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# Propulsion Opportunities for Future Commuter Aircraft

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# PROPULSION OPPORTUNITIES FOR FUTURE COMMUTER AIRCRAFT

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## Abstract

Circa 1990 propulsion improvement concepts are discussed for 1000-5000 SHP conventional turboprop powerplants including engines, gearboxes, and propellers. Cycle selection, powerplant configurations, and advanced technology elements are defined and evaluated using average stage length DOC for commuter aircraft as the primary merit criterion. The paper summarizes a series of five NASA-sponsored studies that addressed this topic and assesses the significance of the resulting overall powerplant improvement potential relative to current production powerplants, engines now in development, and unconventional alternatives such as adiabatic diesels and regenerative turboprops.

## Text

The rapid growth of air transportation since the start of the jet age has wrought ever larger and faster aircraft to satisfy dense and long-range markets. Together with regulatory reform this trend created increasing demand for aircraft designed specifically for short haul markets (fig. 1).

During the 1970's commuter passenger air traffic grew at an average annual rate of 14 percent. This rapid growth is expected to continue--spurned on by the abandonment of air service to small communities by the major airlines as a result of high fuel prices and deregulation. In 1980 commuter airlines carried about 4 percent of air carrier traffic, but by 1990 the commuter portion is estimated to increase to 10 percent. Since current turbofan powered airplanes are too large and inefficient for successful short-haul applications, this market will be satisfied by increased numbers and varieties of propeller-driven aircraft.[1]

In response to this increasing need, many new commuter airplane development programs have been launched as well as the development of several new turboprop powerplants in the 1200-2500 SHP class (e.g., CT7, PW100, TPE 331-15). These new airplanes and their powerplants will generally be somewhat larger than most of the current commuter airplanes, utilize rather conventional configurations, and employ technology advances already defined and well in-hand. There are, of course, longer term technological opportunities that can be envisioned. Such opportunities were the subject of recent NASA-sponsored studies that addressed potential improvements in airplane aerodynamics, structures, systems, and propulsion disciplines. These so-called STAT (Small Transport Aircraft Technology) studies were done initially by several airframe manufacturers who assumed potential powerplant improvements based mainly on judgment.[2] To provide substantive evidence for these powerplant assumptions, a series of complementary propulsion studies was then initiated by NASA with the General Electric Company, Detroit Diesel Allison, and the Garrett Turbine Engine Company to identify and evaluate specific engine technologies for advanced conventional turboprops.

To help focus these studies, guidelines were set forth (Table 1) that included specifying the technology timeframe to be 1988 readiness--i.e., technology brought to a level that is ready for commercial development. This implies that engines using such technology could enter service in the early 1990's. This was an important assumption because the new generation of 1200-2500 SHP engines now in development will enter service in the mid-1980's. Each company selected both a current production engine and a mid-1980's production engine as baselines to measure the benefits of their advanced technology 1990's conceptual engines (Table 2). All of these engines, whether actual or hypothetical, were scaled during the studies to power conventional 30- and 50-passenger twin-engine airplanes designed to fly Mach 0.45 for 600 N.M. However, Allison deleted the 30-passenger airplane and added a 50-passenger, Mach 0.70 airplane in order to complement Lockheed's STAT high-speed airplane designed for executive transport as well as for commuter use. The required takeoff power for these applications ranged from 1300 to 5000 SHP. For completeness, Hamilton-Standard and McCauley investigated advanced propeller technologies.

## Advanced Engine Technologies

To enable a long list of candidate technologies to be screened according to potential value, 100 N.M. stage length DOC was selected as the single most meaningful criterion that properly reflects the relative importance of diverse characteristics--powerplant efficiency, weight, cost, maintenance requirements, size, etc. On this basis, fuel efficiency is the dominant driver since over 1/3 of airplane DOC is fuel cost (fig. 2) and the sensitivity of both DOC and block fuel to engine weight, cost, and maintenance cost is much less than for SFC (fig. 3)

## Compressors

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. 4-5):[3]

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 technologies 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 computation 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. 5).

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

1. Passive clearance control to reduce blade tip clearances by 15 percent (1.1 percent DOC reduction)
2. Hybrid impeller rotor using HIP bonding to attach a cast rim with blades to a forged hub which permits higher tip speeps (-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.[5] Garrett also proposes a comprehensive parametric investigation of tip treatment configurations (e.g., slots) with the goal of improving compressor efficiency two points.

## Combustors

Combustor technologies showing DOC payoff included advanced materials for longer life, better cooling techniques, and better fabrication methods (fig. 6). The use of an oxide dispersion strengthened (ODS) material such as MA956 offers much higher operating temperature capability (+ 600°F) than conventional combustor materials such as Hastelloy X and HS-188. This could be exploited to simultaneously increase life fourfold and reduce the quantity of required cooling air. The reduced cooling airflow means that more dilution air is available to better control the discharge temperature pattern. The more uniform temperature pattern results in less severe cooling problems for the high pressure turbine vanes and shrouds which should increase their life about 15 percent. On the other hand, ODS material costs an order of magnitude more than conventional materials, incurs nonrecoverable property loss in welds, and has unknown fatigue resistance. The higher material cost would raise DOC about 1/4 percent and partially offsets the 1/2 percent DOC maintenance cost savings for a net improvement of approximately 1/4 percent.[3]

Another approach which promises slightly better DOC improvement is the use of thermal barrier coatings (e.g., magnesium zirconate) applied to the hot side surface of the liner and impingement cooling shields to increase the cooling effectiveness in the aft end section. This approach could yield a 50 percent liner life improvement and 15 percent better HPT vane and shroud life with negligiable increase in engine price. General Electric preferred this approach over the ODS material technology.

Both Allison and Gerrett recommended transpiration cooling technology instead of conventional film cooling to increase combustor life twofold. In one such scheme cooling passages are photoetched into sheets of liner material (fig. 6) which are then stacked together and bonded.[4] Small sheets of this material are then shaped and welded to form the combustor assembly. To bring this concept to fruition, fabrication improvements are needed to produce lower stress and temperature values in joints and bend radii. Conventional welding and forming techniques produce high local stress concentrations and restrict the cooling flow. Better manufacturing methods are also required to decrease fabrication costs.

Another alternative to increase durability significantly (by a factor of 2) is to machine the liner which would eliminate hot spots due to sheet metal thickness tolerances and double thicknesses at overlap joints.[5] This alternative also needs more economical fabrication techniques since such a machined ring combustor would cost 50 percent more than one using conventional techniques.

## Turbines

Several advanced high temperature materials were considered that would lower cooling flow penalties (e.g., cast single-crystal nickel-base alloys and directionally solidified eutectic alloys) in the core turbine. However, despite their increased engine efficiency potential of 0.7-1.2 percent, this advantage is outweighed by the much higher initial cost and maintenance costs of these materials.[3-5]

There are DOC savings, though, associated with: Advanced turbine cooling technology, blade tip clearance control, and hybrid material turbines. One recommended cooling improvement is the addition of leading edge impingement film cooling passages in the HPT blades rather than use the existing practice of pure convective cooling (fig. 7). This could save 2 percent in fuel and as much as 1/2 percent in DOC for engines sized for a 50-passenger aircraft. However, this technology is difficult to apply in small engines and the DOC payoff is cut in half for 30-passenger sized engines.[3-4] Cooling flow modulation was identified as another way to save fuel (0.8%) and lower DOC (0.4%).[5]

To combat the problem of maintaining acceptable interstage leakage with practical production tolerances in these small size engines, both passive and active blade tip clearance control methods are attractive. The passive seal concept (fig. 7) uses an abrasive blade tip coating and an abradable coated shroud to reduce the running clearance without risking severe engine damaged during an emergency engine shutdown caused by differential thermal contraction rates. It also makes the engine more tolerant of rotor offset caused by normal production tolerances. This concept has been experimentally verified, but needs additional research effort before production development.[4]

Complementing passive clearance control is the possible use of an active clearance control scheme whereby the tip shrouds are moved radially inward to tighten running tolerances during steady state conditions. Both mechanical systems (Allison) and thermal systems (GE and Garrett) are envisioned (fig. 8).[3-5] The mechanical system has a rapid response time advantage, but is probably more complex and heavier than the thermal system. The thermal system is controlled by modulating the cooling air flow to adjust shroud diameter, but is relatively slow reacting. Neither method offers a large improvement for short range commuter applications due to the short cruise durations.

