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# THE GATE STUDIES - ASSESSING THE POTENTIAL OF FUTURE SMALL GENERAL AVIATION TURBINE ENGINES



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THE GATE STUDIES - ASSESSING THE POTENTIAL OF FUTURE SMALL GENERAL AVIATION TURBINE ENGINES

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ABSTRACT

Four studies have been completed 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 contractors 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.

INTRODUCTION

General aviation's spectacular growth in the 1970's has been propelled by significant changes in the nation's transportation system and in corporate demographics. More and more American businesses are expanding into less populated areas where tax rates are low and working conditions are good. Reaching these small-town areas is difficult without small aircraft and is aggravated by the airlines' continuing trend to cut back on less profitable routes. OPEC's oil embargo persuaded the major lines to cancel 450 flights since 1973 and as many as 600 communities lost service. Further route trimming is expected since the CAB's new deregulation policy facilitates more service cuts. These trends together with large technological improvements (notably in avionics) have been the major factors in establishing general aviation as a vital link in our air transportation system. Consequently, factory billings have experienced rapid, steady growth - reaching $2 billion in 1978 (incl. helicopters), or 55% of the air transport billings, as shown in Fig. 1. Over $600 million of this total is exported.

A persistent myth holds that civil aviation is made up almost entirely of passenger carrying airliners with a sprinkling of light aircraft belonging to a few privileged private owners luxuriating on weekends. On the contrary, 98% of the civil fleet is made up of general aviation aircraft which perform a broad variety of vital public services: flying people and freight, surveying and mapping natural resources, seeding and treating crops, patrolling pipelines, forests and fisheries, firefighting, mineral prospecting, rescue and ambulance services, traffic control, and other utilitarian services. Only 5% of the general aviation operations involve sport flying while 72% of the flights are for business and commercial purposes. Business use is increasing as companies have found that owning planes to transport key people and freight can be cheaper and more convenient than using airlines. Another myth is that the business sector is made up solely of highly paid executives flying opulent business jets. Much of the usage is for middle managers and equipment-maintenance people. About 92% of the business fleet is piston-engine powered - only 8% is turbine powered.

As shown in Fig. 2, all categories, except agricultural, share approximately equally in this $2 billion/year market in terms of net factory billings. However, turbine-powered aircraft sales are increasing at a much faster rate than the reciprocating-powered models. The turboprop segment is particularly strong with a 9.2% 10 - year unit annual growth rate and a 26% increase in 1978 alone. Yet more than 20 times as many piston-powered airplanes are U.S. produced each year (over 15 000 compared to 655 turbines in 1977). Coupling this with the fact that all sectors of aviation have already transitioned to turbine power (Fig. 3) except these small airplanes, questions arise as to why this most numerous segment has not yet transitioned and what are the prospects that it will sometime in the future.

Recognizing that general aviation is an important and rapidly expanding industry and mindful that NASA sponsored engine research has been almost exclusively limited to large aircraft, the NASA Lewis Research Center decided to explore the opportunities for 1990 time frame turbine engines applicable to the smaller end of the general aviation spectrum. This exploration was initiated in 1977 with four contracted studies and one in-house study collectively known as 'GATE' - General Aviation Turbine Engine - with a 1000 SHP upper limit for turboprops and turboshafts, and a 1500 lb thrust limit for turbofans. This paper presents an overview of these studies which are individually documented in much greater detail in separate reports.

## THE 'GATE' STUDIES APPROACH

The four contractors were Garrett/AiResearch, Teledyne CAE, Williams Research, and Detroit Diesel Allison. Each spent 10-12 months of technical effort independently addressing the four Tasks shown in Fig. 4. 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. Desirable 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 categories 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.

Within this basic framework each contractor received only very broad guidelines from NASA which permitted each to emphasize aspects considered important in his judgement. These guidelines were:

- Consider engines up to 1000 SHP (or 1500 lb thrust for turbofans), but emphasize the less than 600 SHP class
- 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

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.

## TURBINE ENGINE OPPORTUNITIES

The most fundamental objective during these iterations was the determination of superior opportunities for advanced turbine engines. Since NASA let the contractors make their own independent selections on this broad issue, it is not surprising that some diversity of views emerged. Allison's study focused on a relatively sophisticated, high-performance engine concept that would compete well against current turbine engines, but was too expensive to penetrate deeply into the reciprocating market. The other three contractors argued on the basis of their analyses that the most challenging and important opportunity involved addressing the issue of turbines versus recips in the size class now dominated by recip engines. Overcoming the turbine engine cost barrier is clearly a requirement in this case, and these contractors devoted their efforts to finding acceptable ways of meeting this difficult challenge.

## SELECTING AN ENGINE FOR LIGHT AIRCRAFT

Since Teledyne, Williams, and Garrett all pursued the low cost versus recip theme, a few comments regarding this issue are offered. Piston engines totally dominate the market up to 400 SHP due almost entirely to their 3:1 cost advantage over turbine engines in a very cost sensitive market. Yet 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. 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. 5 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. 6, 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 lb gross weight.

MAJOR ENGINE IMPROVEMENTS

Engine Size

All of the contractors chose baseline engine sizes within a band from 375 to 565 SHP. These sizes were chosen principally on the basis of the attractive market opportunities, but, to a lesser degree, were also biased away from the 800 SHP class already being addressed by the U.S. Army in its Advanced Technology Demonstrator Engine (ATDE) program.

Performance

After considerable tradeoff analyses wherein engine performance and weight were traded for engine cost, all study participants independently concluded that advanced component technologies can yield 20% BSFC improvements relative to currently produced engines in the 400 SHP class. As shown in Fig. 7 this would extend the flat BSFC trend line down into the 300-400 SHP range and represents a very substantial performance gain. 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. It was also concluded that turbofans were not competitive with turboprops since they had much higher fuel consumption in addition to greater weight and cost. This is not surprising in view of the low flight speed requirements (less than 300 knots) forecasted for GATE applications.

