cost (than a CF6-50C) many of these higher initial cost features permit a lower mature engine maintenance cost estimate. This estimated savings offset the first price penalty and resulted in a further 2% DOC reduction over those DOC estimates done without price and maintenance effects. Table 14 shows the large estimated potential fuel burned savings at the maximum cruise condition for the advanced engine on General Electric study aircraft. For the domestic mission, a 21% reduction is shown and for the intercontinental mission a nearly 28% reduction is possible. Integrated mission fuel savings tend to be somewhat lower, however.

Noise estimates were also developed for the final E^3 study engine installed on advanced General Electric study aircraft. Acoustic design features, shown schematically in Figure 10, were used for the estimates.

Estimated noise levels relative to FAR 36 (1969) and FAR 36 (1977) are shown in Table 15 for both the domestic and intercontinental GE study aircraft.

CONCLUSION

Under NASA Study Contract NAS3-20627 (Energy Efficient Engine) General Electric identified an advanced direct drive turbofan engine capable of meeting (or exceeding) all fuel, economic and emission goals and the FAR 36 (1977) noise standards. The final advanced study engine is estimated to provide an installed SFC reduction (relative to the CF6-50C) of 14.4%. The final advanced study engine would provide significant savings in fuel and DOC over a comparable CF6-50C powered aircraft.

REFERENCES

1. Neitzel, R.E., Hirschkron, R. and Johnston, R.P.: Study of Turbofan Engines Designed for Low Energy Consumption. Prepared for NASA under Contract NAS3-19201, NASA CR-135053 August, 1976.

2. Hirschkron, R., Johnston, R.P., and Neitzel, R.E.: Study of Unconventional Aircraft Engines Designed for Low Energy Consumption. Prepared for NASA under Contract NAS3-19519, NASA CR-135136, December, 1976.

3. Ross, E.W., Johnston, R.P., and Neitzel, R.E.: Cost Benefit Study of Advanced Materials Technology for Aircraft Turbine Engines. Prepared for NASA under Contract NAS3-17805, NASA CR-134702, November, 1974.

4. Hillery, R.V., and Johnston, R.P.: Cost Benefit Study of Advanced Materials Technology for Aircraft Turbine Engines. Prepared for NASA under Contract NAS3-20074, NASA CR-135235, September, 1977.

TABLE 1,- EARLY E^3 STUDY ENGINES

	Reference Engine CF6-50C	Study Engine 1	Study Engine 2	Study Engine 3	Study Engine 4
Fan drive	Direct	Direct	→	Geared	→
Exhaust configuration	Separate	Separate	Mixed	Separate	Mixed
SLS take off F_n, kN	224	157	155	176	177
— (lb)	(50250)	(35300)	(34800)	(39600)	(39800)
Engine bypass ratio, mx.cr.	4.3	7.1	6.3	9.6	8.6
No. of stages Fan/LPC/HPC/HPT/LPT	1/3/14/2/4	1/0/10/2/5	1/0/10/2/4	1/1/10/2/3	1/1/10/2/3

TABLE 2.- EARLY E^3 STUDY RESULTS

	Reference Engine CF6-50C (scaled)	Study Engine 1	Study Engine 2	Study Engine 3	Study Engine 4
Fan drive	Direct	Direct →	→	Geared →	→
Exhaust configuration	Separate	Separate	Mixed	Separate	Mixed
Δ SFC-bare engine, mx. cr.—%	Base	-9.4	-10.6	-13.4	-15.7
Δ SFC installed, mx.cr.—%	Base	-10.0	-12.0	-13.2	-16.0

TABLE 3.- SUMMARY OF COMPARISONS BETWEEN EXHAUST SYSTEMS

	Separate vs Mixed
Fuel Usage	3-6% Disadvantage
DOC	2½ to 3½% Disadvantage
Emissions	No Difference
Growth Potential	No Difference

TABLE 4.- DOMESTIC AND INTERCONTINENTAL MISSION AIRCRAFT DEFINITION

Study Mission	General Electric		Boeing		McDonnell/ Douglas		Lockheed	
	Domestic	Inter.	Domestic	Inter.	Domestic	Inter.	Domestic	Inter.
Des. range — km (n. miles)	5556 (3000)	10190 (5500)	3704 (2000)	10190 (5500)	5556 (3000)	10190 (5500)	5556 (3000)	12040 (6500)
Des. payload — PAX	225	225	196	196	458	438	400	400
Cruise Mach no.	.8	⟶						
Initial cruise — m —(feet)	10668 (35000)	10668 (35000)	10668 (35000)	10058 (33000)	10058 (33000)	9449 (31000)	10668 (35000)	10668 (35000)
No. engines	3	3	2	4	3	3	3	4
Thrust/engine—SLTO, kN —(lb)	113 (25300)	165 (37100)	152 (34200)	100 (22500)	189 (42400)	225 (50500)	158 (35500)	147 (33100)

