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NASA RESEARCH ON GENERAL AVIATION POWERPLANTS

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Abstract

Propulsion systems are a key factor in the design and performance of general aviation airplanes. NASA research programs that are intended to support improvements in these engines are described. Reciprocating engines are by far the most numerous powerplants in the aviation fleet; near-term efforts are being made to lower their fuel consumption and emissions. Longer-term work includes advanced alternatives, such as rotary and lightweight Diesel engines. Turbopropulsion is becoming increasingly important for general aviation. Work is underway on improved turbofans and turboprops.

Introduction

Propulsion systems represent a key element in the design, performance, and economics of general aviation aircraft, just as they do for the large commercial airliners. The proportion of aircraft weight, acquisition cost, and maintenance cost associated with the engine is usually even higher than for the larger vehicles.

In terms of the marketplace general aviation propulsion is definitely a major industry. As shown on the left side of figure 1 the number of engines built for general aviation dwarfs the commercial market. The vast preponderance of the engines are the low-horsepower, conventional reciprocating type. Turboprops and turbofans have captured the more-expensive, high-horsepower region. Due to the much higher cost of the large turbine engines, this picture looks quite different if the distribution of dollar sales is considered (right side of figure). But even on this basis the general aviation industry is impressive: Engine sales approach 1/2 billion dollars per year, which is about two-thirds as much as those of the large commercial engines.

As general aviation has evolved through the years, many improvements have been achieved in propulsion systems. The most obvious one is probably the introduction of turbine power. Less revolutionary changes in reciprocating engines include better reliability and the use of turbocharging and fuel injection. However, fuel shortages, the demand for lower noise and pollution, the threat of foreign competition, etc. prevent complacency and create a continuing pressure for further improvements.

The typical purchaser of a general aviation airplane is highly sensitive to acquisition cost. Therefore, engine performance cannot be improved at the expense of making the engine overly sophisticated and too costly. This is illustrated in figure 2, where point B represents a more efficient engine than point A; however, the engine price has increased so much that the final airplane price is also higher. Similarly, the engine cannot be simplified so much to lower price that performance suffers excessively (point C). Both extremes increase, rather than decrease, airplane price.

NASA has traditionally accepted the responsibility for conducting research to support improvements in the large commercial airplane category. In recent years there has been a growing involvement in work related to general aviation. Figure 3 outlines the major propulsion areas in which research is now going on. The body of the paper is devoted to descriptions of these activities.

Intermittent-Combustion Engine Research

It has already been observed that the predominant general aviation powerplant is the conventional, spark-ignition gasoline engine. Collectively, these familiar engines have established an excellent record for reliability, durability, and economy over the years. Nevertheless, improvements in these and related areas are not only desirable and possible, but necessary to meet future problems in such areas as energy utilization and environmental concerns. The NASA program addresses technology for current-production as well as next-generation gasoline engines and alternative I-C engines (such as diesels or rotaries) which can burn less-expensive fuels.

Gasoline Piston Engines

Figure 4 summarizes NASA's near-term objectives for improved current-production type engines. It also shows a more ambitious set of longer-term goals for an advanced, but all-new, engine of the same general type.

The near-term technology program was initiated several years ago in response to emission standards proposed (but recently withdrawn) by the EPA. Several accomplishments to date deserve mention. Three automated engine test cells (fig. 5) have been built-up which feature real-time data readout via microprocessor technology. Using these in-house facilities and other Lewis resources, together with a continuing series of industry contracts, substantial programs have been completed in such areas as: basic engine characterization;[1] effect of temperature, humidity and lean operation on fuel economy, emissions and cooling requirements;[2] hydrogen enrichment of fuel;[3] and theoretical analyses of cooling fins.[4] Also, progress has been made toward the development of advanced analytical tools such as Otto Cycle and stratified-charge performance and emissions prediction computer codes.[5]

As a result of these efforts, it is expected that, by late 1979, the technology will be demonstrated to achieve a substantial reduction in emissions. Also, most of the emissions work involved lean-operation concepts which led to fuel-conservative accomplishments as well. As a result of several test programs, however, it was found that improvements in several areas were needed to realize the potential 10-percent fuel economy gain offered

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by lean operation. These include variable spark timing, improved fuel injection, and better cooling.

Figure 6 illustrates a hypothetical cylinder head design that incorporates these advancements into a well-integrated package. These improvements collectively appear capable of meeting all of our near-term goals, and possibly of improving upon them. The combination illustrated here has been tested without the variable spark timing and has already demonstrated a 7% cruise fuel economy improvement with emissions reduced significantly below the EPA levels.

To meet the longer term goals, advanced combustion research is essential to obtain further improvements in BSFC and to permit the use of less expensive gasolines. A study is presently underway at Teledyne Continental Motors (TCM) to characterize and define the technology requirements of an advanced (1988) gasoline piston engine.

Alternative Engines

In the longer term, advanced diesel or stratified-charge operation is essential to utilize cheaper, broader-specification fuels. The incentive is that, based on current fuel prices, diesel fuel (for example) is 10% to 15% cheaper per gallon than avgas, yet contains about 10% more Btu's per gallon. Thus a fuel cost saving potential of 20% or more is readily apparent, even if BSFC's are not improved at all.

Diesel Engines. Automotive and military research results indicate that improved combustion of heavy fuels may result from use of an insulated or "adiabatic" diesel combustion chamber. This development, coupled with other related technology advances, underlies the long-term goals shown in figure 7.

An initial feasibility test program was conducted to show that a conventional turbocharged gasoline aircraft engine could be converted to diesel operation at no penalty in weight, power, or fuel consumption. These experiments at the University of Michigan[6] on a dieselized aircraft cylinder, late in FY 78, showed a cruise-power BSFC that was actually better than the baseline gasoline cylinder's. Since the peak firing pressures were within the baseline cylinder's specification capability, no increase in the engine's basic structural weight would be expected. This positive result lends credibility to the thought that an advanced-technology diesel, incorporating the adiabatic combustion chamber and designed specifically as an aircraft diesel engine, could meet the ambitious long-term goals of figure 7.