Engine Cost

While BSFC gains are important, even more significant are the forecast engine cost reductions that accompany them. The average cost reduction of the three "low-cost" engine designs is estimated at 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 16 000/year and a correspondingly greater reduction. These cost reductions are shown in Fig. 8 which also contains a sketch of each company's baseline engine concept along with other pertinent data.

These GATE engine cost predictions are compared with current engine costs in Fig. 9. 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

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 exersized to determine these costs plus the total cost of ownership based on resale after several years of non-revenue service. Table 1 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 contractors and each selected 2 or 3 representative categories for detailed application assessment.

A typical example is given in Table 2 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 3 where a maximum payload 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 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 with full payloads. 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. 10 of all the low-cost theme application studies 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 economic bonus exists which bolsters their position considerably.

Fig. 11 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 significantly 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

Having determined the turbine-powered aircraft performance and economic characteristics, the Task I 1988 market forecasts were updated to reflect the computed aircraft benefits. Representative results are illustrated in Table 4 assuming instantaneous engine maturity. Substantial turbine penetration into the reciprocating domain is forecast with spectacular gains in sales volume and market value. In this Teledyne example, 31450 GATE engines are sold annually with a market value of $120 million per company if two companies split the market about equally. Market potential of this magnitude commands serious attention. The other companys' forecasts are less optimistic but still impressive: Garrett, 15120 total units/year; Williams, 20500; and Allison, 2250.

Another common result is that substantially greater fixed-wing market potential exists than rotory-wing. A direct outcome of this result was the preference for a single-shaft engine configuration by both Teledyne and Williams to save cost.

While the previously discussed cost of ownership savings accrue to individual owners, cummulative fleet savings is a more meaningful parameter when judging the overall impact of GATE technology engines. Teledyne 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.

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. 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 3 axial turbine stages on two shafts, their 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. Fig. 12 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° 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 achievable through advanced fabrication methods and materials. The powder metal/squeeze-cast compressor rotor and other techniques defined on the lefthand side of Fig. 13 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. 13 illustrates one example solution to the problem of accommodating 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.

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. 14) involves design stresses about 1/2 of conventional levels which leads to moderate turbine inlet temperatures (e.g., 1850° F) in an uncooled engine with extremely high time between overhaul (never needs an overhaul). Further downstream could be versions utilizing advanced, high temperature materials to achieve 350° F higher turbine inlet temperature, 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 multi-stage 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. 15). 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 5. 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 3 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 contractor 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 is given in Fig. 16. It consists of several years of component technology efforts followed by experimental core and engine (not a production prototype) phases which integrate the various components into a matched system. 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 government-sponsored support.

SUMMARY

General aviation already constitutes a vital link in our air transportation system and its importance is expanding rapidly. Yet the overwhelming majority of these aircraft have not captured the increased safety, comfort, reliability, productivity, multi-fuel flexability and emission advantages available with turbine engines due to high acquisition 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 engineering, 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. 17). The acknowledged attractive features of turbine engines could in fact usher in a new era of dramatically improved business/commercial air transportation.

TABLE 1 - A REPRESENTATIVE BREAKDOWN OF AIRCRAFT/MISSION DEFINITIONS (TELEDYNE)

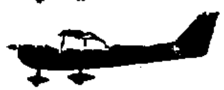
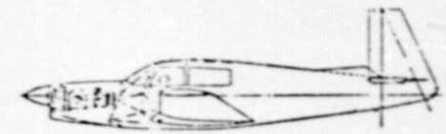
| | | 1988 Mission (Cruise) | | | 1976 | | |
|---|---|---|---|---|---|---|---|
| | | Range N.M. | Speed Kts. | Altitude Ft. | Sales | Price K$ | Typical Product |
|  | 2 Place Trainer | 500 | 120 | 8000 | 2387 | 16-31 | Cessna 150 |
|  | 4 Place Utility | 700 | 170 | 10000 | 7246 | 24-66 | Cessna 172 |
|  | 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 | 1300 | 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 2 - GATE POWERED AIRPLANES WOULD BE CHEAPER TO BUY AND OPERATE, LIGHT-TWIN EXAMPLE (GARRETT)

| LIGHT TWIN AIRPLANE[1] | CURRENT TECHNOLOGY RECIP | PERCENT CHANGES | | |
|---|---|---|---|---|
| | | 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 3 - 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 4 - 1988 MARKET POTENTIAL FOR MATURED GATE TECHNOLOGY ENGINES
(TELEDYNE)

| CATEGORY | POWER-SLS TAKEOFF / MAX RATED | TOTAL AIRCRAFT SALES | % GATE CAPTURE | GATE OEM SALES | |
|---|---|---|---|---|---|
| | | | | TOTAL MARKET | 1 COMPANY |
| 4 PLACE UTILITY | 235/265 | 12 000 | 80 | 9 600 | 4 800 |
| 5-6 PLACE UTILITY | 275/380 | 3210 | 80 | 2 570 | 1 285 |
| 5-6 PLACE UTILITY PRESSURIZED | 320/565 | | | | |
| LIGHT TWIN 6-8 PLACE | 295/530 | 5 500 | 80 | 8 800 | 4 400 |
| AGRICULTURAL 2000 lb PAYLOAD | 400/480 | 1 500 | 100 | 1 500 | 750 |
| HELICOPTER, 2-5 PLACE | 305±75 / SAME | 550 | 100 | 830 | 830 |
| | | TOTAL | | 23 300 | 12 065 |
| | | SPARES | | 8 150 | 4 220 |
| | | GRAND TOTAL | | 31 450 | 16 285 |
| | | MARKET VALUE, 1977 $ | | $220 M | $120 M |

