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NEW OPPORTUNITIES FOR FUTURE, SMALL, GENERAL-AVIATION TURBINE ENGINES (GATE)

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SUMMARY

The results of four independent contracted studies to explore the opportunities for future small turbine engines are summarized in a composite overview. Candidate advanced technologies are screened, various cycles and staging arrangements are parametrically evaluated, and optimum conceptual engines are identified for a range of 300 to 600 hp applications. Engine improvements of 20 percent in SFC and 40 percent in engine cost were forecast using high-risk technologies that could be technically demonstrated by 1988. The ensuing economic benefits are in the neighborhood of 20 to 30 percent for twin-engine aircraft currently powered by piston engines.

INTRODUCTION

The preceding portion of this conference was devoted entirely to business jet external noise and pollution, primarily, and fuel economy, secondarily. This turbofan-powered segment of general aviation represents about one-fourth of U.S. engine net factory billings even though only 2 percent of the general-aviation aircraft engines sold are of this type (fig. 1). The remainder of the conference will address the concerns of the other 98 percent. At the lower cost end are the single-engine airplanes powered by 100- to 300-hp piston engines. About 23 000 of these were produced last year. The twin-piston powered airplanes utilize 200- to 400-hp engines of which about 8000 are produced annually. The turboprop aircraft are mostly twins that require 500- to 1000-hp engines. The U.S. produced about 750 of these last year, and Canada produced approximately the same number. Collectively, these three categories represent 3/4 of the general-aviation engine net billings. Last year the total general-aviation engine billings were about 70 percent as large as those for the large commercial transport turbofans.

The principal problems facing these three categories are not so much environmental as they are economic, fuel, and safety related (fig. 2). Perhaps of greatest concern is the cost and availability of aviation fuels. Continued steep price hikes and the vulnerability of aviation gas to severe production cutbacks, or outright elimination, propels our quest for true multifuel powerplants. The safety of this class of aircraft continues to be questioned - with the spotlight alternating between airplane and automotive safety record comparisons and the controversial one-engine-out twin problem. Engine dependability is especially important in these smaller aircraft. Passenger comfort levels are far less than those of larger turbofan aircraft, and the powerplant is a major cause of the discomfort. Other concerns involve propulsion-related acquisition and maintenance costs - especially for turboprop engines (fig. 3). NASA's involvement in addressing these concerns for the smaller general-aviation powerplants is recent. Two years ago we recognized that the tiny amount of R&T effort devoted to small general-aviation turbines was not in proportion to their actual importance. As the first step in rectifying that situation, we initiated a series of analytic studies - known as the GATE studies - to explore small turbine technology opportunities. The question was: If we hypothesize a brand new, small turbine engine that incorporates, say, 1988 level technology, what size should it be; how should it be configured; and what benefits would it bestow upon us? The purpose, then, became one of providing information to assist us in planning future research. We wanted to emphasize technologies that had high payoff and high risk, but which could be ready for production development by 1988 (given sufficient funding) and for mass production by the early 1990's. These engines could be as much as 1000 hp, but no more, but we emphasized sizes below 600 hp since we perceived this size class to be potentially the most rewarding - and challenging. We also emphasized aircraft cost of ownership as a criterion of merit during the conceptual design process.

The first task of these studies was a 1988 market forecast that considered all types of small airplanes and helicopters. This forecast determined engine power sizes and other requirements of interest. Most of the study effort, however, was devoted to broad-scope parametric analyses wherein various cycles, staging arrangements, and technologies were subjected to trade-off and screening evaluations to determine optimum engine configurations for each important mission identified in the market forecast. Then, anticipating that the marketplace could not afford different optimum engines for each application, an evaluation was made of a single common core to be used in a family of engines. And finally, the required R&T program was defined.

We at NASA did some of these assessments ourselves, but most were done under contract to these four companies working independently: Garrett/AiResearch, Detroit Diesel Allison, Teledyne CAE, and Williams Research. Within a general framework, we permitted the company teams the freedom to pursue directions and opportunities that they (rather than we) perceived as most attractive. This freedom sometimes led to uniformity, for example, all companies expressed a strong preference for turboprops instead of turbofans or turboshafts, and sometimes to interesting diversity, for example, the engine configurations and technologies varied considerably as did engine cost estimates.

The engine cost estimates were especially intriguing in the GATE studies because of the obvious opportunity to turbinize a portion of the piston-powered market. The turbine engine is pretty much accepted as the most desirable type of powerplant because of its many virtures - it has very low vibration levels, high reliability, multifuel capability, a better safety record, low weight, fewer emissions, less maintenance, and smaller installation losses. Despite these advantages, the use of turbine engines has been blocked at about the 500 hp level because of its higher fuel consumption and, especially, its 3:1 price premium (fig. 4). The challenge, of course, is to overcome the cost and fuel barriers without sacrificing all the superior qualities. The trouble is that current technology does not allow this.

If we attempt to lower cost significantly, the efficiency suffers too much (fig. 5). But, if advanced technology could move the cost-efficiency band down far enough, we could certainly design a cost-effective small turbine or, if we choose, a better performer without cost reduction. On the other hand, if advanced technology could not lower the band sufficiently, then only the high performance option is open. In the end, three GATE study team pursued the low-cost turbine versus piston theme, and the fourth pursued a high-performance, advanced turbine versus current turbine theme.

The results of the four contracted studies are presented herein by selective examples that illustrate the main points in a representative fashion. The detailed results are documented in references 1 to 4.

CYCLES AND CONFIGURATIONS

In figure 6, design turbine-inlet temperatures of 1800°, 1900°, and 2200° F are compared in terms of airplane total cost of ownership, fuel consumption, operating cost, acquisition costs, and engine cost. For all of these criteria, the optimum temperature level is 2200° F, or about 400° F above current small-engine levels. Although it appears that temperatures in excess of 2200° F would be even better, 2200° F was judged to be the highest temperature compatible with the materials available in the 1900's. The engine cost of the 2200° F engine is 40 percent less than that of the 1800° F engine because of a combination of factors. First, the physical size is about 40 percent smaller because the specific power improves substantially and because a smaller aircraft is required to do a given mission. In addition, the 2200° F engine incorporates more cost-reducing technology, which retards the normal growth of cost with temperature and which keeps the cost per unit airflow nearly constant. Likewise, the 2200° F engine weighs about 40 percent less than the 1800° F engine. In fact, the airplane fuel consumption is improved 15 percent, not because the cycle efficiency improves (in fact, it is only 1 percent better), but because the engine weight is reduced. The engine weight and cost savings also produce 15 to 20 percent improvements in airplane acquisition cost, operating cost, and total cost of ownership.

In a similar vein figure 7 displays cycle pressure ratio effects. In the lower plot, engine cost is displayed as a band that was drawn from four compressor point designs: a single-stage centrifugal at 9:1 pressure ratio and a relative cost of 1.0, a two-stage centrifugal at 20:1, an axicentrifugal at 11.3:1, and a three-stage axicentrifugal at 15:1. The band width indicates the increasing cost associated with more compressor stages at a fixed pressure ratio. Cost increases rapidly with pressure ratio as more compressor and turbine stages are required. Likewise, at any given horsepower level, weight increases too, so the power-to-weight ratio, shown in the upper part, becomes worse. Unfortunately, at the small airflows required in these applications (2 or 3 lb/sec), the cycle efficiency is not increasing rapidly enough to offset these adverse trends. In fact, as the SFC band shows, things are even worse than that. While the 11.3:1 engine is 6 percent more efficient than the 9:1 engine, the 15:1 and 20:1 engines are actually slightly worse than the 11:1 engine because the component efficiencies are suffering too much at the very small corrected airflows in the final stages. Hence, the minimum fuel solution is about a 12 or 14:1 compressor pressure ratio, but the lowest aircraft cost of ownership solution is about 9:1.

As a third example of these trade-offs, figure 8 presents a summary of one team's efforts to determine the best overall engine configuration for a medium pressurized twin. They considered a turbofan with a gas-generator consisting of a single centrifugal compressor hooked to a one-stage radial turbine. They also considered a free-turbine turboprop in three different versions: The first has the same simple arrangement as the turbofan; the second has a two-stage centrifugal compressor; and the third has an axial turbine replacing the radial turbine. Actually, the little diagrams only show the gas-generator portions, but all four of these configurations also have a two-stage axial-power turbine. And finally, they considered two arrangements of a single-shaft turboprop: both use a single centrifugal compressor, but the first has one axial turbine following a radial turbine, and the second has three axial stages. The evaluation criteria are airplane total cost of ownership, fuel consumption, operating cost, acquisition cost, and engine cost, and the values quoted are all relative to the second option - the simplest free-turbine turboprop. The bars are ordered from left to right in the same sequence as the top little diagrams. The most obvious result is that the turbofan is simply not in the running at all. Its penalties, which are caused by its low efficiency at low flight speeds, run from 25 to 65 percent. Actually, the optimum choice is not the simple free-turbine baseline but rather the even simpler single-shaft configuration with one less turbine stage. However, in consideration of other factors, especially commonality with helicopter turboshaft requirements, this team marginally preferred the free-turbine baseline.

