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Future Propulsion Opportunities for Commuter Airplanes

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FUTURE PROPULSION OPPORTUNITIES FOR COMMUTER AIRPLANES

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ABSTRACT

A summary is presented of a series of recent studies that address commuter airplane propulsion opportunities in the 1990-2000 timeframe. Consideration is given to advanced technology conventional turboprop engines, advanced propellers, and several unconventional alternatives: regenerative turboprops, rotaries, and diesels. Advanced versions of conventional turboprops (including propellers) offer 15-20 percent savings in fuel and 10-15 percent in DOC compared to the new crop of 1500-2000 SHP engines currently in development. Unconventional engines could boost the fuel savings to 30-40 percent. The conclusion is that several important opportunities exist and therefore powerplant technology need not plateau.

AN IMPORTANT PART OF COMMUTER AVIATION PROGRESS is the role played by powerplants. Prior to 1964, commuter aircraft were comparatively small airplanes designed for general aviation applications and powered by reciprocating engines. Then in 1964-65 the newly developed small turboprop engines, the Garrett TPE 331, and the Pratt & Whitney Canada PT6 went into production and helped spawn a revolutionary trend in commuter airplane design and operations (e.g., Beech 99 and DeHavilland Twin Otter). As time progressed these early models grew into families of engines that now cover the 600-1300 SHP power spectrum and competitive engines such as the Allison 250-B17B and the Avco LTP 101 appeared. Today, almost two decades later, these same engines still denominate the commuter marketplace. During the same timespan, meanwhile, the much larger commercial turbine engines underwent considerably more change culminating in the high-bypass ratio turbofans that have 40-45 percent cruise thermal efficiencies compared to about 25% for their smaller turboprop counterparts.

However, that situation is about to change since several new second generation commuter turboprops are now in the final stages of development: the Pratt & Whitney Canada 100 series, the General Electric CT7, and the Garrett TPE 331-15. These new 1500-2000 SHP engines will enter service in the 1983-1985 timeframe and will be 15-20 percent more efficient than their predecessors. This improved efficiency together with estimated major reductions in maintenance cost stemming from modular construction designs should reduce airplane direct operating cost (DOC) about 12 percent (fig. 1). Since the duration of each new engine generation follows a 10-20 year pattern and since it takes about 10 years to develop a new engine, it seems appropriate to now inquire about third generation possibilities--both in terms of potential benefits and also in terms of required technological progress.

To address such issues, NASA sponsored a series of future propulsion opportunity studies as part of a broader effort to provide guidance for future activities in the disciplines of airframe structures, aerodynamics, and subsystems as well as propulsion(1-5)*. The initial propulsion studies focused on advanced conventional type turboprops and were conducted by Detroit Diesel Allison(6), General Electric(7), and the Garrett Turbine Engine Company(8). Common groundrules were established (Table 1) that recognized the upward trend in airplane size, the need for passenger comfort levels approaching B-737 levels, and the need for air traffic compatibility with commercial airliners at airport terminals.

INFLUENCE OF PROPULSION PARAMETERS ON OPERATING COSTS

In order to gain an appreciation of the relative impact of the various propulsion system parameters on airplane economics, a typical DOC breakdown is displayed in figure 2. Overall, the powerplant directly impacts about 60 percent of DOC which certainly qualifies it as a target for future improvement effort. Specifically, the engine and propeller efficiencies are of primary importance due to the large role played by fuel. Improvements in powerplant weight or cost would need to be an order of magnitude larger

*Numbers in parenthesis designate References at end of paper than efficiency improvement to yield identical DOC reduction. Engine maintenance is shown to be about 1/4 as important as efficiency; however, the true impact of maintenance is larger since schedule interruption and loss of revenue are often involved whenever unscheduled maintenance occurs.

ADVANCED CONVENTIONAL TURBOPROP POWERPLANTS

The three engine companies investigated technologies appropriate for a conventional type of turboprop that, if pursued, could be ready for commercial development by 1988. Engines using such technology could not enter service therefore until the early 1990's. As a group, the three studies considered engine sizes ranging from 1500 SHP, for a 30-passenger, Mach 0.45 twin-engine airplane, to 4800 SHP for a 50-passenger, Mach 0.70 twin-engine airplane designed for executive transport application in addition to commuter service.

TECHNOLOGY-Candidate component improvements were identified in every major area: compressors, turbines, combustors, controls, gearboxes, shafts, bearing and seals, and accessories. Changes in component efficiencies, weights, costs, and maintenance were estimated for each improvement concept. These changes were then used to calculate a net change in DOC for each candidate evaluated.

The technology studies used DOC as the main discriminator in screening the many candidate improvement ideas since it is a universally accepted economic criterion and is influenced by all of the predictable changes. While this procedure is generally satisfactory, some potential component improvements are not amenable to such logic. In some cases the important benefit is not associated with the particular component under consideration, but in other components receiving synergistic benefits. For example, a small diameter composite metal shaft by itself hardly alters DOC at all. But because turbine disk bore diameters are also reduced, disk stress levels are lowered and this enables the higher turbomachinery rotating speed capability required for higher efficiency and fewer stages.

Since each company has its own component design philosophy and its own level of technology, it is not surprising that the three teams identified different specific technology elements to achieve improvement. To illustrate this point consider compressor technology. General Electric identified a 3 percent potential efficiency improvement over their CT7-5 axi-centrifugal compressor while maintaining the same 17:1 overall pressure ratio and reducing the number of axial stages from 5 to 3. This could be accomplished by combining four distinct technologies (figs. 3-4):

1. Highly loaded axial stages using customized airfoils
2. Split-blade centrifugal impellers
3. Low-loss diffusers
4. Part-speed stall margin reduction

Advanced three-dimensional, high-speed blade design techniques could provide the capability of accurately generating customized airfoils tailored to the specific flow conditions experienced by each blade row. Applying these techniques to low aspect ratio axial blades would increase overall compressor efficiency by one point and permit three stages to do the job of five. In the split-blade impeller concept, the centrifugal stage is split into a separately bladed inducer section and an impeller section. This permits the inducer section to handle the transonic flow more efficiently than a conventional continuous impeller blade by accommodating higher spanwise twist gradients to better control both the blade loading and the passage throat contour to avoid choking. Higher inlet Mach numbers are permissible without causing separation on the suction side of the blades. In addition, a fresh boundary layer is initiated by the impeller leading edge. The successful execution of this concept depends upon the development of three-dimensional, viscous flow analysis computational methods not yet available. A one to two point centrifugal stage efficiency improvement is possible.

The CT7-5 diffuser dumps low-speed compressor discharge air into a plenum, deswirls it, then discharges it into the combustor. An advanced diffuser could avoid the initial dump pressure loss by controlling the passage contours to deswirl the flow as it negotiates the radial-to-axial turn. This could increase the centrifugal stage efficiency one point. An additional one point may be achievable by reducing the diffuser throat blockage with wall bleed. These two sub-elements could contribute a total of two points to centrifugal stage efficiency (equivalent to one point overall axi-centrifugal efficiency). Another concept to increase compressor efficiency (by 0.5 point) is the exploitation of digital electronic control system technology by adding a compressor discharge Mach number (M_3) sensor to schedule acceleration fuel as a function of M_3 on a closed-loop basis. The improved transient behavior could reduce the required surge margin allowance and ultimately permit higher compressor efficiencies in the high speed operating range (fig. 4).

Detroit Diesel Allison's compressor evaluation also showed improved component performance (~ 4 percent) relative to their PD 370-37 baseline (a turboprop version of the T701). Items identified include:

1. Passive clearance control to reduce blade tip clearances by 15 percent (1.1 percent DOC reduction)
2. Ability to predict compressor rotor/case response during rotating stall to reduce tip clearances and reduce the number of stages or eliminate a bearing and its support structure (-1.3% DOC).

3. Hybrid impeller rotor using HIP bonding to attach a cast rim with blades to a forged hub which permits higher tip speeds (-0.25% DOC).

Garrett proposes the use of powdered metal titanium for centrifugal impellers to reduce cost 25-40 percent without compromising weight or performance. Garrett also proposes a comprehensive parametric investigation of tip treatment configurations (e.g., slots) with the goal of improving compressor efficiency two points.

The above examples illustrate the diversity of ideas that surfaced during the course of these studies. A composite summary of most of the recommended concepts is presented in figure 5. Compressor efficiency could be increased 2-4 percent, turbine efficiencies increased 1-2 percent, combustor durability doubled, gearbox efficiency increased 1/2 percent and cost reduced, nacelle weight reduced 25 percent, and so forth. None of the turbomachinery technologies (gearbox, propeller and nacelle excluded) individually yields large DOC benefits, but collectively they could lower DOC by 5-6 percent and fuel consumption 8-9 percent relative to the new 1983 engines. Full descriptions of all of the advanced concepts and features are contained in references 6-8.

ENGINE CYCLES AND CONFIGURATIONS-Various engine configurations were considered such as single shaft, free turbine with single or dual-spool cores, and boosted versions of the simple free turbine layout. In addition, different staging arrangements were also investigated including single and dual stage centrifugal, axi-centrifugal, and all-axial compressors, and one- or two-stage high pressure turbines. The screening of these options was generally carried out at the same time cycle temperature and pressure levels were selected since these parameters are interrelated. The overall procedure was carried out using projected advanced component characteristics including maintenance cost, acquisition cost, size and weight as well as performance since DOC was the main selection criterion.

Representative results are shown in figure 6 which shows that compressor pressure ratios in the neighborhood of 20 are optimum and design turbine rotor inlet temperatures of 2250-2400°F are best considering technical risk as well as DOC. Since SFC has more impact on DOC than any other parameter, these plots nearly replicate those of the usual SFC versus pressure ratio type. However, whereas a two-stage high pressure turbine (HPT) is optimum using SFC as the criterion, a one-stage HPT shows up optimum on the DOC plot due to the savings in initial cost and maintenance cost. This result was reported by both General Electric and Garrett who limited pressure ratio to 17. But Allison dropped the one-stage HPT because the high equivalent stage work (44 BTU/lb) and expansion ratio (5.3) required to power the 20:1 pressure ratio single-spool compressor they selected is too far beyond the current state-of-the-art to obtain favorable efficiency compared to a more lightly loaded two-stage core turbine.

The turbomachinery configurations and cycles selected for the advanced engines are shown in figure 7. All are conventional free turbine configurations with the sole exception of GE's boosted free turbine configuration for their larger engine. In this case, GE opted for more pressure ratio (20:1) without requiring a second HPT stage (17:1 requires an expansion ratio of 4.2 which is about the upper limit for a one-stage HPT). The only all-axial compressor is Allison's 4800 SHP design which was reported to improve compression efficiency 2 percent at this size compared to an axi-centrifugal. Garrett's baseline choice was a 16.1 pressure ratio two-stage centrifugal compressor. But they also concluded that a 20:1 axi-centrifugal would do even better (1 percent lower DOC) although it would require considerably more development effort.

ADVANCED ENGINE CHARACTERISTICS-Figure 8 shows one of General Electric's proposed engines scaled to the identical power as the CT7-5 baseline. It would be 14 percent more efficient, 11 percent lighter, 12 percent less expensive to manufacture, and 17 percent less expensive to maintain than the CT7. The Allison and Garrett engine improvements are rather similar relative to the same baseline (fig. 9), although they were actually quoted relative to a scaled T701 and a scaled TPE 331-11, respectively. Whereas a significant portion of the second generation improvement over the first generation arises from better cycles (e.g., 14-17:1 pressure ratio vs. 10:1), most of the proposed third generation gains stem from component performance increases rather than cycle improvement. This reflects the difficulty in obtaining high component performance from the smaller airfoils associated with higher cycle pressure ratio. Engine maintenance costs are projected to be better as a result of improved reliability components, on-condition instead of scheduled overhauls, and condition monitoring systems--although much of these improvements are also planned for the second generation (fig. 10).