TABLE 5 - 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 TI 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)

- VITAL PART OF AIR TRANSPORTATION SYSTEM
  - 98% OF AIRCRAFT (170 000)
  - 96% OF AIRPORTS (13 000)
  - 38% OF INTERCITY PASSENGERS (110 million/yr)
- INCREASING IMPORTANCE OF BUSINESS AIRCRAFT
  - INDUSTRY'S DECENTRALIZATION TREND
  - AIRLINE ROUTE TRIMMING TREND
  - AIRCRAFT TECHNOLOGICAL IMPROVEMENTS
- FACTORY BILLINGS UP SHARPLY
  - $2 billion SHIPPED IN 1978
  - $600 million EXPORTED IN 1978
  - BOTH RISING AT 15 to 20%/yr

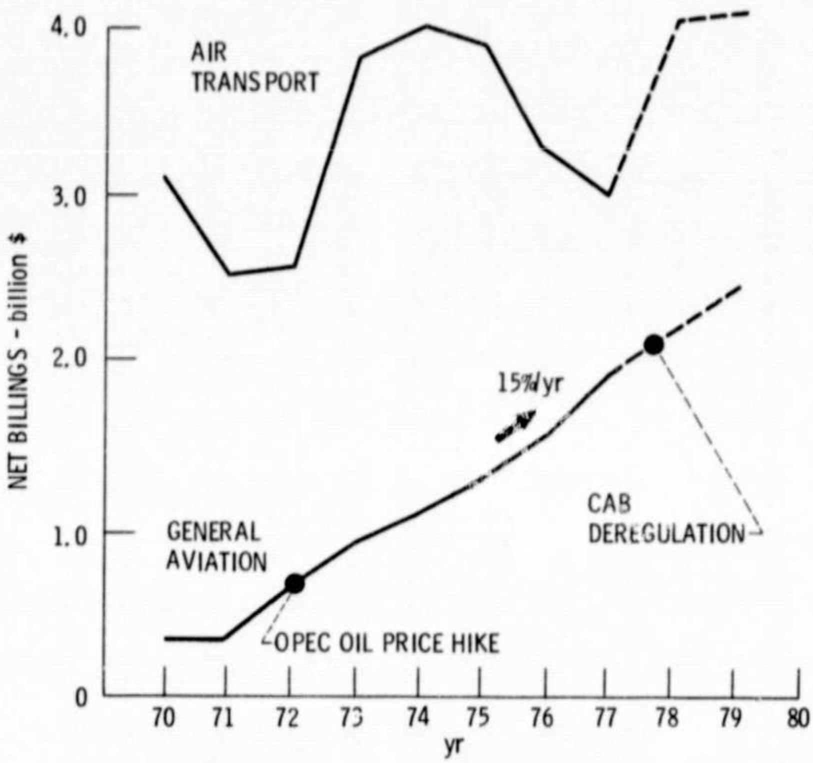



Figure 1. - General aviation is important and expanding rapidly.

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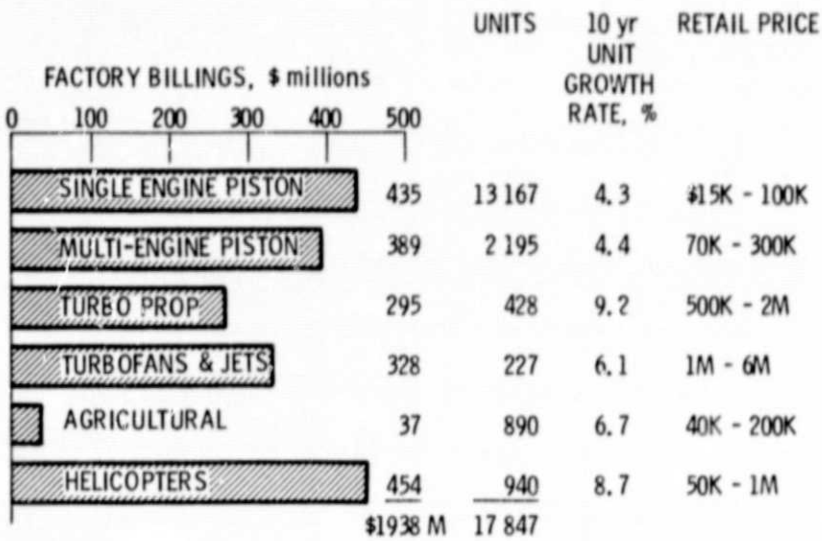


Figure 2. - U.S. general aviation aircraft sales in 1977.

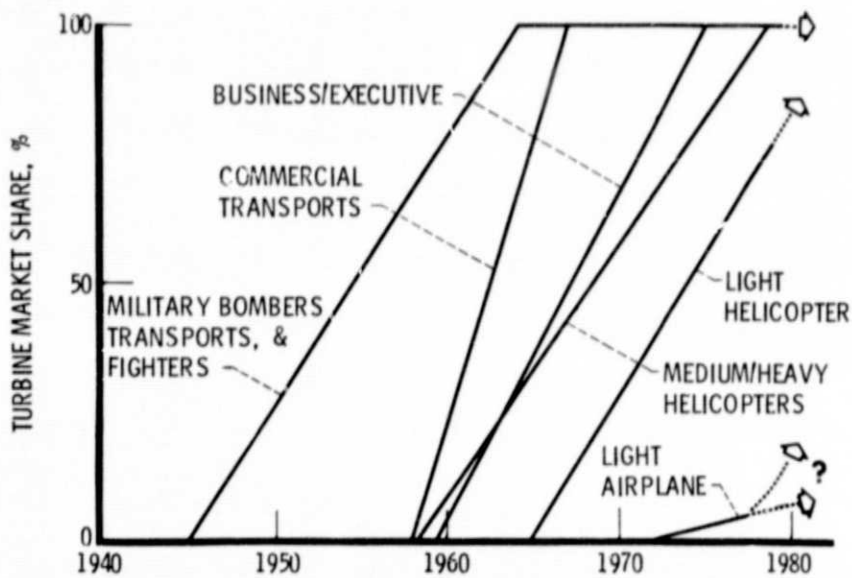


Figure 3. - All aviation segments have transitioned to turbine power except light airplaines.

