1

NASA Technical Memorandum 79073

NASA-TM-79073

NEW OPPORTUNITIES FOR FUTURE SMALL CIVIL TURBINE ENGINES - OVERVIEWING THE GATE STUDIES

William C. Strack
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER to be presented at the
Business and Aircraft Meeting
sponsored by the Society of Automotive Engineers, Inc.
Wichita, Kansas, April 3-6, 1979

E-9890

ABSTRACT

This paper presents an overview of four independent studies that explore the opportunities for future General Aviation Turbine Engines (GATE) in the 150-1000 SHP class. Detroit Diesel Allison, Garrett/AiResearch, Teledyne CAE, and Williams Research participated along with several airframers. These studies forecasted the potential impact of advanced technology turbine engines in the post-1988 market, identified important aircraft and missions, desirable engine sizes, engine performance and cost goals. Parametric evaluations of various engine cycles, configurations, design features, and advanced technology elements defined baseline conceptual engines for each of the important missions identified by the market analysis. Both fixed-wing and helicopter aircraft, and turboshaft, turboprop, and turbofan engines were considered. All four companies predicted sizable performance gains (e.g., 20% SFC decrease), and three predicted large engine cost reductions of sufficient magnitude to challenge the reciprocating engine in the 300-500 SHP class. Key technology areas were recommended for NASA support in order to realize these improvements.

EARLY IN 1977, Detroit Diesel Allison, Garrett AiResearch, Teledyne CAE, and Williams Research independently embarked on NASA-sponsored studies to explore opportunities of using advanced technologies in small civil turbine engines. The motivation was the growing realization that small general aviation aircraft are an important and rapidly expanding segment of the air transportation system. Yet despite substantial R&T investments in large engine propulsion, small engines were being largely ignored. More specifically, NASA has underway in-house and contracted efforts aimed at improving turbofans of 1500 pounds thrust and more (e.g., the EEE, ECI, QCGAT, QCEEE, and MATE programs) as well as some emission and performance activities in the 100-400 SHP internal combustion type engine. But until very recently no work was aimed at turbines in the less than 1000 SHP category - i.e., the size category encompassing nearly all of the 170,000 aircraft in the general aviation fleet.

The general objective was to identify and assess the impacts of candidate 1990 turbine engine technologies. Further, 'What engine sizes offer the greatest opportunities?' and 'How can cost of ownership be reduced?' were central issues to be addressed. This paper presents an overview of the results of these 4 studies which are known as the GATE studies (General Aviation Turbine Engine). Separate reports document the studies in considerably greater detail than reported here.

SETTING THE TASKS

Each of the four contractors arranged either formal or informal support from airframers to enhance the credibility of their efforts (Fig. 1). Each such team spent 10-12 months of technical effort independently addressing the tasks defined in Fig. 2. The first task was to forecast a 1988 market scenario in order to identify the aircraft and missions likely to be suitable for advanced small turbine engines. Desireable turbine engine sizes and requirements were established for both fixed and rotory wing aircraft. In Task II advanced future engines were ultimately selected and evaluated for each of the important aircraft/mission catagories identified in Task I. This was done by subjecting baseline engine definitions to numerous cycle, configuration, and advanced technology tradeoff analyses. During these broad-scope tradeoff studies, the 'optimum engine' definitions were selected on the basis of key aircraft economic criteria such as aircraft acquisition cost, operating cost, and total cost of ownership. Concurrently, a set of advanced technologies was screened to identify those technologies with the greatest potential payoffs.

Then in Task III the set of optimum engines defined in Task II was modified such that a single common core could be utilized for all sizes and types of engines comprising the Task II set. This 'common core' concept was then evaluated for additional economic benefits. Finally, in Task IV, each contractor recommended a technology program plan to develop and demonstrate the key technologies he previously identified as being essential to his conceptual engines.

Although these tasks were basically carried out sequentially, iteration between them was necessary since engine cost and performance are needed in Task I but are not firmly established until the end of Tasks II and III. Conversely, the engine sizes, engine requirements and production volume information predicted in Task I is needed in Tasks II and III to properly conceptualize an engine and to obtain engine cost.

Within this basic framework each company received only very broad guidelines from NASA:

- Consider engines up to 1000 SHP (or 1500 lb thrust for turbofans), but emphasize the size class under 600 SHP
- Search for high risk technologies yielding high payoffs that could be incorporated into 1990 time frame engines
- Emphasize economics of aircraft ownership
- Involve airframers for applications definition and benefit assessments

SETTING THE GROUNDRULES

The groundrule stressing the low end (under 600 SHP) of the power spectrum but allowing up to 1000 SHP sizes to be considered reflects several uncertainties. First, the U.S. Army has already initiated an Advanced Technology Demonstrator Turboshaft Engine program (ATDE) in the 800 SHP size. While the ATDE technology level is early 80's rather than late 80's, it is not obvious that improvement beyond the ATDE level would be large enough to warrent a concurrent effort in the 800-1000 SHP class. Secondly, a huge market potential exists in the under 400

SHP class now totally dominated by piston engines. The high acquisition cost of the turbine engine has simply precluded its introduction into this extremely cost-sensitive market. An obvious issue, then, concerns the possibility of penetrating the piston market where the opportunity could be enormous but where the risk is correspondingly large.

THE TURBINE VERSUS RECIP ISSUE

This issue ultimately emerged as the most intriguing one addressed in the course of the GATE studies. Despite their 3:1 cost disadvantage, turbine engines possess many superior qualities: three times lighter, much lower maintenance, less installation penalties, higher reliability, much lower vibration, noise and emissions, multifuel capability, and a better safety record. To elaborate, consider just one of these qualities - better safety. Theoretically there are several reasons to expect turbine engines to improve aircraft safety as listed in Fig. 3. That these generally acknowledged factors do in fact result in enhanced safety is always difficult to conclusively establish since maintenance practices, pilot proficiency differences, etc. fog the comparison. But because the historical safety record of the popular turbine engines is 3-6 times better than recips (Table 1), it is difficult not to conclude that turbine engines are in fact considerably safer. The importance of these highly desirable turbine qualities must be weighed carefully in selecting the most suitable power plant type. The challenge is to capture these acknowledged benefits by lowering engine cost sufficiently to tip the scales in favor of turbines.

Fig. 4 depicts the current situation and indicates that, in addition to the engine cost disadvantage, turbine engines also burn more fuel. Turbine SFC's are about 0.55 - 0.65 lb/HP-hr compared to 0.40 - 0.50 lb/HP-hr for recips. However comparing bare SFC's is often misleading unless other factors such as installation losses, fuel type, and engine weight are also compared. As shown in Fig. 5, installation losses for recips reduce its cruise SFC advantage considerably. Cylinder cooling losses can amount to 10% of the total aircraft drag. Nacelles for the larger recip engines produce more drag. And, at least theoretically, recip propellers are less efficient due to their thicker structure required to withstand the high vibratory stresses caused by the pulsating power generation process. Furthermore, turbine fuel contains 10% more energy/gallon and costs about 10% less - for a 20% total cost advantage over Avgas. Also, the 3:1 weight advantage of turbines saves fuel since it permits a significantly smaller aircraft size. The combination of these factors neutralizes the apparent recip SFC advantage in many applications. Thus the fuel penalty of turbines is more apparent than real. The 3:1 cost difference is the only true barrier to its widespread usage in airplanes below 8000 pounds gross weight.

THE LOW-COST THEME EMERGES

Basically each company was permitted to explore the opportunities most important in its own judgement. Understandably this led to differences in viewpoints, approaches, and depth of analysis. Rather than describe each company's pursuit, an overall composite is presented here using representative examples from each of the studies where appropriate. Also, instead of recounting the iterations between the tasks only the final results are presented.

After considerable tradeoff analyses of various engine configurations, cycles, and advanced technologies, the companies selected the baseline conceptual engines illustrated in Fig. 6 with the cycles, performance, weights, and costs defined in Table 2. They are all turboprops since the market analyses uncovered no need for speeds in excess of 260 knots and at these speeds the cycle analyses showed 15% fuel penalties as well as increased cost and weight for turbofans. Of greatest interest are the impressive performance results and, for three companies, the very low cost estimates. These three companies aggressively pursued the search for low cost concepts after concluding that competing with the piston engine in the 250-565 SHP size class represented the most rewarding (and challenging) opportunity.