PROPELLER TECHNOLOGY-The smaller commuter aircraft use general aviation type propellers which are relatively simple and low performance compared to the more sophisticated technology employed in the larger commuter airplanes. The low cost propellers are typically constructed with solid aluminum blades having circular shanks which contributes to low performance and high weight. The more sophisticated propellers, on the other hand, utilize such weight-saving construction techniques as aluminum spar-fiberglass shell blades and such performance improvements as airfoil shanks, advanced airfoils, and low activity factors.

Despite the high performance levels currently available or in development (0.87 cruise efficiency), recent technology studies by Hamilton-Standard, the McCauley Division of Cessna, and Purdue University(9-10) have identified important further opportunities (fig. 11). Proplets or bi-blades could increase efficiency nearly 2 percent through reduced tip losses. Advanced materials could reduce fuel consumption about 1 percent through direct blade weight savings and even more indirectly. The indirect benefit arises from the ability to use more blades while maintaining sufficient blade retention strength in the thinner root sections. This permits more efficient, lightly loaded blades with activity factors about 70 compared to currently limiting values of 90-95 that would be constructed, for example, with a steel or metal matrix spar with a Kevlar or graphite shell. The shell could be load-sharing, unlike current designs, and the blade specially tailored to avoid aeroelastic flutter problems at high propeller speeds.

Another attractive concept is synchrophasing the left and right propellers to within a technically challenging one degree in phase angle. Experimental evidence indicates that an 8 dB noise reduction potential exists for precision synchrophasing which could eliminate large fuselage acoustic weight penalties for typical wing-mounted engine configurations (800+ lb. savings for 30-passenger, Mach 0.45 airplanes with B-737 cabin noise level).

These advanced propeller concepts could reduce fuel burned about 5 percent relative to the best of today's propellers assuming no precision synchrophasing weight saving or 7 percent including it. The corresponding DOC benefits are 3 percent and 6 percent, respectively (fig. 12).

OVERALL POWERPLANT BENEFITS-The value of using advanced technology was established by hypothetically installing such powerplants in 30- and 50- passenger aircraft resized to accomplish a fixed mission and comparing the results with similarly flown existing and mid-1980's engines (fig. 13). The combined DOC benefit including engine, gearbox, propeller, and nacelle improvements is estimated to be 9-13 percent relative to the second generation powerplants now in development. The corresponding fuel saving is 15-19 percent (fig. 14).

UNCONVENTIONAL ENGINES

The foregoing conventional engine opportunities offer significant benefit potential yet are somewhat restricted in scope when viewed from a totally open perspective. Since engine efficiency exerts such a powerful influence on airplane DOC, it is logical to extend the investigation to include further out fuel saving technologies such as regenerative turbine engines and advanced intermittent combustion engines. Interest in such engines has been almost non-existent for commuter applications yet recently completed analyses offer evidence that they ought to be taken more seriously.

TURBINE ENGINES-The present state of propulsion technology for low-powered aircraft is depicted in figure 15. Turbine engines are the preferred type of powerplant but their efficiency worsens as size is reduced. This adverse trend eventually becomes so severe that below 400 SHP piston engines are more competitive--partly due to their higher efficiency and partly because they cost 1/3 as much as similar sized turbine engines. Even in the 1500-5000 SHP category, though, turbine engines are 1/3 less efficient than their large commercial counterparts. The fundamental reason for the poorer small engine efficiencies is the practical size limit (about 1/2 inch) of small turbomachinery airfoils. This limit is set partly by our inability to manufacture very small blades with the necessary accuracy in airfoil profile, blade angle setting, and intricate cooling networks, and partly by adverse aerodynamic scaling effects such as disproportionately high tip clearances and low Reynolds number surface roughness loss. Together with material temperature limits, these constraints limit cycle pressure ratios and turbine inlet temperatures to relatively modest values (fig. 16).

Besides striving to increase component efficiencies, at least two other approaches are apparent (fig. 17) to mitigate these small engine limits. One is to substantially eliminate the material temperature limit and the associated turbine cooling penalties. This might be achievable with advanced ceramic technology or metal matrix composite technology. Efforts have already started in this direction in the government sponsored ceramic automotive engine programs(11). To be sure, this approach is quite risky since the technology is immature and the component reliability problems are very challenging indeed. But success could raise turbine temperature levels 300-400°F and would essentially eliminate the turbine cooling penalties.

The other approach is to partially recover the waste heat in the exhaust flow by transferring it to the combustor inlet airflow--regeneration. Regenerative cycles obtain high efficiency without the need of high compressor pressure ratios (values near 15 are usually optimum). Hence, these cycles are especially attractive in small engine sizes. Recent Army sponsored studies(12) at 500 SHP show efficiency gains of 10-20 percent compared to the simple turboshaft cycle, while other military studies involving 5000 SHP engines show only 5-7 percent gain. The main drawback of regeneration is the extra weight required by the heat exchanger system which is variously estimated at 30-50 percent of the simple cycle weight. The technical challenge is to manufacture the heat exchanger compactly and leak-free, and to survive the corrosive environment and thermal stresses induced by engine on-off cycling.

Each of these approaches, if applied to commuter sized powerplants, could increase engine efficiency about 17 percent above comparable technology conventional engines (fig. 18). If both ceramic and regenerative technologies were used together, substantially higher gains are possible--as much as 40 percent beyond an advanced conventional cycle, for a total gain of 55 percent beyond the new crop of mid-1980's turboprops. The risk and resources required to establish the technology is, however, commensurate with the potential benefits.

INTERMITTENT COMBUSTION ENGINES-Returning to figure 15, it is clear that current piston engine are not well suited to commuter applications principally because they are too heavy. They also vibrate more than turbines, are noisier, bulkier, require more maintenance and require avgas--a supply and price vulnerable special fuel. Yet all of these shortcomings can be overcome if different mechanical configurations and advanced intermittent combustion technologies are successfully pursued. The key to lower weight lies in light-weight configurations (i.e., rotary or 2-stroke, radial diesel) accompanied by increased BMEP and RPM. These in turn require high speed, high pressure fuel injection and ignition technology, advanced turbocharger technology, and low-friction sliding seal systems. Multifuel capability requires stratified charge combustion systems. Higher efficiency can also be sought--mainly by recovering waste heat via turbocompounding and heat insulated or adiabatic structures (fig. 19).

Rotary and diesel engines have been defined that incorporate two levels of such advanced technology (fig. 20). The "advanced" versions imply a technology readiness date in the late 1980's assuming sufficient resources whereas the "very advanced" versions incorporate further steps such as lighter materials, adiabatic structures, high temperature lubrication, and non-contacting apex seals or piston rings (fig. 21). Additional description of these engines and their technologies is contained in reference 13 and 14.

BENEFITS-The efficiency and weight characteristics of these hypothetical powerplants are summarized in figures 22 and 23. Perhaps the most interesting observation is that the intermittent combustion types continue to look attractive on an efficiency basis even out to 2500 SHP or beyond and their weights, although heavier than turbine engines, are not so high as to automatically rule them out. To determine the net effect of these better efficiencies and weights, preliminary airplane sizing and fuel burned calculations were carried out using a modified version of the GASP computer program(15) and the 30-passenger, Mach 0.45 airplane groundrules defined earlier.

The results are depicted in figure 24 which shows how fuel burned varies with cruise BSFC and engine specific weight. Spotted on this parametric plot are the potential values for each of the previously discussed powerplants. Relative to the mid-1980's new engines, an advanced conventional cycle turboprop could save 10-20 percent in fuel not including advanced propellers or nacelles. The unconventional engine fuel savings are considerably greater--as much as 30-35 percent for the rotary, diesel, and regenerative turboprop, and 40 percent for a ceramic, intercooled version of the regenerative turboprop. Gains of this magnitude clearly represent quantum improvements and go beyond the customary evolutionary trend. Of course, the particular values assigned to the various candidates are subject to uncertainty due to the inherent technical risk with such concepts. If necessary, this plot can be used to quickly redetermine the fuel benefits for alternative engine assumptions.

The results just quoted apply to engines in the 1500 SHP class. For smaller engine sizes the unconventional engine benefits would be somewhat greater and for larger engines just the reverse is true (fig. 25). This trend occurs because the main fuel driver is SFC and the SFC advantage of the unconventional engines decreases with size (since the conventional turboprop becomes more efficient in larger sizes).

ON-GOING ACTIVITIES

Current commuter powerplant activity is focused on the development of the 1500-2000 SHP class of second generation engines, gearboxes, and propellers(16-20). Limited basic research activities continue on the more advanced technologies discussed previously. At NASA's Lewis Research Center, for example, generic efforts are underway to gain the necessary knowledge required to raise performance levels of small turbine engine components (fig. 26). These efforts include advanced computational modeling, experimental rig testing to verify and calibrate the analytic models, and the investigation of novel concepts such as those identified earlier. Industry is also researching some of these concepts (fig. 27). However, most of the government and industry efforts are quite modest at present and a comprehensive advanced technology program is not in place. Similarly, a small amount of basic research in intermittent combustion type aviation engines is in progress(14).

CONCLUDING REMARKS

The principal message to be gleaned from these studies is that several very important propulsion opportunities still exist for commuter air transportation. Powerplant technology has not been brought to a plateau status or even a diminishing return status. Instead we have arrived at a technological crossroad. We may choose to continue down the evolutionary path with its 9-13 percent DOC reward over the second generation powerplants that are now nearly ready for production. Or we may choose to accept a much larger challenge in pursuit of a much larger reward. This would require a comprehensive research effort addressing both the conventional and unconventional technologies.

The rather surprising competitiveness of the intermittent type engines in such large power sizes is bound to be viewed suspiciously. Actually the issue is not so much the efficiency or weight estimates that may be questioned as it is the secondary characteristics such as reliability, maintenance, and vibration. These secondary characteristics have not been addressed in depth and probably cannot be within a purely analytic framework.

These studies have provided information to help guide future technology activities. Since all of the alternative engine types appear attractive, it would be premature to eliminate any of them from contention at this early stage.

REFERENCES

1. L. J. Williams and T. L. Galloway, "Design for Supercommuters," Astronautics and Aeronautics, Vol. 19, No. 2, February 1981, pp. 20-23, 26-30.
2. C. Adcock, C. Coverston, and B. Knapton, "Application of Advanced Technologies to Small, Short-Haul Air Transports," General Dynamics, Convair Div., San Diego, Calif., September 1980. (NASA CR-152364.)
3. T. G. Coussens and R. H. Tullis, "Application of Advanced Technologies to Small, Short-Haul Transport Aircraft," Lockheed-California Co., Burbank, Calif., LR-29450, July 1980. (NASA CR-152363.)
4. E. Kraus, "Small Transport Aircraft Technology," Cessna Aircraft Co., NASA CR-152362 (final report in review).
5. P. P. Renze and J E. Terry, "Application of Advanced Technologies to Derivatives of Current Small Transport Aircraft," Beech Aircraft Corp., Wichita, Kans., July 1981. (NASA CR-166197.)
6. J. C. Gill, R. V. Earle, D. V. Staton, P. C. Stolp, D. Huelster, and B. A. Zolezzi, "Propulsion Study for Small Transport Aircraft Technology (STAT)," Detroit Diesel Allison, Indianapolis, Ind., DDA-EDR-10470, December 1980. (NASA CR-165499.)
7. C. E. Smith, R. Hirschkron, and R. E. Warren, "Propulsion System Study for Small Transport Aircraft Technology (STAT)," General Electric Co., Lynn, Mass., R80AEG068, May 1981. (NASA CR-165330.)
8. C. F. Baerst, et. al., "Small Transport Aircraft Technology (STAT), Garrett Turbine Engine Company, NASA CR-165610, May 1982.
9. J. P. Sullivan, L. K. Chang, and C. J. Miller, "The Effect of Proplets and Bi-Blades on the Performance and Noise of Propellers," SAE paper No. 810600, April 1981.
10. I. D. Keiter, "Impact of Advanced Propeller Technology on Aircraft/Mission Characteristics of Several General Aviation Aircraft," SAE paper No. 810584, April 1981.
11. J. A. Byrd, "Ceramic Applications in Turbine Engines," AIAA-82-1168, June 1982.
12. A. E. Easterling, "A Comparative Study of Simple, Regenerative, and Variable Capacity Cycles for Gas Turbine Engines, "Army Aviation Research and Development Command, St. Louis, MO., USAAVRADCOM-TR-81-D-1, October 1980.
13. A. P. Brouwers, "Lightweight Diesel Engine Designs for Commuter Type Aircraft," Teledyne Continental Motors, Muskegon, Mich. REFT-995, July 1981. (NASA CR-165470.)
14. E. A. Willis, "Development Potential of Intermittent Combustion Aircraft Engines for Commuter Transport Applications," SAE paper No. 820718, May 1982.
15. D. S. Hague "GASP-General Aviation Synthesis Program, Volumes 1-9," Aerophysics Research Corp., Bellevue, WA., January 1978. (NASA CR-152303.)
16. N. Stoten, "Design Features of a New Commuter Turboprop Engine," SAE paper No. 820717, May 1982.
17. A. Brooks and R. Hirschkron, "A Review of Commuter Propulsion Technology, SAE paper No. 820716, May 1982.
18. J. E. Harper and J. N. Hoopes "TPE 331-14/15 Design and Development," SAE Paper No. 820715, May 1982.
19. J. G. Russell, "Modern Propellers for Commuter Airlines," SAE paper No. 820719, May 1982.
20. R. G. Daigneault and D. G. Hall, "Advanced Propeller Technology for New Commuter Aircraft," SAE paper No. 820720, May 1982.