The program is now focussed on a radial, two-cycle concept which features the adiabatic combustion system and a unique, self-powered turbocharger concept. Results to date from the Teledyne-General Product Division (TGPD) study indicate that the long-term goals can be met, contingent on technology advances in several key areas:

(1) Adiabatic combustion and variable-compression piston technologies, now being developed for Army four-cycle tank engines, must be refined to lightweight, two-cycle applications.

(2) Advanced turbocharger technology is required, in terms of improved component efficiencies, higher turbine temperatures, and a variable-area turbine.

(3) Advanced materials are needed for piston rings and bearings.

Rotary Engines. The rotary or Wankel engine (fig. 8) is of interest because of its turbine-like attributes of simplicity, lightweight, compactness, low-drag installation features, low vibration and reduced cabin noise. Its reputed disadvantages of high fuel consumption and emissions have been at least partially overcome by continued research. For example, various modifications of an aircraft rotary engine have been tested during the past few years under NASA contract.[7] By increasing the compression ratio and other refinements, the initially disappointing BSFC was improved by 15% while the engine met the former EPA emission standards. Its specific weight of about 1.25 lb/hp-hr is already attractive, and its compact envelope would result in significant installation advantages if properly integrated into an airplane design. Foreseeable improvements in such areas as variable ignition timing, timed fuel injection, and better seal materials could improve the current test values to a specific weight of about 1.0 lb/hp and a cruise BSFC about equal to current recips by the early 1980's.

To meet the longer term goals, however, will require major technology advances on several fronts.

(1) Direct-injected, stratified-charged (DISC) operation is essential to obtain a true multifuel capability. Rotary DISC combustion research now underway shows promising results but must be extended to the much higher speeds and chamber pressures envisioned for the advanced aircraft engine. (Research is currently limited to 6000 rpm or less by "state-of-the-art" diesel injection equipment.)

(2) An overall electronic control system is needed to optimally coordinate the ignition and fuel-delivery functions.

(3) Improved apex seal designs and materials are needed to provide acceptable durability and friction-loss characteristics with the higher pressures, speeds, and temperatures associated with high specific output powers.

(4) To approach the diesel's BSFC levels, it will be necessary to decrease the rotary's presently large heat losses by insulating the rotor and housings in a manner analogous to the adiabatic diesel. This is a completely unexplored area of technology.

(5) Turbocharging and possibly turbocompounding will be required to meet the specific power and BSFC goals. Because of the rotary's characteristically high exhaust gas temperatures (which will be even higher if a solution to the combustion-chamber-insulation problem is found), high temperature turbine materials will be needed. Turbocharger component efficiencies will need improvement.

Turbofan Engines

At the present time, the major NASA activity in this area is the QCGAT (Quiet, Clean General Aviation Turbofan) program. The objective of this near-term project is to demonstrate the applicability of available large turbofan engine technology to small engines in order to obtain significant reductions in noise and pollutant emissions, while reducing or maintaining fuel consumption levels. Following initial studies, contracts were awarded to AiResearch and AVCO-Lycoming to each design, fabricate, test, and deliver to NASA a QCGAT engine. These contracts were awarded in FY 1977 and involve a total value of $8.4 million, of which $1.7 million is cost-shared by the contractors.

The general approach of the program is outlined in figure 9. To minimize costs, use of existing cores was specified and testing is to be accomplished with a boiler-plate nacelle; however, the internal aerodynamic characteristics are correctly simulated and all rotating parts are flight-worthy.

In order to provide a basis for assessing propulsion system performance, the contractors have designed hypothetical twin-engine executive-type aircraft around their engines (fig. 10). Although the aircraft appear similar, they are considerably different in size and design. The AiResearch aircraft is an uprated version of a Learjet 35 weighing 19,1[illegible] pounds at takeoff. Its cruise design point is at Mach 0.8 at a 40,000-foot altitude. It can carry a 14-passenger payload including crew 1780 nautical miles.

The AVCO-Lycoming aircraft was designed specifically for the QCGAT engine by the Beech Aircraft Company under subcontract to AVCO. Its design flight characteristics are similar to the Cessna Citation cruising at approximately Mach 0.6 at 33,000 feet. It has a takeoff gross weight of 7800 pounds with a payload capability of six passengers including crew flying for a 1500-nautical-mile range.

Figure 11 shows cutaway views of the two QCGAT engines in an installed configuration. Acoustic treatment and the internal mixer nozzle for performance improvement and noise reduction are evident. The AiResearch Company chose the core and supercharger of their Model TFE 731-3 engine for the QCGAT engine. The basic TFE 731-3 is a 3700-pound-thrust turbofan with two spools and a geared fan. It is currently used in the Dassault Falcon 10, Learjet 35/36 and others. As modified for QCGAT it incorporates a new reduction gear box, combustor, and power turbine. The engine has a moderate bypass ratio (4.2)and fan pressure ratio - a design that is typical for the high altitude, high-speed design of the aircraft. The mixer nozzle is a key element in reducing takeoff noise and improving performance as model tests have shown. A low fan tip speed and proper fan rotor-stator spacing are other design features for low noise.

The AVCO-Lycoming engine shown on the lower portion of the slide has similar installation features. The AVCO engine uses a modified LTS 101 core. The basic LTS 101 core can provide fan engines having thrust levels in the order of 1000 to 1300 pounds. The turboshaft version has flown in helicopters of two aircraft companies and was FAA certified in 1975. An improved core was offered for the QCGAT program, which includes the addition of a new supercharger stage on the core compressor and increased turbine inlet temperature requiring an aircooled turbine. A new fan, reduction gear box, combustor, and power turbine make up the unique QCGAT engine parts. The installation features a mixer nozzle and acoustic treatment in the inlet and fan duct. A relatively high bypass ratio (8.5), low fan pressure ratio, and low fan tip speed are characteristics selected to satisfy the low noise requirements imposed on the propulsion system. This cycle is also nearly optimum for the selected engine-airframe combination.