To put these potential engine improvements into perspective, examine first Fig. 7 which shows that GATE's 20% efficiency gain relative to current production engines would delay the small engine BSFC rise down to the 300 SHP region. This is rather significant in view of the increasingly difficult problem of acheiving good efficiency in small sizes due to adverse scale effects. The trend toward better small engine fuel economy is also bolstered by the Army's

ATDE engine program. The Army has established a goal of 0.55 SFC at 480 SHP for an 800 SHP class turboshaft engine.

Even more significant is that the average cost reduction of the three "low-cost" engine designs is about 50%. This is the inherent cost reduction through application of GATE advanced component and manufacturing technologies and based on current production rates of about 500 units annually per manufacturer. Once the cost barrier is breached by such a magnitude, the market analyses' cost-demand relationships dictate that much greater sales rates are triggered. This, in turn, opens up the possibility of a dedicated manufacturing facility which would reduce engine costs even further. Garrett and Williams foresee 6000-8000 units/year per manufacturer and a total cost reduction of about 60% while Teledyne foresees about 16000/year and a correspondingly greater reduction. These production numbers assume two manufacturers share the market equally.

These GATE engine cost predictions are compared with reciprocating engine costs in Fig. 8. Here the three low-cost GATE engines are plotted twice. The upper square represents current turbine production rates of about 500 units per year per company, while the lower square accounts for the additional effect of high volume production. Clearly neither advanced technology nor high production volume alone can push the turbine engine into a solid competitive position with recips. It takes both factors, but the key that unlocks this potential is advanced technology (described later).

Allison's theme differed in that they preferred a relatively sophisticated high-performance engine. They concentrated mainly on a turbine engine which produced better fuel economy at lower weight and reduced installation volume in comparison with their latest production small gas turbine engine. Their GATE conceptual engine costs more than their latest production engine which has a relatively large advantage in price primarily due to long production experience. Their theme, then, was to determine if the performance advantage of a new high pressure ratio air-cooled engine was sufficient to offset the price advantage acquired by engines with long production runs (e.g., their 250 series).

THE EFFECT ON AIRCRAFT ECONOMICS

Are the forecasted GATE SFC and engine cost improvements large enough that, when combined with the turbine's low maintenance, low weight, and long TBO, turbine engines can effectively challenge recips on purely economic grounds? The impact of using GATE technology engines on aircraft economics was analyzed by each company with assistance from airframers. The cost analyses involved flying synthesized GATE--powered aircraft over typical missions to determine fuel consumption and aircraft sizes. Aircraft acquisition and operating cost models were then exercized to determine these costs plus the total cost of ownership based on resale after several years of non-revenue service. Table 3 illustrates a typical aircraft/mission category breakdown resulting from the market analyses. The aircraft and missions at the small sizes range from 2-place trainers up to 12-place heavy twins, plus ag-planes and light helicopters. Only modest changes in aircraft capabilities are forecast during the next decade except for the hi-performance single-engine category where a new demand is emerging for pressurized, high-altitude flight using sophisticated avionics such as weather radar. Not surprisingly, the GATE screening process eliminated the smallest category as an attractive turbinization candidate. These categories differed somewhat among the companies and each selected 2 or 3 representative categories for detailed application assessment.

A typical example is given in Table 4 that illustrates the large economic improvements of GATE technology turboprop-powered aircraft compared to recip-powered aircraft. The example is a light unpressurized twin which is resized for several alternative powerplant options to fly identical missions with same-technology airframes. Only very modest improvements result from postulating an advanced recip with 10% better SFC than current recips. And a current technology turboprop (e.g., scaled-down T700 rather than existing production engine technology) is only a standoff in economic terms. But an advanced technology turboprop aircraft would be 20% cheaper to own, burn 8% less fuel and cost 14% less to purchase than an equivalent aircraft powered by today's recip engines. It is even 15% cheaper to own than the postulated advanced recip aircraft.

Two other examples are shown in Table 5 where the comparison is done on a retrofit basis for existing airframes instead of all new airframes as in the previous figure. Here gross weight is fixed and the current maximum payload assumed. The retrofitted turboprop is derated from 390 SHP to 352 SHP for the twin-engine Aerostar 601P and to 305 SHP for the single-engine Mooney 201. The GATE turboprop retrofit results in faster climbs to higher cruise altitudes and far greater ranges (considerably greater payload capability would have resulted if range had been fixed instead). GATE fuel economy is equal to the recip version for the smaller Mooney and 54% better in the Aerostar case. Productivity is improved by 12% for the Mooney and 62% for the Aerostar.

The results shown in Fig. 9 summarize all the low-cost theme application studies and reveal important cost of ownership trends. As expected, larger aircraft benefit more from GATE turbinization than smaller aircraft. Light to medium weight twins show impressive 20 to 33% improvements. Even medium performance single-engine models in the 200-HP class reap some economic benefit. The conclusion to be drawn is that despite the fact that the case for turbine engines is predicated on its numerous non-economic advantages (e.g., safety, comfort, reliability and multifuel capability), a very important potential economic bonus exists which bolsters their position considerably.

Fig. 10 summarizes both the economic benefits and the other desirable qualities (size independent) of GATE technology engines as assessed by Garrett, Teledyne, and Williams. The economic incentives range from strong for twins, to moderate for retractable singles, to neutral or negative for fixed gear singles (not shown). This includes significently less fuel burned in concert with the national energy policy. Similar economic benefits were determined in Allison's high-performance theme except that the benefits occur only in comparison to current turbine engines - with 20% lower cost of ownership due to lower SFC, lower weight, and longer overhaul periods.

IMPACT OF GATE ON MARKET

Whereas recip-powered aircraft production is forecast to increase at about 4% per year, turboprop/turboshaft production is forecast to rise more than twice as rapidly even without the influence of GATE technology - to 4000-6000 units annually by 1988. In this unperturbed market situation turboprops and turboshafts share the turbine market under 1000 SHP approximately equally. Perturbing this situation with the impact of GATE technology is summarized in Fig. 11 for each of the studies. This is the result of interacting the turbine engine cost and performance improvements with the cost-demand relationships established in the market analyses. The market impacts range from relatively modest (Allison, up 39%) to spectacular (Teledyne, up 6-fold) and of course reflect differing degrees of optimism. The average of the three low-cost theme predictions calls for over 25000 turbine engines annually. Most of these are turboprops and thus a basic shift away from the relative importance of turboshafts takes place. Further data is given in Table 6 for only the GATE portion (less than 600 SHP) of the market. The potential GATE engine market value is $120-240 million which is certainly large enough to command serious attention. Note that these 1988 estimates only represent the GATE impact as if these engines reached instantaneous maturity earlier than actually possible since all-new engines based on GATE technology would not be introduced into service until at least 1990.

A composite picture of the projected impact on total general aviation 1988 sales is displayed in Figs. 12 and 13. While unit production of turboprops is expected to grow from only 2% to 5% of the total market during the period without GATE, it could grow to 35% with GATE. Similarly, net factory billings would rise to as high as 44% of the market under the GATE scenario while the recip fraction would drop from 45% currently to 11% in 1988. Again, this time table is too rapid for 1988 but does represent the mature market potential.

ADVANCED TECHNOLOGY - The foregoing shows that the potential improvements in small turbine engines could lead to dramatic aircraft benefits and a major shift toward turbinization of the general aviation fleet. Teledyne, for example, estimates that if GATE engines attained sales maturity within 5 years, the average total GATE-powered fleet savings would amount to nearly $350 million per year. But what does it take to unlock this potential? The ingredients of the hypothetical assault on the all-important cost barrier consisted of: innovative advanced component and manufacturing technologies, judicious engine design concepts, and parts commonality over a wide range of engine sizes and applications. This section will discuss the individual approaches advocated and identify the key technologies. But due to the sheer bulk of concepts involved and their often proprietary nature detailed discussion is avoided.