TABLE I - STUDY GROUNDRULES

- 600 N.M. DESIGN RANGE (PLUS IFR RESERVES FOR 100 N.M. ALTERNATE AND 45 MIN. HOLD)
- 4000 FT. FIELD LENGTH ON 90°F DAY AT SEA LEVEL
- 250 KNOT MINIMUM IAS FROM 6000 THROUGH 10000 FEET
- 180 KNOT MINIMUM IAS WITH GEAR AND FLAPS EXTENDED
- 93 KNOT MAXIMUM STALL SPEED IN LANDING CONFIG. AND WEIGHT
- FAR 36 STAGE 3 MINUS 8 EPNdB NOISE LIMITS
- 85 dB OASPL MAX. CABIN INTERIOR NOISE
- TECHNOLOGY MERIT CRITERION: DOC AT 100 N.M. STAGE LENGTH

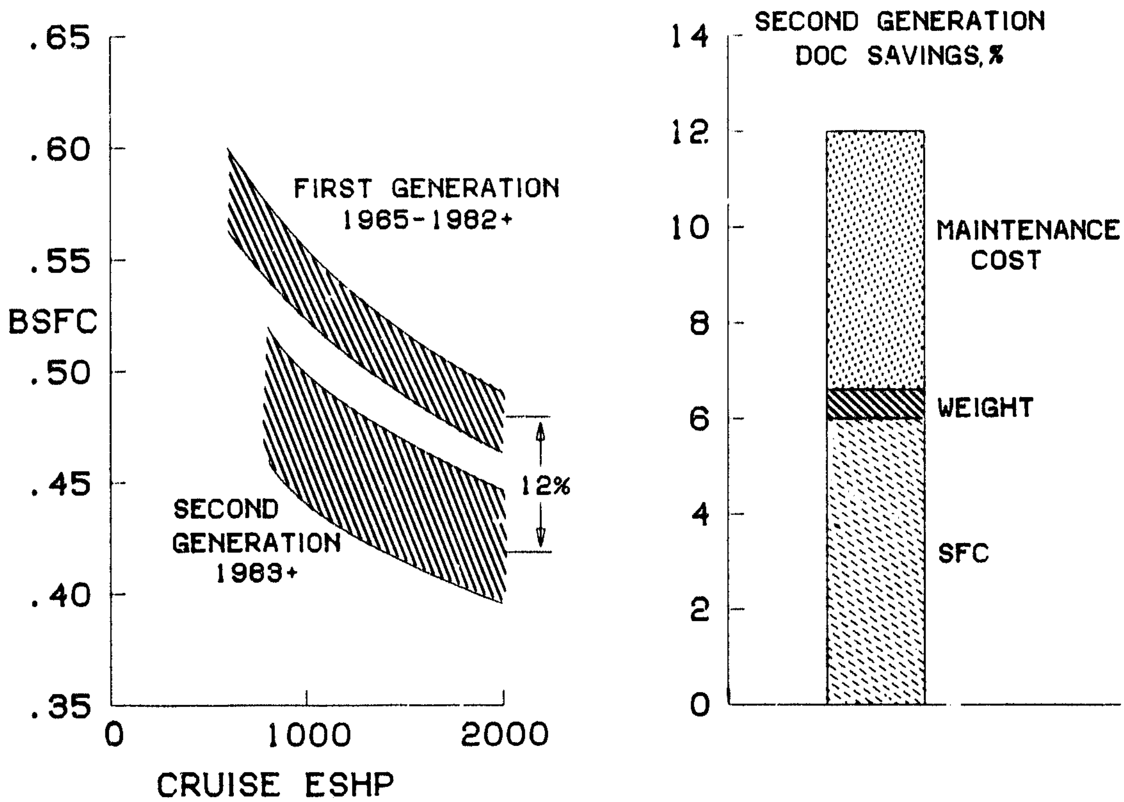


Figure 1. - Commuter aircraft powerplant status. Mach 0.45; 15 000 ft cruise; turboprop engines.

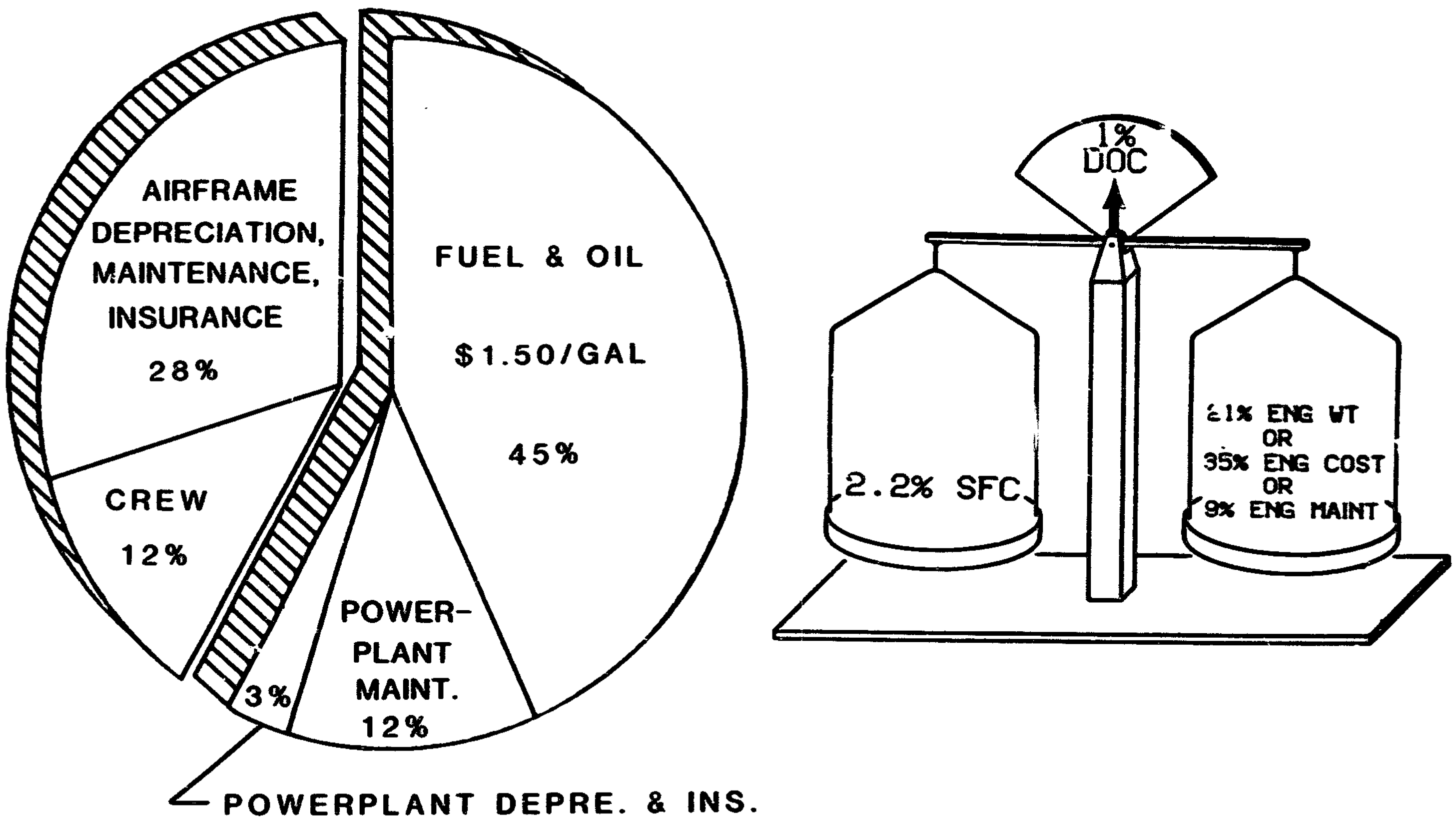
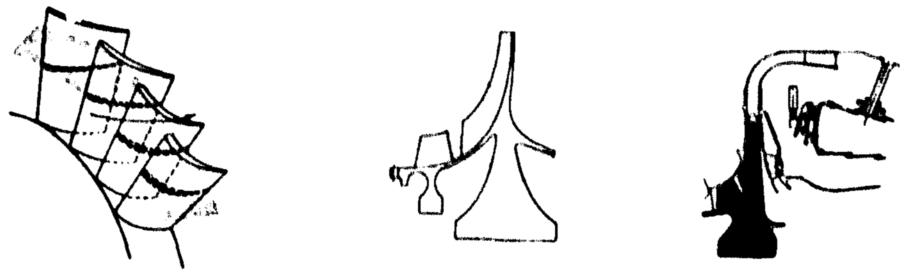


Figure 2. - Typical airplane DOC composition.

	CUSTOMIZED AIRFOILS	SPLIT-BLADE IMPELLER	ADVANCED DIFFUSER



CONCEPT	• TAILOR AIRFOILS FOR LOCAL FLOW CONDITIONS	• SPLIT ENERGY INPUT INTO TWO REGIONS TO ELIMINATE GEOMETRY CONSTRAINT	• CONTROL CONTOUR PASSAGES TO DESWIRL FLOW & FORM RADIAL TO AXIAL TURN • USE WALL BLEED AT THROAT TO REMOVE BOUNDARY LAYER
ENABLEMENT	ACCURATE 3-D VISCOUS FLOW ANALYSES & EXPERIMENTAL DATA BASE		
BENEFITS	• + 1% OVERALL EFFICIENCY • FEWER STAGES (3 VS. 5)	• BETTER CONTROL OF BLADE LOADING • FRESH BOUNDARY LAYER (+ 1% OVERALL EFFICIENCY)	• REDUCE PRESSURE LOSS (+ 1% OVERALL EFFICIENCY)

Figure 3. - Compressor aerodynamics technology.