After many trade-offs such as these and iterations with the marketing analyses, the four teams settled on the cycles and configurations shown on the right-hand side of figure 9. These engines are all turboprops ranging from 335 to 565 hp and are aimed primarily at the high-performance single-engine and twin-engine airplane applications. For comparison, both a representative current production turboprop (uncooled, old technology) and a hypothetical turboprop incorporating currently available modern technology are illustrated on the left-hand side of this figure. Allison's choice is a cooled, 2200° F maximum turbine-inlet temperature, 14:1 pressure ratio, free turbine design. Two centrifugal compressors are driven by two axial turbine stages, and another two-stage turbine drives the propeller load on a second spool. This design differs from both the current production engines and the hypothetical modern engines mainly in having a better cycle and higher component efficiencies. Its performance is much better, although its estimated cost differs little. Garrett also chose a two-stage free power turbine, but selected a single 9:1 centrifugal compressor driven by a one-stage radial turbine in their pursuit of lowering cost. Teledyne's low-cost engine quest led to an engine family that is described later. But its basic element is a very simple core engine which consists of a single centrifugal compressor connected to a single radial turbine. This turbine also drives the propeller load on a common shaft. Their turbine rotor is uncooled and requires a very sporty, very advanced design, which is discussed later. Finally, Williams Research sought low cost through a very unconventional approach. Rather than the conventional idea of eliminating cost by eliminating parts, they propose utilizing known ways of producing very inexpensive parts at lower cost. The result was an uncooled, single-shaft, axicentrifugal arrangement with six axial compressor stages and four axial turbine stages at modest temperature but relatively high pressure ratio. This concept is described in more detail later also.

ENGINE PERFORMANCE AND COST

The performance estimates for these engines are summarized in figure 10. Usually we think of SFC rising smoothly as we decrease engine size because of adverse scaling effects. However, whenever a new engine is introduced, it may distort our expected curve simply because of its advanced technology relative to older, well-established engines. This happened a few years ago when the T700 was introduced. It yanked the curve down to form a "knee" in the trend curves at 1500 hp. Exactly the same thing would happen again if GATE technology engines were introduced at 400 to 600 hp, since they would be 20 percent more efficient than current production engines of the same size. The technologies that lead to this are described later.

The three low-cost-theme study teams projected engine costs in two ways. The first presumes no increase in production rates and simply reflects the intrinsic cost-reduction potential of using advanced technology (fig. 11). The magnitude of this saving is about 40 percent. In other words, GATE engines would be 40 percent cheaper to produce than today's engines. But, once a saving of this size materializes, it would trigger increased sales, and this opens up the possibility of a new manufacturing facility dedicated specifically to GATE engines, which, in turn, would cause even further savings - for a total reduction of as much as 60 percent. At the same time, market demand would increase to the neighborhood of 10 000 engines/year/company (assuming that two companies split the market equally). Hence, without sacrificing too much performance, the pursuers of the low-cost theme are predicting that GATE technology could provide the key that unlocks this potential. To put the cost estimates in better perspective, figure 12 shows engine specific cost estimates for all four companies against a backdrop of the current cost situation. Current turboprops cost about three times as much as piston engines. But remember, turboprop production rates are two orders of magnitude less than piston engine rates. Allison's rather sophisticated machine is estimated to cost about the same as current turboprops, and it triggers modest increases in sales. The low-cost theme estimates of Williams, Garrett, and Teledyne at 10 000 units per year closely approach the piston engine cost band, and this obviously represents a major departure from today's scenario. Of course dollars per horsepower alone is not sufficient since differing lapse rates, installation factors, fuel consumption, etc., are equally important considerations. The net effect of all these factors is shown later in the mission analysis results.

TECHNOLOGIES

But what are the technologies behind these improvements? Certainly nobody could go out today and start building engines like these. Actually, it is somewhat difficult to succinctly summarize the advanced technologies identified in these studies because each study team incorporated different ones - at least in detail they are different. Nevertheless, figure 13 lists some of them in a composite fashion, although not all of these would be present in a single design. In the gearbox area the use of powdered-metal gears and laser hardening was recommended by several teams to reduce cost and improve properties. Composite material gear cases were recommended by Allison for stiffness and weight savings, while Teledyne suggested die-cast aluminum for a cost saving. Teledyne also recommended a composite drive shaft, and nearly all teams recommended full authority digital controls. However, the key elements in all of the concepts involved the rotating machinery. Except for Williams, each team sought high-performance centrifugal compressors using advanced analysis techniques, some form of passive clearance control, and backward curvature. High stage loadings without severe performance penalties were prevelant. And new manufacturing processes, such as using powdered-metal titanium for the rotors, appeared.

Technologies for the core turbine were especially diverse. Two companies selected high-temperature radial dersign: Teledyne, with an uncooled, powered-metal concept and Garrett with a cooled, laminated construction process. Allison selected a high-temperature axial arrangement with a cooled, dual-property rotor and possibly ceramic stators. Again, passive clearance control was cost effective, and improvement of efficiency through better three-dimensional flow analysis is required. Similar improvements were identified for combustors and power turbines.

The first of several example key technology elements is illustrated in figure 14. This one represents the attainment of a 9:1 pressure ratio compressor, at high efficiency, in a single stage. It requires advanced three-dimensional blading with high tip speeds and high inducer Mach numbers, an improved three-dimensional diffuser, better flow analysis and better experimental measurements, improved surge margin, and a low-cost fabrication technique that yields essentially a net shape part from powered-metal titanium. The benefit is to improve compressor efficiency by 3-1/2 points relative to a current technology 9:1, single-stage machined compressor, while reducing cost to be competitive with cast designs. While the 4 percent, engine cost saving is not as large as for some other components, it also saves 6 percent in engine weight, compared with a two-stage compressor that would otherwise be required with current technology.

The second example is Teledyne's proposed uncooled, but high-temperature, radial-inflow turbine. Its concept is based on their recent development experience with a 120-hp turbogenerator set for the Army plus some encouraging analytical work. Figure 15 shows the results of a preliminary analysis to verify the concept's life potential. The stress-rupture life was evaluated for two different blade geometries. One is relatively thin in the root region and has a cross-sectional area that tapers down at the tip to 1/16 that at the root (i.e., it has an area taper ratio ATR of 16). The other is thicker at the root and has a taper ratio of 31. The evaluation assumed the use of equiaxed IN-100, a current material, to give a high confidence level. Actually through, advanced materials and directional solidification would probably be used to increase the design's integrity. This design is very highly loaded, with tip speeds approaching 2500 ft/sec and transonic exit velocities at a maximum turbine gas temperature of 2250° F. Under these conditions, the blade metal temperature is 1800° F at the tips, and the lifetime is only 200 to 100 hr. However, their engine is flat rated and will not require such high temperatures at takeoff or at any other normal condition. At cruise, the gas temperature is down to 1950° F, which yields 1552° F maximum metal temperatures. This yields a 3000-hr life for the 16:1 ATR design or a 10 000-hr life for the 31:1 ATR design. However, it is not certain that the 31:1 ATR is practical because of increasing flow-path restrictions in the root regions (more detailed analyses are required to determine an optimum ATR).

The third example is Garrett's cooled, radial turbine concept (fig. 16). It consists of a set of photoetched laminates diffusion-bonded to form integral cooling passages. After bonding, the part is electrochemically milled to the full three-dimensional desired aerodynamic shape. Advanced powdered-metal sheet stock fabrication methods must be used to lower cost and thereby permit the use of high-strength materials such as Astroloy. The net benefit would be a 9.8 percent efficiency improvement relative to current, cooled axial turbines while reducing cooling bleed 20 percent and engine cost 21 percent.