TABLE 5.- ADVANCED ENGINE COMPARISON

	Reference SF6-50C (scaled)	Advanced Direct Drive	Advanced Gear Drive
Exhaust configuration	Separate	Mixed	Mixed
Overall nacelle length - m —(inches)	6.55 (258)	5.66 (223)	5.92 (233)
Δ Installed weight—kg —(lb)	Base	-476 (-1050)	+191 (+420)
Max. climb fan pressure ratio	1.76	1.71	1.55
Δ SFC installed, mx. cr.—%	Base	-12.1	-14.6

TABLE 6.- E^3 STUDY (ENGINE-AIRFRAME) INTEGRATION — RESULTS SUMMARY OF COMPARISON BETWEEN ADVANCED GEARED AND DIRECT DRIVE ENGINE AND CF6-50C INSTALLED ON DOMESTIC TRANSPORT

	CF6-50C	Direct	Geared
Δ SFC — %	Base	-12.1	-14.6
Δ W_f — %	Base	-17.8	-18.7
Δ DOC — %*	Base	- 8.2	- 6.9
Emissions	—	Meets 1981 std. except NO_x	Meets 1981 stds.
Noise	—	Meets FAR 36 (1977)	Meets FAR 36 (1977)
Growth potential	—	Meets reqmts.	Meets reqmts.

* No price or maintenance effects

TABLE 7.- IMPROVED ADVANCED ENGINE STUDY RESULTS

(EQUIVALENT INSTALLED MAXIMUM CLIMB THRUST)

	Final Geared Drive	Final Direct Drive
Bypass ratio — mx. cr.	8.6	6.98
Fan pressure ratio mx. cl.	1.55	1.65
Installed weight — kg —(lb)	+482 (+1065)	Base
Δ SFC installed — % (Rel. base line)	-.7	Base
Δ DOC — % (domestic mission)	+2.1	Base
Δ W_f (fuel burned) — %	+1.9	Base

TABLE 8.- FPS EMISSIONS ESTIMATE INTEGRATED MISSION EVALUATION

	FPS Base line	1981 EPA Standards
CO	2.0	3.0
HC	.1	.4
NO_x	3.0	3.0
Smoke no.	15	20

TABLE 9.- CONTRIBUTIONS TO IMPROVED INSTALLED SFC

(Relative to CF6-50C)

Contributor	ΔSFC — %
Engine component improvements	—4.0
Pressure drop improvements	— .6
Reduced cooling flows	— .4
Cycle effects — T_{41}, P/P, bypass ratio	—6.0
Mixed exhaust	—2.7
Reduced installation drag	- .7
Total Improvement	—14.4

TABLE 10.- GENERAL ELECTRIC ADVANCED AIRCRAFT ASSUMPTIONS

Wing characteristics	— 30° sweep ¼C, ar = 10, supercritical design
Aircraft structure	— Partial composite, advanced materials 5% lighter wing, fuselage, gear and pylons than 1976 10% lighter tail than 1976 15% lighter surface controls than 1976
Active controls	— .95 factor applied to tail area and wing weight
Aerodynamics	— 1% reduction in interference drag vs 1976 levels
Engine configuration	— Trijet

TABLE 11.- BENEFIT ANALYSIS DERIVATIVES

	Domestic Trijet	International Trijet
Design range — km —(n. mile)	5556 (3000)	10190 (5500)
Avg. mission range — km —(n. mile)	1296 (700)	3704 (2000)
Passenger capacity	225	225
Load Factor — %	55	55
Fuel costs $/m^3 (¢/gal)	92.50 (35)	118.90 (45)

	Δ's — %				Δ's — %			
	DOC	ROI	TOGW	W_f	DOC	ROI	TOGW	W_f
1% SFC	.53	-.17	.57	1.31	.93	-.36	1.12	1.69
45.4 kg engine/nacelle wt. (100 lb)	.19	-.08	.31	.26	.19	-.09	.28	.26
$1/flt. hr. - maint. cost	.16	-.03	—	—	.14	-.03	—	—
$10000 engine/nacelle price	.05	-.04	—	—	.03	-.03	—	—

TABLE 12.- SUB-CONTRACTOR EVALUATION OF ADVANCED TECHNOLOGY ENGINE ON ADVANCED AIRCRAFT

(RELATIVE TO REFERENCE CF6-50C)