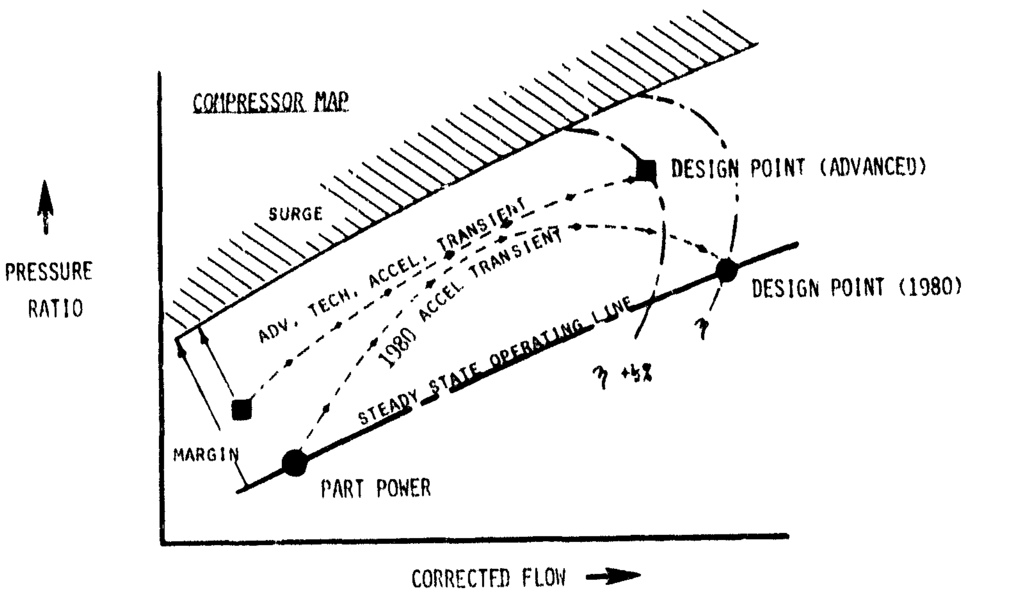


Figure 4. - Increased compressor efficiency via reduced surge margin. Requires closed loop engine acceleration control using digital electronics and compressor exit mach number sensor.

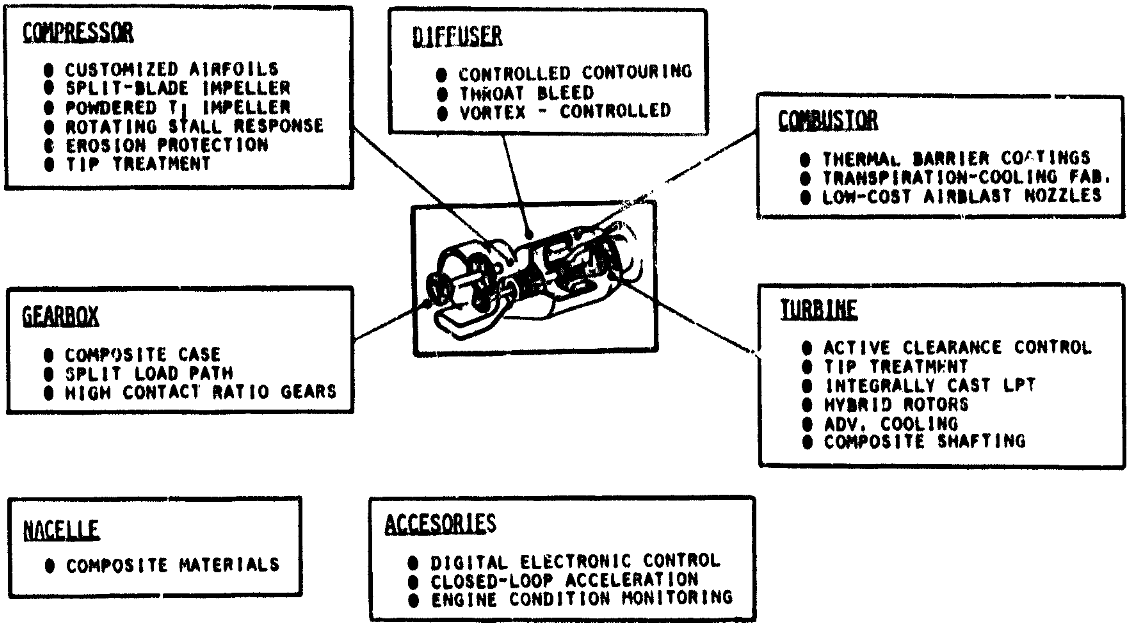


Figure 5. - Composite summary of advanced turboprop technologies.

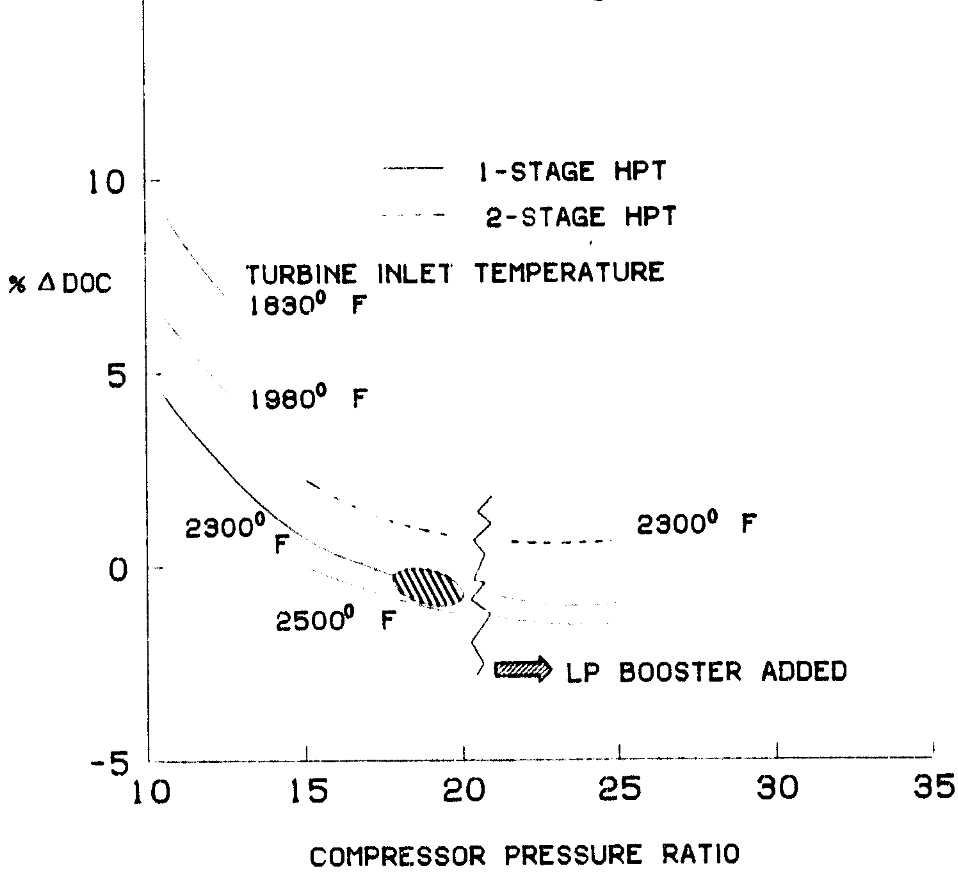


Figure 6. - Advanced commuter engine cycle selection. 100 n mi DOC; $1.50/gal fuel; 30 passenger; Mach 0.45; 1500-shp engine.

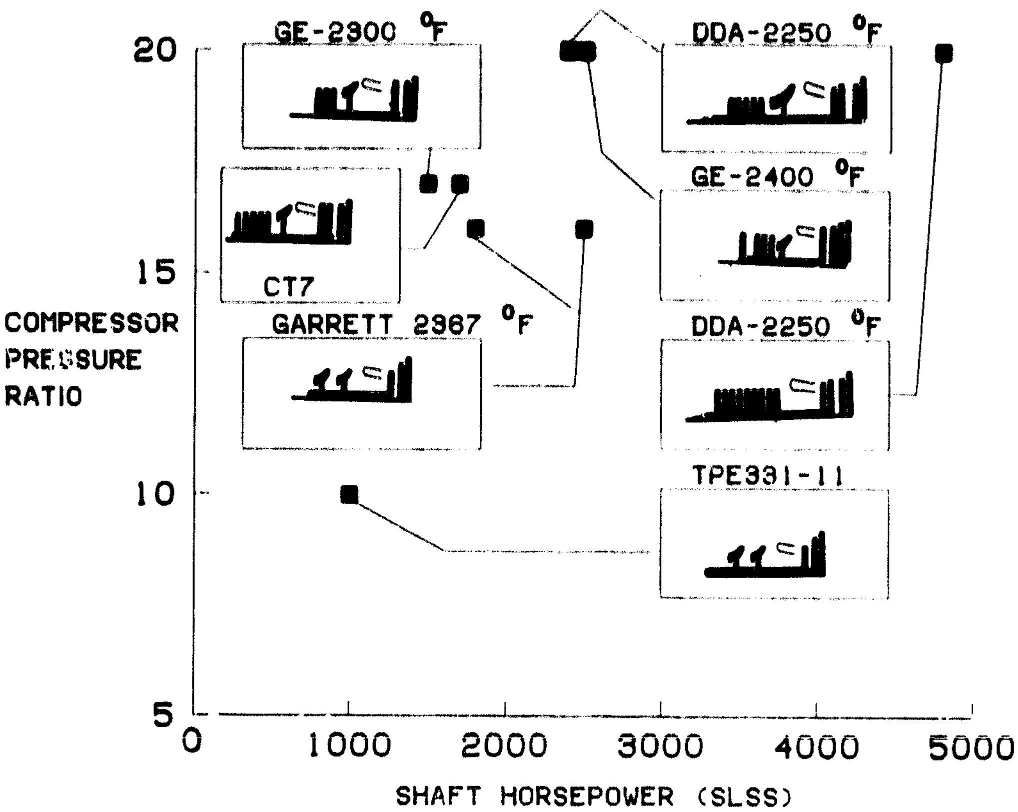
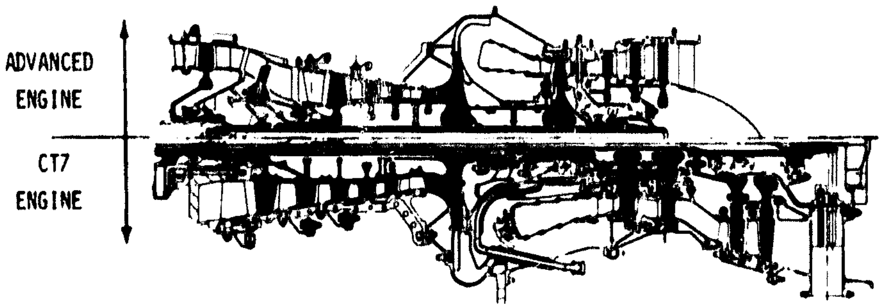


Figure 7. - Advanced engine configurations/cycles.



	CT7-5	ADVANCED ENGINE
TURBINE TEMP.	2290°F	2400°F
PRESSURE RATIO	17	20
CRUISE BSFC	.43	-14%
WEIGHT	1070 LB	-11%
COST	BASE	-12%
MAINTENANCE COST	BASE	-17%

Figure 8. - Advanced technology turboprop engine. GE design scaled to 1620 takeoff shp.