The final example is that of an approach that does not apply specifically to a single component but rather influences the entire engine. It is Williams' unconventional approach to lowering cost through the use of restricted-geometry blade and vane aerodynamic shapes. The concept is to design for very low, rather than high, stress levels as depicted in figure 17. This allows perhaps a 150° to 200° F increase in turbine metal temperature without cooling, or, with an advanced material, much higher temperatures to exploit their specially shaped temperature-stress curves. With MA 6000E, for example, an extra 300° is possible. Either way, the lower stresses (perhaps 1/2 of conventional) imply lower design speeds, and this, in turn, means lower blade loadings, which permit the use of low-cost, simplified blade manufacturing techniques. Specifically, all compressor blades could have the same airfoil section, be of constant chord and camber, and be uniformly twisted; in fact, because only the lengths would differ, the parts cost would be dramatically lowered. The corollary is that higher pressure ratios are obtainable without much cost penalty. Then all the blades are held in place as the hub is formed around them in a single operation. The compressor vanes and all of the turbine airfoils are formed in the same way. The total result is a very different looking small engine concept which attempts to achieve low cost without performance sacrifice by incorporating a large number of very low-cost parts instead of a very small number of relatively expensive parts.

COMMON CORE

Another concept for reducing engine cost involves using a common core for a family of engines. Retaining parts commonality without sacrificing too much performance is the key here because each of the diverse mission applications prefers a different optimum engine. One approach to this dilemma is illustrated in figure 18 which shows Teledyne's C9 core engine slightly modified to accommodate some additional parts that are required to reconfigure the engine for more power. This is done by adding a supercharging axial compressor stage, an axial turbine stage to provide the extra power, and a set of extra gears, which are duplicates of the first set to handle the increased power. This allows a 335-hp engine to grow 70 percent to a 565-hp derivative with on a 4-inch extension (from 34 to 38 in.), a 31-lb weight increase (from 172 to 203 lb), and a 54 percent increase in cost (fig. 19). At the same time, the SFC is 10 percent lower due to the increased cycle temperature and pressure and component rematching. The price of commonality in this case is a 2 percent SFC penalty for the basic core engine. This results from the lower turbine temperature required to accommodate a common fixed-area nozzle. The benefits of this approach to commonality are a 7 percent lower cost and a 16 percent weight reduction for the C9 335-hp version relative to the next best approach, which is using a single, large configuration and then shaving the flowpath area to reduce power.

AIRCRAFT BENEFITS

The effect that these technologies, both individually and collectively, would have if GATE engines were installed in conventional but slightly improved airframes flying missions moderately more difficult than today's will be illustrated with several examples. In each case the hypothetical aircraft is resized to accommodate the new engines. First, the Allison GATE engine was compared with a scaled turboprop version of their most recently improved 250 series turboshaft engine. Their GATE engine incorporates considerable materials and aerothermodynamic improvement which accounts for higher cycle efficiency and smaller size. Specifically, a dual-property, axial, high-pressure turbine, while slightly more expensive initially, yields long life and much less engine maintenance cost. Similarly, a transpiration cooled, Lamilloy combustor, while not inexpensive itself, allows the use of a short, compact, and long-TBO (time between overhauls) combustion system. Ceramic rotors were not judged appropriate for manned aircraft application in this time frame, but Allison suggested that ceramic stators may be, although even they are only marginal. Lastly, a fiberglass/polyimide composite gearbox showed a slight cost advantage. Allison's advanced technology engine yielded 20 percent better SFC and 23 percent less weight. It costs 3 percent more to buy, but 35 percent less to maintain than a comparable current turboprop. A range of aircraft benefits are shown in the following list corresponding to the three aircraft types that they investigated (an unpressurized twin, a heavy twin, and a twin-engine helicoper):

Technologies:

1. Advanced materials and aerothermodynamics - higher cycle efficiency and smaller size
2. Dual property axial high-pressure turbine - much lower maintenance cost (5000 hr TBO)
3. Ceramic turbine stator - slight cost reduction
4. Lamilloy combustor - permits 5000 hr TBO at high temperature
5. Composite gearbox case - slight cost reduction

Engine improvements:

1. SFC - 20 percent
2. Weight - 23 percent
3. Cost -3 percent
4. Maintenance cost - 35 percent

Aircraft benefits:

1. Fuel burned - 23 to 32 percent less
2. Gross weight - 11 to 21 percent less
3. Purchase price - ±7 percent
4. Ownership cost - 8 to 20 percent less

Although the purchase prices do not change much, 23 to 32 percent less fuel is burned, and ownership costs drop 8 to 20 percent.

In a similar way, the other companies listed the technology elements that survived their screening processes and ordered them as shown in table I, a Garrett example. The benefits of each of the advanced technologies are given relative to a hypothetical, all-new engine using currently available technology. For example, the high-pressure laminated turbine technology raises the core turbine efficiency by 9.8 percent, reduces engine cost 21 percent, weight 7 percent, and SFC 7.4 percent and yields a benefit cost ratio of 561. The benefit is defined as the ownership saving over 20 years for a fleet of 15 000 medium-sized, twin-engined airplanes. The cost is the research investment required to demonstrate technology readiness. The single-stage powdered metal titanium advanced compressor is 1 percent less efficient than a machined two-stage current technology compressor; yet it costs and weighs enough less to offset this penalty. Another technology with large benefits is a low-pressure turbine that operates at a high work factor but low speed. Collectively, these technologies provide a 36 percent lower cost reduction, 20 percent lighter weight, and 13 percent better SFC relative to the best that we could do with today's available technology. One of the key elements is clearly the laminated turbine technology, which provides roughly one-half of the benefits.

Aircraft Fuel

Now we can return to the most challenging issue, identified at the outset: comparing advanced GATE type engines with piston engines. One of the disadvantages of current turboprops is that they consume too much fuel: about 10 percent more than current piston engines for a typical twin-engine aircraft mission. This is because their installed cruise thrust-SFC is inferior. GATE engines would eliminate most of this SFC difference as shown in figure 20. Since their installed engine weight is only 1/3 or 1/4 as much as a reciprocating engine, the resulting GATE-powered airplane would actually save 5 to 15 percent fuel. Since avgas costs as much as 20 percent more per BTU, the real fuel cost savings are substantially greater than that.

Aircraft Economics

A representative illustration of how a GATE-powered airplane compares with a reciprocating-powered airplane in economic terms is shown in table II for a light-twin airplane that cruises at 10 000 feet at 225 knots for 1100 nmi, is flown 500 hr/yr, and is sold after 3 years. The baseline is a current-technology, reciprocating-powered airplane that requires two 380-hp piston engines weighing 550 lb, each, that together burn 172 gallons of fuel. The airplane takeoff weight is 6200 lb; the engines cost $11 000 each; the airplane costs $207 000 total; it costs $51/hr to operate and, for the three-year ownership period, costs a total of $170 000. The percent changes for three different advanced engine options are shown in the right-hand columns. The first is an improved reciprocating engine presuming simply 10 percent lower SFC. It produces rather modest aircraft economic improvements: 5 percent in total cost of ownership. Option 2 is a current technology turboprop, but produced at a rate of 10 000 units per year. It too is not very attractive - only a 3 percent net savings. Option 3, one of the low-cost GATE turboprops, is much more attractive. This airplane would be 20 percent smaller and burn 8 percent less fuel, and, although the engine cost is up 23 percent, the complete aircraft cost is down 14 percent, and the operating cost is down 28 percent, for a total ownership saving of 20 percent.

If we expand our scope to include the other low-cost GATE versions and other applications (fig. 21), we see that, as a class, the twin-turboprop airplanes would cost 15 to 25 percent less to buy and 30 to 40 percent less to operate than their piston-powered counterparts. However, the benefits for high-performance, single-engine airplanes are only one-third to one-half as much. Nevertheless, any economic benefits at all must be considered a bonus, inasmuch as the argument for turbinization could be predicated on noneconomic virtues alone. The obvious question is: When do these economic benefits disappear? A rough estimate of this is shown in figure 22 where a few data points from each study are plotted in terms of the reduction in ownership cost of GATE-powered airplanes relative to current reciprocating-powered airplanes as a function of the required shaft horsepower for the reciprocating aircraft version. The twin-engine airplane data looks impressive, showing 20 to 30 percent benefits. The single-engine data are too sparse to be certain, but it appears as though the economic incentive goes to zero somewhere in the 200-hp region. Of course, even at zero or slightly negative economic change turbinization is still attractive.