Teledyne - Teledyne's general approach is to utilize the higher component efficiency levels made possible through advanced technology to drastically reduce the parts count while simultaneously retaining high performance. For example, whereas a typical 700 SHP current production engine might consist of two centrifugal compressor stages and three axial turbine stages on two shafts, Teledyne's 335 SHP conceptual GATE engine contains only a single, uncooled radial turbine connected to both a single centrifugal compressor and the load with a single shaft. Figure 14 illustrates this approach and the amount of engine cost savings attributable to each item. The key component in this approach is the high temperature (2250 deg F max) uncooled radial turbine. It is predicated on the use of high tip speeds (2500 ft/s) and advanced materials - rapid solidification rate powdered metallurgy. This is a high risk technology to be sure, but it also has the high potential payoff of a 16% engine price reduction. The second largest price drop comes via the replacement of hydromechanical controls with electronic controls. This is actually judged to be a relatively low-risk item and capitalizes on the low-cost electronic controls technology anticipated for the automotive industry. A total engine cost reduction of 49% is estimated through advanced engine technology alone.

In addition to this savings, an additional 17% savings is estimated to be acheivable through advanced fabrication methods and materials. The powder metal/squeeze cast compressor rotor and other techniques defined on the lefthand side of Fig. 15 become economically attractive at production rates in excess of 2000 units annually.

Finally, and as an example of the Task III common core evaluation, the righthand side of Fig. 15 illustrates one example solution to the problem of accomodating various engine size and type requirements. The simple 335 ESHP design is uprated to 565 ESHP through the addition of an axial compressor and an axial turbine stage plus a duplicate set of gears to handle the increased loads (as shown in the diagram) Thus cost is only added when needed and affordable. Preliminary analysis also indicates that one satisfactory way to obtain a lower power version (265 ESHP) is through the addition of inlet guide vanes to reduce airflow while maintaining constant turbine inlet temperature. Lastly, since helicopter turboshafts are preferably free turbine configurations, a free turbine may be added to the baseline design (and gearbox removed) to obtain commonality of core parts over a complete family of engines. The extra cost of the free turbine version is judged a reasonable compromise in view of the much more numerous airplanes and the reduced emphasis on cost for helicopters. The power range investigated by Teledyne in this approach was wider than the others and helps to explain their larger market expectations.

An example of the worth of specific GATE technologies is given in Table 7 for a 6-8 place twin-engine airplane. In this case the uncooled radial turbine technology is the major contributor to a total of $72,510 cost of ownership savings over a 5-year period. This is the savings per aircraft relative to all-new engines that could be built using 1977 technology.

Williams - Williams Research advocates a unique approach that begins with known low-cost manufacturing techniques and attempts to achieve acceptable engine performance within the geometric constraints imposed by such techniques. The concept (Fig. 16) involves design stresses about 1/2 of conventional levels which leads to moderate turbine inlet temperatures (e.g. 1850 deg F) in an uncooled engine with extremely high TBO (never needs an overhaul). Further downstream could be versions utilizing advanced, high temperature materials to achieve 350 deg F higher TIT still uncooled and fully compatible with low cost manufacturing techniques. The manufacturing techniques for these low-stress, low-speed designs lend themselves to the choice of multistage axial compressors and turbines which is seemingly expensive in comparison to single-stage radial components. However, by restricting the blade geometry in order to capture the ultra-low cost manufacturing advantages of using simplified blade shapes and attaching them to a single hub at one time, significant cost savings are feasible. The resulting constant-chord, constant airfoil section, constant camber and uniform twist configuration departs radically from traditional concepts in its attempt to properly trade off performance for cost. Some limited hardware work has already been done with these manufacturing techniques in conjunction with the WR-33 limited life expendable turbojet. To date, the results have been encouraging but, of course, are very preliminary.

Garrett - Garrett's approach is generally similar to Teledyne's, namely, design a simple engine by sacrificing some performance and weight (mainly weight) to obtain fewer and less difficult to manufacture parts. The baseline design differs from Teledyne's in that Garrett selected a two-spool design with a 2-stage axial power turbine for all sizes and applications. It also differs considerably in the kinds of technologies required to achieve low-cost (Fig. 17). The key technology is a cooled radial gas generator turbine constructed of many photoetched laminates activated-diffusion bonded together for a near net-shape piece. Another important technology is the near net-shape single-stage centrifugal compressor using powdered titanium metallurgy.

Screening assessments of each technology element were also carried out as illustrated in Table 8. Shown are the fundamental changes in engine criteria which ultimately react on aircraft economics for each technology surviving the screening. Only those technologies that survived are shown here, many others were considered but rejected. The changes are relative to a hypothetical baseline representing current state-of-the-art technology - i.e., the best turbine engine that could be built today without GATE advancements. For example, the current technology baseline engine would use a cooled, axial HP turbine configuration with inserted blades. But the use of a cooled radial turbine of laminated construction could by itself reduce engine cost 22%, SFC 8%, weight 7%, and airflow 10%.

The three righthand columns of this table show the overall cost saving for a total fleet of GATE-powered medium pressurized twins over a 20 year period and the estimated development cost in order to rank the technologies on a benefit/cost ratio basis. The actual development cost estimates are not shown here (propriety), rather they are normalized such that the total component development cost was arbitrarily set to $10 million. Although the radial HP turbine technology is twice as expensive as any other element, its high benefit gives it the top priority position.

Allison - As already mentioned, Allison concentrated on performance, weight, and maintenance improvements rather than initial cost. Consequently their concept evolved into a relatively sophisticated 2-spool design with two centrifugal compressors (14:1 P/P), two cooled axial gas generator turbines, and two uncooled axial power turbines. While some cost saving features were identified (e.g, composite gearbox housings and shafts, powdered metal gears, ceramic turbine vanes and tip shrouds) most of the technologies recommended by Allison were of the traditional component performance improvement variety. Interestingly, the resulting improvements in engine performance yielded lower aircraft gross weight and reduced airframe costs such that 10 to 15% reductions in aircraft ownership costs were realized in comparison with their latest engines with long production run cost advantages.

RECOMMENDED TECHNOLOGY PROGRAMS (TASK IV) - As a result of their studies, each company recommended a 5-year technology program to NASA that would establish the technical readiness and economic validity of his concept. A general picture of these programs in given in Fig. 18. It consists of several years of component technology efforts followed by experimental core and engine phases which integrate the various components into a matched system (but not a prototype). The key technologies required to obtain the large estimated benefits are definitely high-risk types beyond those expected to become available through ordinary private funding sources. Hence the likelihood of actually experiencing these benefits depends critically on the degree of external support.

SUMMARY

The overwhelming majority of general aviation aircraft have not captured the advantages available with turbine engines due to high acquistion cost in relation to piston engines in small sizes. The technological progress in small civil gas turbine engines has traditionally been slower than in large engines due to the inherently more difficult design problems compounded by a lack of research funding. Despite these impediments, it now seems probable that a proper combination of advanced component technologies, improved materials, innovative manufacturing techniques, and design

simplifications could overcome the turbine engine cost barrier. The resulting engine improvements are so major that the turbine engine could be expected to successfully challenge the reciprocating engine in all sizes above 250 SHP (Fig. 19). In turn, the ensuing GATE-technology powered aircraft would be superior products with benefits for all sectors of our society. At the highest level, our nation's technological leadership would be preserved with attendant prestige, energy conservation, and trade balance payoffs. Business and industry would profit from greater productivity, reduced ownership costs, and improved reliability. And pilots and passengers would enjoy greater flight safety and comfort. In fact, these engines could usher in a new era of dramatically improved business/commercial air transportation.