	Boeing		McDonnell/Douglas		Lockheed	
Mission	Domestic	Intercont.	Domestic	Intercont.	Domestic	Intercont.
Range, km (n. miles)	3704 (2000)	10190 (5500)	5556 (3000)	10190 (5500)	5556 (3000)	12040 (6500)
PAX	196	196	458	438	400	400
Δ W_f–% (fuel burned)	-14.8	-20.3	-17.1	-16.6	-17.5	-22.2
Δ DOC–%*	N/A	N/A	- 8.1	- 9.3	- 5.5	-10.2

*No price or maintenance cost effects

TABLE 13.- E^3 FPS PRICE AND MAINTENANCE

vs

SCALED CF6-50C DOC EFFECTS

	Mission Sized			
	Domestic		International	
	Design Value	Δ DOC–%	Design Value	Δ DOC–%
Installed cost — K$	+107.3	+.5	+124.5	+.4
Maint. cost — $/flt. hr. (Parts + labor + o.h.)	-14.51	-2.3	-17.90	-2.5
		-1.8		-2.1

Fuel cost 35¢/gal. domestic
45¢/gal. international

TABLE 14.- FPS ENGINE Δ W_f BREAKDOWN

vs

CF6-50C REFERENCE (SCALED)

	Mission Sized (Mx. Cr. Condition Only)			
	Domestic		International	
	Design Value Δ	Δ W_f—%	Design Value Δ	Δ W_f—%
Installed wt. — kg (lb)	-412 (-909)	-2.4	-643 (-1398)	-3.6
Installed SFC — % (Mx. cr. — std day)	-14.4	-18.9	-14.4	-24.3
Total %		-21.3		-27.9

TABLE 15.- ESTIMATED ENGINE NOISE NOMINAL SUPPRESSED NOISE LEVELS — NO MARGIN

	Domestic Mission FPS Engine			International Mission FPS Engine		
	T/O	App	SL	T/O	App	SL
Engine noise, EPN^{d}B	93.1	96.0	90.9	96.5	98.2	91.3
Relative to:						
FAR 36 (1969)	-9.4	-9.8	-14.9	-9.2	-8.8	-15.7
FAR 36 (1977)	-4.5	-5.8	-8.0	-3.6	-4.9	-9.2

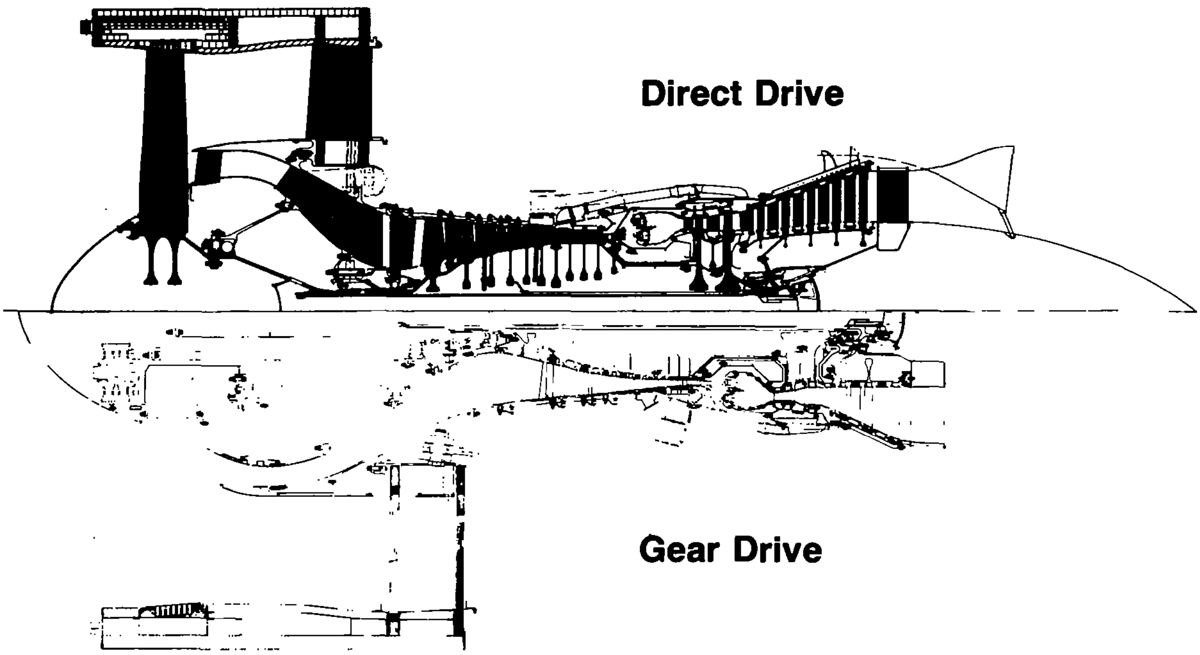


Figure 1.- E^3 study advanced engines.