MARKET IMPACT

Obviously, major benefits of this magnitude cause a large impact in the marketplace. The marketing forecasts that go along with the preceding are summarized in figure 23 for each study team in terms of the total number of turbine engines produced, both with and without an instantaneously mature GATE engine in 1988. Since GATE technology engines could not actually even enter service until the early 1990's, this is merely an indication of impact rather than an actual forecast. The picture is certainly striking because of the quite different estimates. Allison's modest forecast is in agreement with their more conservative cost estimates, while Teledyne predicts a huge gain due to their lower cost estimates and broad engine-size family. All of the estimates are much greater than the 1500 engines produced in 1976. Half of these were turboshaft engines for helicopters. However, the future GATE scenario forecasts that the turboprop would strongly dominate. A composite average of these four forecasts is shown in figure 24. A total of 20 000 GATE technology turbine engines would be manufactured annually, mostly turboprops, compared with one-fourth as many without GATE technology. The aircraft market results are shown with the pie charts, both with and without GATE technology engines. Without GATE, the turboprop share is forecast to grow from its current level of 2 percent to a level of 5 percent. With GATE, it would grow to about 35 percent, or a sevenfold increase. The twin-piston market would practically disappear, from 12 to 2 percent, while the single-engine piston portion would shrink from 68 to 47 percent, but it still would remain very large.

CONCLUSIONS

A summary of what we perceive the major study result to be is displayed in figure 25. The most challenging, but rewarding, opportunity for small general-aviation turbine engines lies in the 300 to 600 hp region. Here, the proper combination of simpler design, improved materials, higher component efficiencies, cheaper manufacturing technologies, and core commonality could result in sufficiently lower engine cost, SFC, and weight to overcome the traditional turbine engine cost barrier at the 500 hp size. Plotted here are the trends of aircraft cost versus engine size, and the large gap between reciprocating-powered and turboprop-powered aircraft is apparent. GATE technology permits large improvements in aircraft economies at the upper end of the reciprocating-powered class and fills in the gap between the relatively inexpensive reciprocating aircraft and the expensive turboprop aircraft. In turn, this brings the many other virtues of turbine engines to a much broader spectrum of users and applications.

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Table I

ADVANCED TECHNOLOGY BENEFITS

TECHNOLOGY	Δ η, PTS	Δ COST, %	Δ WT, %	Δ SFC, %	BENEFIT/ COST RATIO
HP LAMINATED TURBINE	+9.8	-21	-7	- 7.4	561
PM Ti SINGLE STAGE COMPRESSOR	-1.0	- 4	-6	+ 1.4	232
LOW COST FUEL NOZZLES	----	- 1	0	0	144
ELECTRONIC CONTROL	----	- 2	0	0	132
HIGH WORK/LOW SPEED LP TURBINE	+6.0	- 5	-7.0	-7.0	498
LASER HARDENED GEARS	----	- 3	0	0	226
TOTAL	----	-36	-20	-13.0	402 (AVG)

NOTES

1. CHANGES ARE RELATIVE TO HYPOTHETICAL CURRENT TECHNOLOGY TURBINE ENGINE
2. CLEARANCE CONTROL BENEFITS ARE INCLUDED IN ABOVE
3. BENEFIT DEFINED AS OWNERSHIP COST SAVINGS OVER 20 yr FOR 15 000 MEDIUM TWIN A/C
4. COST IS NASA R & T COST

SOURCE: GARRETT

CS-79-4210

Table II

GATE TURBOPROP AIRPLANES WOULD BE CHEAPER

LIGHT TWIN AIRPLANE[1]	CURRENT TECHNOLOGY RECIP	% CHANGES		
		ADV TECH RECIP (-10%SFC)	CURRENT TECH TURBOPROP[2]	GATE TURBOPROP[2]
SHP, SLS TO	380	- 2	- 11	-14
ENGINE WEIGHT	550 lb	- 3	- 68	-75
MISSION FUEL	172 gal	-10	10	- 8
GROSS WEIGHT	6 200 lb	- 4	- 15	-20
ENGINE COST	$11 020	- 2	113	23
ACQUISITION COST	$ 207 K	- 3	6	-14
OPERATING COST	$ 51/hr	- 6	- 14	-28
TOTAL COST OF OWNERSHIP	$ 170 K	- 5	- 3	-20

[1]CRUISES AT 10 000 ft, 225 KNOTS FOR 1100 n. m., 500 hr/yr FOR 3 yr
[2]ASSUMING 10 000 ENGINES/yr PRODUCTION