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 4. - Gate study approach.

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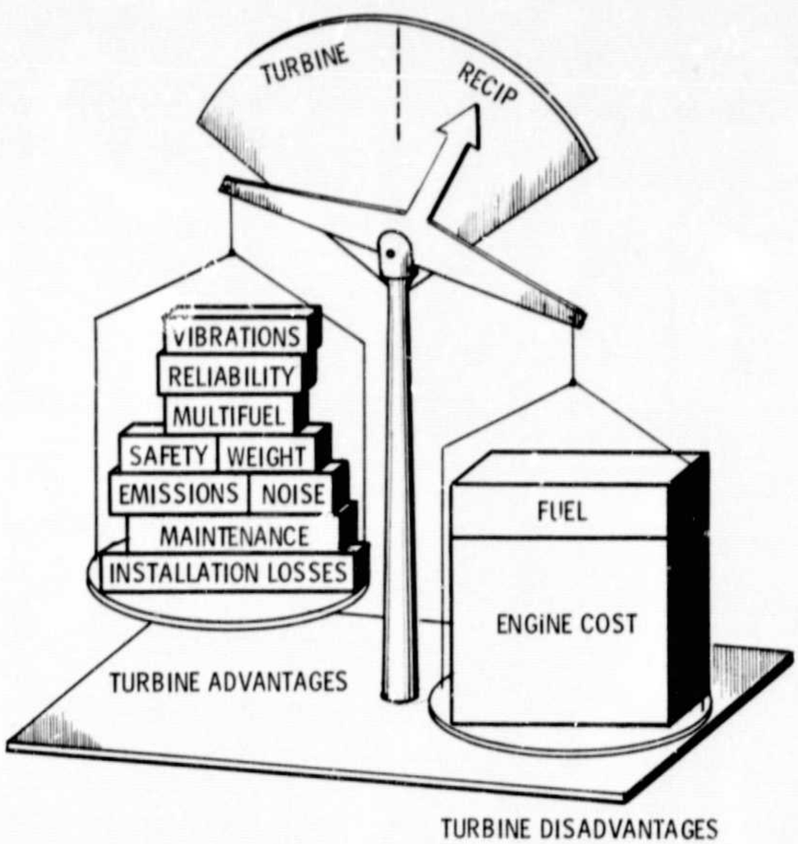


Figure 5. - Current engine selection for light airplanes.

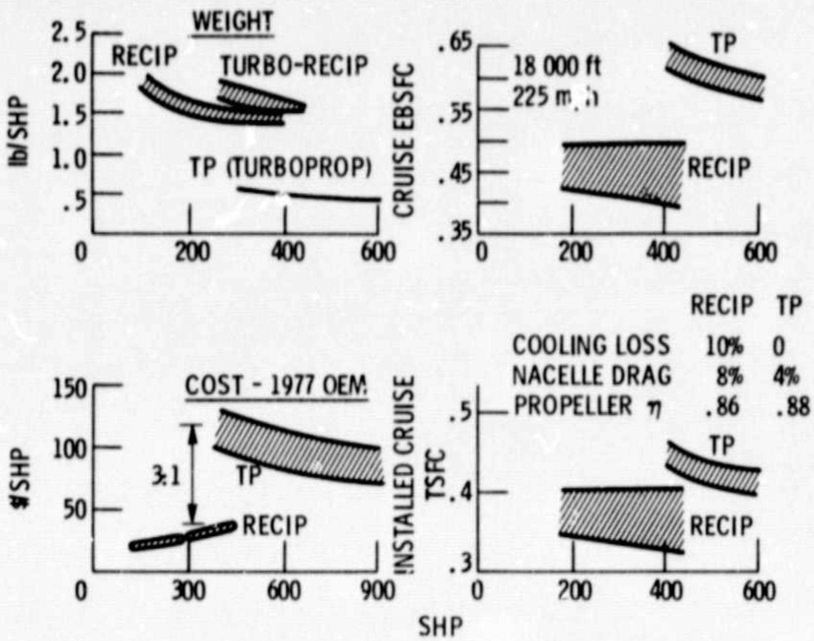


Figure 6. - Current small engine trends.

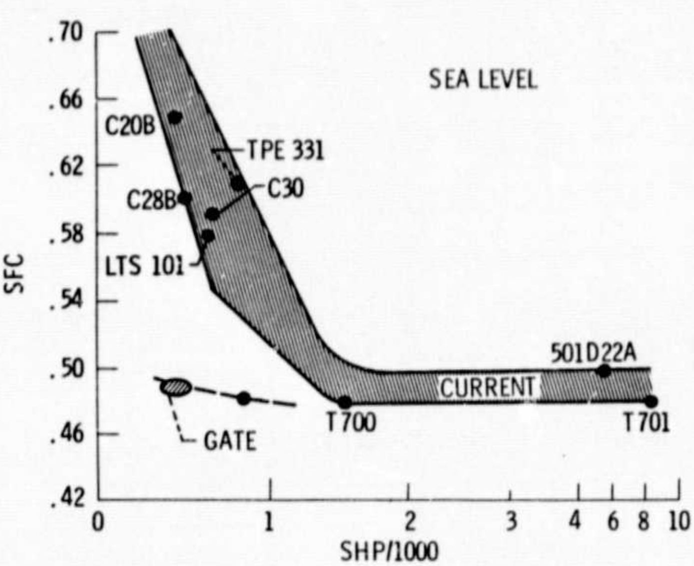


Figure 7. - Gate SFC improvements.