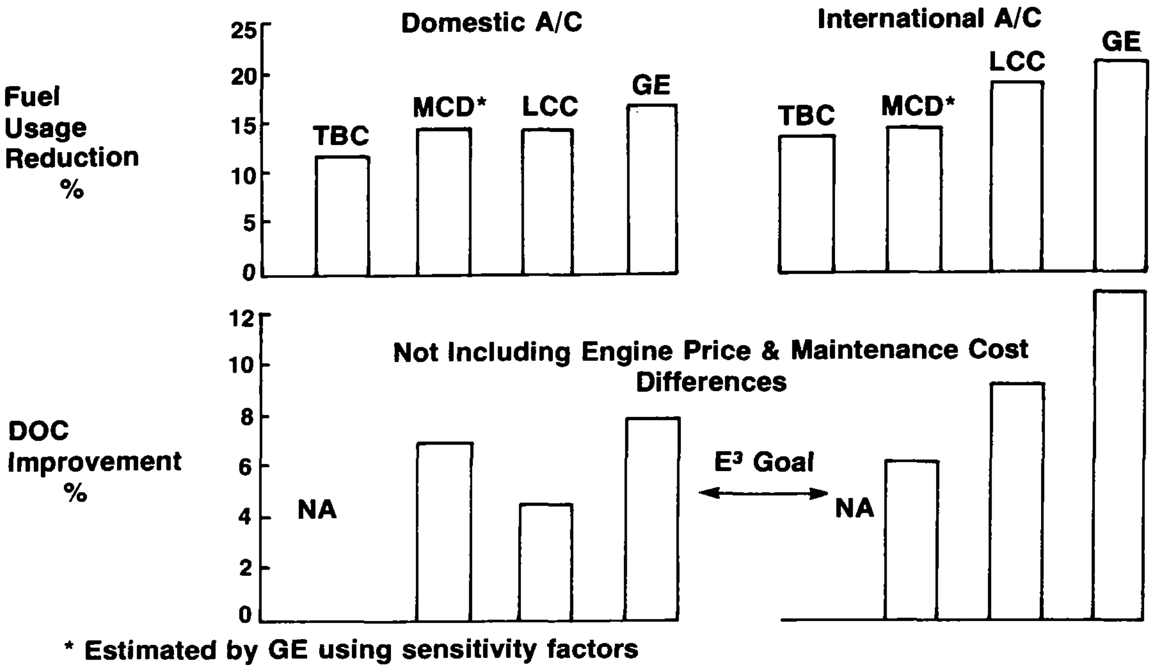


Figure 2.- Advanced direct drive engine benefits (CF6-50C reference).