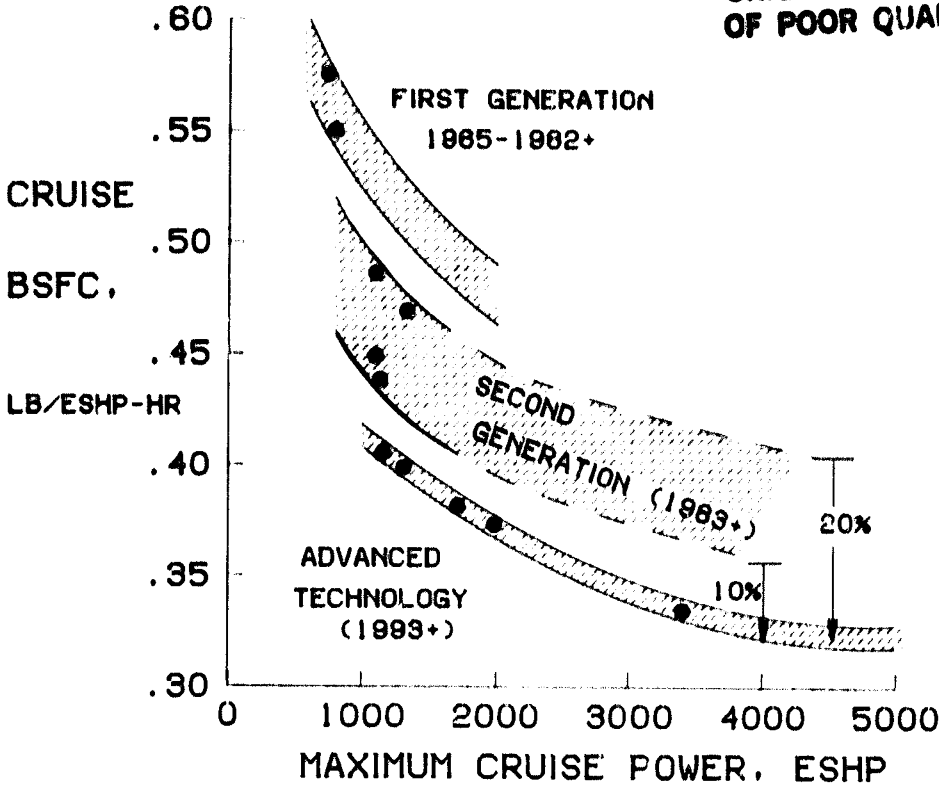


Figure 9. - Commuter turboprop efficiency levels. Mach 0.45; 15 000 ft.

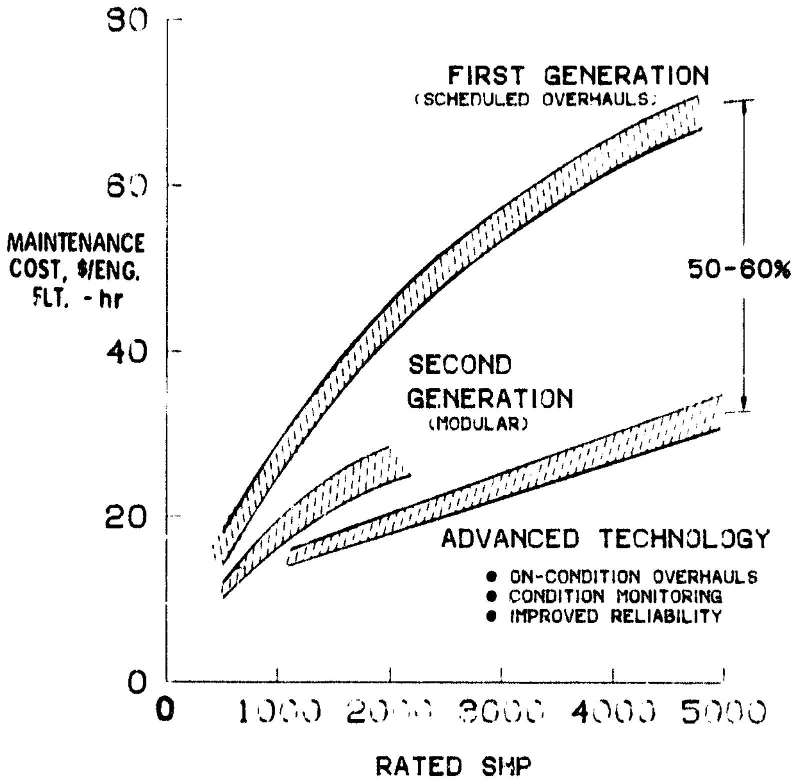


Figure 10. - Maintenance cost reduction. 100 n mi stage length.

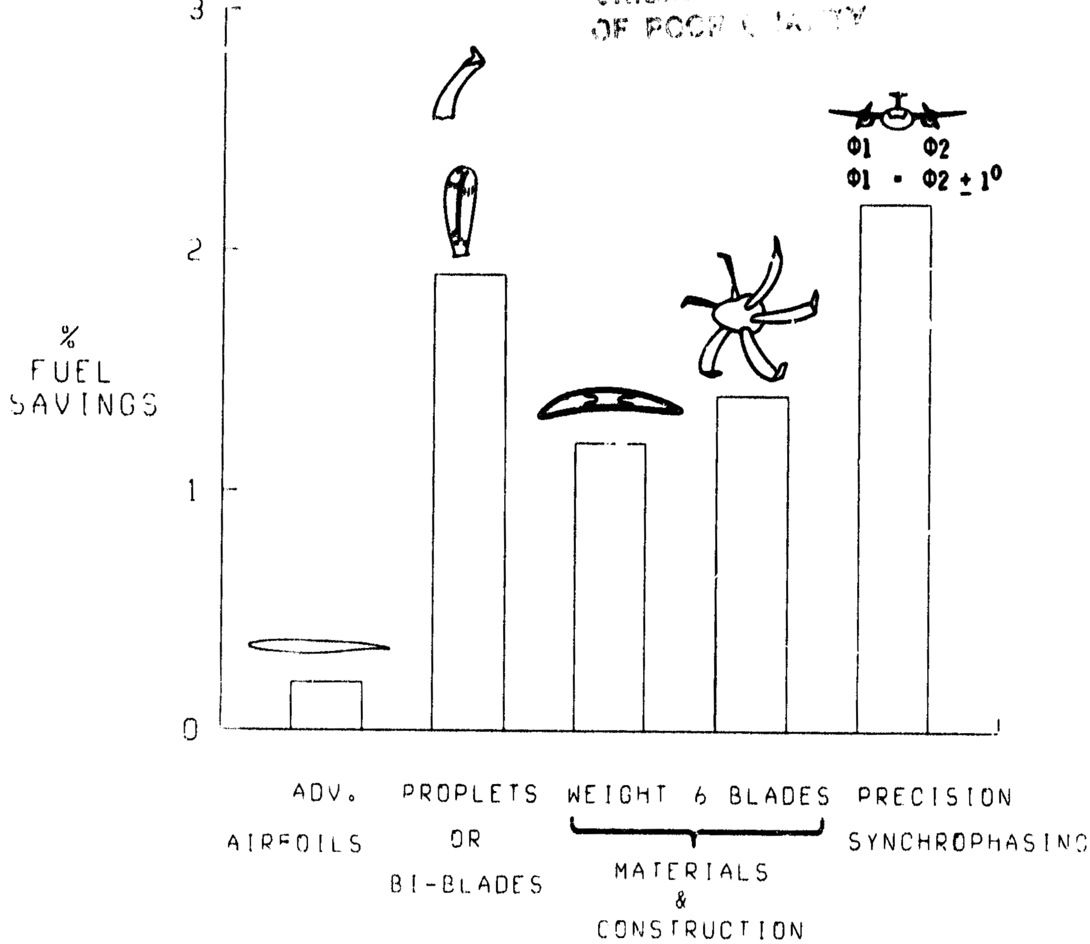


Figure 11. - Advanced propeller concepts.

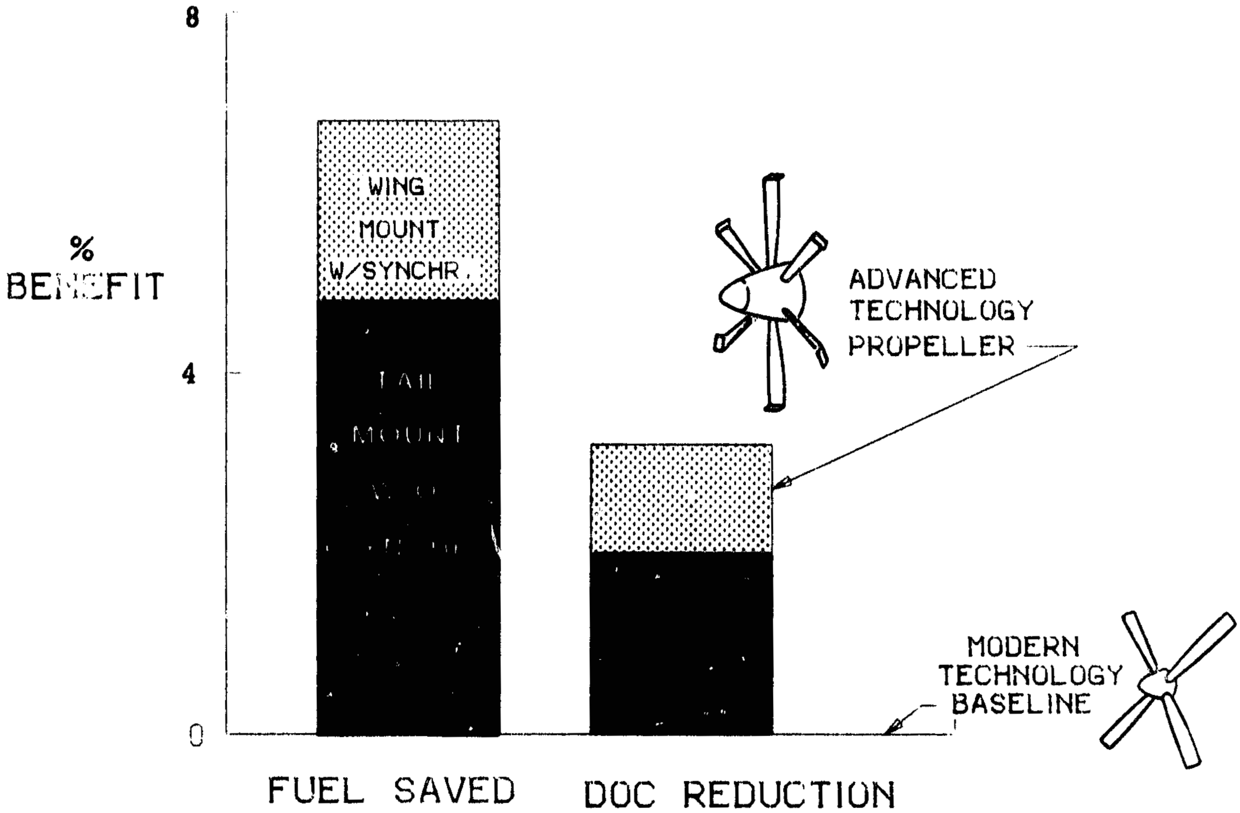


Figure 12. - Advanced propeller technology benefits. 30 passengers; Mach 0.45; 100 n mi; $1.50/gal fuel.

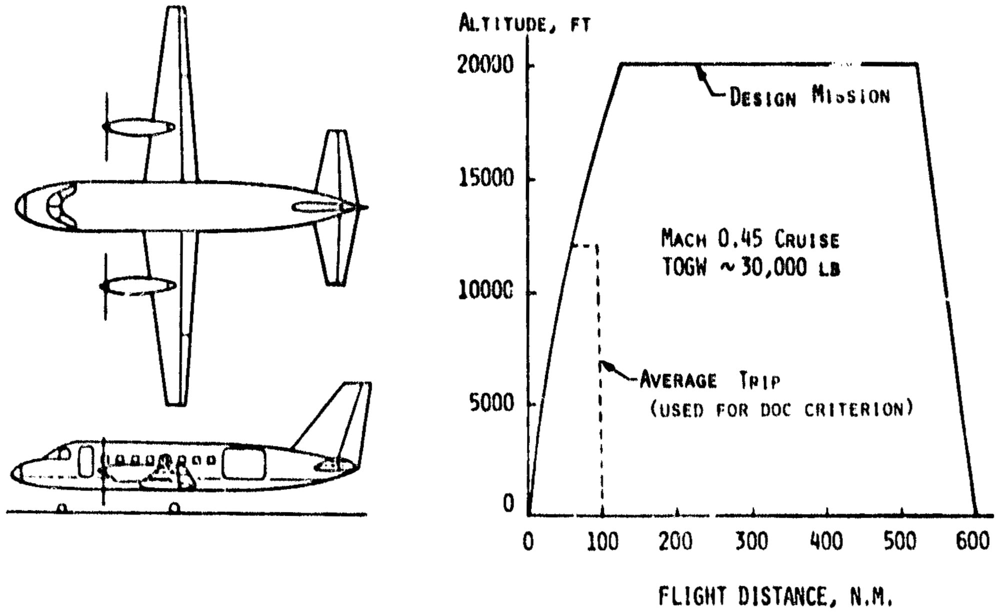


Figure 13. - Typical 30-passenger airplane and mission.