TABLE 1. - TURBINE ENGINES ARE SAFER

1972-1976 COMMULATIVE POWERPLANT-CAUSED ACCIDENTS

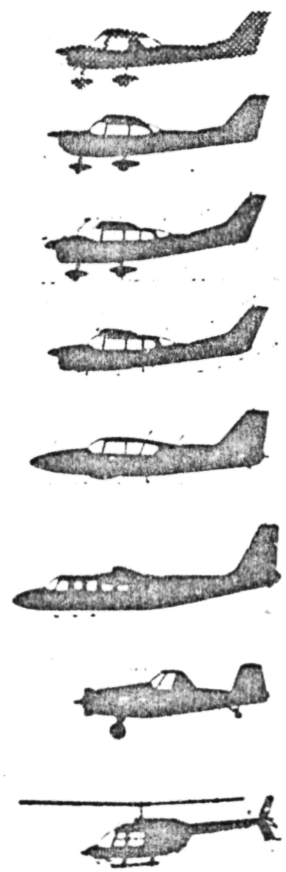
SOURCE: NTSB, GAMA, MFG'S. DATA

	PISTON ENGINE		TWIN TURBINES		
	SINGLE	MULTI	ALL TP, TJ, & TF	PT6	331
AIRCRAFT FLIGHT HOURS, 10^6	112	25.3	9.5	5.7	3.3
POWERPLANT ACCIDENTS					
- TOTAL	1971	114	20	8	5
- FATAL	126	62	7	3	2
POWERPLANT ACCIDENT RATE (PER 100,000 A/C HRS.)					
- TOTAL	1.76	0.89	.21	.14	.15
- FATAL	.11	.24	.07	.05	.06

TABLE 2. - GATE CONCEPTUAL TURBOPROP ENGINE CHARACTERISTICS

	ALLISON	GARRETT	TELEDYNE	WILLIAMS
BASELINE SIZE, SLS, SHP	500	420	565	375
COMPRESSOR - TYPE	2-CENTRIF.	1-CENTRIF.	1-CENTRIF.	6-AXIAL/CENTRIF.
- P/P	14	9	9	10.3
CORE TURBINE - TYPE	2-AXIAL	RADIAL	RADIAL	4-AXIAL
- COOLED	YES	YES	NO	NO
LOW-SPOOL TURBINE - TYPE	2-AXIAL	2-AXIAL	NONE	NONE
AIRFLOW, LB/S	3.09	2.69	3.02	3.49
WEIGHT, LB	179	186	206	182
TBO, HR	5000	3500	3500	
EBSFC, UNINSTALLED, LB/HR-HP				
TAKEOFF	.487	.493	.51	.55
CRUISE	.450	.445	.451	.447
	250 KN/ 15000 FT	210 KN/ 20000 FT	265 KN/ 18000 FT	280 KN/ 25000 FT
COST, OEM, 1977 $ (@ 500 UNITS/YR)	79300	27000	28300	21100

TABLE 3. - A REPRESENTATIVE BREAKDOWN OF AIRCRAFT/MISSION DEFINITIONS (TELEDYNE)



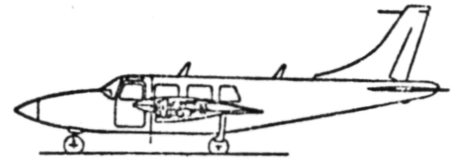
	1988 Mission (Cruise)			1976		
	Range N.M.	Speed Kts.	Altitude Ft.	Sales	Price K$	Typical Product
2 Place Trainer	500	120	8000	2387	16-31	Cessna 150
4 Place Utility	700	170	10000	7246	24-66	Cessna 172
5-6 Place Utility	850	190	10000	2171	46-91	Cessna 206
5-6 Place Utility Pressurized	900	210	18000	0		New Product
Light Twin 6-8 Place	1200	265	18000	1484	90-330	Piper Aztec
Med.-Heavy Twin 6-12 Place	1800	260	20000	1083	200-1400	T. Commander
Agricultural 2000 lb payload	4-1/2 hr	110	0	1111	40-80	Thrush
Helicopter, 2-5 Place	330	110	0	1030	100-900	Jet Ranger

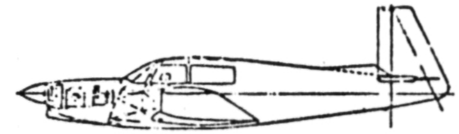
TABLE 4. - GATE POWERED AIRPLANES WOULD BE CHEAPER TO BUY AND OPERATE, LIGHT-TWIN EXAMPLE (GARRETT)

		PERCENT CHANGES		
LIGHT TWIN AIRPLANE[1]	CURRENT TECHNOLOGY RECIP	ADV. TECH. RECIP (-10%SFC)	CURRENT TECH. TURBOPROP[2]	GATE TURBOPROP (FREE TURBINE)[2]
SHP, SLS TO	380	- 2	- 11	-14
ENGINE WEIGHT	550 LB	- 3	- 68	-75
MISSION FUEL	172 GAL	-10	+ 10	- 8
GROSS WEIGHT	6200 LB	- 4	- 15	-20
ENGINE COST	$11020	- 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 10000 FEET, 225 KNOTS FOR 1100 N.M., 500HR/YR FOR 3 YEARS
(2) ASSUMING 10,000 ENGINES/YEAR PRODUCTION

TABLE 5. - GATE ENGINES RETROFITTED ON EXISTING AIRFRAMES (WILLIAMS RESEARCH)





	AEROSTAR 601P (6 PASSENGERS)		MOONEY 201 (4 PASSENGERS)	
	STANDARD TURBOCHARGED PISTON ENGINES	GATE TURBOPROPS RETROFITTED	STANDARD PISTON ENGINE	GATE TURBOPROP RETROFITTED
GROSS WEIGHT, LB.	6000	6000	2740	2740
ENGINE RATED HORSEPOWER	290	352*	200	305*
TIME TO CLIMB TO 25,000 FT, MIN.	21.8	15.4 (-29%)		
MAX. RANGE CRUISE (45 MIN. RESERVE)				
OPT ALTITUDE, FT	25,000	35,000	8000	35,000
SPEED, KTS	239	233 (-3%)	162	195 (+20%)
RANGE, NM	605	2260 (+274%)	524	726 (+38%)
SEAT-NM/GAL	39	59 (+54%)	56	56 (0%)
(LB PAYLOAD/HR)/GAL @ TP RANGE	0.26	0.42 (+62%)	2.4	2.7 (+12%)

*DERATED TURBOPROP WITH 390 SHP THERMODYNAMIC RATING

TABLE 6. - FORECASTED 1978 GATE MARKET POTENTIAL ASSUMING A MATURE ENGINE (1977 $)

COMMON CORE ENGINE	GARRETT	TELEDYNE	WILLIAMS	ALLISON
- Power Class, SLS SHP	225-650	265-565	180-390	400-600
- Average OEM Price, @ 500/yr	$27,000	$28,300	$21,100	$79,300
@ GATE RATES*	$16,000	$ 7,630	$19,500	$62,700
TOTAL GATE MARKET ANNUAL PRODUCTION				
- *Number of Engines Manufactured	15,120	31,450	16,000	1,950
- Monetary Value	$242 M	$240 M	$312 M	$122 M

TABLE 7. - EFFECT OF GATE TECHNOLOGIES ON COST OF OWNERSHIP OVER A 5-YEAR PERIOD OF A 6 - 8 PLACE TWIN (TELEDYNE)

TECHNOLOGY ADVANCE	EFFECT	Δ SFC-%	Δ WT. - LB.	SAVINGS PER A/C
9:1 P.R. COMPRESSOR	+2% $\Delta\eta_C$	−2	− 6	$ 15,150
UNCOOLED RADIAL TURBINE	+300° TIT	−2	−28.5	35,300
ABRADABLE COATINGS	+1% $\Delta\eta_C$	−0.9	− 2.5	5,520
	+1% $\Delta\eta_T$	−2.1	− 4.5	12,280
TiBORSIC SHAFT	−1.4 LB.	0	− 1.4	627
GEARBOX COST	−10%	-	-	435
ELECTRONIC FUEL CONTROL	-	-	-	3,200
			TOTAL	$ 72,510

TABLE 8. - ADVANCED TECHNOLOGY BENEFITS (GARRETT)

TECHNOLOGY	CHANGES RELATIVE TO CURRENT TECHNOLOGY ENGINES (2)				A/C FLEET BENEFIT / TECHNOLOGY COST		
	ΔCOST %	ΔWT %	ΔSFC %	ΔAIR-FLOW %	BENEFIT $M (3)	R&D COST $M (4)	BENEF /COST
HP LAMINATED TURBINE (1)	-22.	-7	-8.0	-9.8	1432	3.5	409
PM T_I SINGLE STAGE COMPRESSOR (1)	-3	-6	+1.0	+1.3	388	2.1	185
COMBUSTOR AND FUEL NOZZLES	-1	0	0	0	127	1.2	106
ELECTRONIC CONTROL	-2	0	0	0	82	0.8	102
HIGH WORK/LOW SPEED LP TURBINE (1)	-5	-7	-7.0	-6.8	706	2.1	336
LASER HARDENED GEARS	-3	0	0	0	70	0.4	175
TOTAL	-36	-20	-14.0	-15.3	2805	10.0	280