## Shafting

The pursuit of better engine efficiency continues the trend toward high cycle pressure ratio which dictates higher rotor speeds and smaller engine diameters. This situation compounds the problem of transmitting torque from the power turbine through the high pressure spool to the propeller shaft. For these advanced engines it becomes impossible to use conventional forged-steel shafts without incurring critical speed problems (shaft speed passing through bending critical response speeds). The most promising solution to this problem appears to be the use of metal matrix composite shafts to increase the stiffness to density ratio about 40 percent (fig. 9). This would permit subcritical shafts thin enough to keep the turbine disk bore diameters small. The simular bore diamters reduce disk stress levels enough to enable the higher turbomachinery rotation speeds required to raise compressor and turbine efficiencies with fewer stages.[3-4]

## Structure

Another problem aggrevated by the use of fewer and more highly loaded compressor stages is the maintenance of tight rotor tip clearances during periods of rapid thermal gradients and during surge and rotating stall transients. It is important, therefore, to improve our capability to accurately predict the tip clearance variation during periods of dynamic structural response induced by rotating stall, for example, (fig. 10). Current analytical techniques do not account for asymmetric effects in rotor/case coupled structural response. These asymmetric effects include such items as flanges and bleed manifolds that can be very important to the structural dynamic response.[4]

Apart from the engine itself, the use of composite nacelles rather than aluminum is estimated to reduce weight 20-25 percent and reduce cost 25-30 percent. These improvements lead to DOC reductions of 0.3-0.4 percent.[3]

## Gearboxes

Improvement concepts for gearboxes are identified in figure 11. Split power geartrains such as the dual compound idler system can reduce the number of gears significantly which increases efficiency and reduces weight and cost. Externally mounted propeller and aircraft accessories and lube system components, and on-condition maintenance are design factors which contribute to less maintenance. High contact ratio gearing reduces gear tooth dynamic loads thereby producing smoother load transmission with less noise and vibration, as well as less weight.

Composite gearbox housings also save weight. Vacuum melt, high purity steels offer large improvement in bearing material properties that could lead to weight savings and extended bearing life. Bearing longevity can also be enhanced considerably with advanced lubricants exhibiting high film strength and flat viscosity versus temperature behavior. Collectively, these potential improvements could raise gearbox efficiency about 1/2 percent while reducing weight about 14 percent, cost 20 percent, and maintenance cost 80 percent. These yield DOC reductions of 1.2-1.7 percent.[3]

## Design Features

In addition to the advanced concepts just discussed, several design features were considered that do not necessarily involve technology improvement, but do represent departure from current design practice.

### Modular Construction

Modular design to permit on-the-wing replacement of major component groups such as the gearbox, compressor, HP turbine, and power turbine would facilitate easy maintenance and has been frequently identified as a desirable feature of any new engine. The new second generation engines, in fact, incorporate much modularity to help reduce maintenance. Garrett and Allison incorporated modularity into their advanced engine designs as well as other maintenance reduction features such as providing extra balance material on high-speed rotors, threaded inserts to facilitate the removal of loose studs, welded assemblies rather than brazed, and inserted rather than integral blades.

GE, however, reported that their modular design actually increased DOC. Their modular configuration requires an extra bearing and sump in the turbine region compared to a non-modular configuration.[3] This added complexity increases the part replacement cost which offsets the labor savings, resulting in a small net increase in engine maintenance cost. The modular design also weighs more and costs more initially, and its overhung high-pressure turbine requires larger tip clearance to prevent rubs during maneuver load deflections (0.6% SFC penalty). These adverse affects combine to yield a net 0.4% DOC increase. On the other hand, concluding that a modular hot-end design is detrimental also presumes that engine maintenance can be performed overnight without loss of revenue due to service interrruption. Thus, it appears that airplane operators knowledgable of their own requirements and also aware of the above penalties can best judge the overall usefulness of modularity.

### Foreign Object Protection

Both the frequency of major engine damage and the rate of blade erosion due to foreign object ingestion can be reduced with inlet protectors. Two types were considered: a swirl-vane scavenge system powered by a continuously operating blower and a vaneless bleed driven ejector operated at takeoff only to minimize performance losses (fig. 12). While both systems would be quite effective in reducing FOD incidents, the maintenance cost savings would not offset the increased weight, cost, and SFC of these devices. The powered swirl vane system would incur a 2% DOC penalty while the vaneless ejector type would cause of 0.4% DOC increase.[3] Despite these penalties, some form of protector may nevertheless be necessary on the 30-passenger sized engines to pass FAA requirements for bird, ice, and gravel ingestion.

### Diagnostic Data Recording

The current practice of scheduling engine overhauls based only on the number of operating hours increases aggregate fleet maintenance costs since the overhaul interval is selected on the basis of the most severe duty cycle anticipated. The opposite extreme to regular overhauls is to overhaul only when each life-limited part needs replacement. But this alternative would also entail waste since the shop visit rate would be needlessly high. An intermediate strategy that recognizes the value of replacing all parts approaching the end of their useful life whenever a shop visit is required is better than either of the above extreme strategies.[3-4] It requires, however, a good cycle life-prediction model and an on-board diagnostic system to: (1) sense and record the operational severity and duration for each key component, (2) compute individual component remaining life, and (3) display such data as maintenance and failure alerts in the cockpit. As conceived, it also needs the support of a ground based data processing system to properly implement a fleet maintenance strategy (fig. 13). Thus it is more appropriate for larger operators who can afford this ground-based support system.

### Alternate Engine Ratings

Several alternative rating methods were considered: (A) conventional flat rating below a specified ambient temperature, to reduce average service severity, (B) derating, which means installing the same sized engines as alternative A and having identical cruise power, but using less takeoff and climb power, and (C) automatic power reserve (APR), whereby the engine is physically downsized about 5 percent to lower cost, weight, and cruise SFC (higher throttle setting) while still satisfying one-engine-inoperative (OEI) requirements.[3] Derating 10 percent reduces engine maintenance about 1/3 due to lower turbine temperatures and is clearly advantageous (1.5% DOC improvement relative to flat rating) whenever conditions permit pilots to exercise this option--e.g., cold days, long runways, low takeoff weights, and low altitude airports. Automatic power reserve involves tradeoffs between lower initial cost, lower engine weight, less fuel burned, but greater maintenance cost due to higher climb and cruise turbine temperatures. The net result for APR is almost no DOC change relative to flat rating.

The above examples illustrate the diversity of ideas that surfaced during the course of these studies. Tables 3 and 4 provide example lists of selected technologies and their fuel and DOC benefits. 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 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.

## Engine Cycles and Configurations

The scope of these studies included the determination of appropriate thermodynamic cycles and engine configurations in addition to the identification of component improvement concepts. 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. Different staging arrangements were also investigated including single and dual stage centrifugal, axi-centrifugal, and all-axial compressors, and oneor 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.

Cycle and staging arrangement selections were based mainly on minimum DOC, but were biased toward somewhat lower than optimum turbine inlet temperatures in recognition of material limits and associated technical risk (fig. 14).[3] This process yielded 17:1 to 20:1 compressor pressure ratios (CPR) and 2250°F to 2500°F maximum turbine rotor inlet temperature (TRIT) which represents large improvement over existing production engines, but lessor increases relative to the new crop of mid-1980's engines:

| | Existing | Mid-1980's | Future |
|---|---|---|---|
| CPR | 10-11 | 14-17 | 17-20 |
| Max. TRIT, °F | 2000 | 2000-2300 | 2250-2500 |

Since SFC has much more impact on DOC than any other parameter, figure 14 nearly replicates that 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.

Turbomachinery configurations, cycles, and major characteristics of representative engines are illustrated in figures 15-18. All are conventional free turbine configurations with the sole exception of GE's boosted free turbine configuration for their larger 2125 SHP engine. In this case, GE opted for 20:1 pressure ratio rather than 17:1 to reduce DOC 1 percent. This may be achieved by driving a booster stage with the power turbine--this avoiding a second HPT stage (17:1 requires an expansion ratio of 4.2 which is about the upper limit for a one-stage HPT). Cross-sections of both the GE 30-passenger engine and the GE 50- passenger engine are shown in figure 15. These two advanced engines are scaled to 1625 SHP to facilitate comparisons with the CT7 which is shown in the upper half on the each diagram. The better cycle and higher component efficiencies of the 50-passenger version results in greater SFC and weight improvements, but less maintenance cost improvement.

The only all-axial compressor is Allison's 5025 SHP design (fig. 16) which was reported to have a 2 percent efficiency advantage over an axi-centrifugal arrangement in this size class. Allison's 2495 SHP design utilized a six-stage axi-centrifugal compressor arrangement at 20:1 pressure ratio and a two-stage HPT as mentioned above (fig. 17). It also utilized an in-line gearbox rather than an off-set type as used in all of the other designs.

Garrett's two engines spanned a relatively narrow size range (1842 to 2384 SHP) which prompted their decision to retain only a single design. Although figure 18 shows a twin-centrifugal compressor driven by a two-stage HPT, this only represents Garrett's initial definition which was subsequently revised to a one-stage HPT for use at 16:1 pressure ratio. They also recommend a 20:1 axi-centrifugal which requires a two-stage HPT, but yields even better performance and lower DOC albeit at higher research and development cost.

The advanced technology STAT engines would be about 25 percent more efficient than same-sized current production engines and 8-16 percent better than the second generation of engines now in the final development stages (fig. 19). They would also weigh 10-20 percent less than the second generation engines, cost within 10 percent, and require significantly less maintenance (fig. 20). At 100 N.M. stage lengths these improvements lead to 10-23 percent trip fuel reductions and 7-22 percent DOC reductions depending on the selected baseline engine and engine size (fig. 21). For longer stage lengths these benefits generally increase somewhat as shown in figure 22.