The AiResearch engine was recently delivered to to NASA-Lewis Research Center for further testing while the AVCO-Lycoming engine is still in test at Stratford, Connecticut, and will be delivered to NASA in mid 1979. Current estimates and early test results indicate both engines will either meet or beat the stringent noise goals established by NASA. These goals and the estimated values for each engine are shown below.

	AVCO-Lycoming		AiResearch	
	Goal	Actual	Goal	Actual
Takeoff (3.5 n. mi. from runway threshold)	65.1	64.7	73.3	74.3
Sideline (0.25 n. mi. sideline)	78.4	71.8	82.3	79.0
Approach (370 ft. altitude 1 n. mi. from runway end)	85.4	73.6	87.3	83.5

Early engine test results indicate performance and emission goals will probably also be met.

Small Turboprop Engines

Turbo-propulsion is generally acknowledged to be desirable for a number of reasons, e.g., low weight and vibration, long time between overhaul, multifuel capability, etc. as shown in figure 12. For these reasons, turbines have entirely captured the military and large commercial markets plus the higher-powered end of general aviation. However, the two detrimental features of excessive engine price and high fuel consumption have thus far prohibited inroads into the smaller sizes, which represent the great majority of all engines manufactured (fig. 1).

Starting in 1977 NASA has sponsored studies aimed at exploring the possibility of achieving substantial improvements in cost and performance for small-size engines of less than 1000 horsepower. In this so-called GATE program (General Aviation Turbine Engine), contracts were let with four manufacturers of small engines. The main differences between GATE and the just-described QCGAT program are:

- GATE initially encompassed turbofan, turboshaft, and turboprop engines, but the contractors' marketing studies resulted in the principal emphasis being placed on the turboprop as having the major sales potential.
- QCGAT employs currently available technology while GATE is aimed at advanced engines that might be feasible in 1988.
- The QCGAT engine sizes are representative of the high-powered executive jets, whereas the GATE market studies directed major emphasis toward the more populous, 300 to 500 horsepower class.

- QCGAT emphasizes noise and emissions, whereas GATE design concepts were heavily slanted to the achieving of low production cost.

Turboprops are, of course, presently being produced for general aviation uses. However, in the smaller sizes that are of greatest present interest, they are much more costly than the well-established reciprocating engines (fig. 13). Three of the four GATE contractors are projecting that this difference in cost can be greatly reduced, especially if high production rates can be established. (The approach of the fourth contractor led to reduced life-cycle costs for his advanced engine concepts, although this is not evident from the figure.)

As pointed out in the Introduction, low initial cost is not attractive if engine performance is allowed to deteriorate. As shown in figure 14 a further prediction by the GATE contractors is that the poorer performance that has, in the past, been experienced in small engines can be nearly eliminated through improved component technologies.

The types of airplane that then becomes feasible with GATE-type engines are illustrated in figure 15. Their cost and fuel characteristics are considerably superior to comparable airplanes employing current-technology reciprocating engines. (It should be remembered, of course, that efforts are underway to achieve advances in reciprocating engines, also.)

Figure 16 indicates the market impact if the GATE expectations materialize and the reciprocating competition does not advance. Instead of the present 400/year production rate of turboprop-powered airplanes, which is limited by an engine cost barrier, a substantial penetration into the 16,000/year reciprocating region would take place. This becomes possible through the various techniques indicated at the top of the figure: essentially a coupling of low-cost design, improved component technology, cheaper manufacturing techniques, and high production rates.

The initial GATE studies have now been completed, and NASA is considering possible follow-on programs in these areas.

Propeller Technology

Along with the previously described efforts to improve reciprocating and turboprop engines, NASA has initiated activities aimed at improving the propellers that will be driven by these engines.

A number of contracts and grants have been let through the Langley Research Center with various universities. These studies encompass work on propeller performance, noise, airframe interference, aerodynamic loads, and structural dynamics. The work involves analysis, wind-tunnel testing (in both university and Langley facilities), and airplane flight testing.

Complementary work at the Lewis Research Center is anticipated, guided by the results of a recently-let contract to McCauley that will analytically explore the benefits of applying various advanced technologies to general aviation propellers. Another program is already underway at Lewis that is of potential applicability to general aviation. As part of the effort to improve the fuel efficiency of commercial aircraft, experiments are being performed on advanced propellers that could permit the use of turboprop propulsion at the speeds and altitudes presently flown by large airliners. Figure 17 shows one of the new designs installed in a wind tunnel. Such propellers may be equally applicable to high-speed executive-type aircraft.

Concluding Remarks

The general aviation industry is currently enjoying a period of strong growth. To assure continuance of this happy situation, a long-term effort to improve the performance, economy, and safety of the airplanes is highly desirable. The enormous diversity of general aviation applications leads to an equivalent variability in the appropriate types of powerplants that find use. This paper has described the research activities within NASA to support industry's efforts to improve the various engines of the future.

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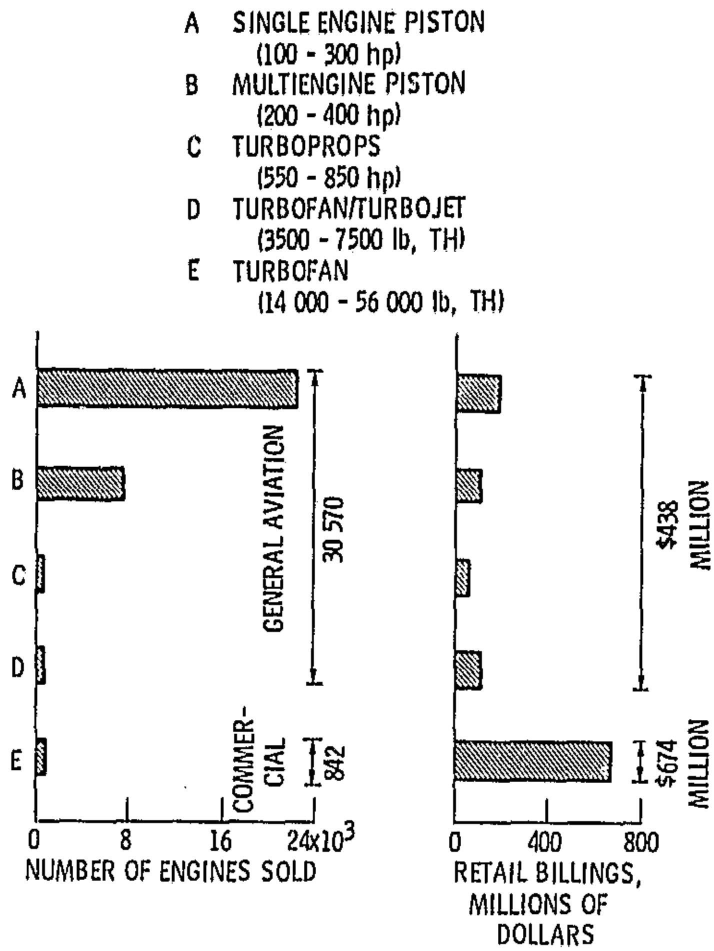