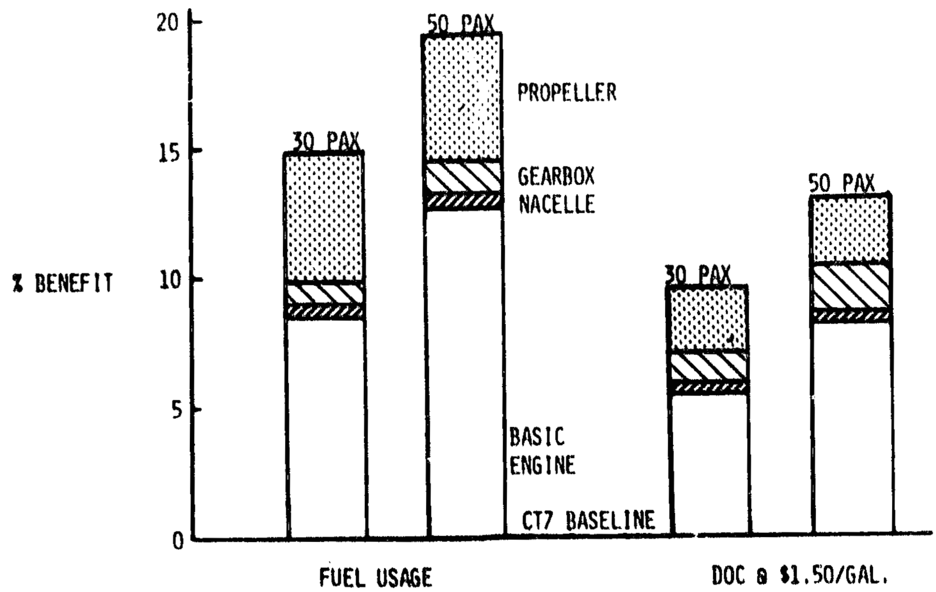


Figure 14. - Advanced propulsion benefit summary. Mach 0.45, 100 n mi trip.

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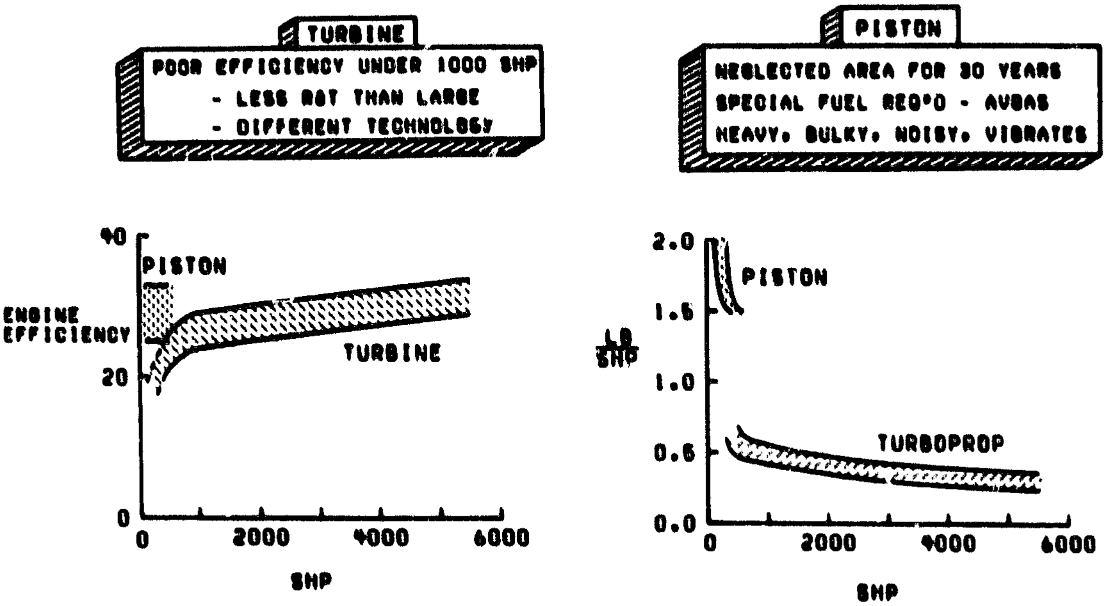


Figure 15. - Small engine technology status.

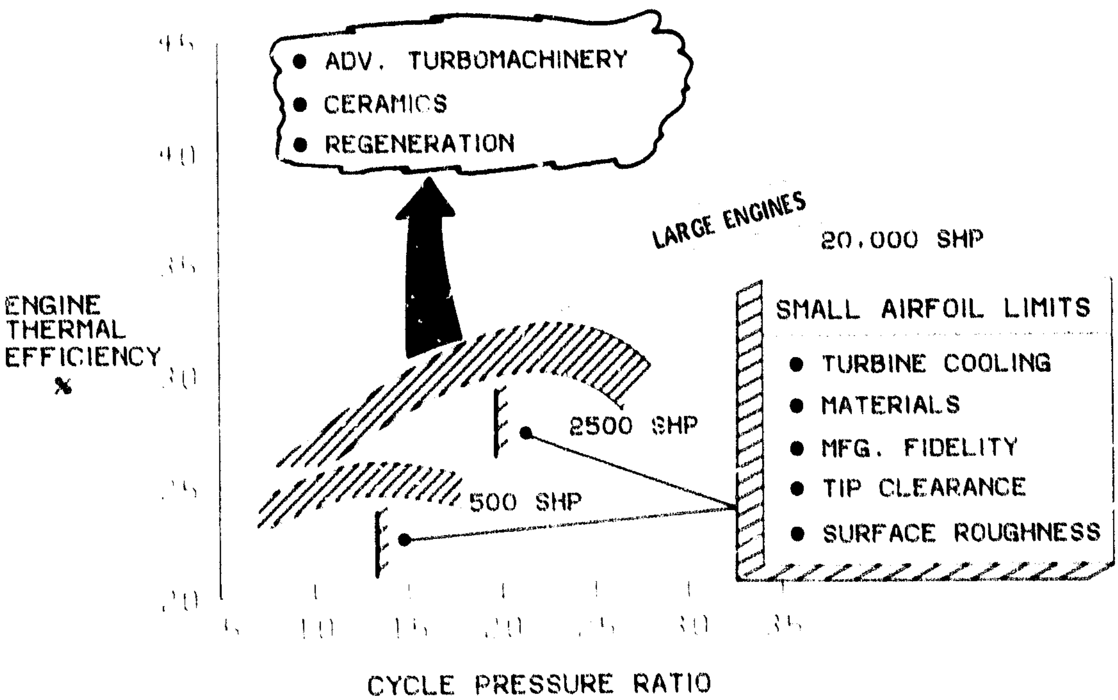


Figure 16. - Barrier and opportunities for greater efficiency. Small turbine engines.

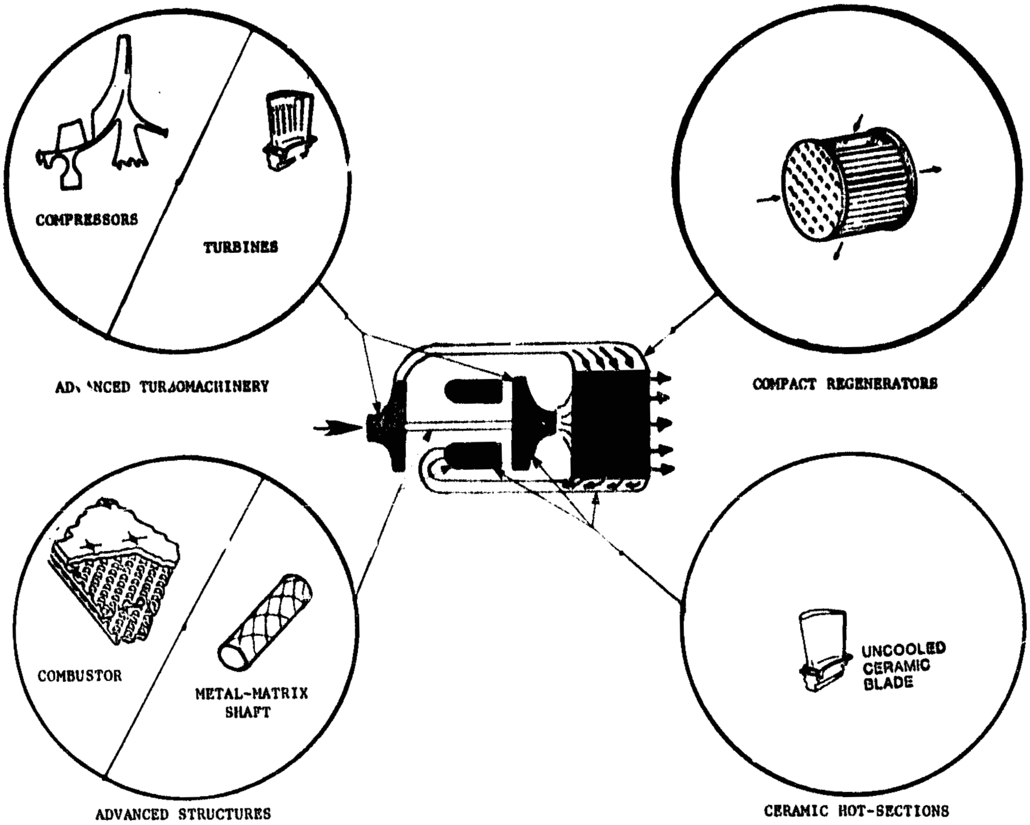


Figure 17. - Small turbine engine technologies.