SOURCE: GARRETT

CS-79-4190

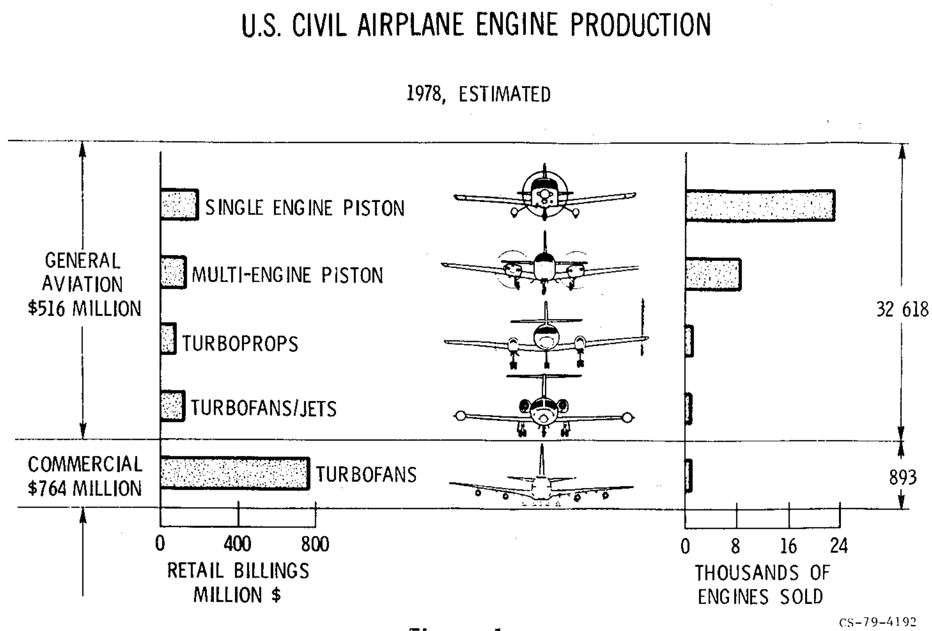


Figure 1

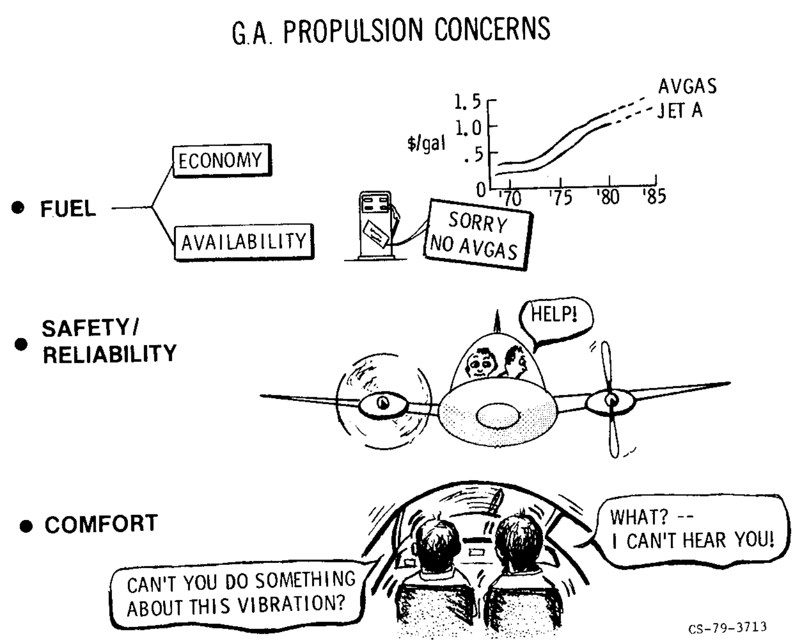


Figure 2

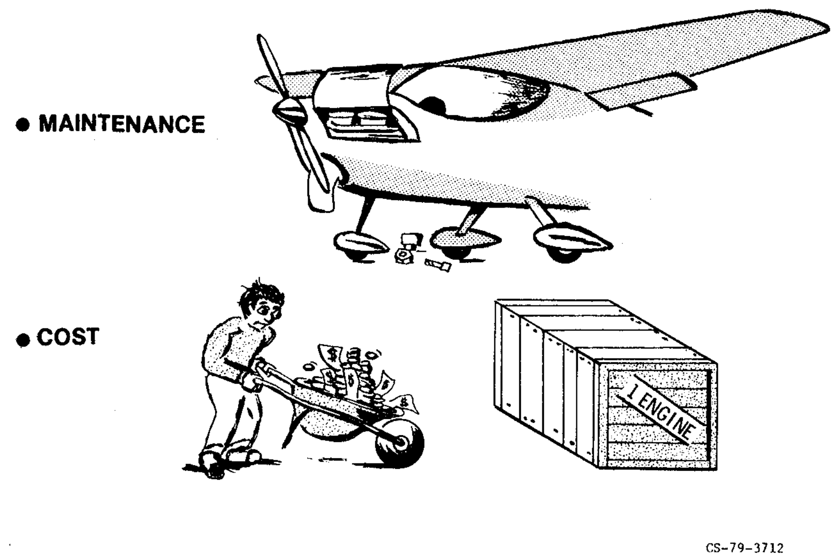


Figure 3

CURRENT ENGINE SELECTION FOR LIGHT AIRPLANES

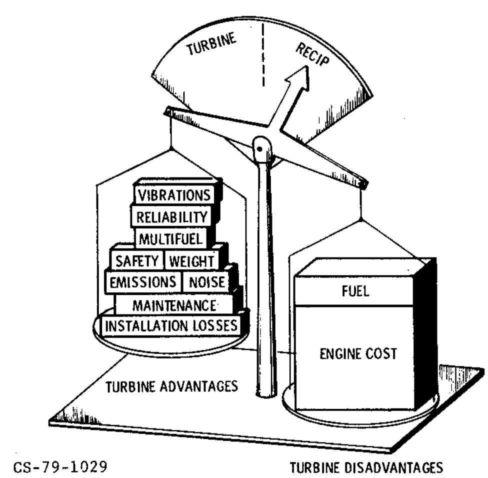


Figure 4

EXPLOITING ENGINE TECHNOLOGY DIFFERENTLY

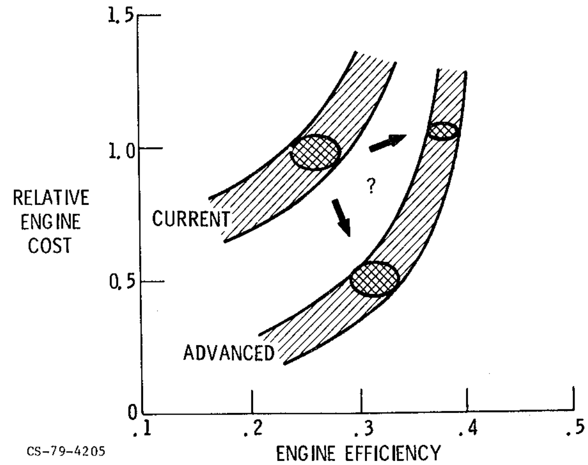


Figure 5

TURBOPROP MEDIUM PRESSURIZED TWIN

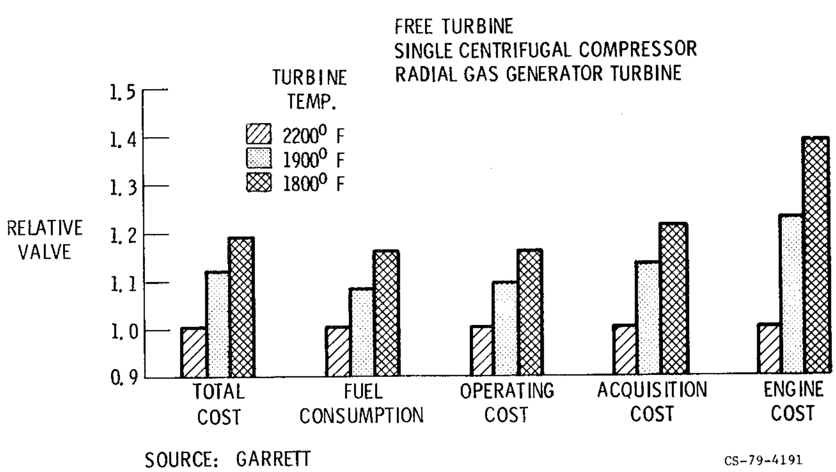


Figure 6

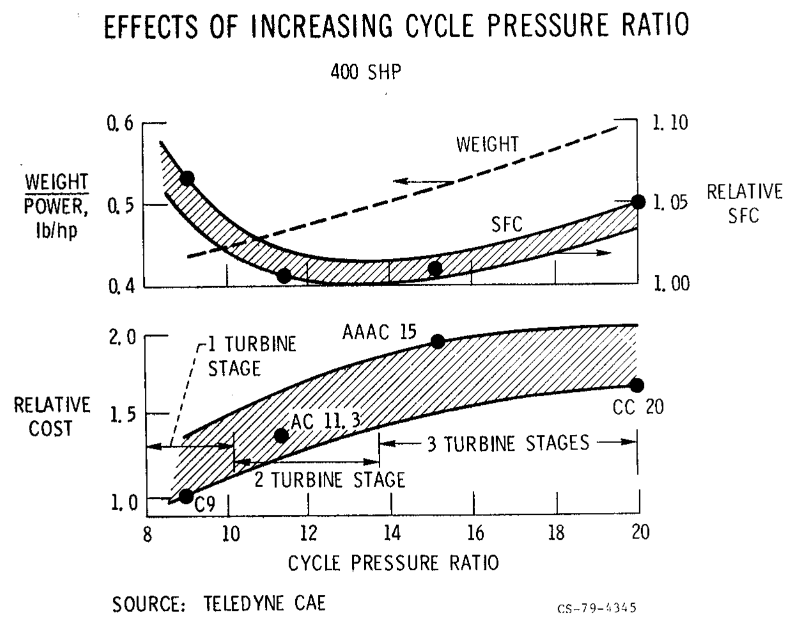


Figure 7

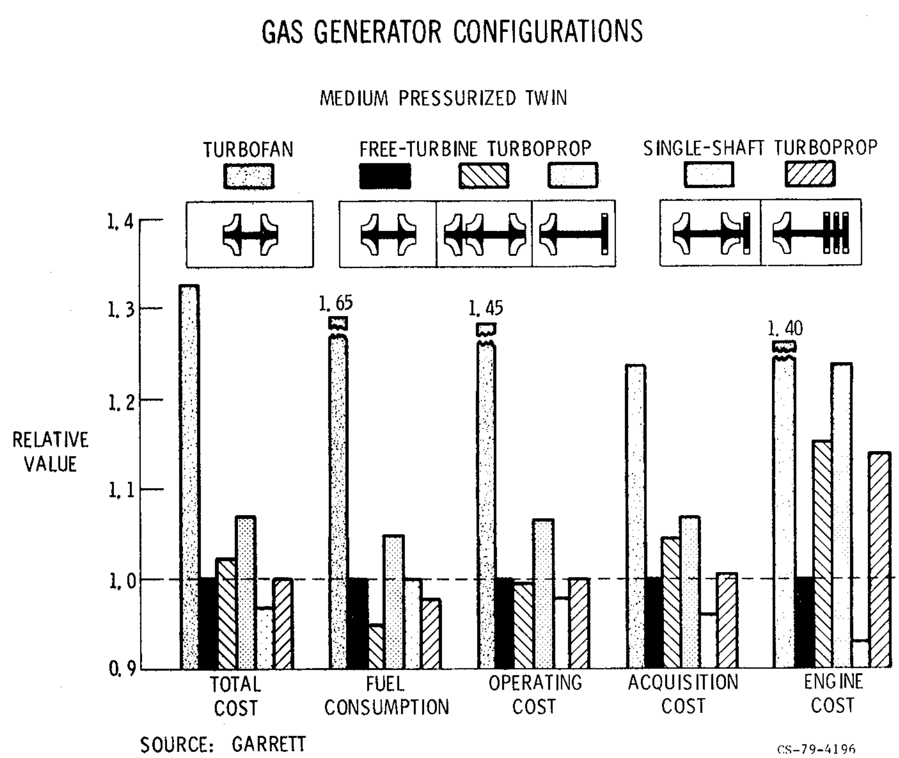


Figure 8

FUTURE TURBINE ENGINE ALTERNATIVES FOR SMALL GENERAL AVIATION AIRCR...