Figure 1. - U. S. engine production 1977, estimated.

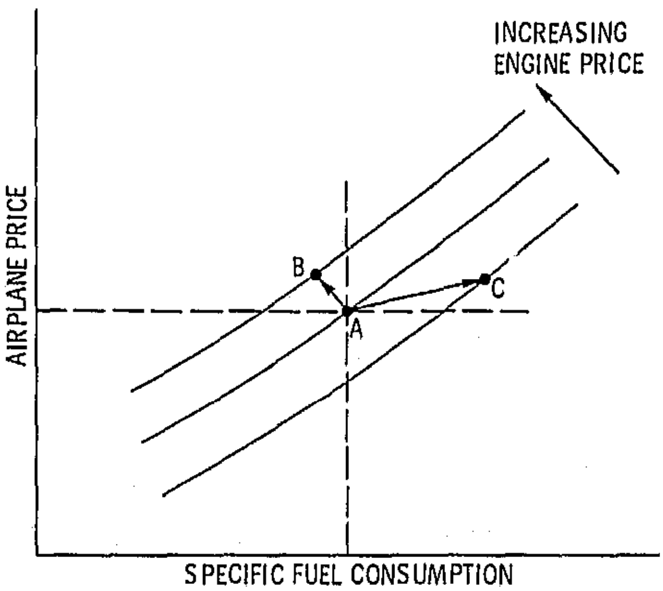


Figure 2. - Engine price versus performance.

NASA PROPULSION RESEARCH

- INTERMITTENT - COMBUSTION ENGINES
  CONVENTIONAL RECIPROCATING
  ALTERNATIVE CONCEPTS
- TURBINE-POWERED ENGINES
  TURBOFAN
  TURBOPROP
- PROPELLERS

Figure 3. - Areas of NASA propulsion research for general aviation.

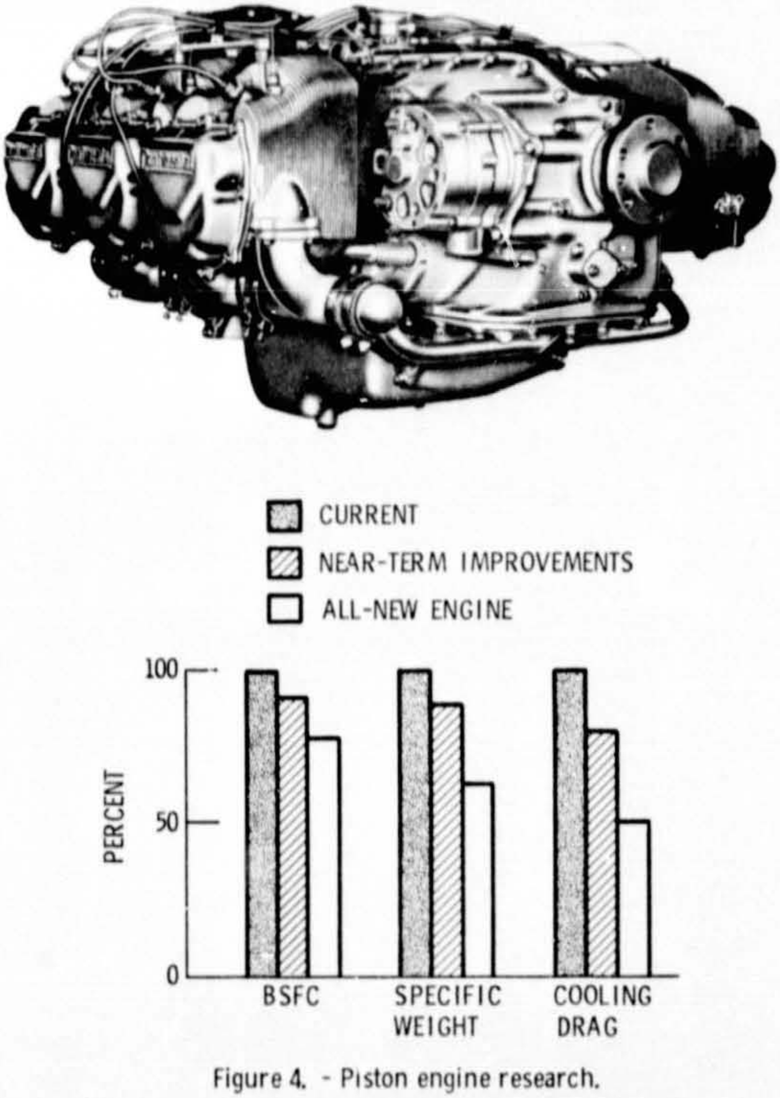


Figure 4. - Piston engine research.