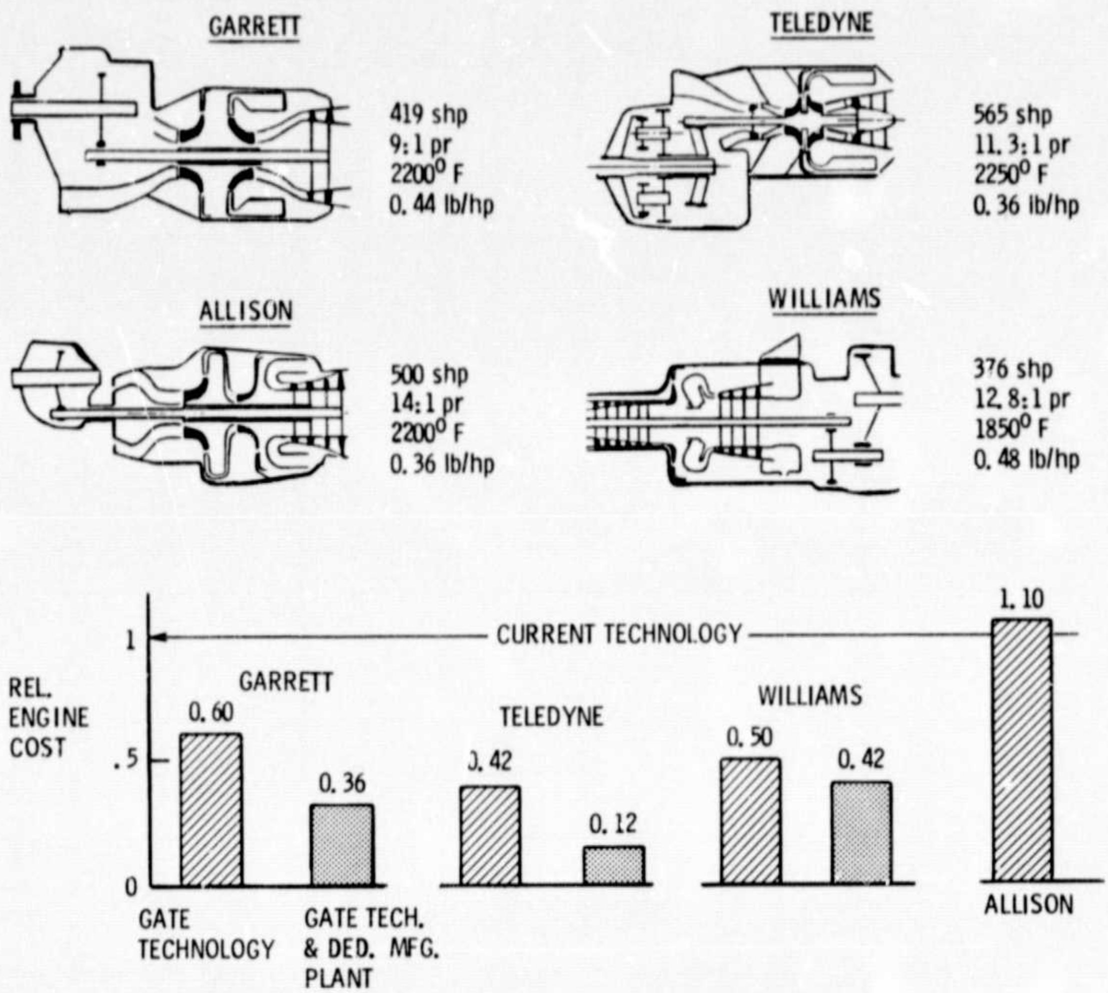


Figure 8. - The conceptual gate baseline engines and forecasted costs.

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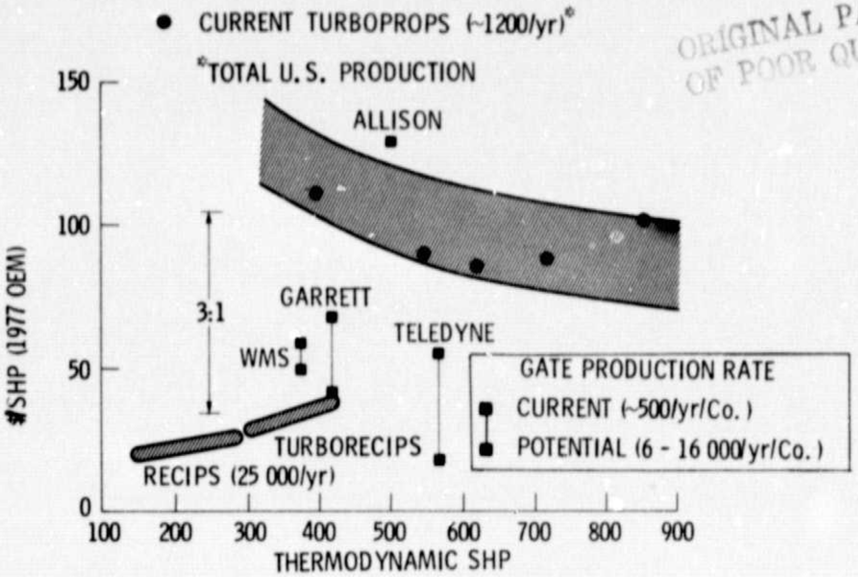



Figure 9. - Gate engines are forecast to be nearly cost competitive with reciprocating engines.