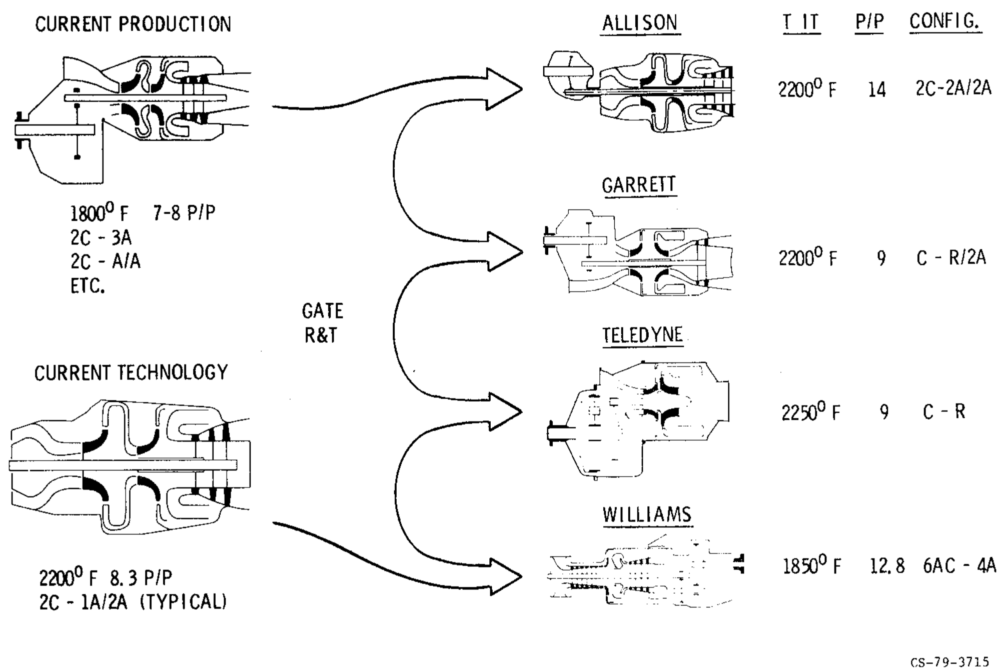


Figure 9

GATE SFC IMPROVEMENTS

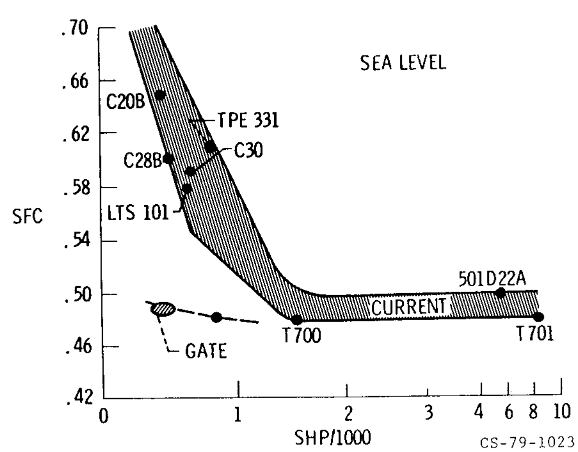


Figure 10

BARRIER TECHNOLOGY

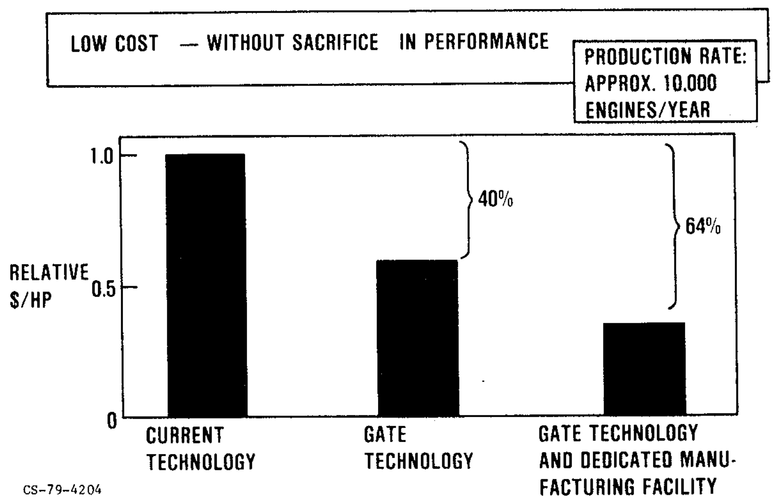


Figure 11

COST REDUCTION FORECAST FOR GATE TECHNOLOGY ENGINES

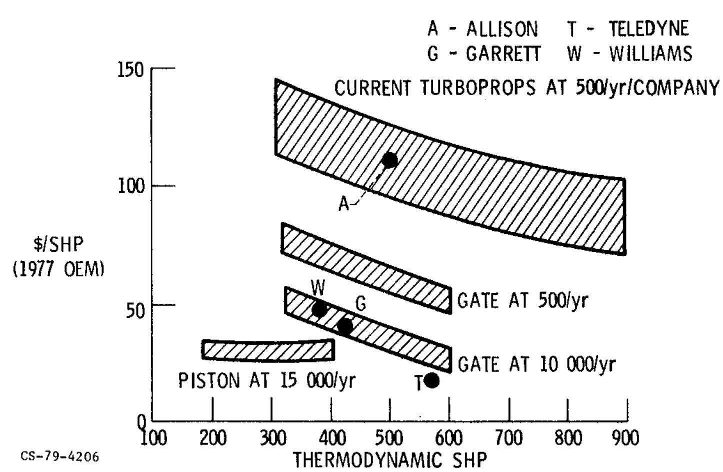


Figure 12

GATE TECHNOLOGIES

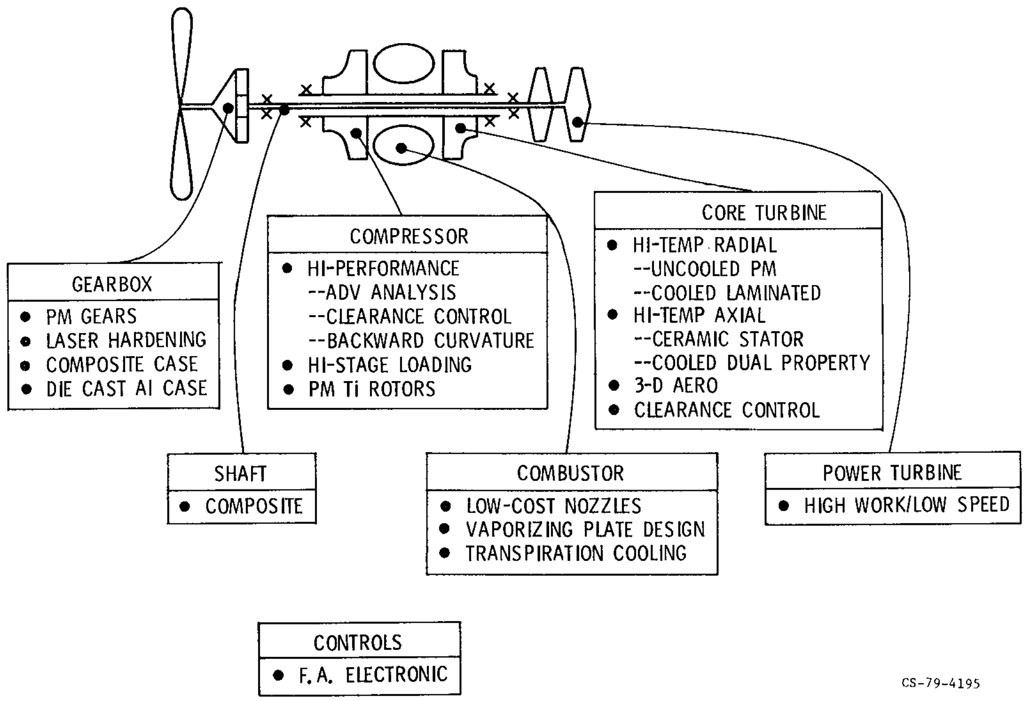
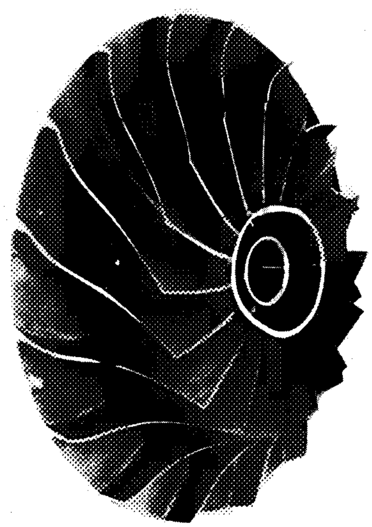


Figure 13

SINGLE STAGE CENTRIFUGAL COMPRESSOR



TECHNOLOGY

- HIGH STAGE LOADING
- ADVANCED ANALYSIS
- LDV MEASUREMENTS
- OPTIMIZED DIFFUSION RATIO
- 3D DIFFUSER
- BOUNDARY LAYER BLEED
- CLEARANCE CONTROL
- GOOD SURGE MARGIN W/O VAR GEO
- HIP PM TI NET SHAPE