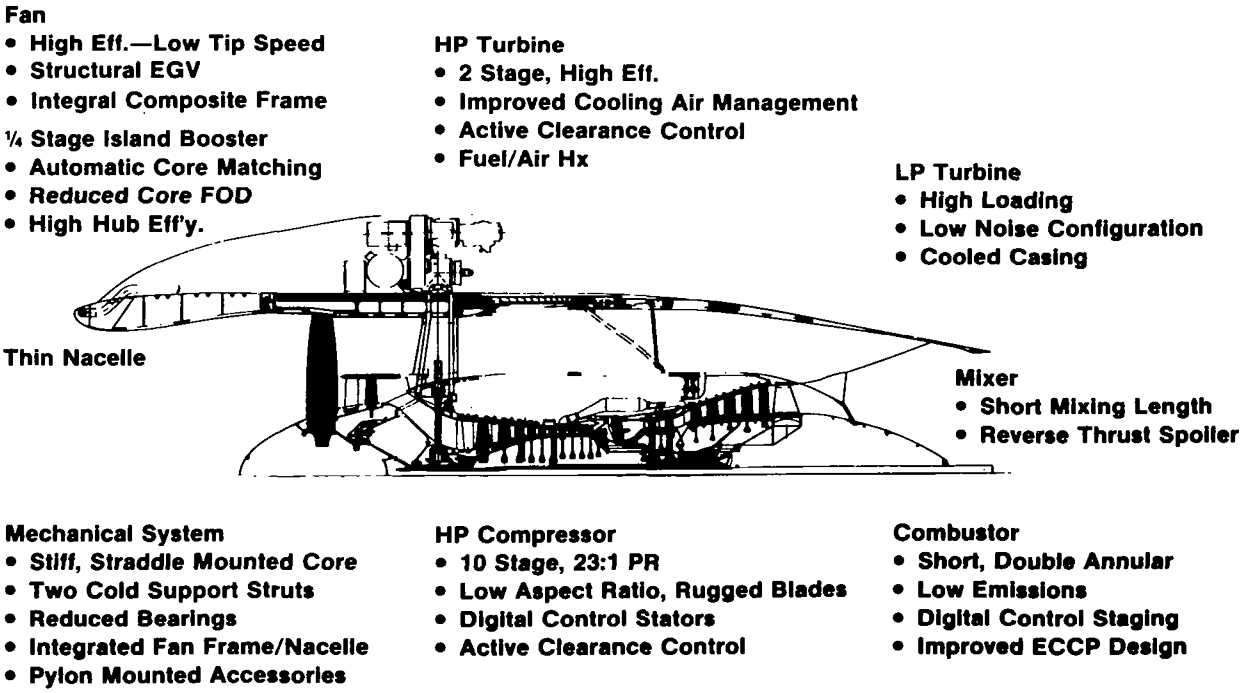


Figure 3.- Advanced technology features.

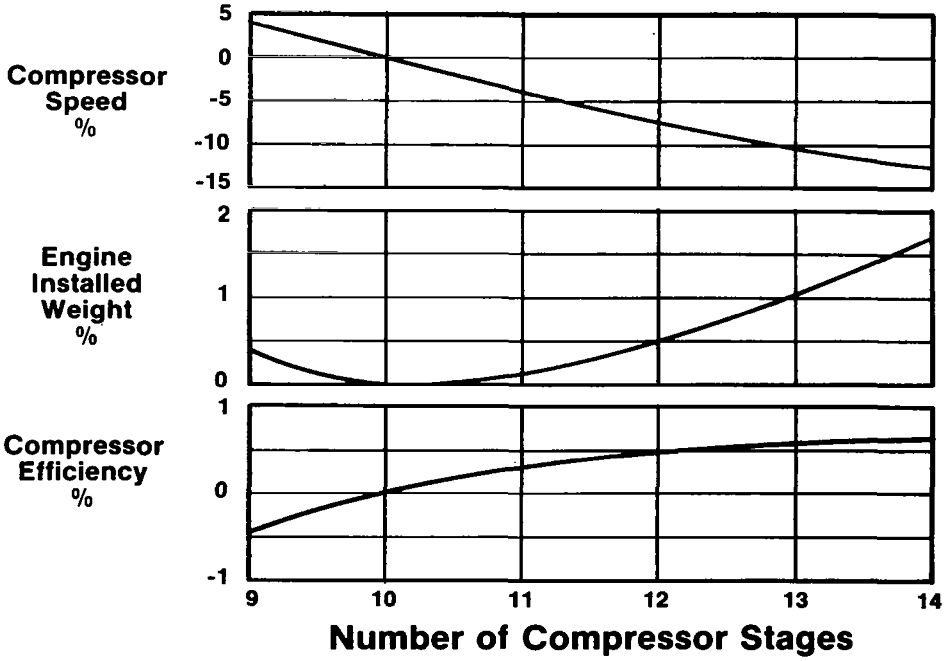


Figure 4.- Effect of compressor stage number.