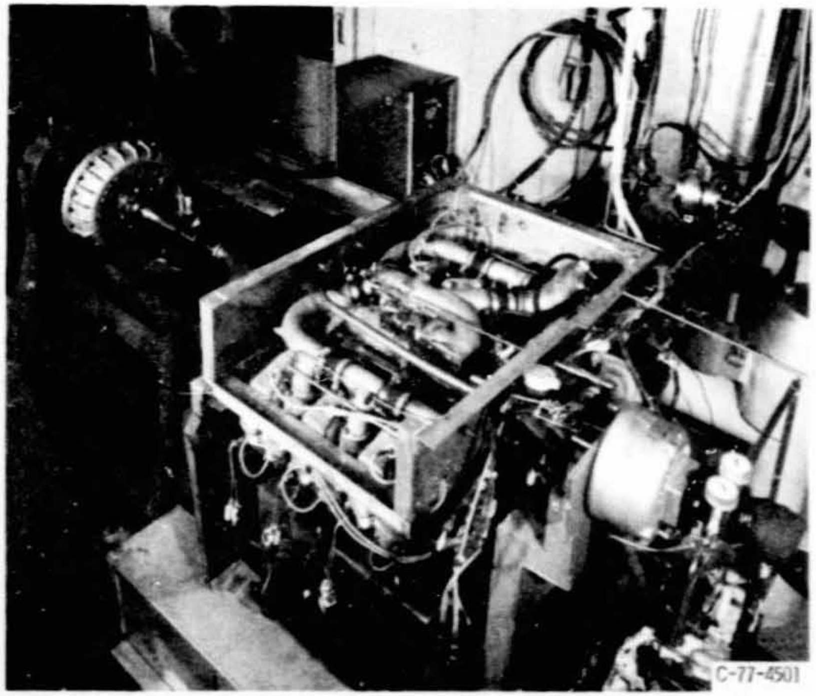


Figure 5. - General aviation reciprocating engine test facilities.

TEST RESULTS

	BASELINE	COMBINED CONCEPTS
EMISSIONS, % EPA 1980 LEVELS		
CO	185	45
HC	122	25
NO_x	20	62
BSFC, % CHANGE		
T/O	0	-17%
CRUISE	0	-7%

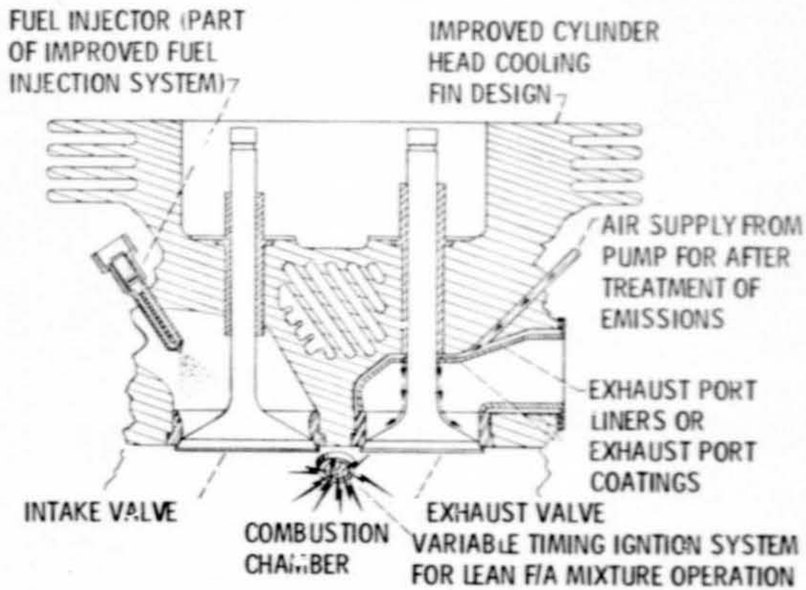


Figure 6. - Advanced cylinder head concept integration.

LONG-TERM TECHNOLOGY GOALS (1988)

BSFC: 0.32 - 0.35 lb/Bhp - hr

SP. WT: 1.2 - 1.5 lb/Bhp

EMISSIONS: MEET EPA '80

FUEL: DIESEL 2, JETA

COOLING: ZERO OR MINIMAL

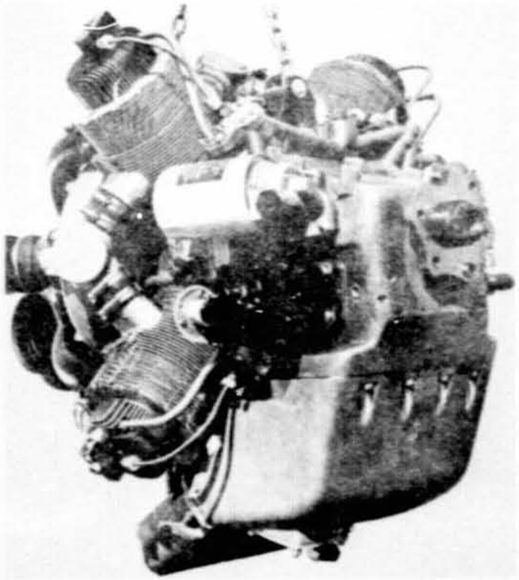
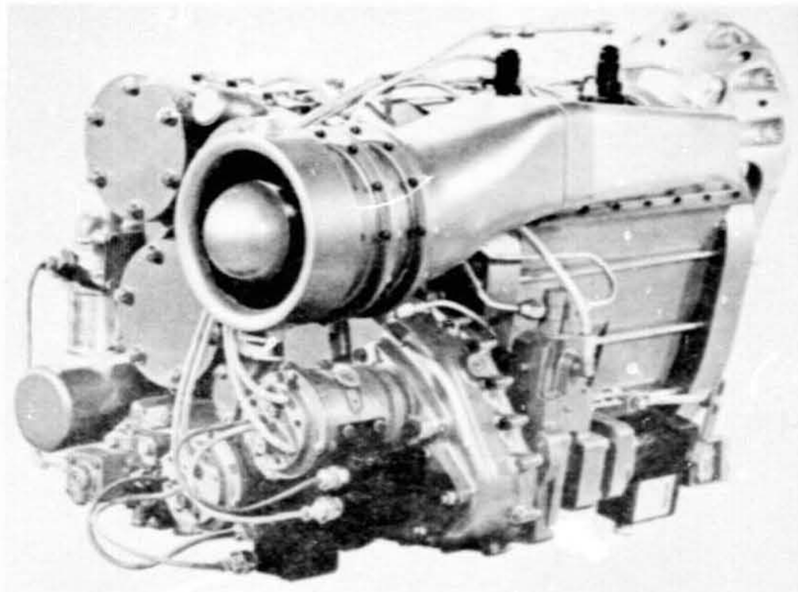


Figure 7. - Lightweight diesel engine research.