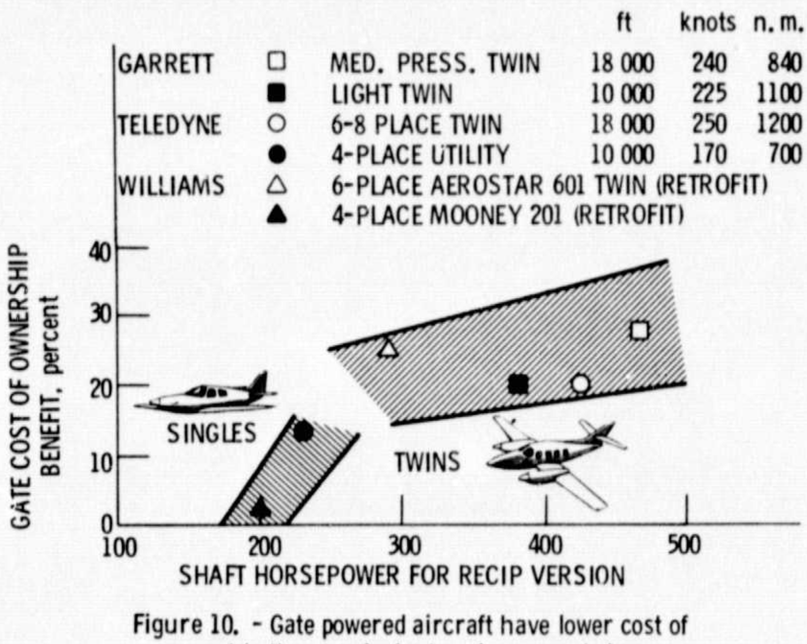
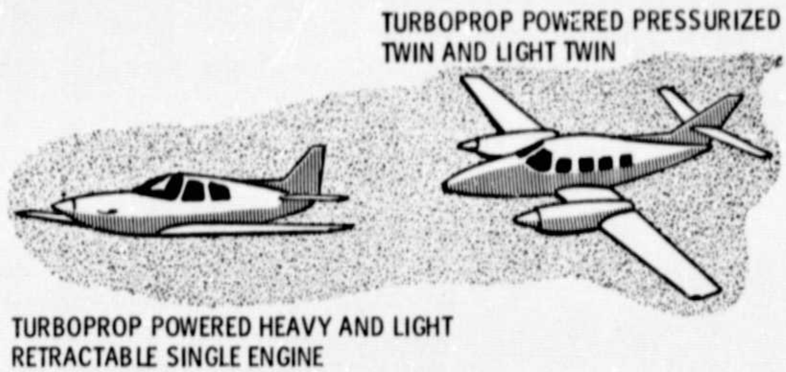


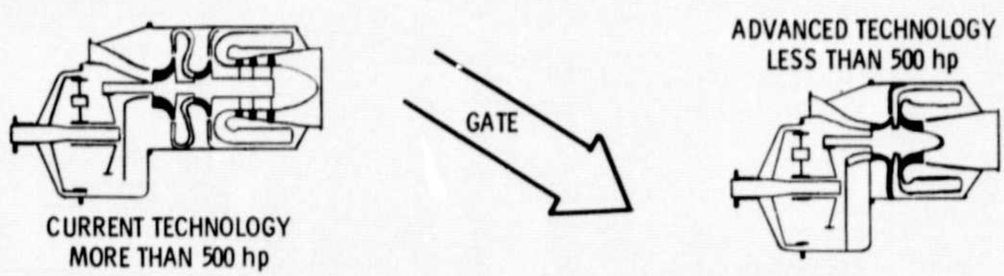

Figure 10. - Gate powered aircraft have lower cost of ownership than equivalent recip powered aircraft.




| | | |
|---|---|---|
| 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 11. - Benefits relative to current reciprocating engine.