(1) CLEARANCE CONTROL EFFECTS INCLUDED

(2) 432 SHP CURRENT TECH ENGINE VS 420 SHP ADVANCED ENGINE (RESIZED A/C)

(3) 20-YEAR COST OF OWNERSHIP SAVINGS FOR FLEET OF 15,000 PRESSURIZED MEDIUM TWINS

(4) VALUES SHOWN BASED ON ARBITRARILY ASSUMING $10 MILLION TOTAL (ACTUAL VALUES ARE PROPRIETARY)

CONTRACTORS
- DETROIT DIESEL ALLISON
  - REVIEWERS: CESSNA, BELL
- GARRETT/AiRESEARCH
  - SUBCONTRACTORS: CESSNA & HUGHES
  - SUPPORT: BELL
- TELEDYNE CAE
  - SUBCONTRACT: BEECH
  - SUPPORT: BELL, HAMILTON STANDARD
- WILLIAMS RESEARCH
  - SUPPORT: GULFSTREAM AMERICAN, MOONEY, PIPER

IN-HOUSE
- MISSION ANALYSIS BRANCH/NASA-LEWIS

Figure 1. - Gate study participants.

TASK I - MARKET SURVEY (3 months)
- FORECAST 1988 MARKET SCENARIO FOR G.A. ENGINES IN THE 150-1000 horsepower CLASS
- FIXED & ROTARY WING AIRCRAFT
- SELECT MAJOR TURBINE ENGINE SIZES AND CONFIGURATIONS
- DEFINE AIRCRAFT CHARACTERISTICS

TASK II - BROAD-SCOPE TRADEOFF STUDIES (4 1/2 months)
- FORECAST APPLICABLE ADVANCED TECHNOLOGY
- CONDUCT PARAMETRIC STUDY (PERFORMANCE, COST & WEIGHT)
- SELECT & EVALUATE OPTIMUM ENGINE FOR EACH APPLICATION

TASK III - COMMON CORE CONCEPT EVALUATION (1 1/2 months)
- EVALUATE THE USE OF A SINGLE CORE ENGINE FOR ALL OR SOME OF THE TASK II APPLICATIONS

TASK IV - TECHNOLOGY PROGRAM PLAN
- DEVELOP A PLAN TO DEVELOP AND DEMONSTRATE ADVANCED TECHNOLOGIES FOR SMALL TURBINE ENGINES

Figure 2. - Gate study approach.

HIGHER ENGINE RELIABILITY

REDUCED PILOT FATIGUE
- LESS CABIN NOISE
- LESS CABIN VIBRATION
- HIGHER ALTITUDES AVOID TURBULENCE

LESS VOLATILE FUEL

HIGH ALTITUDE CAPABILITY AVOIDS DANGEROUS WEATHER

ELIMINATES RISK OF LEAKY EXHAUST HEATER

Figure 3. - Turbine engines improve safety.

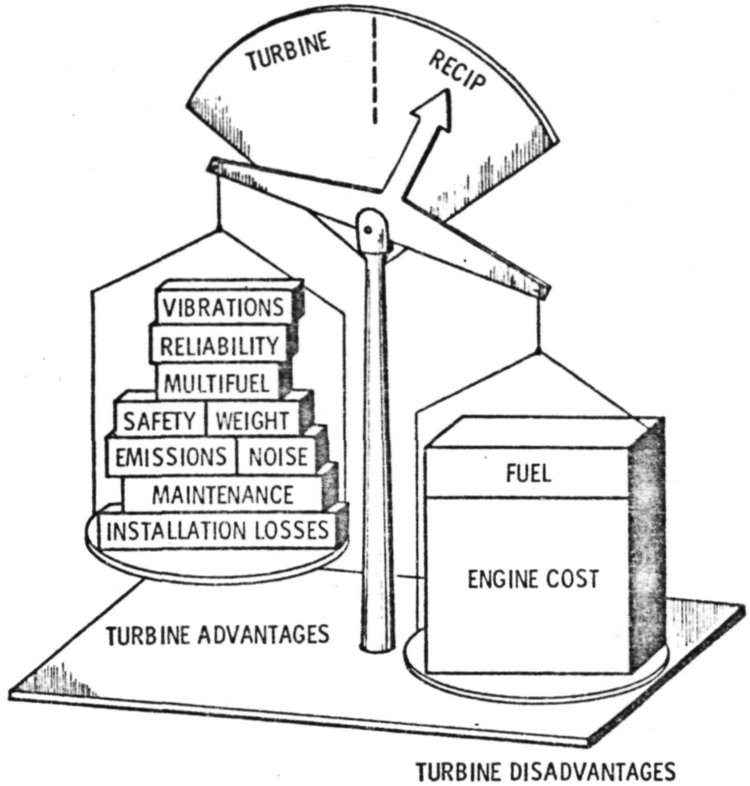


Figure 4. - Current engine selection for light airplanes.

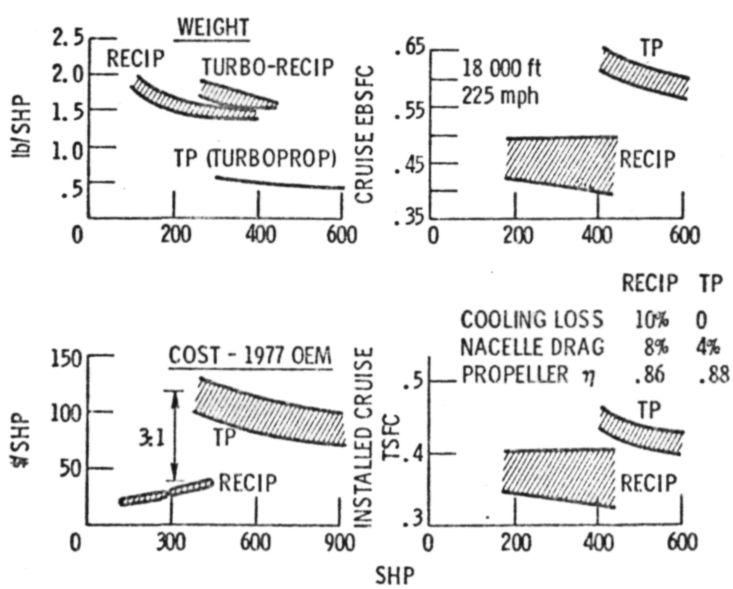


Figure 5. - Current small engine trends.

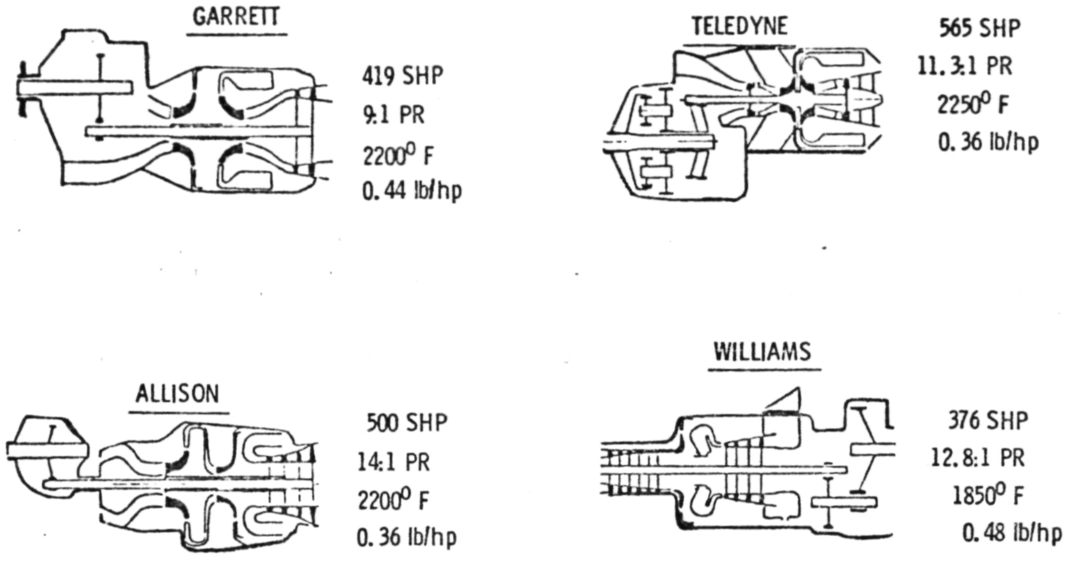


Figure 6. - The baseline gate conceptual engines.