LONG TERM TECHNOLOGY GOALS (1988)

BSFC: 0.38 - 0.40 lb/bhp-hr

SP. WT: $\leq$0.75 lb/bhp

EMISSIONS: MEET EPA '80

FUEL: MULTI-FUEL

COOLING: LIQUID, LOW DRAG INST'L

Figure 8. - Rotary engine research.

GOAL

APPLY AVAILABLE LARGE-ENGINE TECHNOLOGY TO OBTAIN LOW NOISE AND EMISSIONS

APPROACH

- USE EXISTING SMALL CORES
- MODIFY COMBUSTOR PLUS NEW LOW SPOOL
- FLIGHT-WORTHY ROTATING PARTS INSTALLED IN BOILER-PLATE NACELLE

Figure 9. - Quiet, clean, general aviation turbofan (QCGAT) program.

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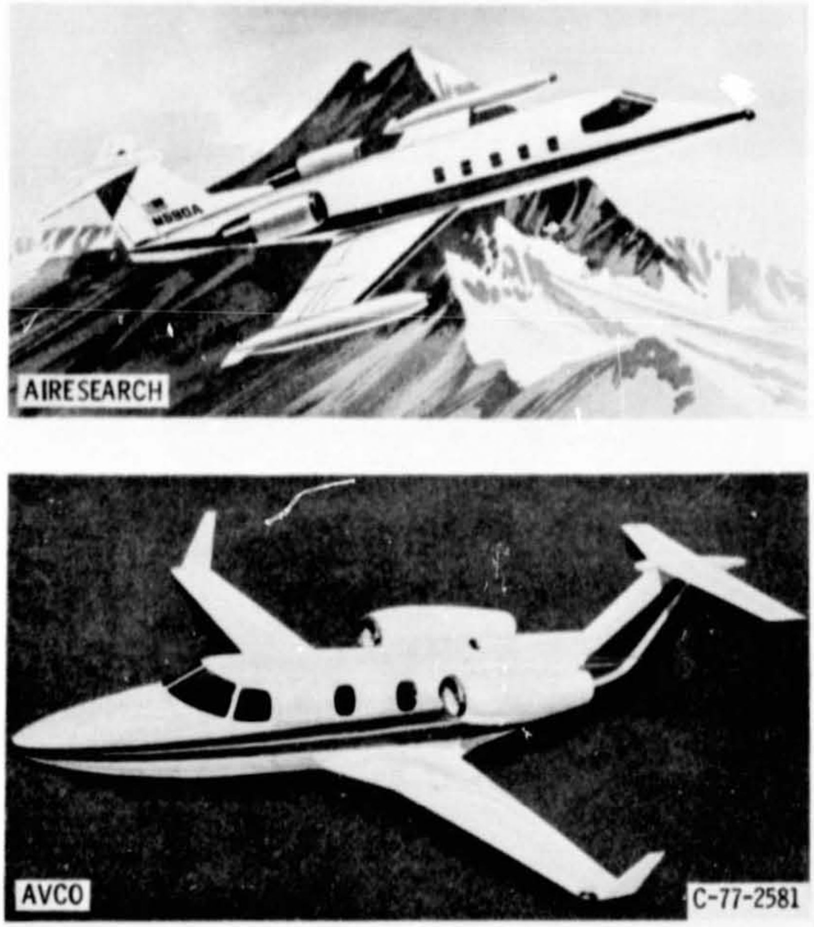
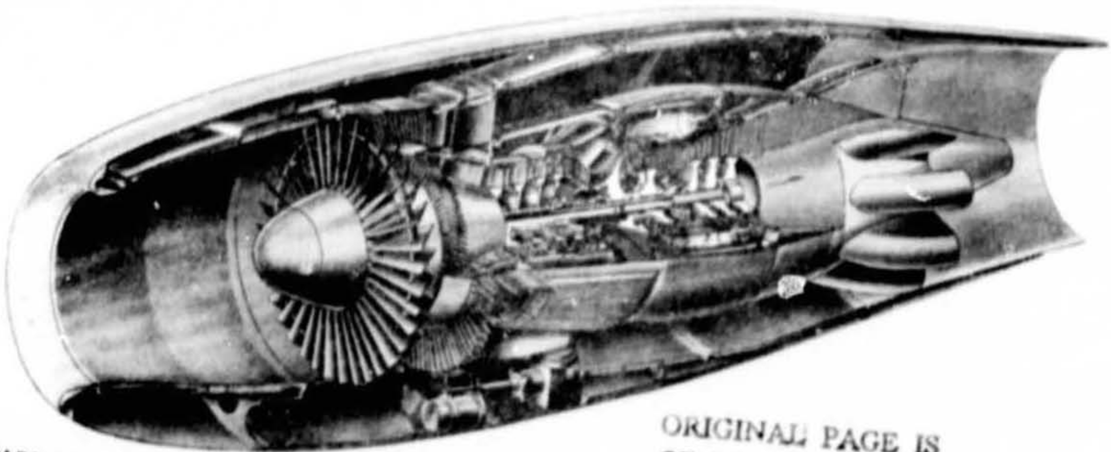


Figure 10. - QCGAT airplanes.