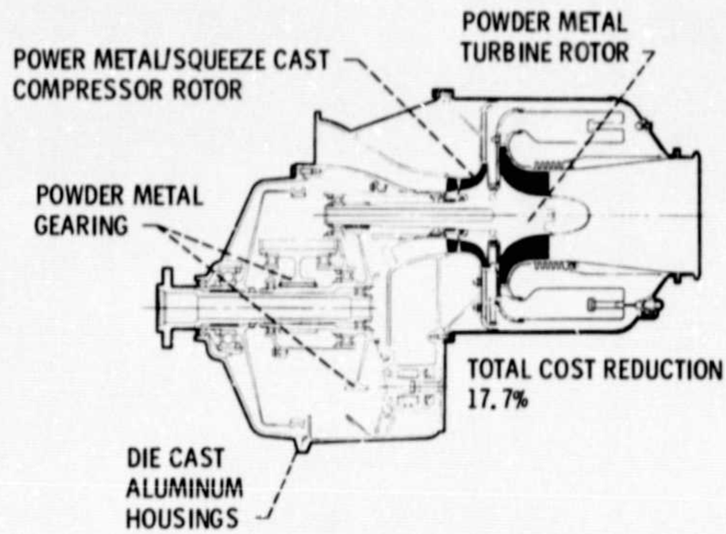




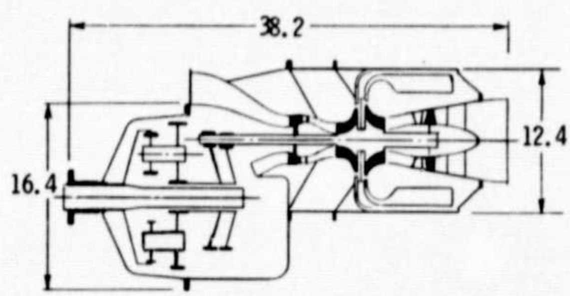

| CURRENT TECHNOLOGY | ENGINE COST SAVINGS, percent | ADVANCED TECHNOLOGY |
|---|---|---|
| 2 CENTRIFUGAL COMPRESSORS | 10 | 1 CENTRIFUGAL COMPRESSOR |
| 3 AXIAL TURBINES | 16 | 1 RADIAL TURBINE |
| HYDROMECHANICAL CONTROLS | 12 | ELECTRONIC CONTROL |
| ATOMIZING COMBUSTOR | 2 | VAPORIZING PLATE COMBUSTOR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

Figure 12. - Advanced technology investment reduces engine price (teledyne).

ADVANCED FABRICATION
METHODS & MATERIALS




COMMON CORE APPROACH




| | 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 13. - Additional engine price reduction concepts (teledyne).

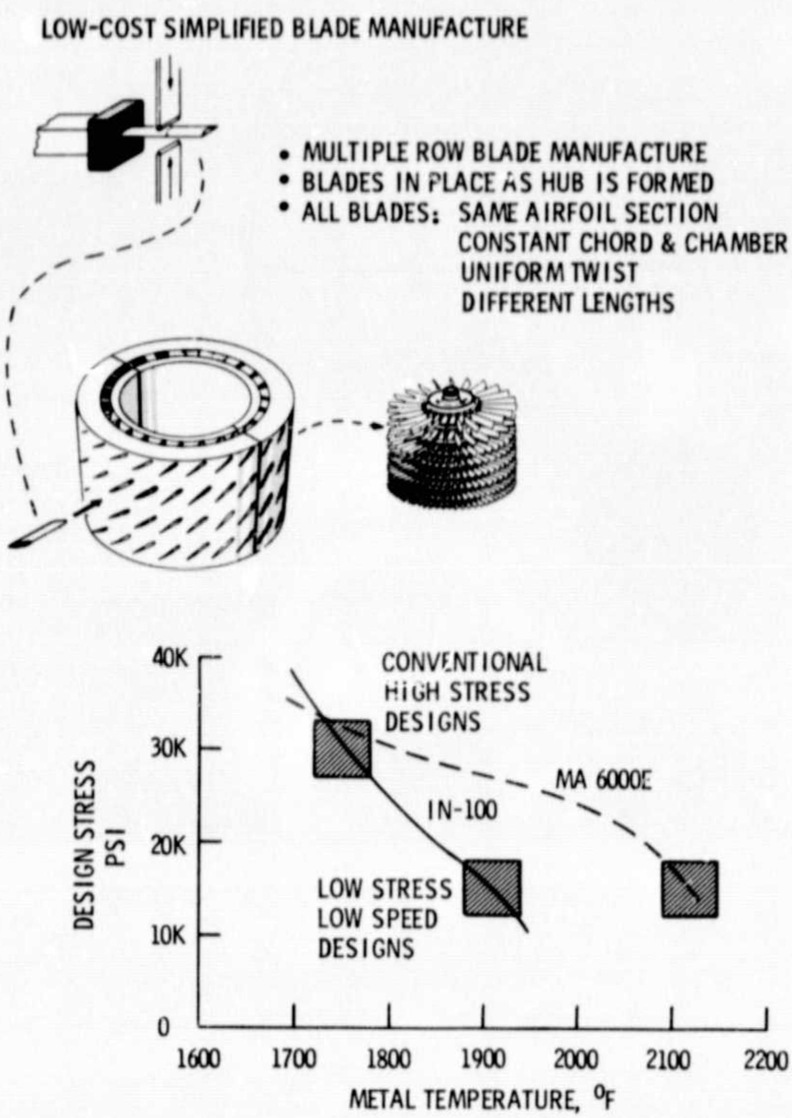



Figure 14. - Manufacturing technology areas compatible with restricted aerodynamic shapes (Williams).

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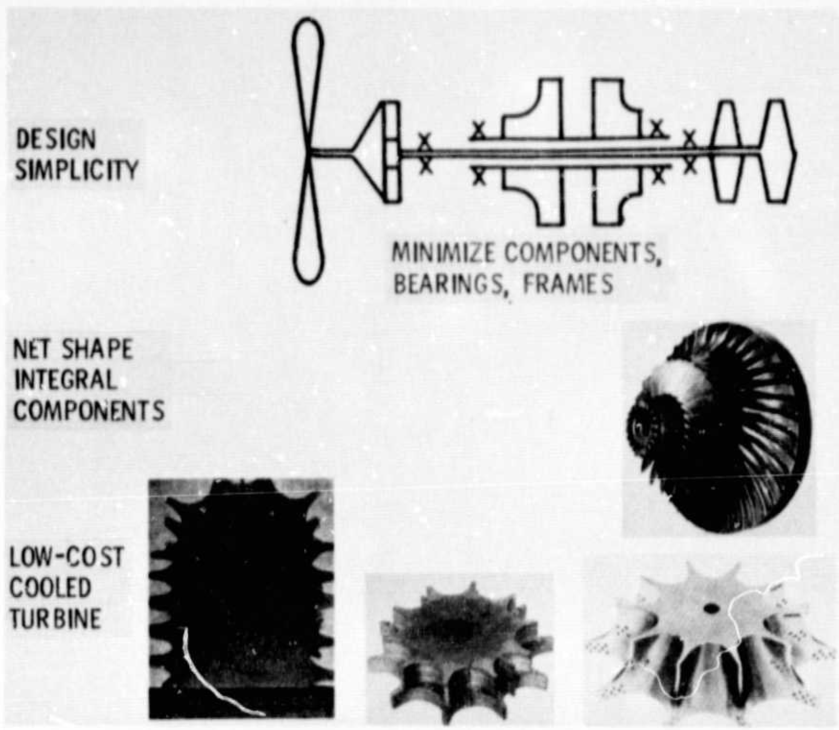


Figure 15. - GATE approaches to low cost (Garrett).