E-9390

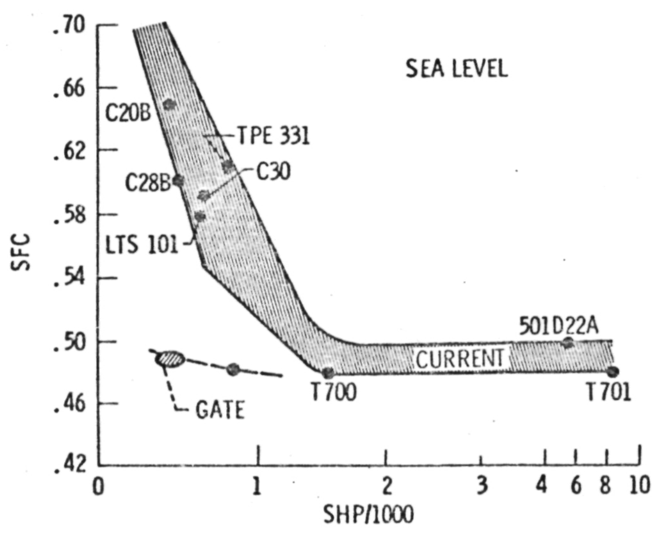


Figure 7 Gate SFC improvements.

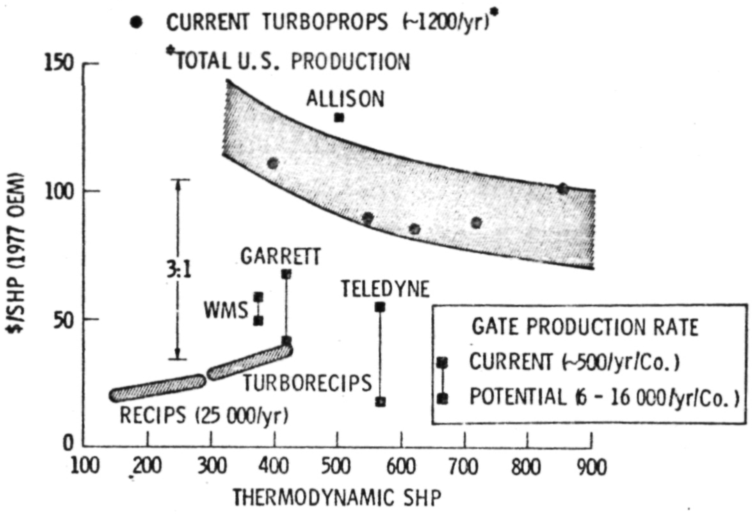


Figure 8. - Gate engines are forecast to be nearly cost competitive with reciprocating engines.

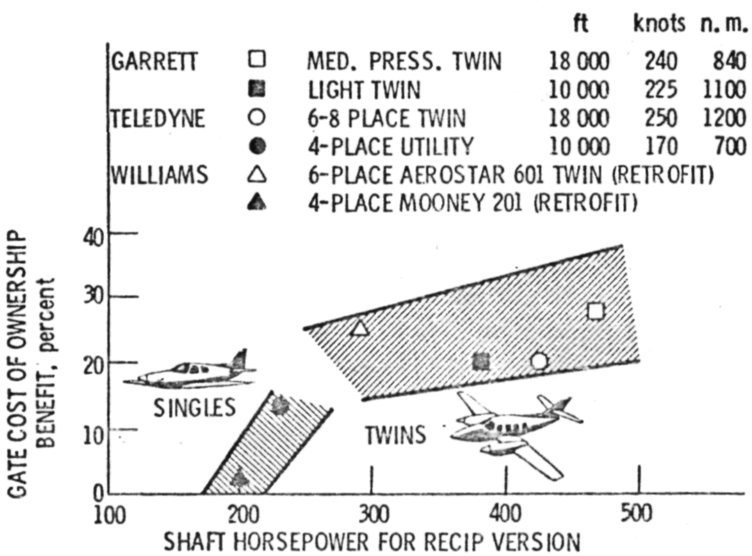
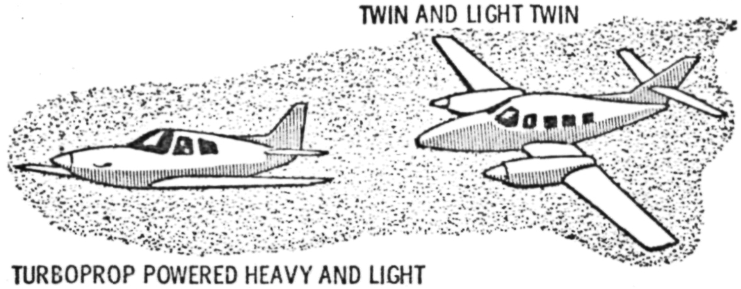


Figure 9. - Gate powered aircraft have lower cost of ownership than equivalent recip powered aircraft.

E-9090



10 - 15%	LESS GROSS WEIGHT	20 - 25%
0 - 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	

Figure 10. - Benefits relative to current reciprocating engine.

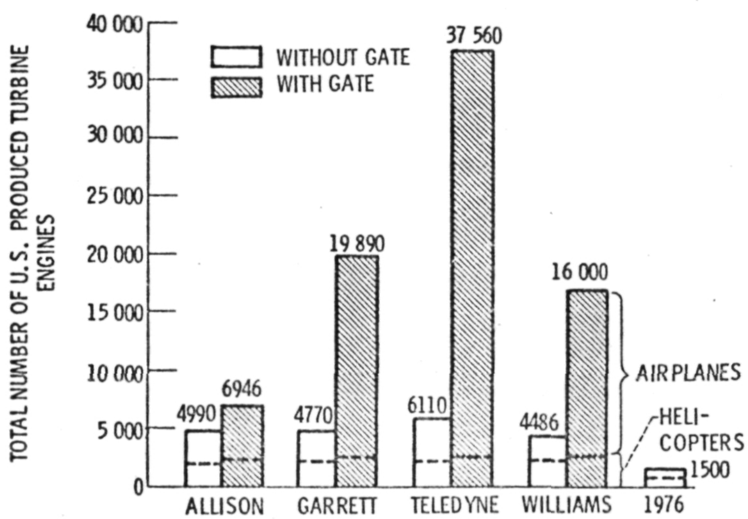


Figure 11. - 1988 civil turbine engine market under 1000 SHP (total OEM plus spares).