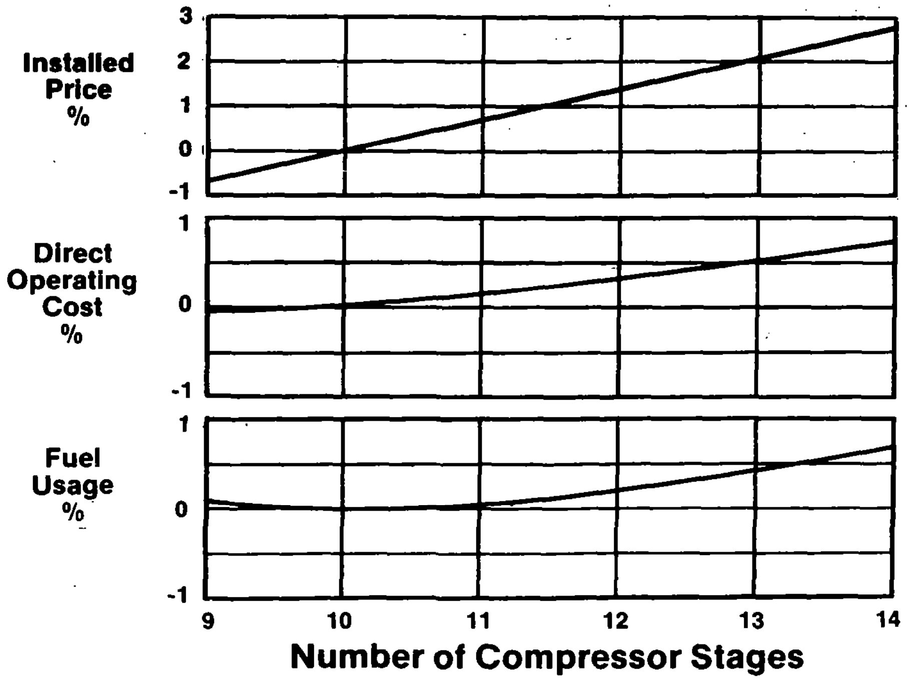
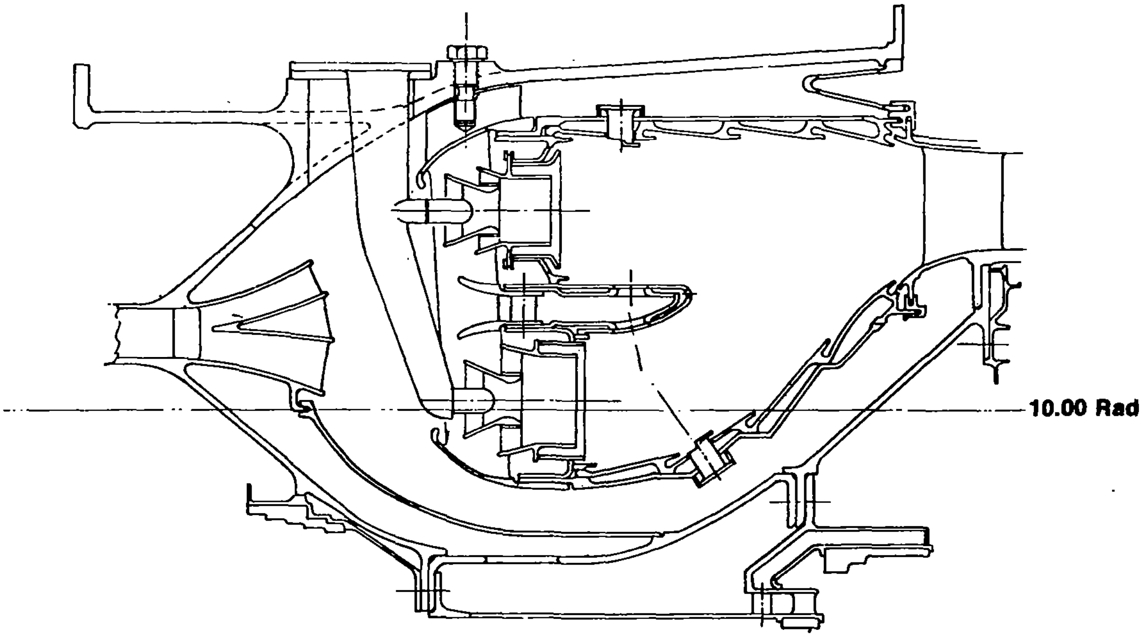


Figure 5.- Economic results.



Derived From NASA Experimental Clean Combustor Program

Figure 6.- Double annular combustor.