## Propeller Technology

The smaller commuter aircraft use general aviation type propellers which are relatively simple and low performance compared to the more sophisticated technoloty 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), the STAT technology studies by Hamilton-Standard and the McCauley Division of Cessna have identified important further opportunities.[6-7]

A summary of the Hamilton-Standard defined improvements is shown in figure 23 for a 30-passenger low speed design. The fuel savings relative to current general aviation technology has been separated into low-risk and high-risk portions as viewed by the author. "Low risk" implies that the required technology is either already available or could be through normal industrial R&T effort, and "high risk" implies that additional long-term R&T effort is needed beyond normal industrial activities. Of the 16.8 percent total fuel savings, 9.3 percent is attributable to the difference between existing general aviation technology now under development and mid-80's commuter technology now under development (i.e., low-risk portion), while the remaining 7.5 percent represents high-risk future opportunity. For example, while the new 14 RF/SF seris propellers will utilize a new family of airfoils designed specifically for the DeHavilland Dash 8, another 1/4 point in efficiency is thought to be obtainable through advanced airfoil research. Proplets are high-risk and offer nearly a 2 percent fuel savings through reduced tip losses. Increasing the number of blades improves efficiency, but requires advanced materials and construction techniques to maintain sufficient blade-retention strength in the thinner root sections. Blade activity factors of 70 are needed to achieve this gain (the activity factor of the 14 RF/SF series will be 91-93) which, in turn, assumes the use of advanced techniques such as a steel or metal matrix spar with a Kevlar or graphite shell--possibly load-sharing and tailored to increase critical speeds. Although counter rotation offers a theoretical efficiency improvement, the gain is too small to warrent the associated higher level of complexity.

Experimental evidence on a T56-powered P3 indicates that a 6-8 dB OASPL reduction in cabin noise is possible if the left and right propellers can be synchrophased to within a technically challenging one degree.[7] Applying this source noise reduction to a 30-passenger, Mach 0.45 commuter required to meet an 85 dB OASPL cabin noise constraint would eliminate 844 pounds of fuselage acoustic treatment otherwise needed in a wing-mounted propulsion configuration. Of course, if the noise constraint (B-737 cabin level) were met by mounting the powerplants on the airplane tail this gain is absent. In fact, without a noise constraint the propeller design would be reoptimized and the fuel improvement would be reduced about 2 percent as indicated in the summary fuel and DOC benefit chart (fig. 24).

The McCauley study of propellers designed for 19-seat, Mach 0.45 airplanes identified similar technologies. Although the benefits were only quoted relative to moderate performance general aviation type propellers (fig. 25), the benefits relative to current state-of-the-art commuter propellers would be similar to those mentioned above.

## Complete Powerplant Benefits

Figure 26 summarizes the STAT powerplant study results. Potential incremental improvements in all turboprop components plus the propeller lead to sizable total powerplant improvements in efficiency, weight, maintenance, and noise. The lower values listed on the figure denote average improvement potential relative to the second generation engines while the higher values denote improvements relative current to first generation powerplants. The conservative propeller improvements of figure 24 were assumed (i.e., gains measured against the modern technology commuter propellers now in development and no credit for precision synchrophasing). The trip fuel savings and DOC benefits are also listed in pairs with an identical interpretation implied. These potential gains are large enough to conclude that the future for third generation 1500-5000 SHP turboprop powerplants holds as much promise over the new second generation powerplants as the second generation holds over the first generation.

## Toward Higher Risk and Greater Payoff

Notwithstanding the importance of the STAT studies and the general conclusion just drawn, there is some evidence that considerably greater opportunities exist involving revolutionary engine technologies. It is commonly recognized that small turbine engines have considerably lower thermal efficiency than large ones. Current 1500 SHP class turbine engines, for example, have thermal efficiencies near 27 percent compared to 37 percent for 20,000 SHP machines (fig. 27).

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. 27).

Besides striving to increase component efficiencies, at least two other approaches are apparent 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 refractory metal matrix composite technology. Efforts have already started in this direction in the government sponsored ceramic automotive engine programs. 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 at 500 SHP show efficiency gains of 10-20 percent compared to the simple turboshaft cycle,[8] 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 estimated at 30-50 percent of the simple cycle weight in small sizes, but perhaps 100 percent or more at 5000 SHP. 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. 28). 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, considerable higher than for the conventional engines.

Figure 29 shows how fuel burned varies with cruise BSFC and engine specific weight for a typical 30-passenger, Mach 0.45 airplane. Spotted on this parametric plot are the estimated values for all of the above discussed turboprop powerplants plus several advanced intermittent combustion engines (IC) discussed in a companion paper.[9] Relative to the mid-1980's new engine, an advanced conventional cycle turboprop could save 10-20 percent in fuel not including advanced propellers or nacelles. The fuel savings for unconventional engines 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 a 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. This trend occurs because the main fuel driver is SFC and the SFC advantage of the unconventional engines decreases with increasing size (since the conventional turboprop becomes more efficient in larger sizes).

## Concluding Remark

The principal message to be gained 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. Significant improvements are feasible in both the short term and the long term with risks ranging from moderate to very high.

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TABLE 1. - 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

TABLE 2. - BASELINE ENGINES

| | ALLISON | | GARRETT | | GENERAL ELECTRIC | |
|---|---|---|---|---|---|---|
| | BASE 1 | BASE 2 | BASE 1 | BASE 2 | BASE 1 | BASE 2 |
| ENGINE DESIGNATION | T701 | T701 DERIV. | 331-11 | 331-15 | CT7-5 | CT7-5 DERIV. |
| YEAR OF INTRODUCTION | 1979 | 1986 | 1980 | 1984 | 1983 | 1986 |
| TURBINE INLET TEMP, °F | 2250 | 2250 | 2004 | 2045 | 2290 | 2390 |
| COMPRESSOR PRESSURE RATIO | 12.7 | 17.7 | 10.6 | 10.8 | 16.9 | 20.8 |
| SEA LEVEL STATIC, 59°F | | | | | | |
| ESHP, HP | 8935 | 11600 | 1045 | 1712 | 1630 | 2325 |
| ESFC, LB/HP-HR | .419 | .373 | .531 | .482 | .451 | .430 |

TABLE 3. - ADVANCED ENGINE TECHNOLOGIES IDENTIFIED BY GENERAL ELECTRIC

CT7-5 BASELINE

| | Development Cost | Probability of Success | Δ DOC | | | | Relative Value* | | | | ** Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 30 PAX | | 50 PAX | | 30 PAX | | 50 PAX | | |
| | | | \$1.00 /Gal | \$1.50 /Gal | \$1.00 /Gal | \$1.50 /Gal | \$1.00 /Gal | \$1.50 /Gal | \$1.00 /Gal | \$1.50 /Gal | |
| Axial Compressor | 1.9M | 80 | -.89 | -.96 | -.95 | -1.03 | 56 | 72 | 68 | 84 | 3 |
| Multi-Blade Impeller | 2.0M | 50 | -.50 | -.60 | -.58 | -.68 | 19 | 27 | 25 | 33 | 4 |
| Adv. Diffuser | 1.3M | 80 | -.63 | -.74 | -.71 | -.82 | 57 | 81 | 75 | 97 | 2 |
| Combustor Cooling | 0.4M | 90 | -.30 | -.25 | -.26 | -.23 | 100 | 100 | 100 | 100 | 1 |
| Clearance Control | 1.5M | 80 | -.01 | -.08 | -.05 | -.12 | 1 | 8 | 5 | 11 | 8 |
| HP Turbine Blade | 0.7M | 75 | - | - | +.19 | 0 | - | - | -35 | 0 | 9 |
| LP Turbine Blisk | 1.6M | 75 | -.08 | -.07 | -.08 | -.07 | 6 | 6 | 6 | 6 | 7 |
| Composite Shaft | 0.4M | 50 | -.03 | -.04 | -.04 | -.05 | 6 | 9 | 9 | 12 | 6 |
| Closed Loop Accel. Control | 1.7M | 50 | -.13 | -.20 | -.19 | -.26 | 6 | 10 | 10 | 15 | 5 |

* Relative value = -(ΔDOC) (Prob. of Success)/(Devel. Cost)
** Rank

TABLE 4. - ADVANCED ENGINE TECHNOLOGIES IDENTIFIED

BY GARRETT (TPE 331-11 BASELINE)