BENEFITS

- +3.5 POINTS IN EFFICIENCY
- 4% ENGINE COST REDUCTION
- 6% ENGINE WEIGHT REDUCTION

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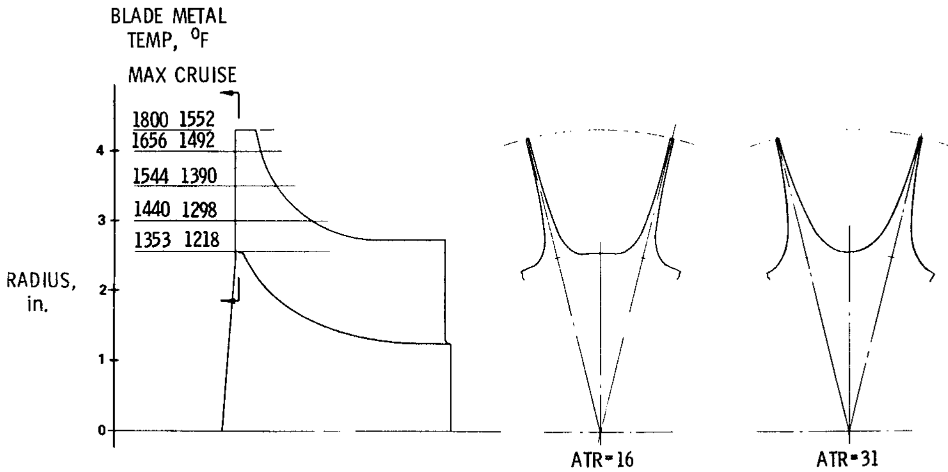
Figure 14

RADIAL TURBINE LIFE



STRESS RUPTURE LIFE, hr		
ATR = 16		ATR = 31
3000	CRUISE (1950° F)	10 000 PLUS
20	MAX T. I. T. (2250° F)	100
70	MAX -50° (2200° F)	300
MATERIAL: 1978 EQUIAXED IN-100		
SOURCE: TELEDYNE CAE		

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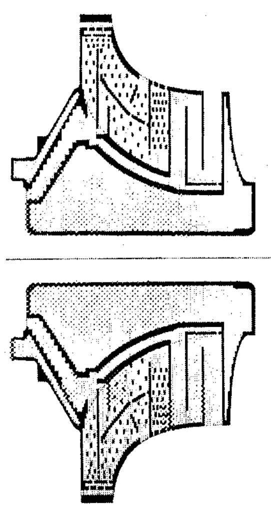
Figure 15

INTEGRAL COOLED RADIAL HP TURBINE



SOURCE: GARRETT

TECHNOLOGY

- ADVANCED ANALYSIS
- LDV MEASUREMENTS
- END WALL EFFECTS
- COOLING FLOW OPTIMIZATION
- MINIMUM INCIDENCE LOSS
- CLEARANCE CONTROL
- LAMINATED CONSTRUCTION
- ADVANCED ADB
- ADVANCED ECM

BENEFITS

- +9.8 POINTS IN EFFICIENCY
- 20 PERCENT REDUCTION IN COOLING FLOW
- 21 PERCENT REDUCTION IN ENGINE COST

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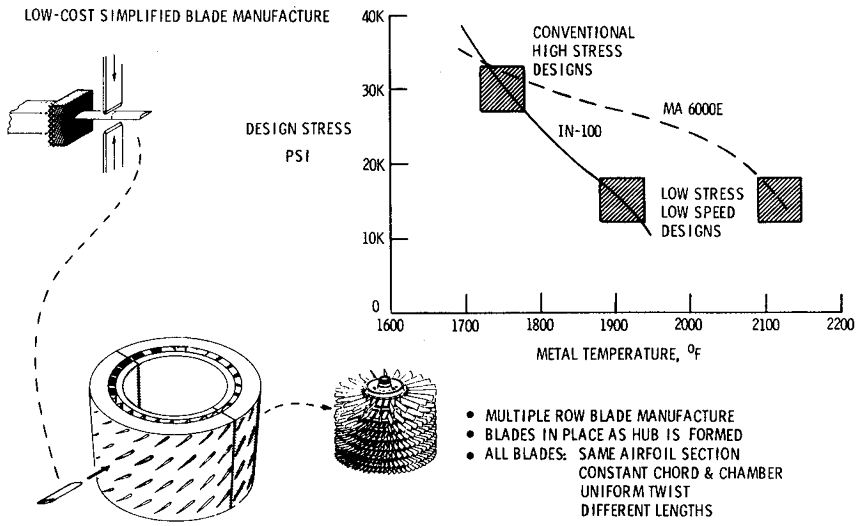
Figure 16

MANUFACTURING TECHNOLOGY AREAS COMPATIBLE WITH RESTRICTED AERODYNAMIC SHAPES



SOURCE: WILLIAMS RESEARCH

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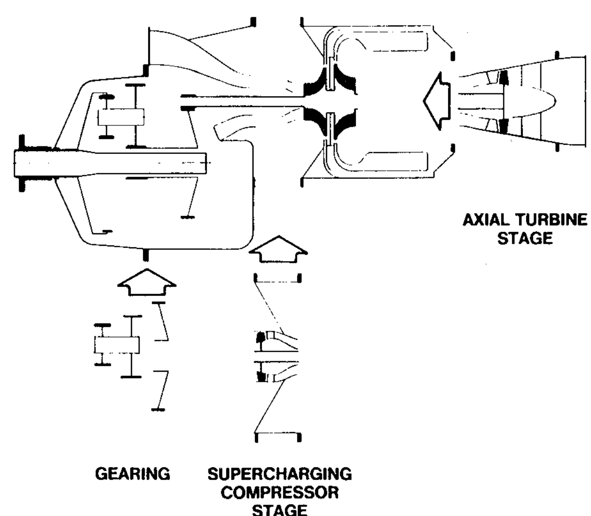
Figure 17