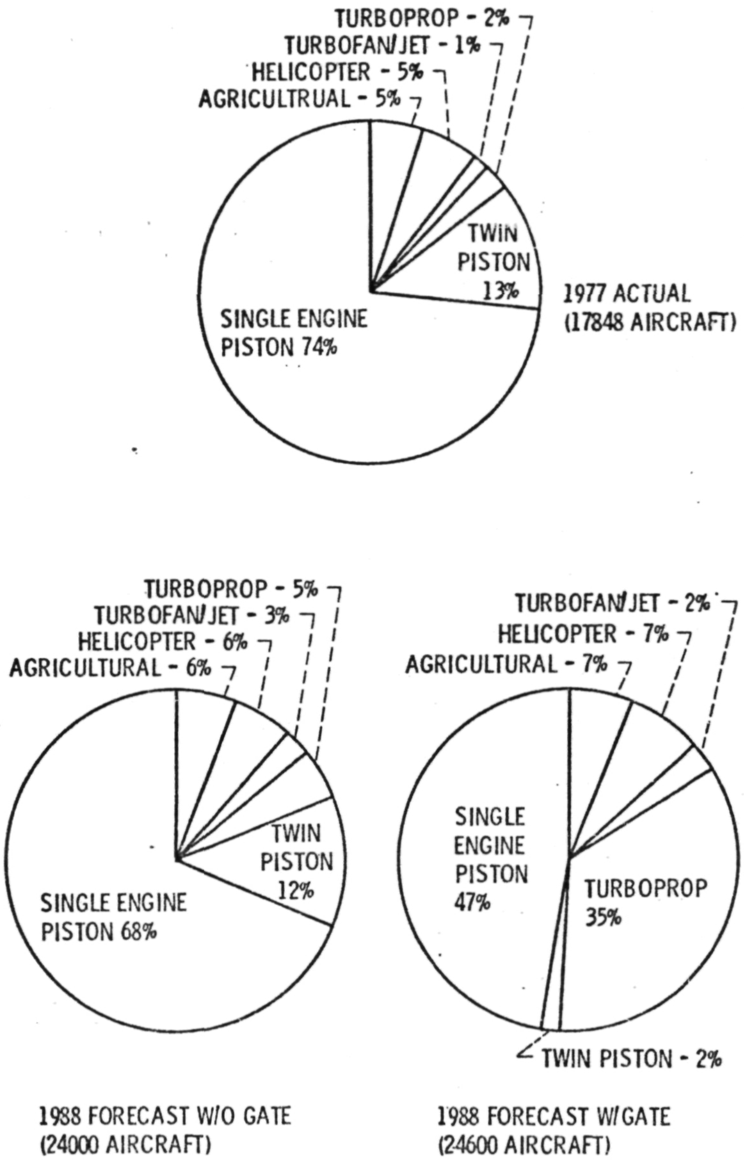


Figure 12. - Projected general aviation sales - units (composite forecast of four companies).

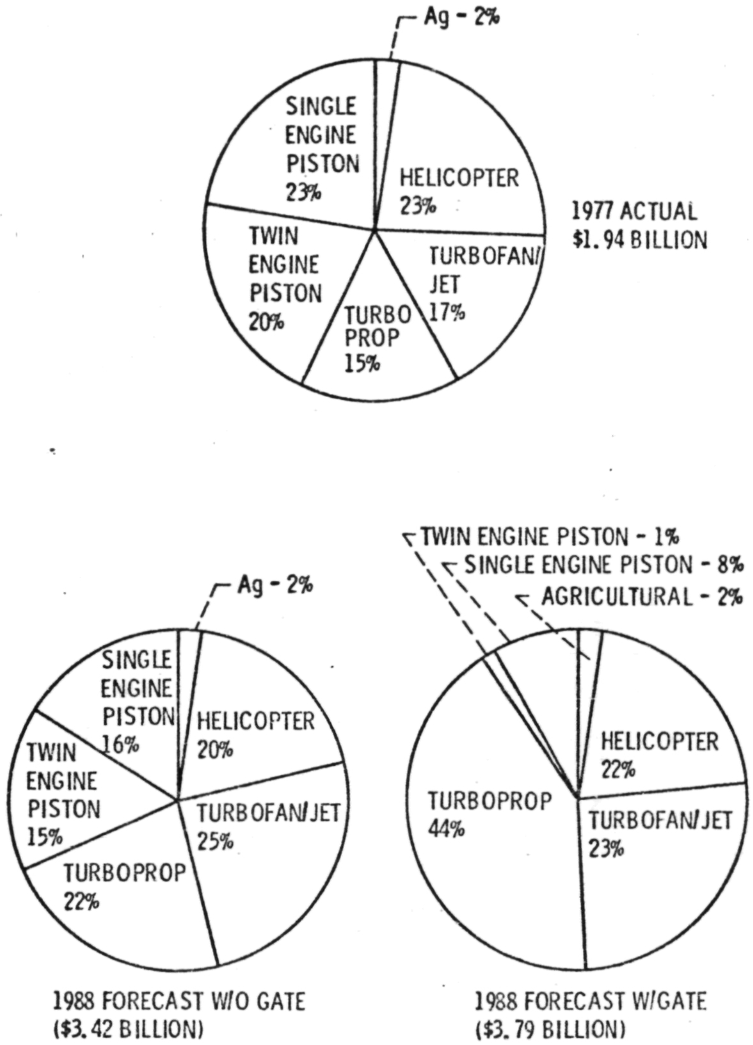
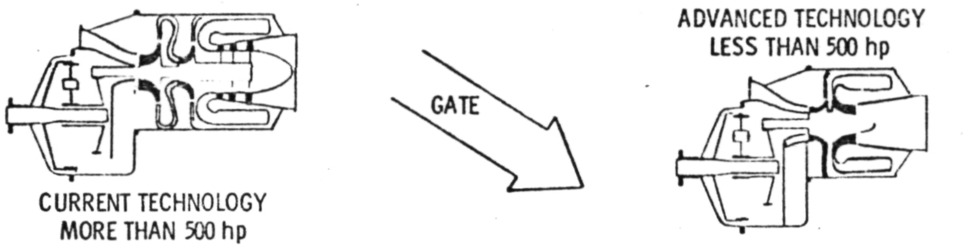


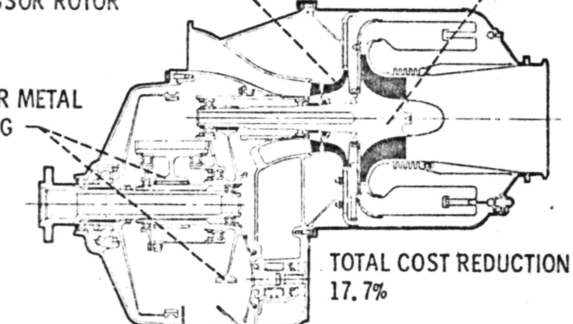
Figure 13. - Projected general aviation factory billings, 1977 $ (four company composite).

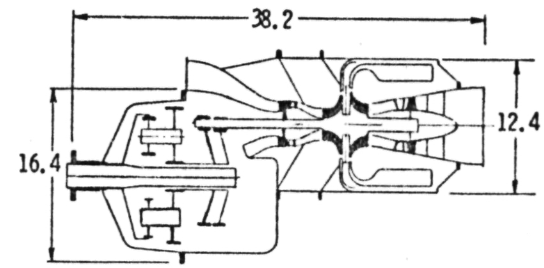
E-9890



Current technology	ENGINE COST SAVINGS, percent	Advanced technology
2 CENTRIFUGAL COMPRESSORS	10	1 CENTRIFUGAL COMPRESSOR
3 AXIAL TURBINES	16	1 RADIAL TURBINE
HYDROMECHANICAL CONTROLS	12	ELECTRONIC CONTROL
ATOMIZING COMBUSTOR	2	VAPORIZING PLATE COMBUSTOR
8 1/2 PR/1900° F CYCLE	9	9.0 PR/2250° F CYCLE
	49	

Figure 14. - Advanced technology investment reduces engine price (Teledyne).





	ESHP	lb	ESFC	lb/s	$-OEM
BASELINE	565	203	0.46	2.9	7 830
REMOVE AXIALS & GEARS	335	172	.52	2.2	5 080
ADD IGV & REMATCH	265	172	.54	1.8	5 080
ADD FREE TURBINE	565	178	.46	2.9	18 230

Figure 15. - Additional engine price reduction concepts (Teledyne).