100-N. MI. MISSION, $1.00/GAS FUEL

| | | Percent DOC Change | | Percent Change in Block Fuel | |
|---|---|---|---|---|---|
| | | 30 Pax | 50 Pax | 30 Pax | 50 Pax |
| | **Compressor** | | | | |
| 1 | Powdered Aluminum First-Stage Centrifugal | -0.07 | -0.05 | -0.04 | 0 |
| 2 | Powdered Titanium Second-Stage Centrifugal | -0.22 | -0.12 | 0 | 0 |
| 3 | Single-Stage 12:1 Centrifugal | +3.13 | +2.87 | +3.86 | +3.47 |
| 4 | Two-Stage 20:1 Centrifugal | -0.30 | -0.40 | -0.81 | -0.74 |
| 5 | 20:1 Axial-Centrifugal (4 and 5 Axial Stages) | -0.88 | -1.03 | -2.44 | -2.28 |
| 6 | 20:1 Two-Spool Axial-Centrifugal | -0.33 | -0.62 | -2.44 | -2.27 |
| | **High-Pressure Turbine** | | | | |
| 7 | Single-Stage HPT | -1.21 | -0.77 | +0.38 | +0.33 |
| 8 | Uncooled [1477 K (2200°F), CRS, MA 6000, SC] | +1.06 | +0.79 | +0.44 | +0.35 |
| 9 | Cast Blades (SC, NASAIR-100) | +0.58 | +0.11 | -0.29 | -0.32 |
| 10 | Tip Treatment | -0.40 | -0.42 | -0.44 | -0.46 |
| 11 | Cooling Flow Modulation | -0.40 | -0.42 | -0.44 | -0.46 |
| 12 | Active Clearance Control | -0.43 | -0.35 | -0.48 | -0.38 |
| 13 | Net Shape PM Disk | +0.11 | +0.03 | 0 | 0 |
| 14 | 1089 K (1500°F) Disk Alloy | -0.09 | -0.07 | 0 | 0 |
| | **Low-Pressure Turbine** | | | | |
| 15 | Active Clearance Control | -0.58 | -0.58 | -0.64 | -0.63 |
| 16 | Titanium-Aluminide Second Stage | +0.33 | +0.23 | 0 | 0 |
| 17 | Single-Stage LPT | +0.65 | +0.60 | +1.27 | +1.10 |
| | **Gearbox** | | | | |
| 18 | Laser Hardened Gears | -0.13 | -0.11 | 0 | 0 |
| 19 | Roller Gears | +0.51 | +0.45 | +0.05 | +0.04 |
| 20 | Composite Housing | +0.56 | +0.39 | +0.01 | 0 |
| 21 | SPF/DB Gearbox | +3.80 | +3.06 | 0 | 0 |
| | **Combustor** | | | | |
| 22 | Machined Ring Burner | +0.02 | +0.02 | 0 | 0 |
| 23 | Photo Etched Burner | -0.15 | -0.12 | 0 | 0 |

TABLE 5. - DESIGN FACTOR RANKING

| ITEM | Δ DOC | | | | RANK |
|---|---|---|---|---|---|
| | 30 PASSENGER | | 50 PASSENGER | | |
| | $1.00/GAL | $1.50/Gal | $1.00/GAL | $1.50/GAL | |
| MODULAR CONSTRUCTION | +.41 | +.46 | +.45 | +.50 | 4 |
| VANELESS FCP | +.39 | +.44 | +.46 | +.52 | 3 |
| DIAGNOSTIC DATA RECORDING | -.89 | -.77 | -1.01 | -.85 | 2 |
| 10 % DERATE | -1.58 | -1.41 | -1.37 | -1.22 | 1 |

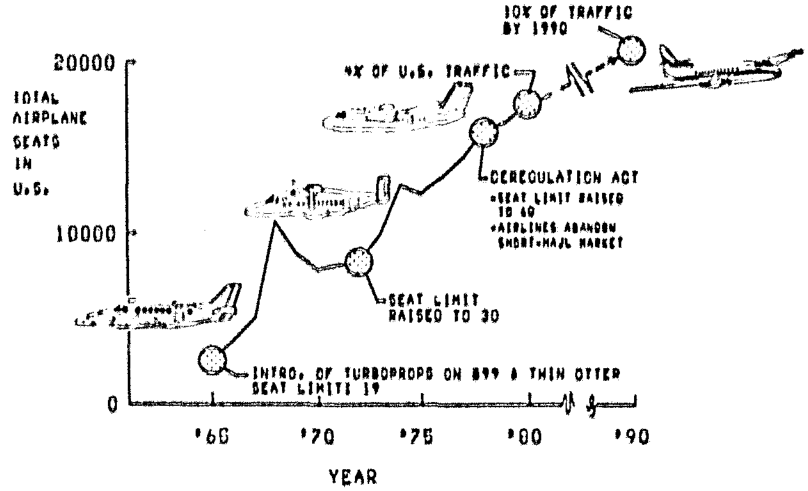



Figure 1. - Commuter aircraft marketplace expanding rapidly. Passenger traffic grew 11% per annum during 1970's.

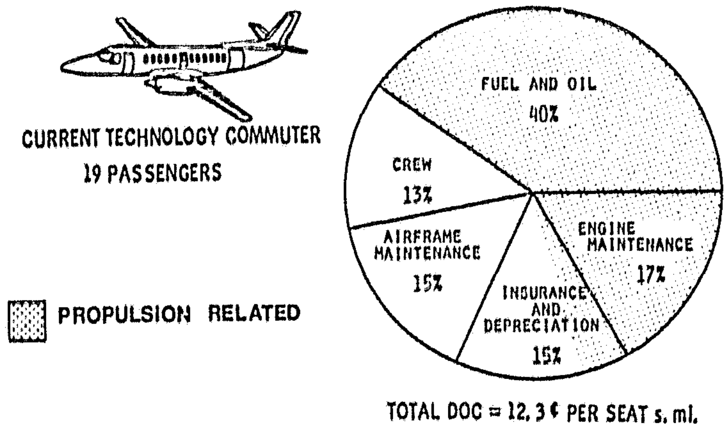
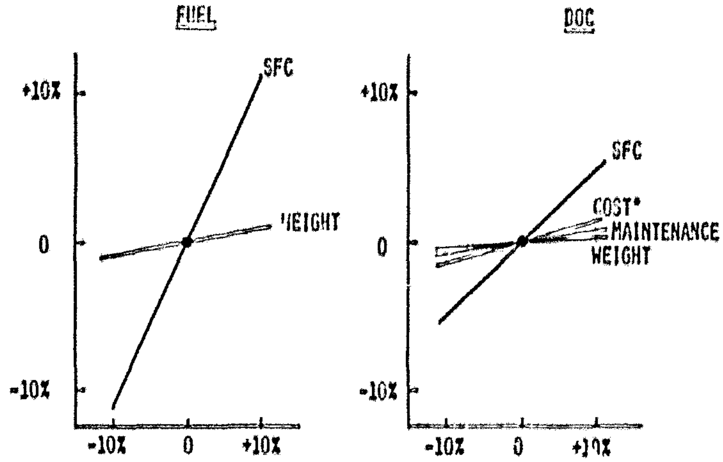
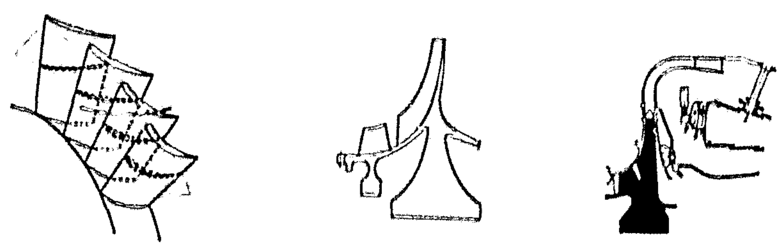



Figure 2. - Commuter aircraft direct operating costs - 1981 dollars, $1.25/gal fuel, 100 n. mi. trip.




*INCLUDED SPARES & MAINTENANCE

Figure 3. - Stat 30 - passenger airplane sensitivities - 100 n. mi., $1.50/gal, 1979 $, engine and gearbox.



| | 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<br>• USE WALL BLEED AT THROAT TO REMOVE BOUNDARY LAYER |
| ENABLEMENT | ACCURATE 3-D VISCOUS FLOW ANALYSES & EXPERIMENTAL DATA BASE | | |
| BENEFITS | • + 1% OVERALL EFFICIENCY<br>• FEWER STAGES (3 VS. 5) | • BETTER CONTROL OF BLADE LOADING<br>• FRESH BOUNDARY LAYER (+ 1% OVERALL EFFICIENCY) | • REDUCE PRESSURE LOSS (+ 1% OVERALL EFFICIENCY) |

Figure 4. - Compressor aerodynamics technology.

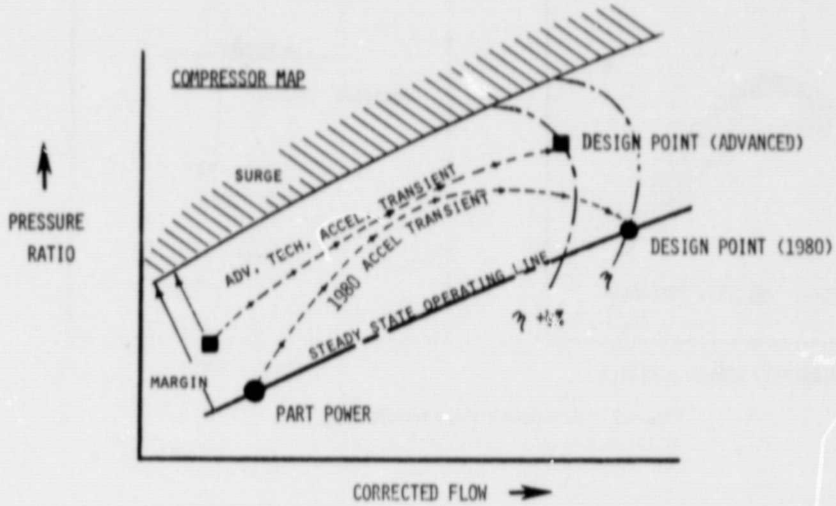



Figure 5. - Increased compressor efficiency via reduced surge margin. Requires closed loop engine acceleration control using digital electronics and compressor exit mach number sensor.