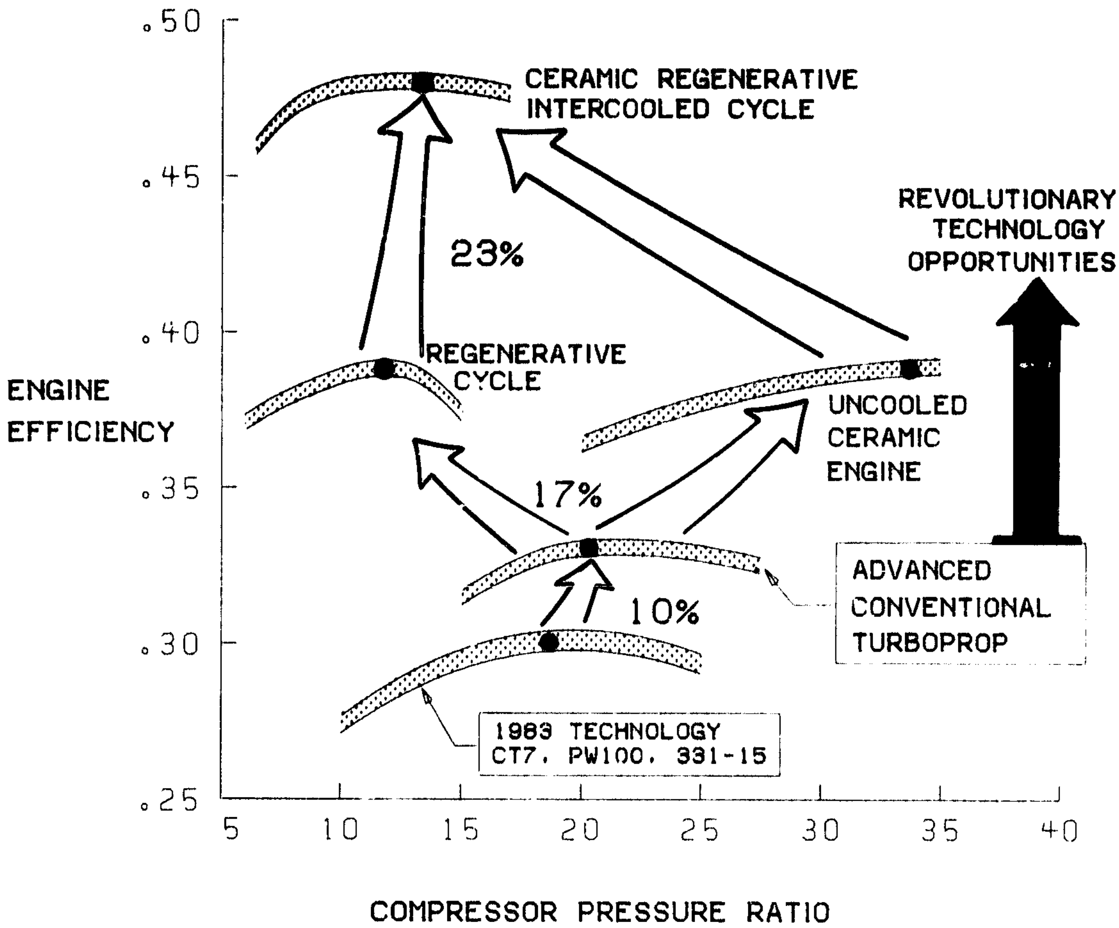
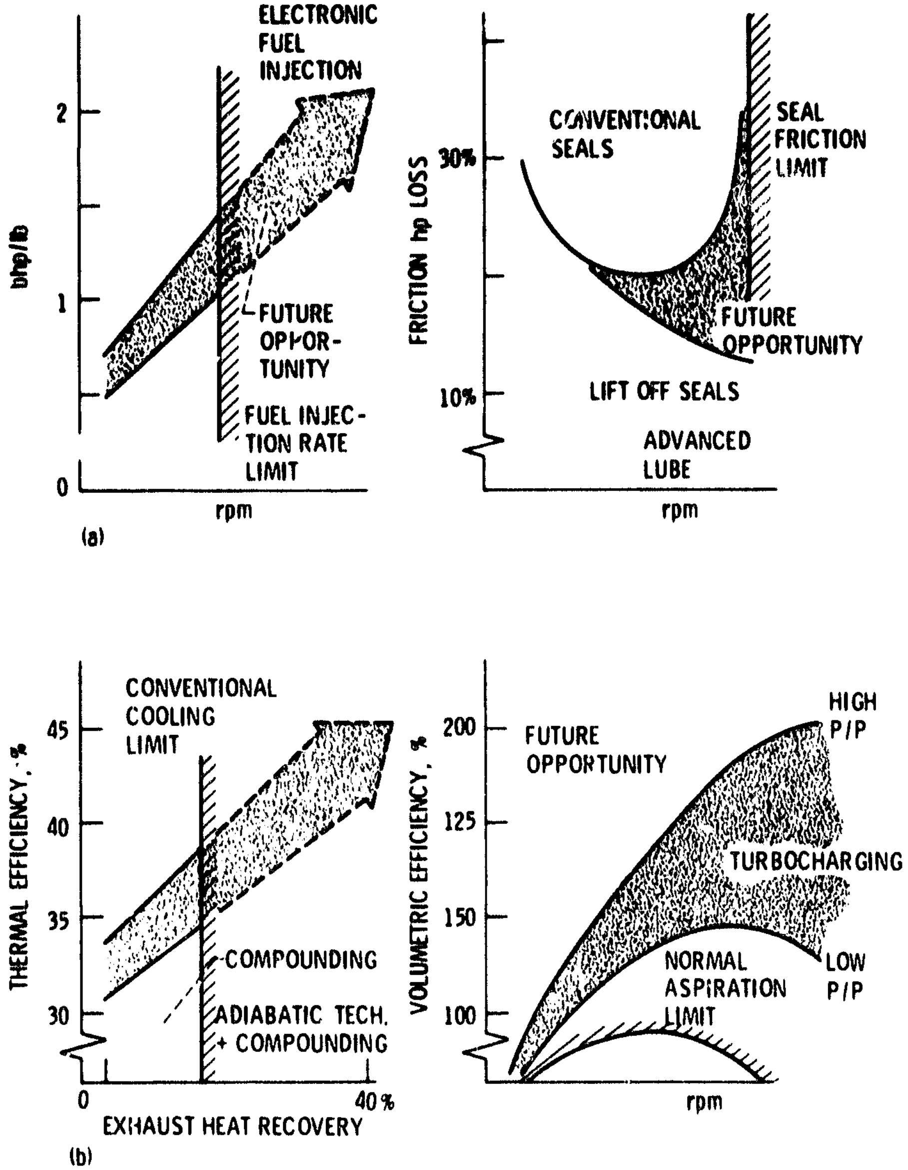


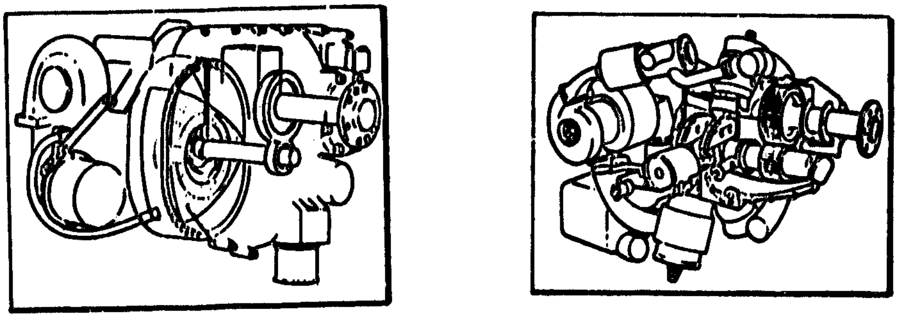
Figure 18. - Small gas turbine engine opportunities. 1500-shp class.



(a) Barriers and opportunities for greater power.

(b) Barriers and opportunities for increased efficiency.

Figure 19. - Intermittent combustion engines.



TARGETS*	ROTARY		DIESEL	
	ADVANCED	VERY ADV.	ADVANCED	VERY ADV.
o BSFC - LB/BHP-HR	0.33	0.30	0.30	0.28
o SP. WT. - LB/BHP	0.95	0.85	0.80	0.70
o TBO - HR	2000	3000	2000	3000
o MULTIFUEL	✓	✓	✓	✓

*15,000 FT., 2000 SHP MAX. CRUISE POWER

Figure 20. - Advanced intermittent combustion engines.

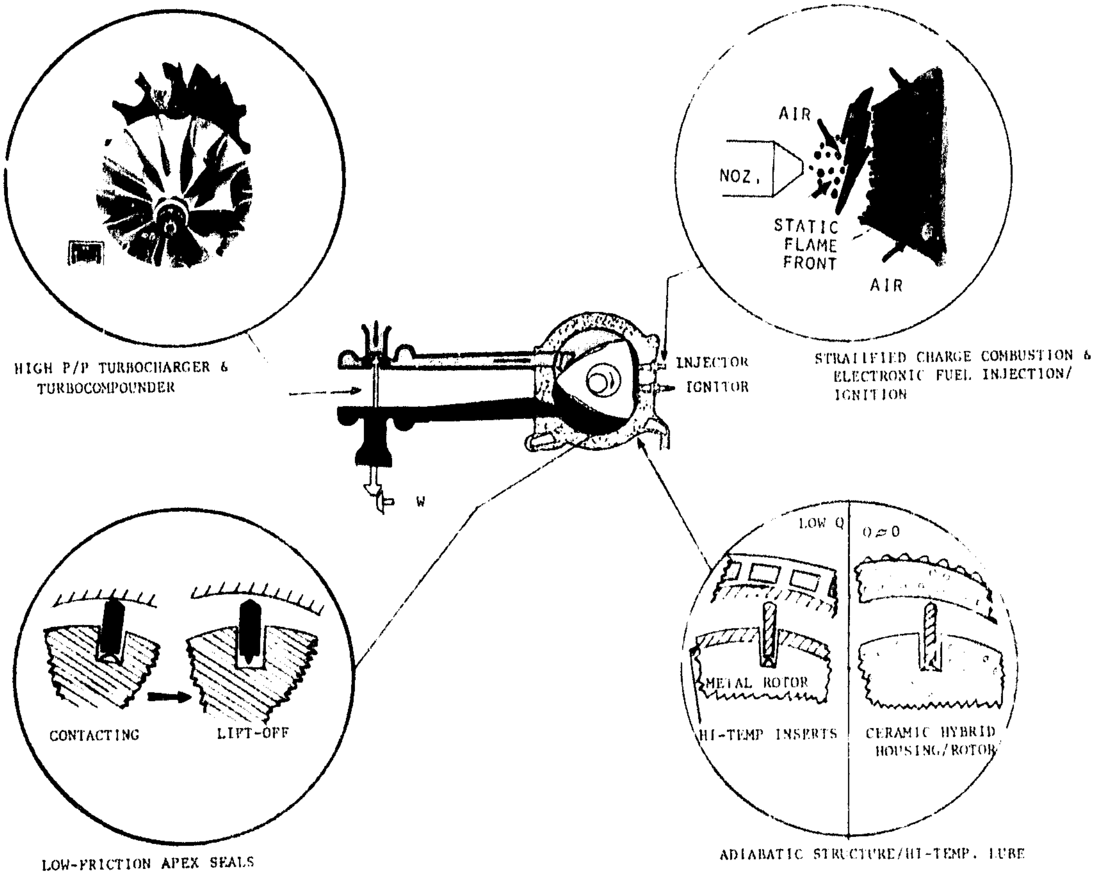


Figure 21. - Intermittent engine technologies.

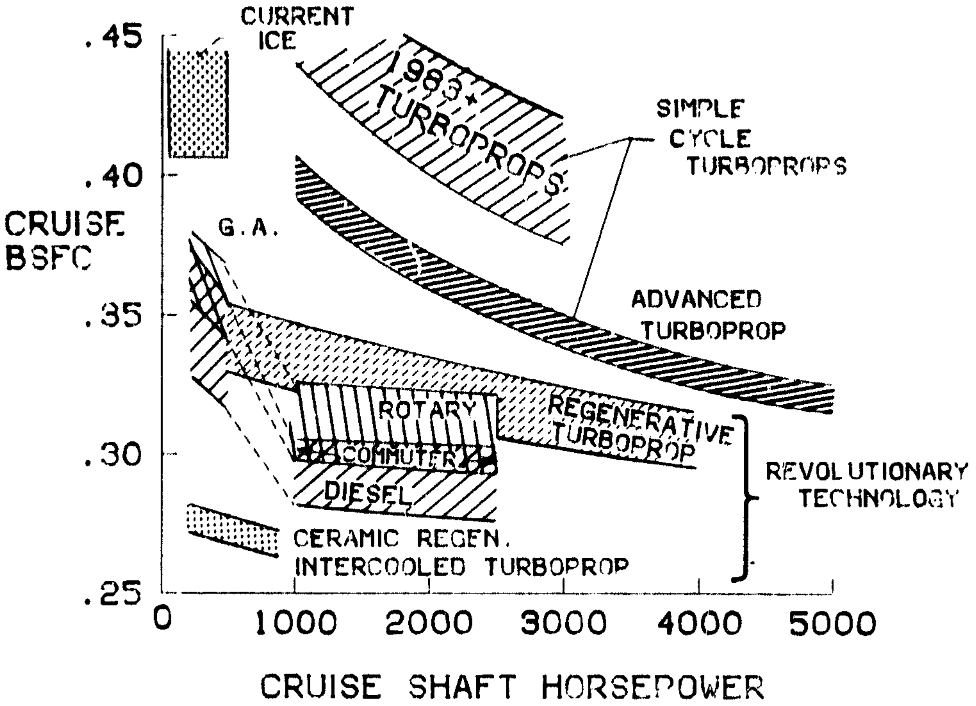


Figure 22. - Efficiency of advanced small aircraft engine candidates. Mach 0.45; 15 000 ft; uninstalled.