GARRETT AIRESEARCH

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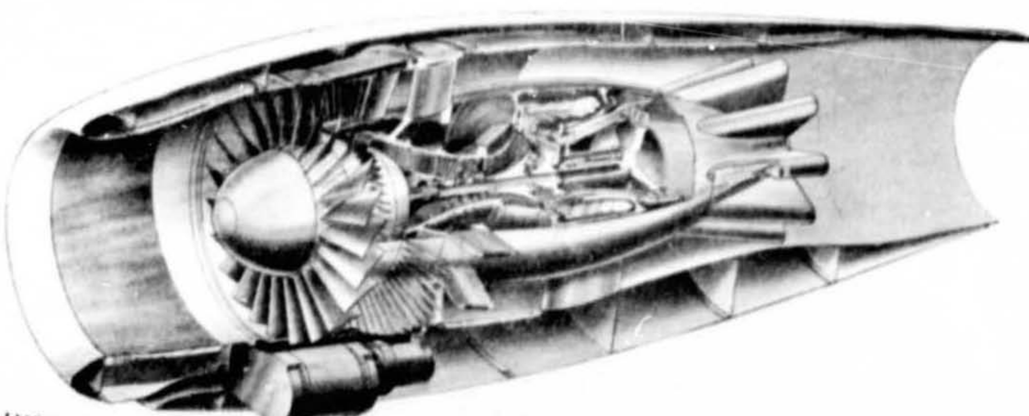

AVCO LYCOMING

Figure 11. - QCGAT engines.

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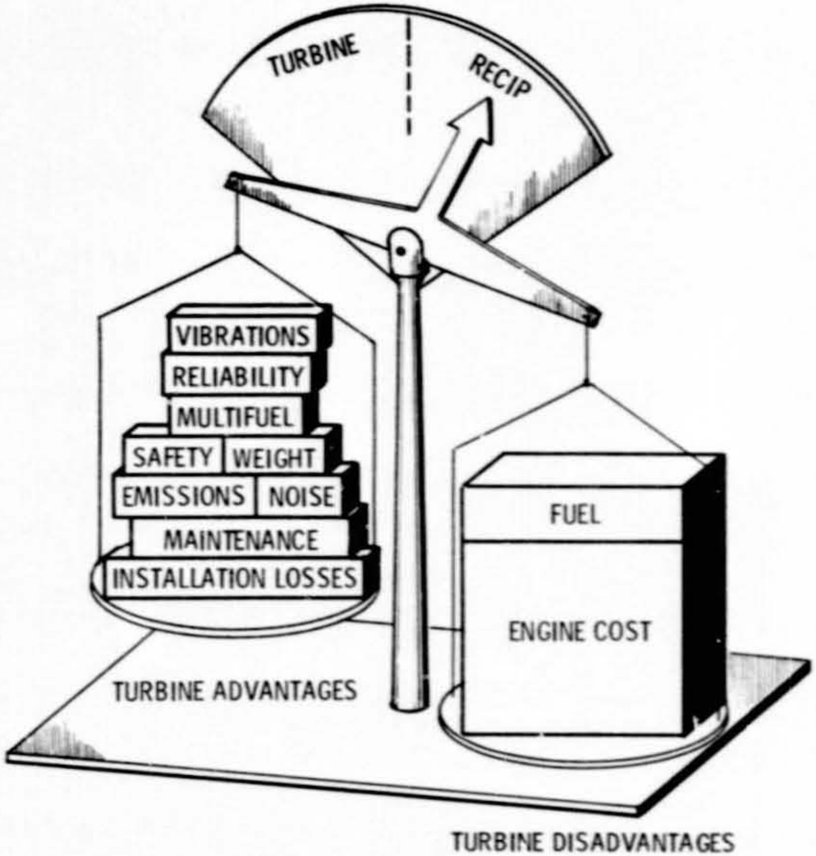


Figure 12. - Current engine selection for light airplanes.

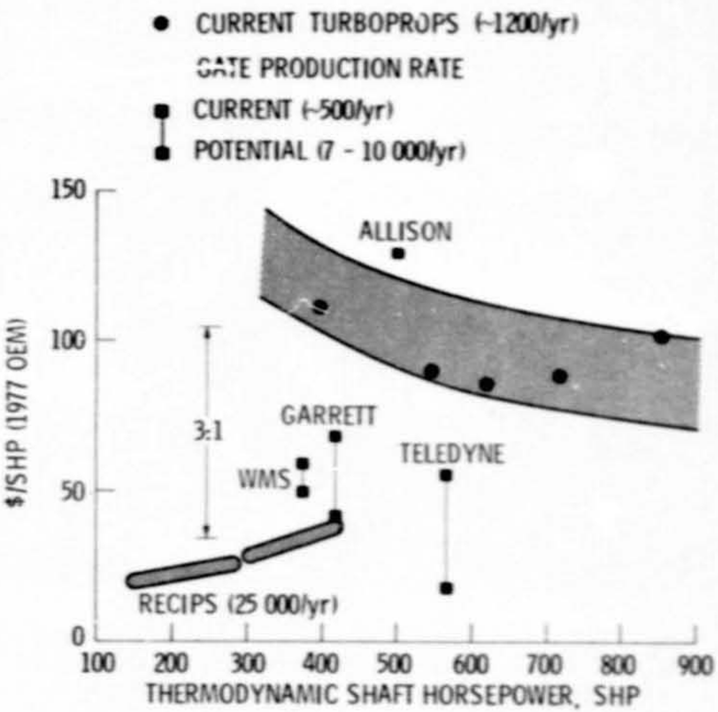


Figure 13. - Gate engine cost forecasts.