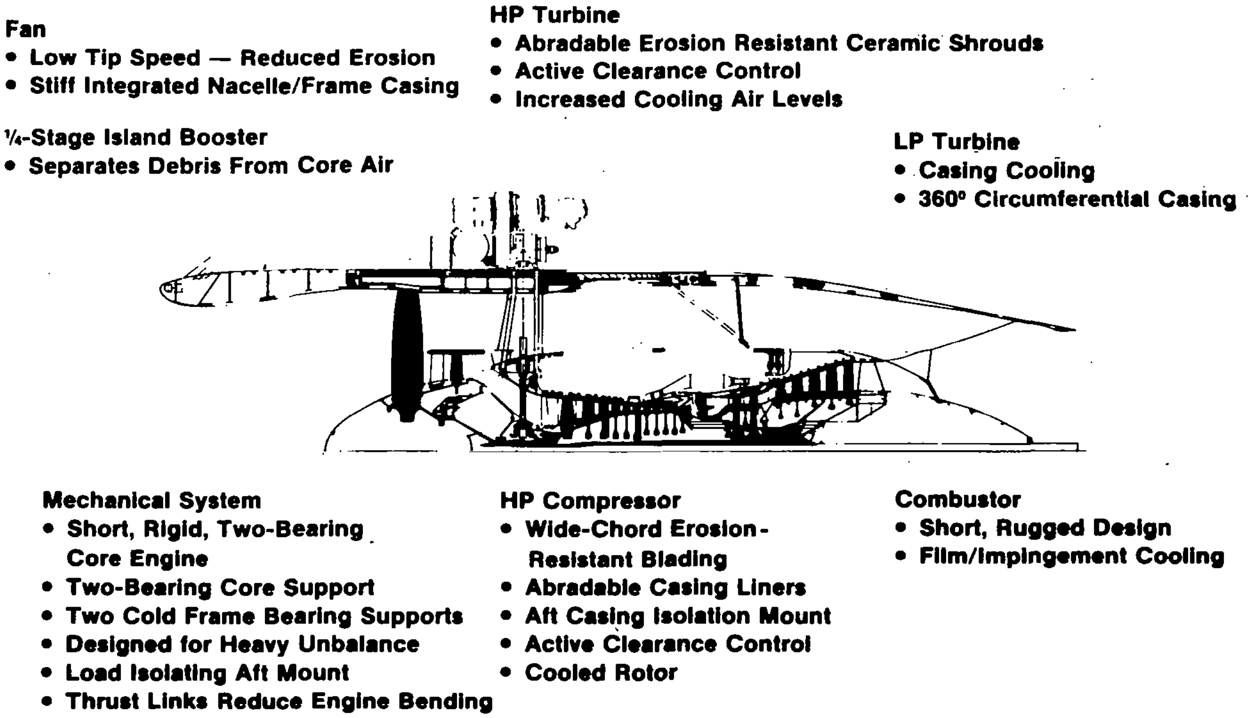


Figure 7.- Performance retention features.

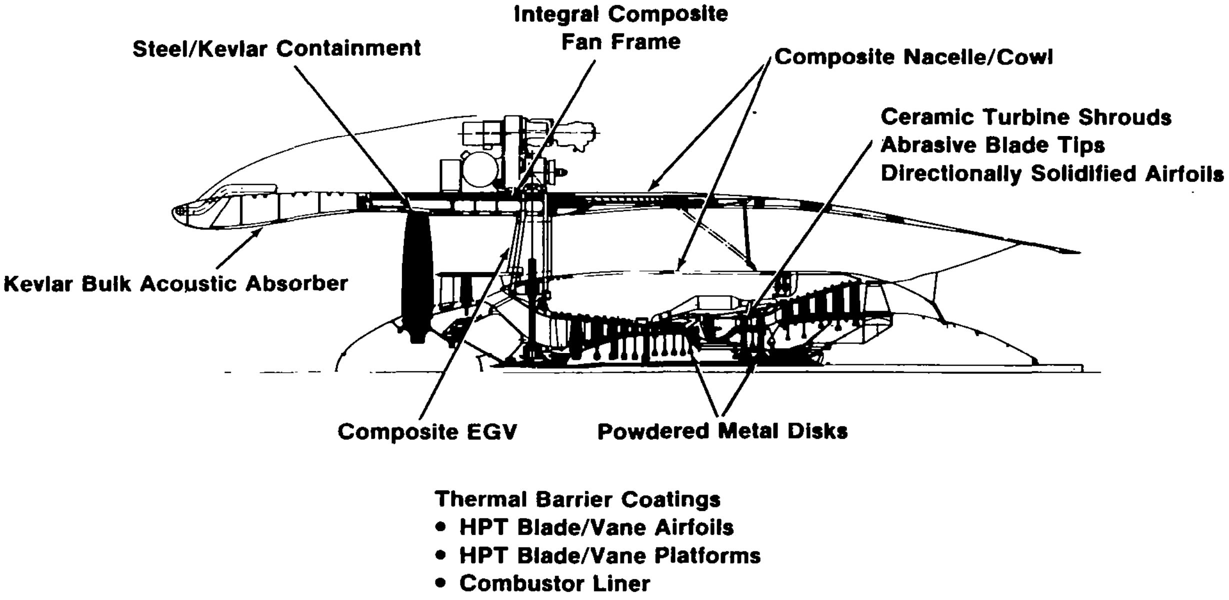


Figure 8.- Advanced materials.