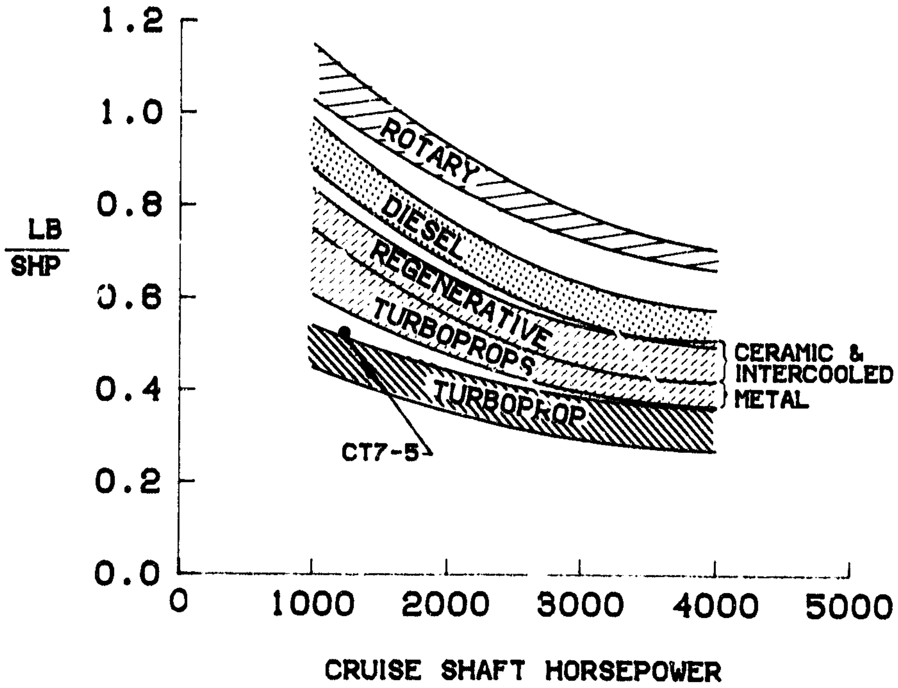


Figure 23. - Weight of advanced small aircraft engine candidates. Mach 0.45; 15 000 ft; uninstalled gearbox included.

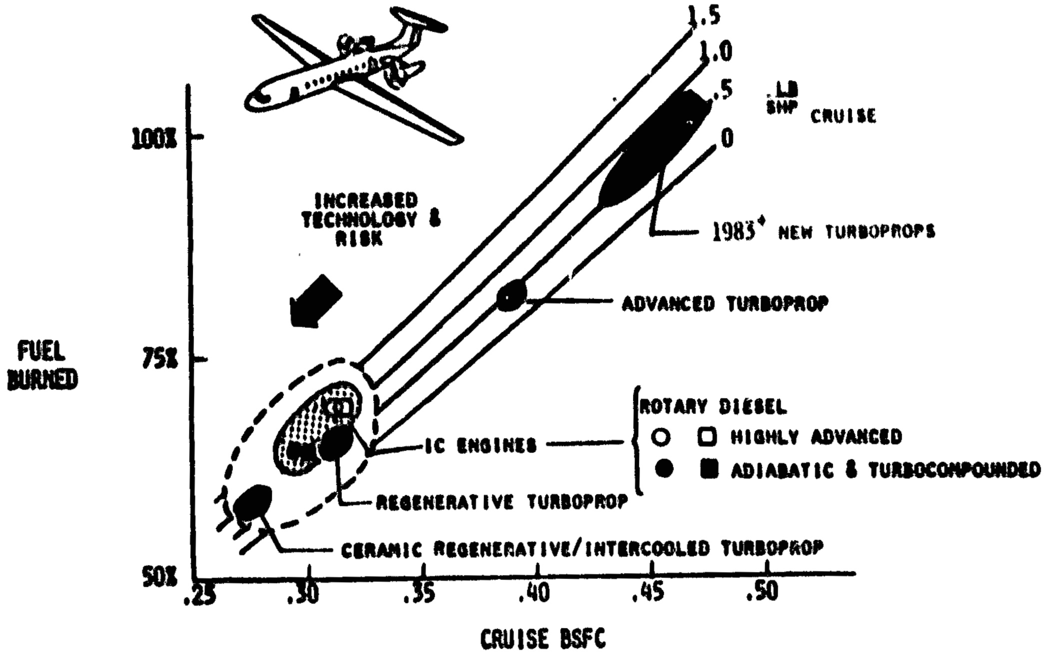


Figure 24. - Commuter aircraft propulsion opportunities. 30 passengers; mach 0.45; 15 000 ft; ~ 1500-shp SLSS.

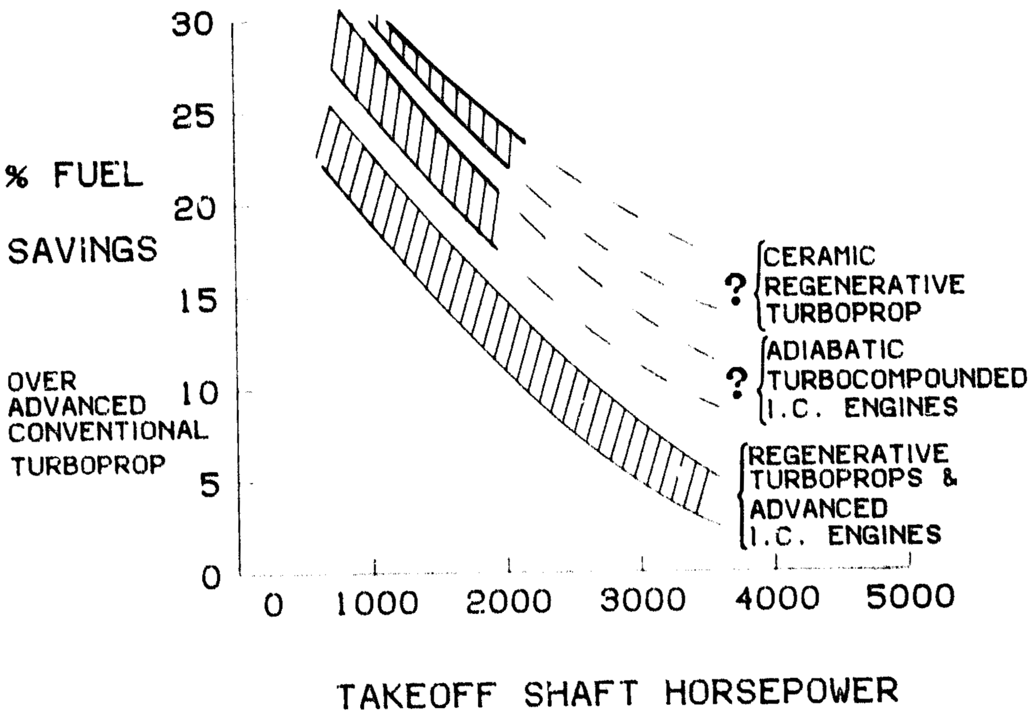
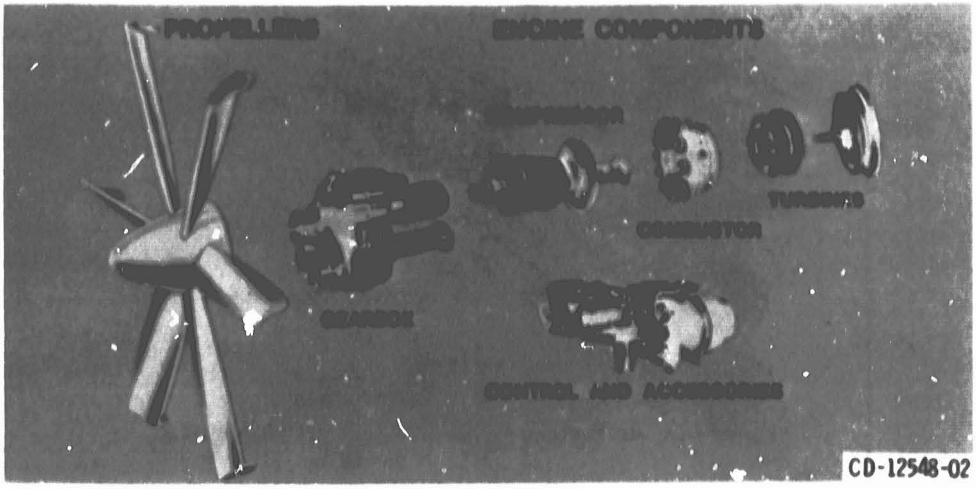


Figure 25. - Unconventional engine advantage is in small sizes. Mach 0.45; 15 000 ft; commuter aircraft.



BASIC RESEARCH TO GAIN KNOWLEDGE AND IMPROVE COMPONENT PERFORMANCE; PURSUIT OF ADVANCED CONCEPTS.

(a) COMPUTATIONAL MODELING. (b) EXPERIMENTAL RIG TESTING.

Figure 26. - LeRC small turbine propulsion current generic research.

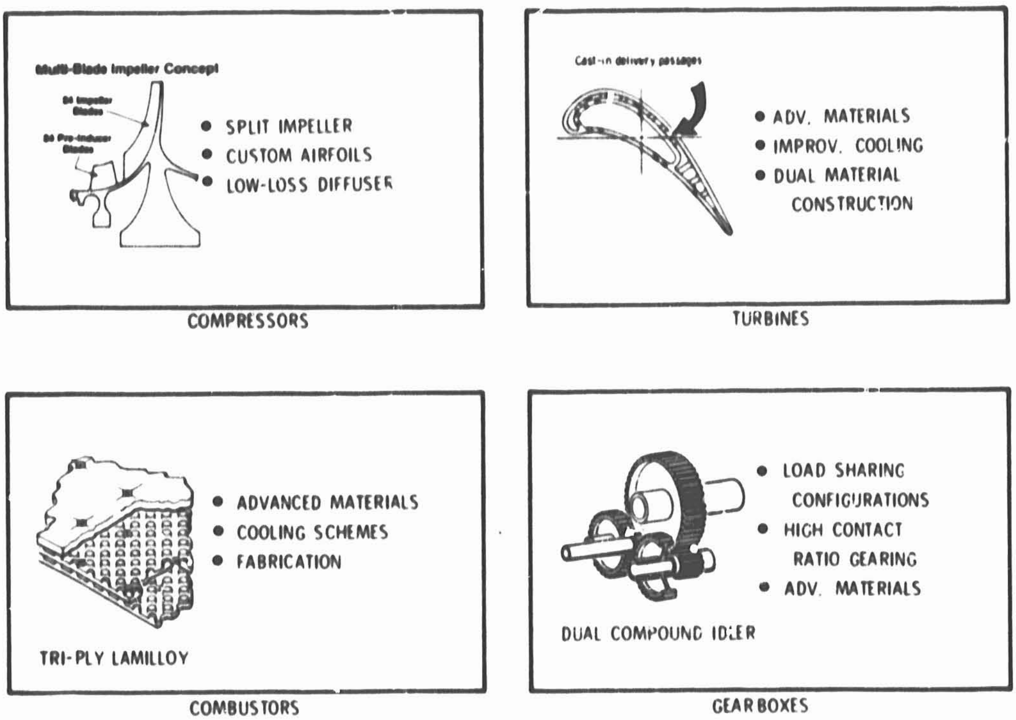


Figure 27. - Small turbine engine technology.