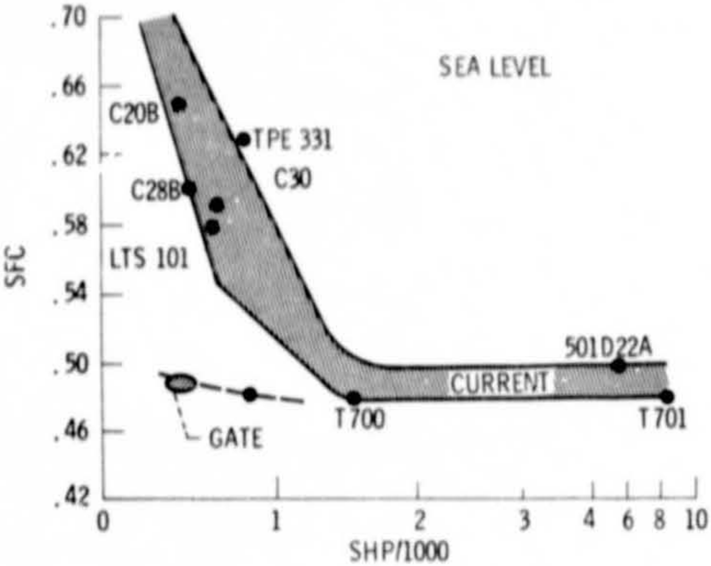
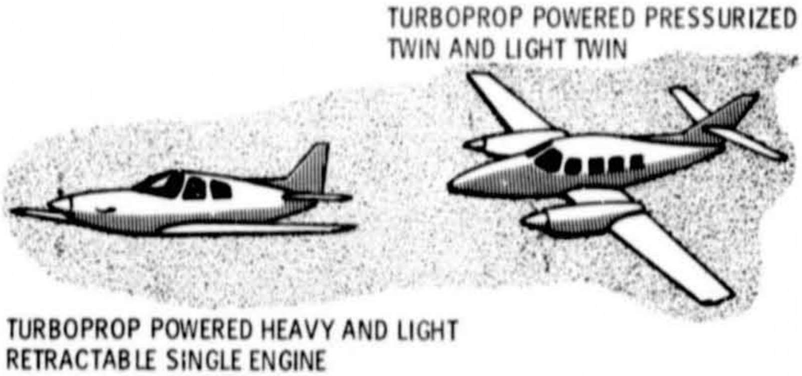


Figure 14. - Gate SFC improvements.



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 15. - Benefits relative to current reciprocating engine.

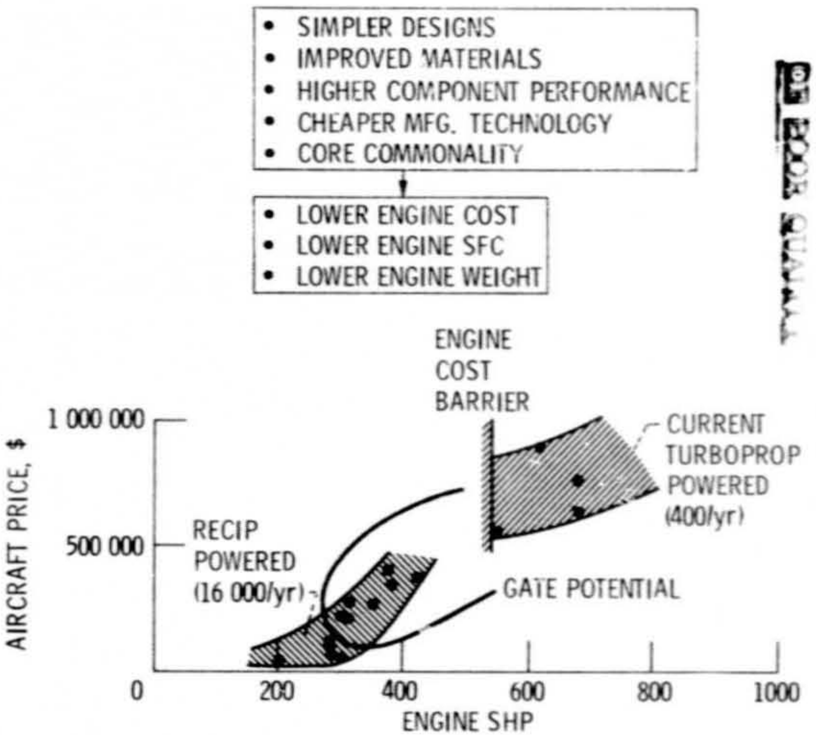


Figure 16. - Gate technology could expand domain of small turbine engines.

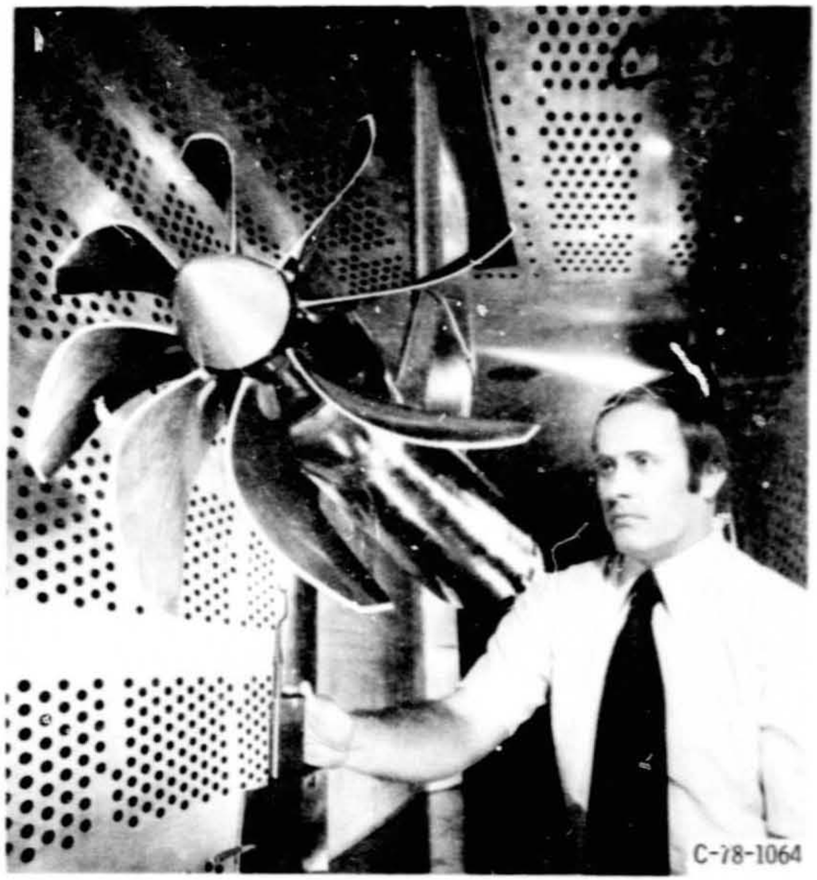


Figure 17. - High-speed propeller test model.