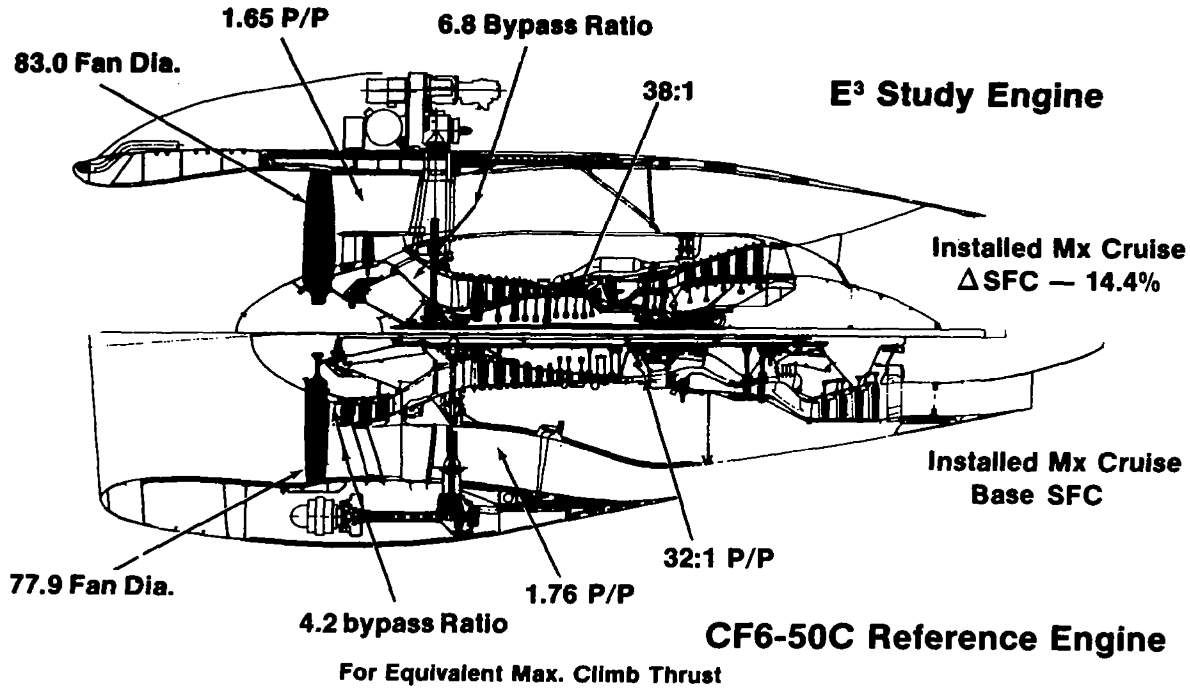


Figure 9.- Engine comparison.

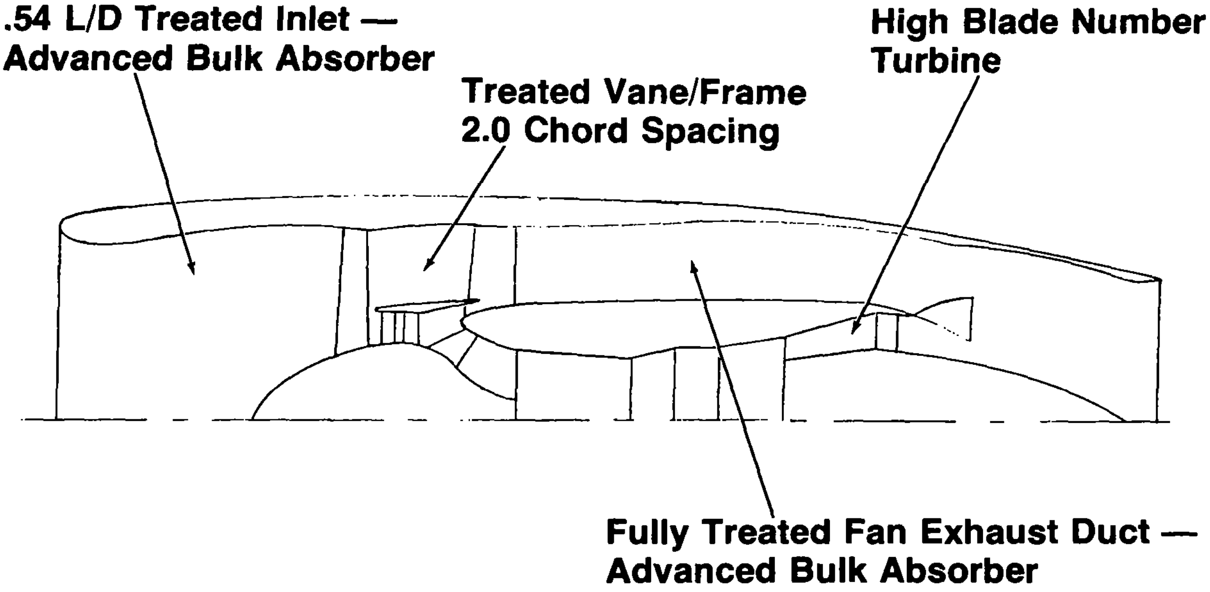


Figure 10.- Advanced engine installation low noise features.