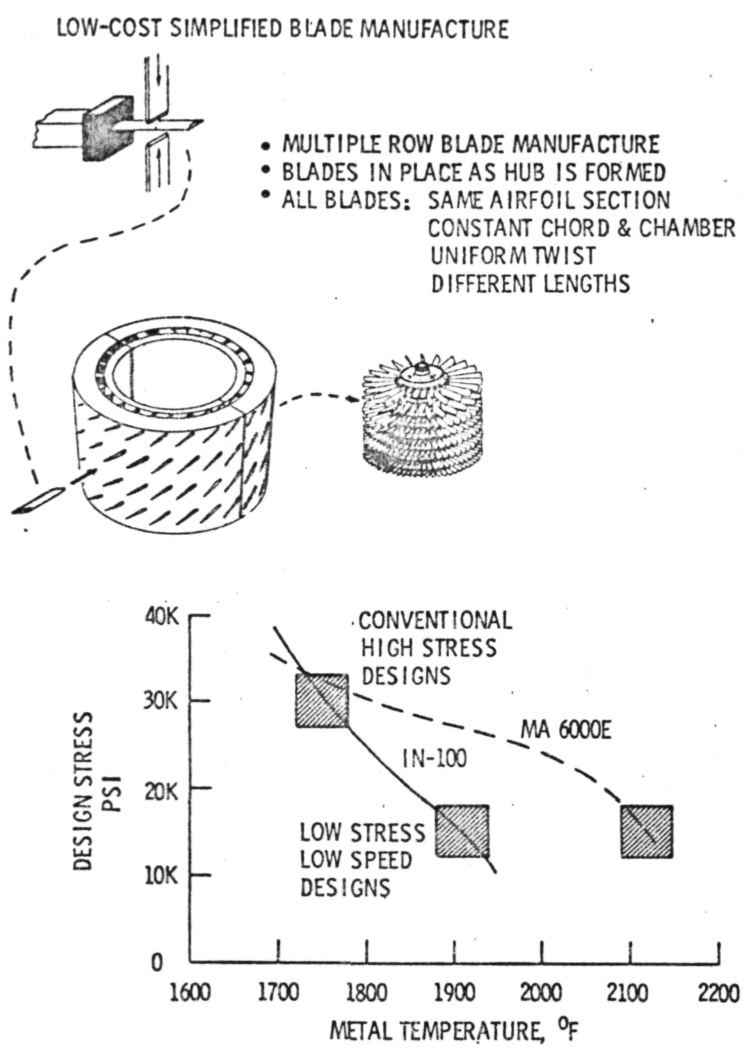


Figure 16. - Manufacturing technology areas compatible with restricted aerodynamic shapes (Williams).

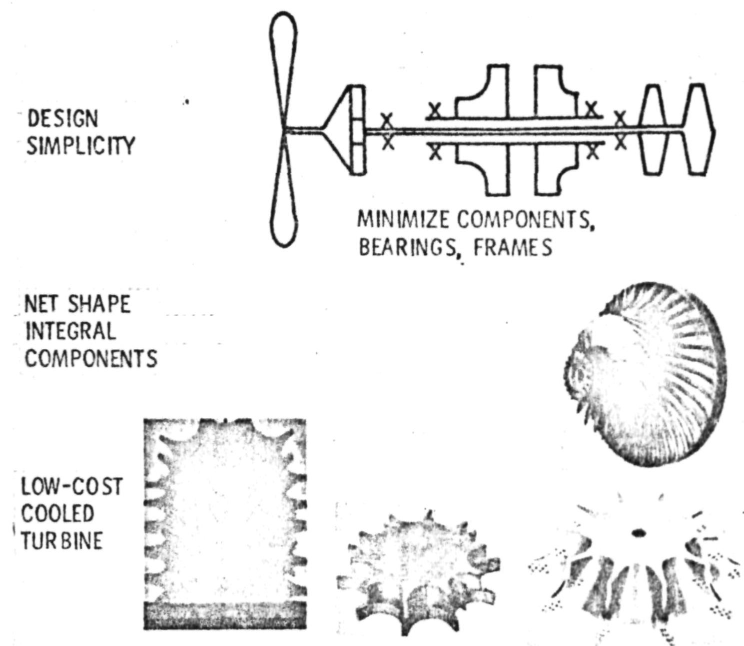


Figure 17. - GATE approaches to low cost (Garrett).

E-9890

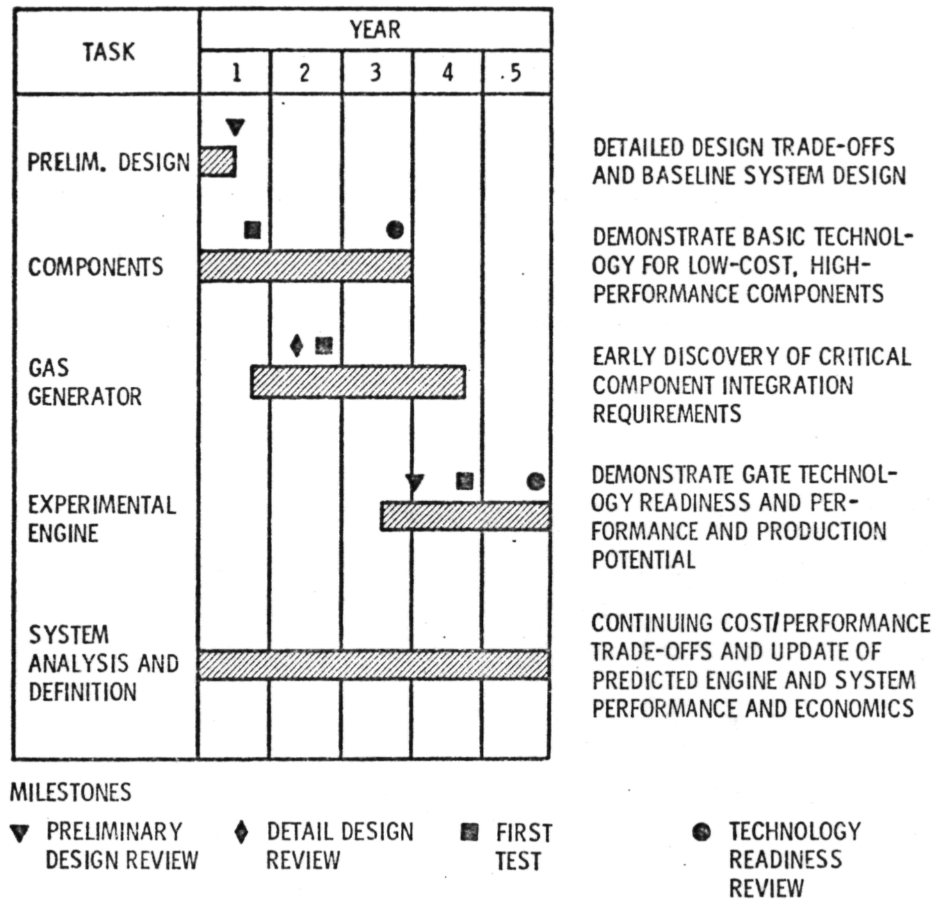


Figure 18. - Candidate gate technology program (Garrett).

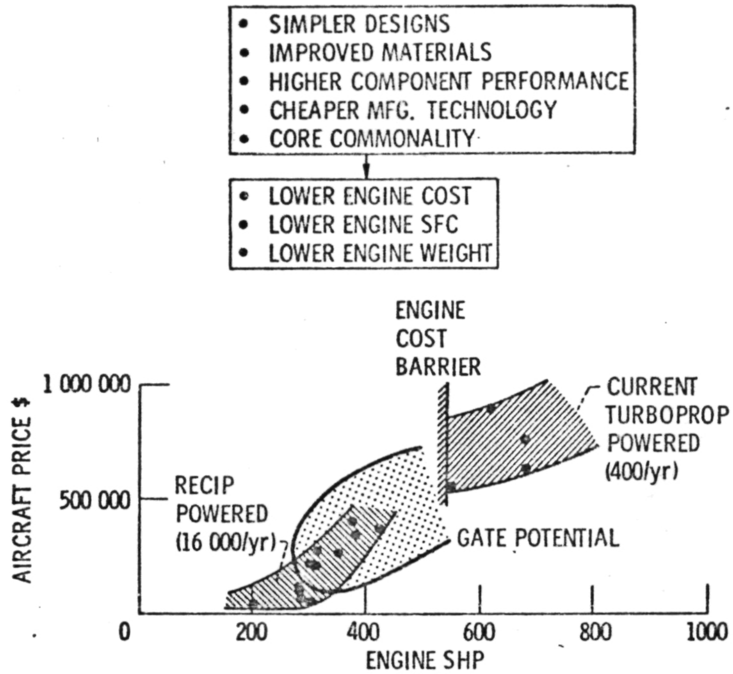


Figure 19. - Gate technology could expand domain of small turbine engines.

John Keith 352/33N/5L/510-P./St. 22423 4 MAR 31 S

6/11/93 200634