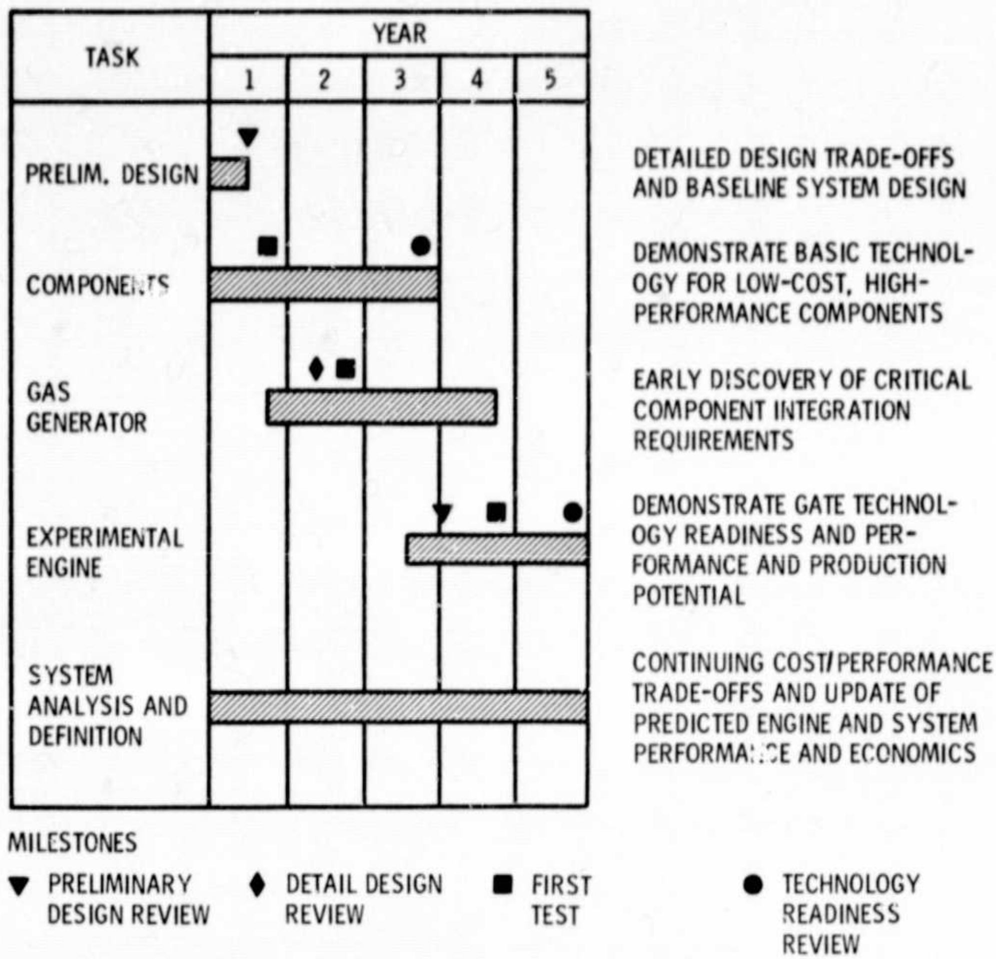


Figure 16. - Candidate gate technology program (Garrett).

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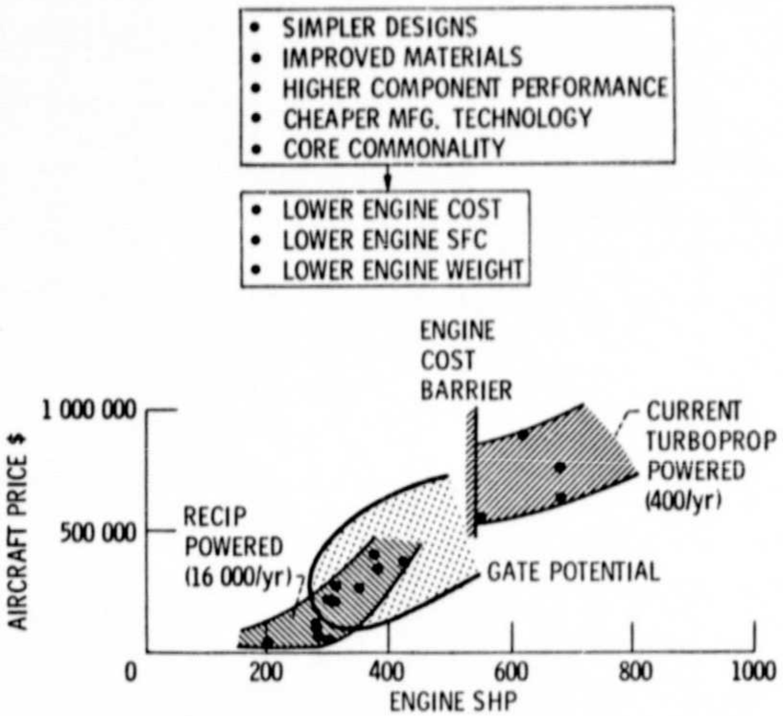


Figure 17. - Gate technology could expand domain of small turbine engines.