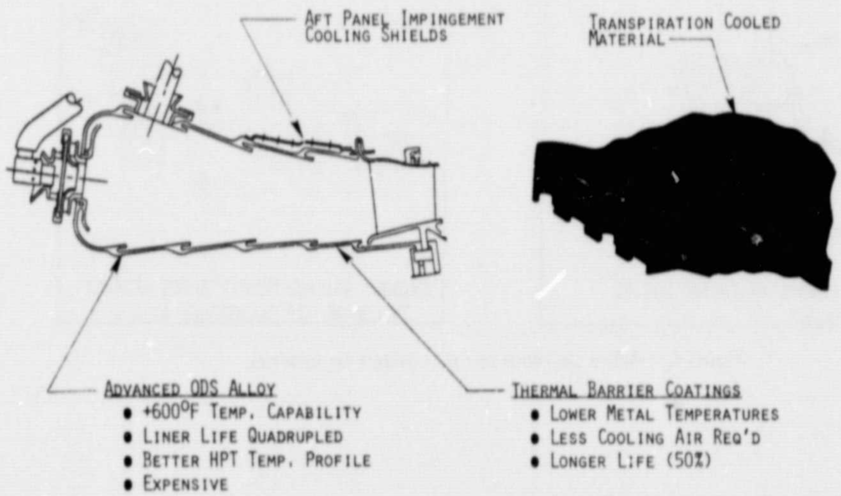



Figure 6. - Advanced combustor technologies.

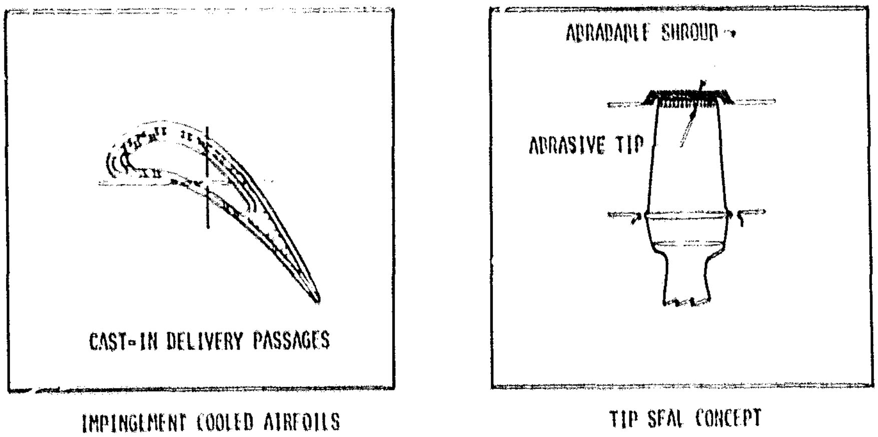



Figure 7. - Advanced turbine technologies.

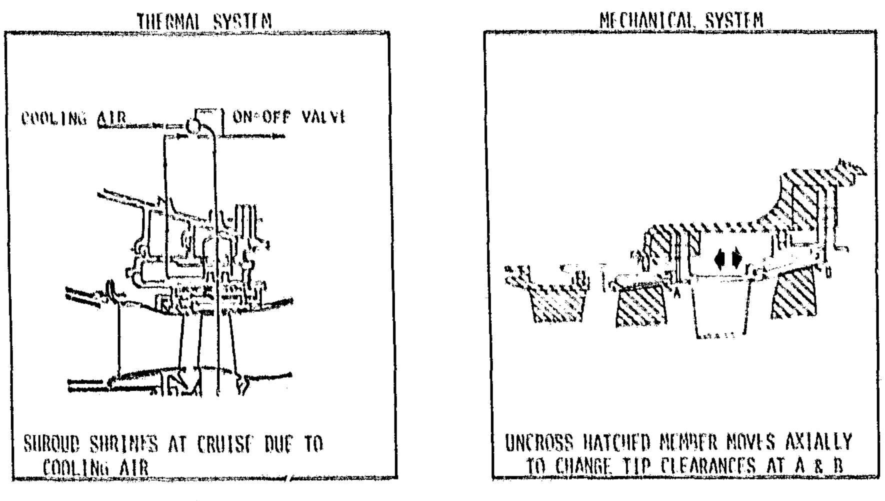
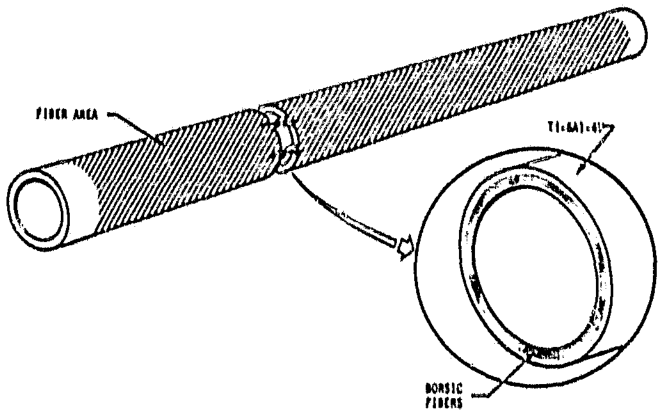



Figure 8. - Active clearance control concepts for turbines.




ADVANTAGE

40% GREATER CRITICAL SPEED

- REDUCED DISK BORE SIZE
- LOWER DISK STRESS
- HIGHER TIP SPEED TURBO-MACHINERY

TECHNOLOGY

- FINITE ELEMENT ANALYSIS FOR LAMINATES
- MANUFACTURING (END FITTINGS, BIASED PLY LAYUPS)

Figure 9. - Metal matrix composite shaft technology.

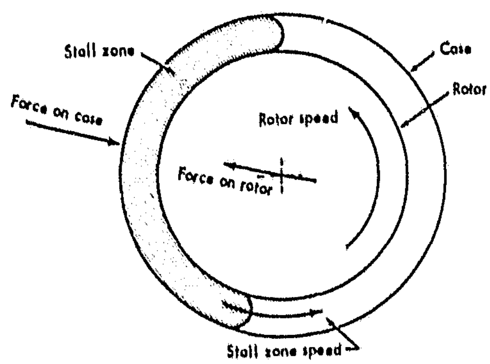



Figure 10. - Rotating stall phenomenon.

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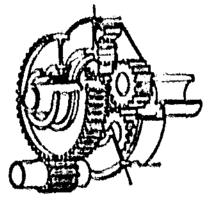
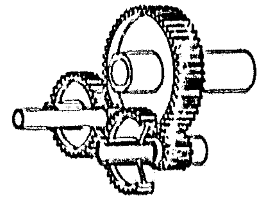


CURRENT TECHNOLOGY



ADVANCED TECHNOLOGY

| CURRENT TECHNOLOGY | | ADVANCED TECHNOLOGY | | |
|---|---|---|---|---|
| PINION-BULL-STAR | | DUAL COMPOUND IDLER | | |
| 9 GEARS/17 BEARINGS | | 6 GEARS/10 BEARINGS | | |
| NON-MODULAR | | EXTERNALLY MOUNTED ASSESSORIES | | |
| CONVENTIONAL TOOTH PROFILES | | HIGH CONTACT RATIO TOOTH PROFILES | | |
| CONVENTIONAL STEELS | | HIGH PURITY STEELS | | |
| FIXED OVERHAUL INTERVALS | | ON-CONDITION MAINTENANCE | | |
| EFFICIENCY | BASE | +0.5% | | |
| WEIGHT | | -13 % | -1.0-1.3 | ΔFUEL |
| COST | | -22 % | -1.2-1.7 | ΔDOC |
| MAINTENANCE | ↓ | 1/4 | | |

Figure 11. - Advanced gearbox technologies.

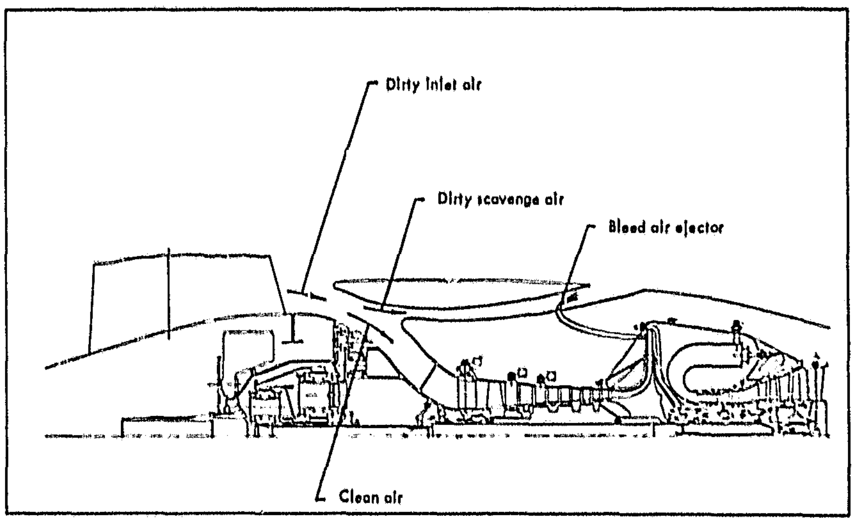



Figure 12. - Vaneless particle separator/foreign object protector concept.