ADD COMPONENTS TO C9 CORE



SOURCE: TELEDYNE

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Figure 18

COMMON CORE APPROACH

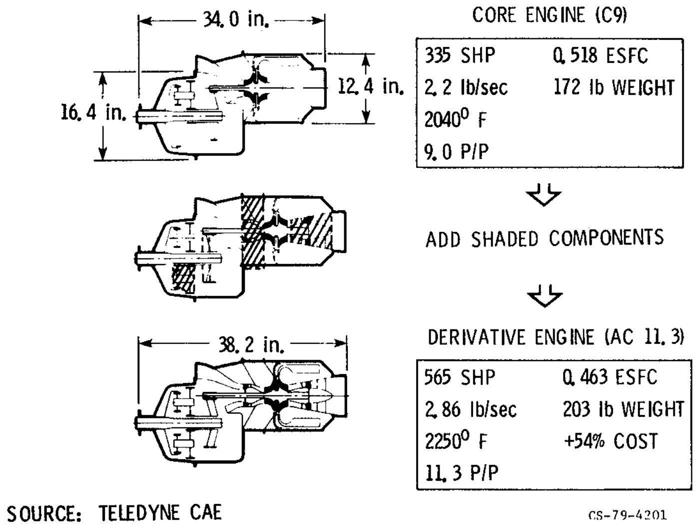


Figure 19

EFFICIENCY IMPROVEMENT PLUS WEIGHT ADVANTAGE SAVES FUEL

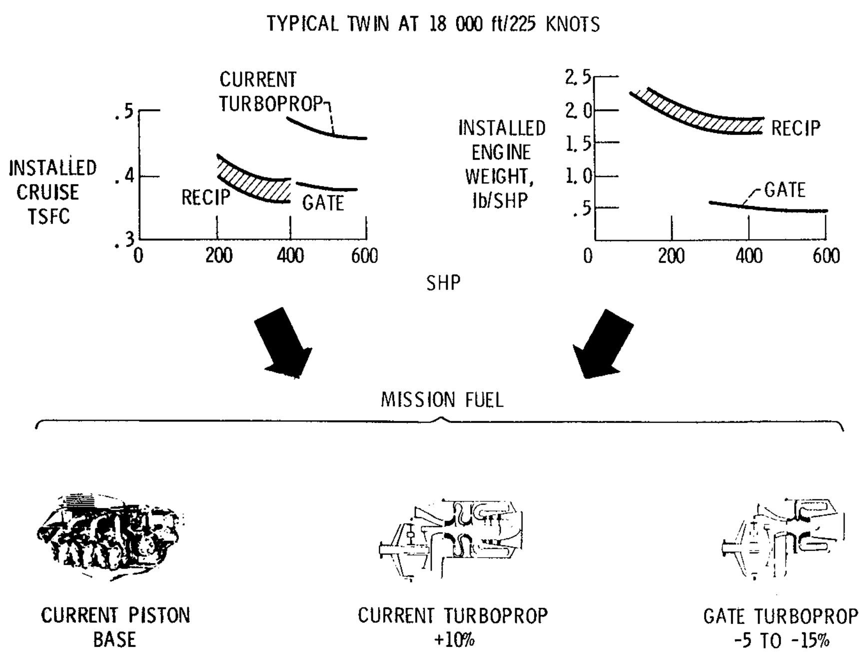
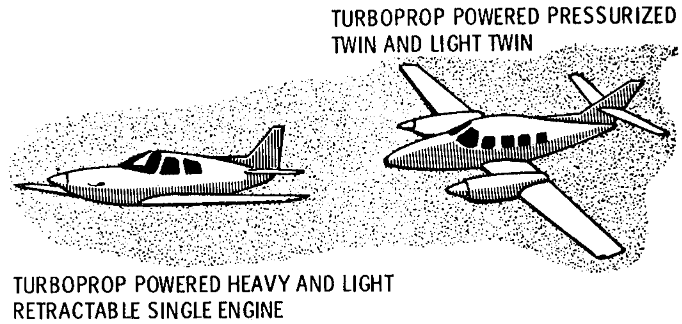


Figure 20

BENEFITS RELATIVE TO CURRENT RECIPROCATING ENGINE



10 - 15%	LESS GROSS WEIGHT	20 - 25%
5 - 15%	LESS FUEL BURNED	10 - 15%
10 - 15%	LESS INITIAL COST	15 - 25%
7 - 15%	LESS OPERATING COST	30 - 40%
8 - 15%	LESS LIFE-CYCLE COST	25 - 35%
	HIGHER RELIABILITY	
	GREATER SAFETY AND COMFORT	
	QUIETER AND CLEANER	
	MULTIFUEL CAPABILITY	

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Figure 21

GATE POWERED AIRCRAFT HAVE LOWER COST OF OWNERSHIP THAN EQUIVALENT RECIP POWERED AIRCRAFT

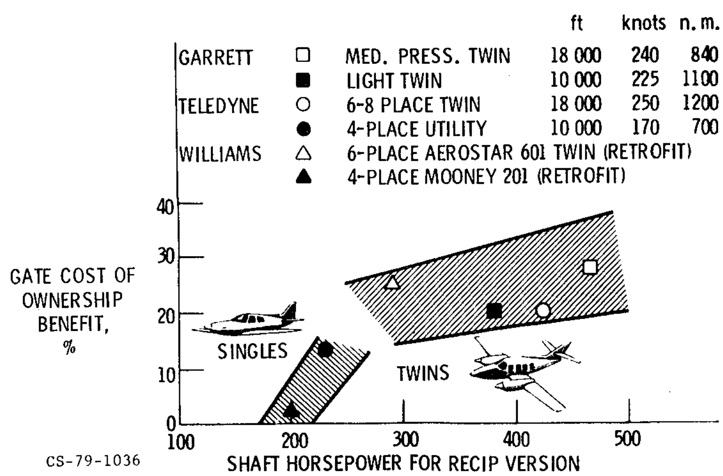

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Figure 22

1988 CIVIL TURBINE ENGINE MARKET UNDER 1000 SHP

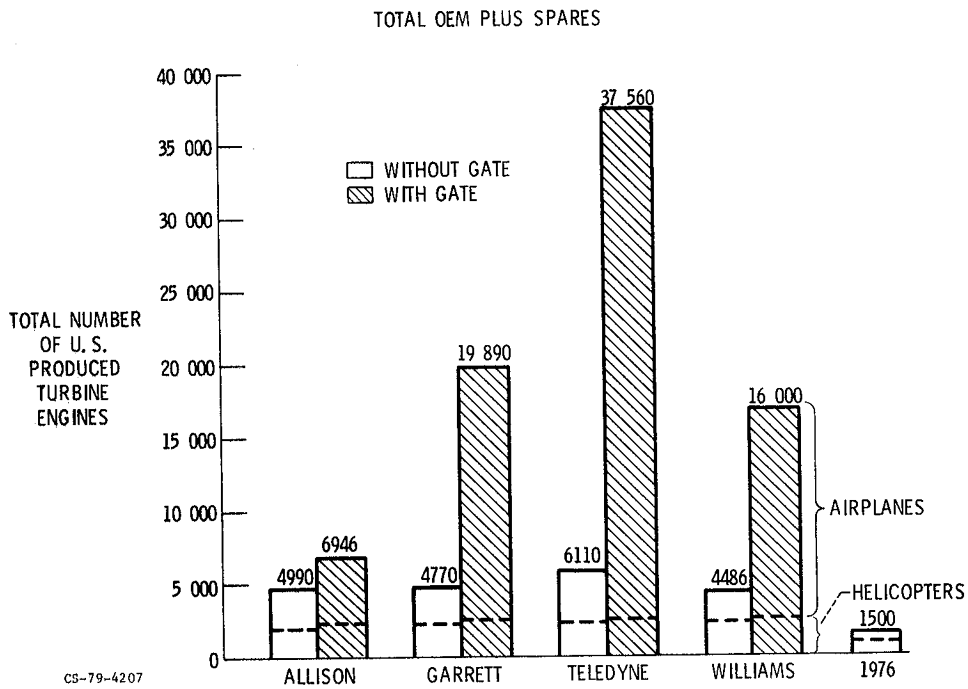

Figure 23

1988 PRODUCTION FORECASTS

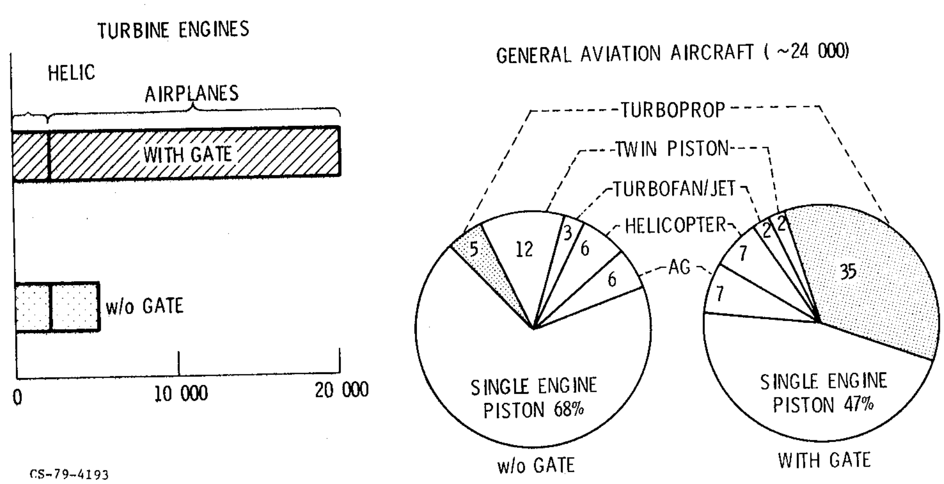

Figure 24

GATE TECHNOLOGY COULD EXPAND DOMAIN OF SMALL TURBINE ENGINES

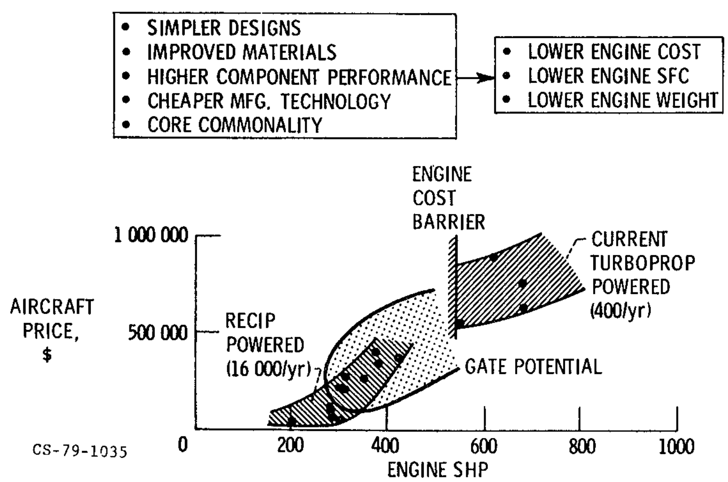

Figure 25