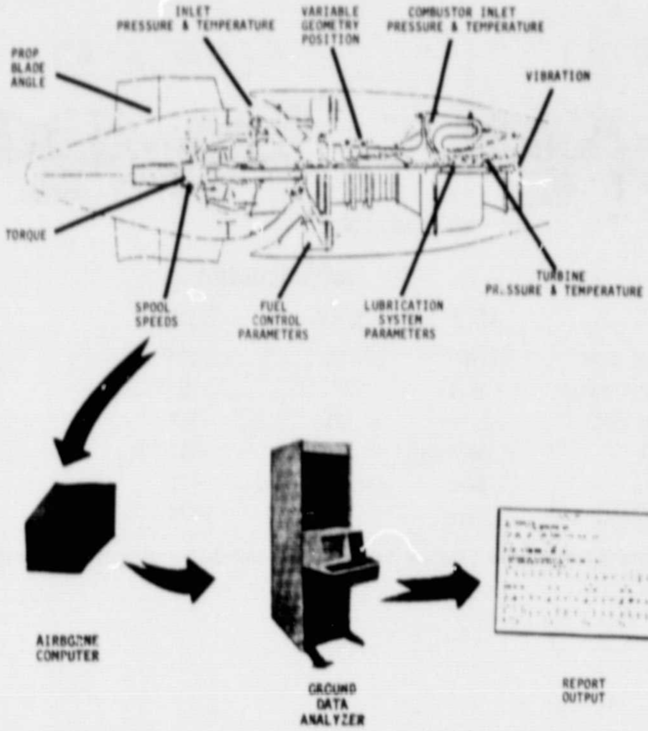



Figure 13. - Powerplant monitoring system for reduced maintenance.

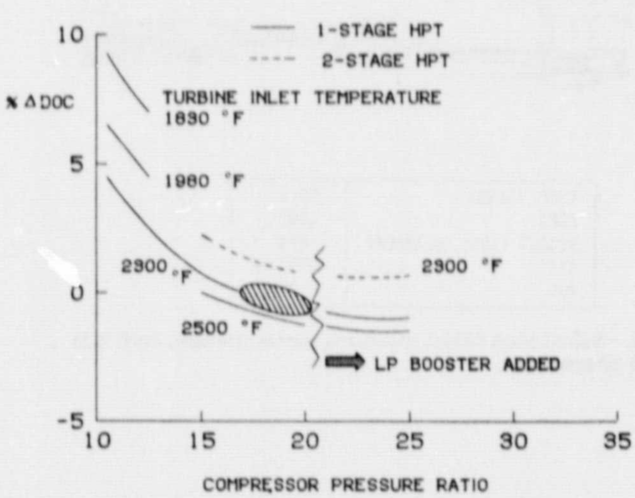
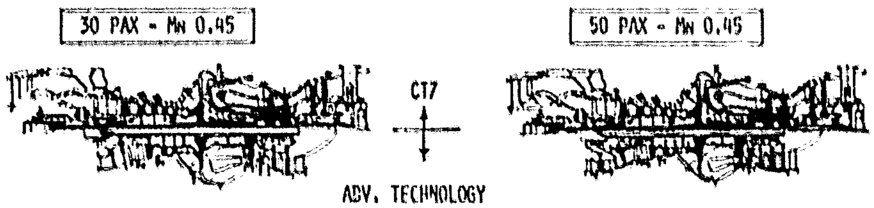
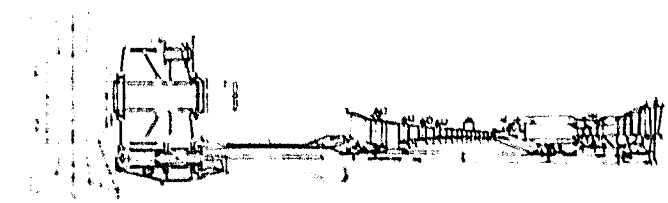



Figure 14. - Advanced commuter engine cycle selection - 100 n. mi. DOC, $1.50/gal fuel, 30 passenger, Mach 0.45, 1500 SHP/ENG.



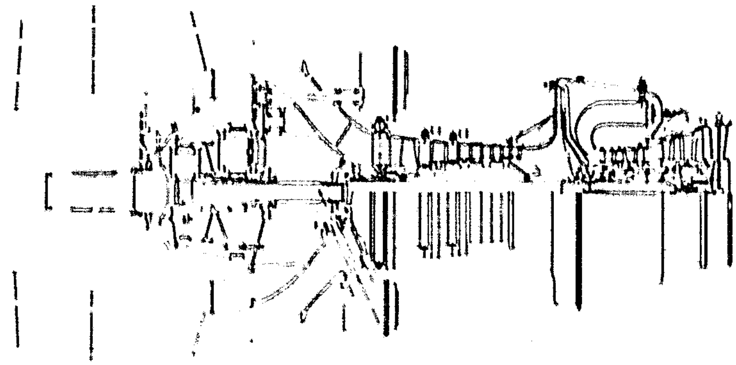

| | | ADVANCED ENGINES | |
|---|---|---|---|
| | CT7-5 | 30 PAX | 50 PAX |
| TURBINE TEMP. | 2200°F | 2300°F | 2400°F |
| PRESSURE RATIO | 16.9 | 17 | 20 |
| CRUISE BSFC | .46 | -9% | -14% |
| WEIGHT | 1070 LB | -9% | -11% |
| COST | BASE | -11% | -12% |
| MAINTENANCE COST | BASE | -21% | -17% |

Figure 15. - Advanced technology small transport engines. General Electric designs scaled to 1625 SHP, 90° F.



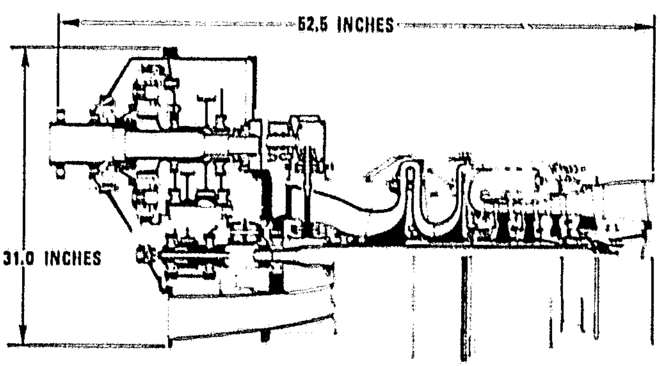
| | |
|---|---|
| ESHP (SLSS) | 5025 |
| ESFC | .366 |
| WEIGHT (INCL. GEARBOX) | 879 |
| TIT | 2250 °F |
| P/P | 20 |

Figure 16. - Detroit diesel Allison engine and gearbox schematic Mach 0.70 aircraft (50 passenger).



| | |
|---|---|
| ESHP | 2495 |
| ESFC | .403 |
| WEIGHT (INCL. GEARBOX) | 703 LB |
| TIT | 2250 °F |
| P/P | 20 |

Figure 17. - Detroit diesel Allison engine and gearbox schematic - Mach 0.45 aircraft (50 passengers).




| | 30 PASSENGER AIRCRAFT | 50 PASSENGER AIRCRAFT |
|---|---|---|
| SHAFT HORSEPOWER | 1842 | 2384 |
| CRUISE SFC | .415 | .415 |
| WEIGHT (INCL. GEARBOX), LB | 623 | 824 |
| TURBINE TEMPERATURE, °F | 2350 | 2350 |
| COMPRESSOR PRESSURE RATIO | 16 | 16 |

Figure 18. - Garrett advanced technology small transport engine.

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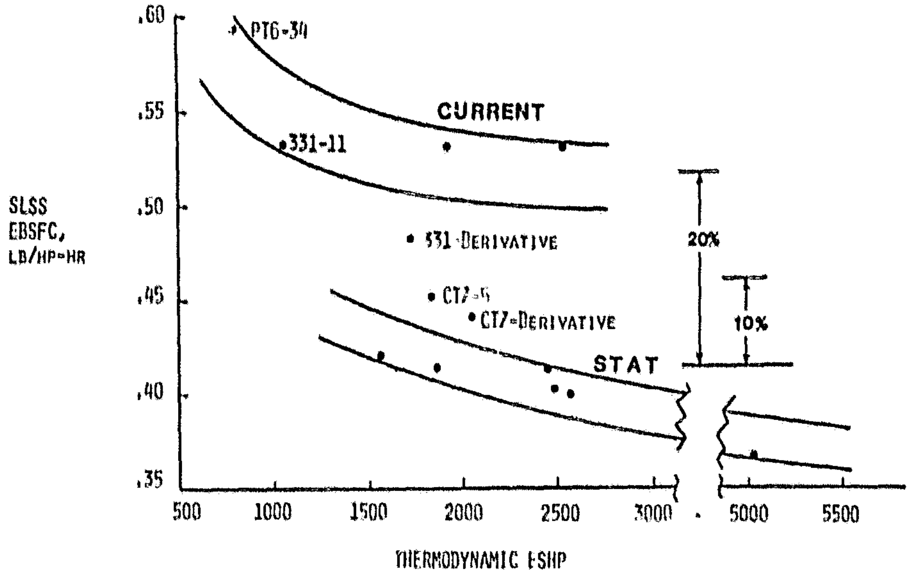


Figure 19. - Turboprop efficiency levels.

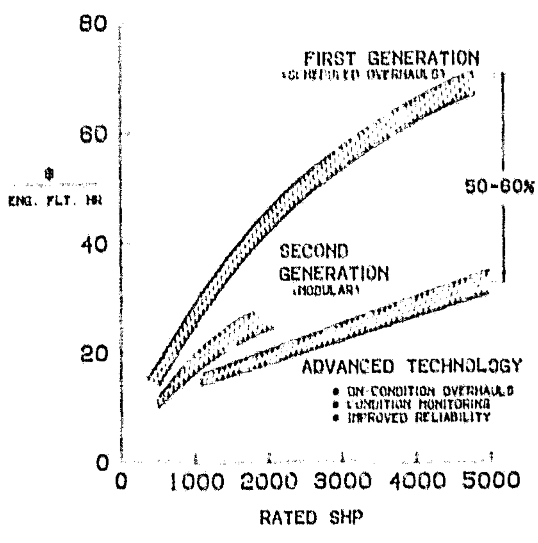


Figure 20. - Maintenance cost reduction - 100 n. m. stage length.

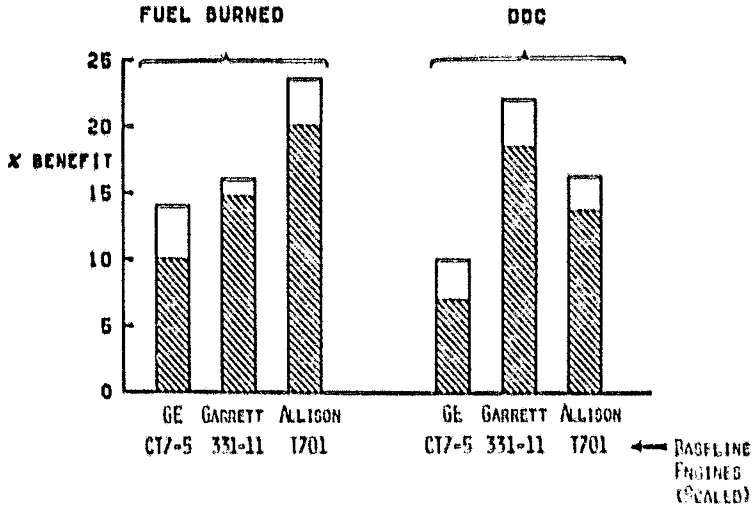


Figure 21. - Advanced engine benefits summary - 30-50 pax, Mach 0.45 - 0.70.

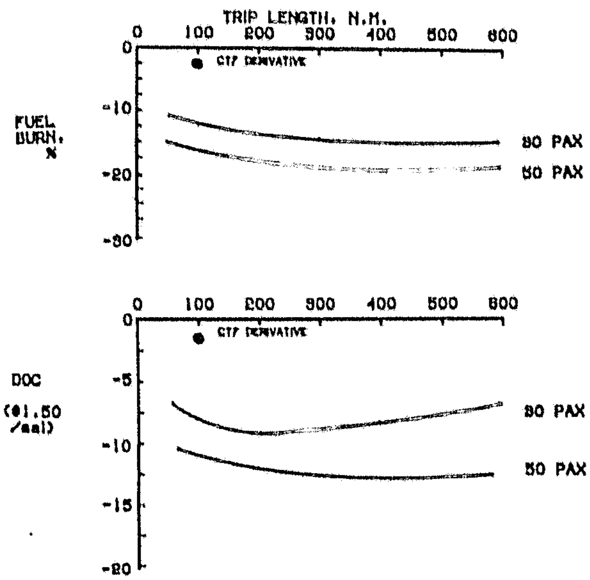


Figure 22. - Fuel and DOC savings - GE CT7-5 baseline.

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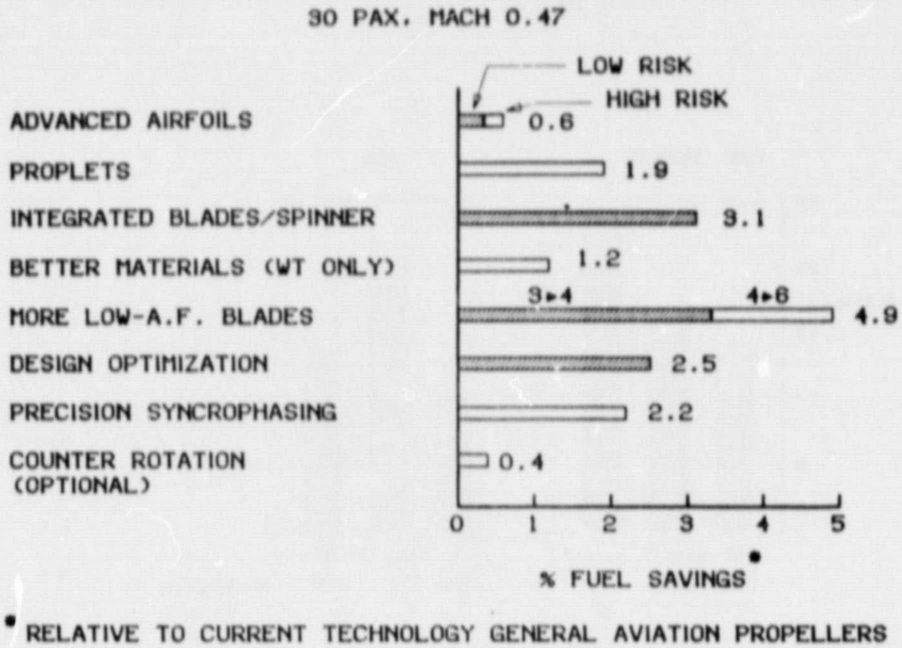


Figure 23. - Commuter propeller technologies save fuel.

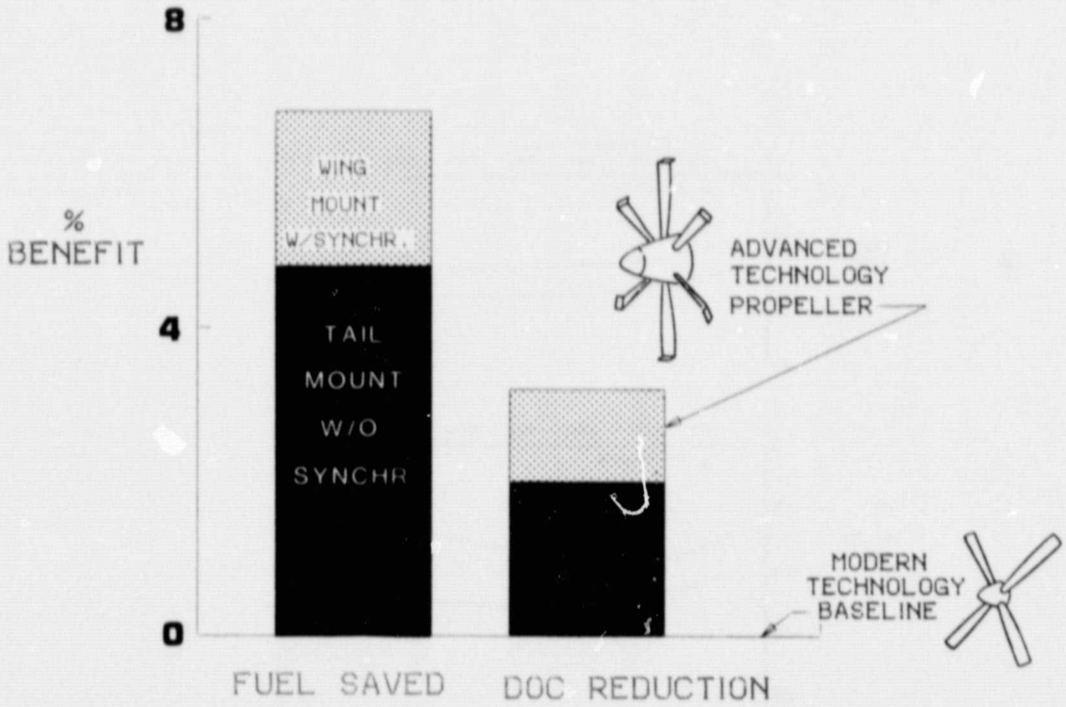


Figure 24. - Advanced propeller technology benefits - 30 passengers, Mach 0.45, 100 n. mi., $1.50/gal fuel.

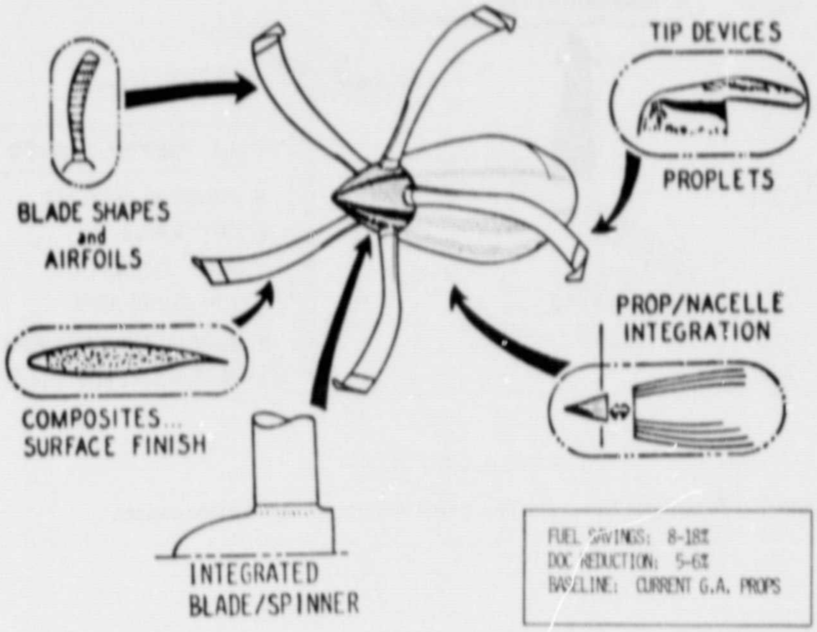


Figure 25. - Cessna/McCauley advanced propeller technologies.

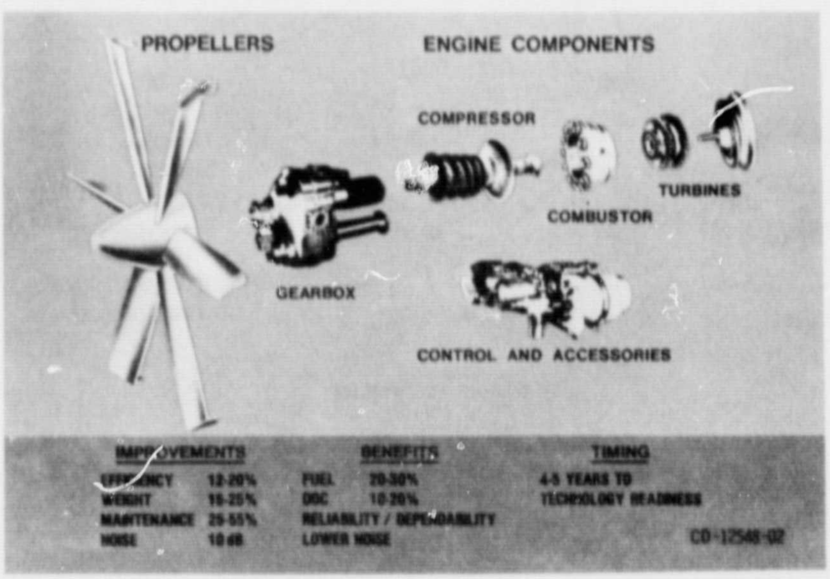


Figure 26. - Stat propulsion technology.

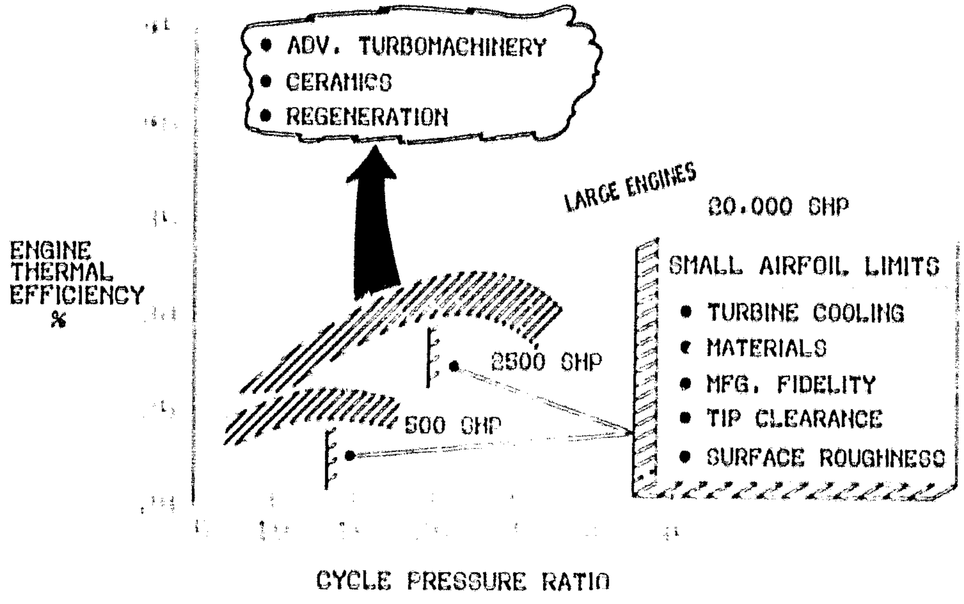


Figure 27. - Barrier and opportunities for greater efficiency. Small turbine engines.

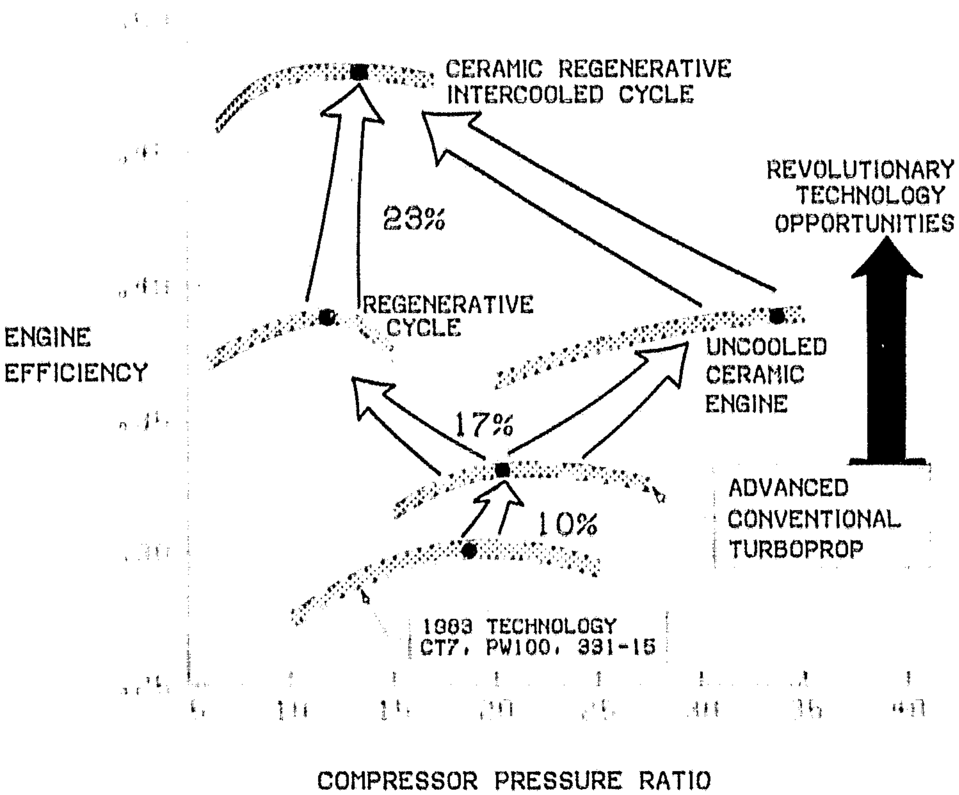


Figure 28. - Small gas turbine engine opportunities - 1500-shp class.

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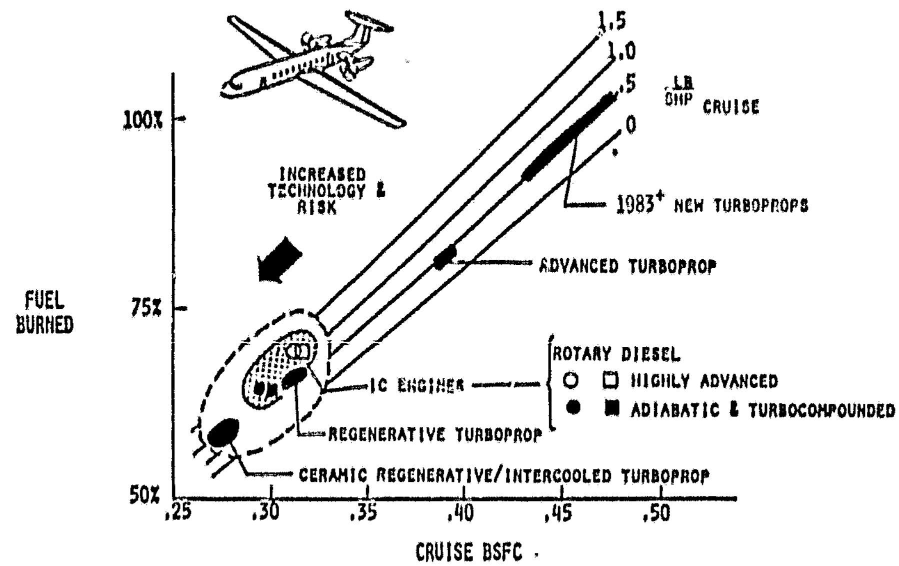


Figure 29. - Commuter aircraft propulsion opportunities - 30 passengers, Mach 0.45, 15 000 ft, ~1500 SHP SLSS.