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GENERAL AVIATION ENERGY-CONSERVATION RESEARCH PROGRAMS AT NASA-LEWIS RESEARCH CENTER

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ABSTRACT

A review is presented of non-turbine general aviation engine programs underway at the NASA-Lewis Research Center in Cleveland, Ohio. The program encompasses conventional, lightweight diesel and rotary engines. It's three major thrusts are, in order of priority: (a) reduced SFC's; (b) improved fuels tolerance; and (c) reducing emissions. Current and planned future programs in such areas as lean operation, improved fuel management, advanced cooling techniques and advanced engine concepts, are described. These are expected to lay the technology base, by the mid to latter 1980's, for engines whose total fuel costs are as much as 30% lower than today's conventional engines.

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By Edward A. Willis

Lewis Research Center

SUMMARY

A review is presented of non-turbine general aviation engine programs underway at the NASA-Lewis Research Center in Cleveland, Ohio. The program encompasses conventional, lightweight diesel and rotary engines. It's three major thrusts are, in order of priority: (a) reduced SFC's; (b) improved fuels tolerance; and (c) reducing emissions. Current and planned future programs in such areas as lean operation, improved fuel management, advanced cooling techniques and advanced engine concepts, are described. These are expected to lay the technology base, by the mid to latter 1980's, for engines whose total fuel costs are as much as 30% lower than today's conventional engines.

INTRODUCTION

General aviation fuel costs have nearly doubled since 1973 and the industry has been plagued by intermittent shortages of specialized fuel grades. The oil companies statements at this Conference, for instance, indicate that avgas may rise to $1.50 per gallon or more by 1982. This situation is believed likely to continue and become progressively worse in the forseeable future. It is particularly a problem for the piston-engine segment of the general aviation fleet, because these engines reflect a W.W. II level of technology and require very specific grades of gasoline. The industry apparently lacks the independent financial and technological means in such areas as advanced combustion and cooling research, to significantly enlarge the fuel tolerance of either current or next-generation engines. Although the ~200,000 general aviation airplanes supply essential transportation services to about 13,200 airports (compared to 425 served by commercial airlines), avgas represents only about 0.3% of the total transportation fuels market. This may be too small to significantly constrain the refiners' future product split decisions. Government pressures toward the most energy-efficient product split from available crudes and other raw materials, may well have a greater impact on these decisions. It is therefore appropriate that Government technology be applied to help solve the resulting problems.

STAR Cat. 07

At Lewis, the General Aviation Branch was formally established earlier this year, following several years of initial facility and instrumentation development and preliminary efforts aimed at emissions reduction. More recently, in view of the EPA's apparent intent to withdraw the emissions standards, the emphasis of the program has shifted toward fuel conservation and multifuel and/or broad specification fuels capability. Figure 1 illustrates our relation to other general aviation programs within the Lewis organization.

In broad terms, our aim is to enable light planes to burn as little as possible of the cheapest fuels available. More specifically, our long-term (1985) objective is to lay the technology base for an efficient, reasonably priced multifuel or alternative fuel engine whose fuel costs (based on 1977 dollars and prices) could be as much as 30% less than present day engines. Because of product longevity and comparatively low annual production rates, the benefits of a next-generation multifuel engine, although valuable to the individual owner or operator, would require a period of years to significantly upgrade the overall fleet. Hence the program necessarily also includes consideration of applicable technology for current-production type engines. We would prefer, however, to leave any detailed discussion of near-term developments to the respective engine companies. This discussion will therefore address the longer-term prospects, including a couple of often-overlooked and much-neglected concepts -- the rotary and the lightweight diesel -- that we now see as having considerable promise in the 1985-1990 era.

PROGRAM TO DATE

Several Lewis accomplishments to date deserve mention. Three sophisticated engine test cells have been built from scratch, with one more in progress. Figure 2 indicates the capabilities and leading features of the currently-operational cells. Figure 3(a) is a view inside the aircraft engine test cell, with the engine (a TSIO-360) in the foreground. The cooling-air hood has been removed for clarity and the electric motoring dynamometer may be seen at the left. The associated control room is shown in Figure 3(b). These highly automated cells feature real-time data readout via microprocessor technology, and we believe that they compare favorably with any of their kind in the world. An example of our on-line data readout is given in Figure 4, which illustrates in bar-chart format, the IMEP measured for 100 successive cycles of one cylinder on the Chevrolet engine. The two samples shown, both for the same speed and load, illustrate what can happen when the engine is excessively leaned out. At left, the mixture strength was about stoichiometric and there was little variation between the IMEP's of successive cycles. The engine was then leaned out, but not to the point where the operator could detect visual or audible signs of rough running. Nevertheless, many slow burns and one outright misfire (the small negative bar) can be seen. This results in increased HC emissions and SFC. The high IMEP's seen in other cycles is indicative of high peak pressure and possibly detonation. With the aid of such real-time data capabilities, the test engineer can make sure to get good data the first time, every time. Lengthy delays for data reduction are largely eliminated. If properly utilized, the automated test cell can be an order of magnitude more productive than a conventional cell.

Using these in-house facilities and other Lewis resources, together with a continuing series of industry contracts, we have completed substantial programs in such areas as: basic engine characterization (Ref. 1); effect of temperature, humidity and lean operation on fuel economy, emissions and cooling requirements (Ref. 2); hydrogen enrichment of fuel (Ref. 3); and theoretical analyses of cooling fins (Ref. 4). Also, progress has been made toward the development of advanced analytical tools such as an Otto Cycle performance and emissions prediction computer code (Ref. 5).

The results from these plus the contract programs are such that we expect to demonstrate, by the end of 1979, the technology base to approach or meet the former emissions standards. This is not a moot accomplishment, since reducing emissions is clearly desirable even if no longer mandatory. Also, most of the programs led to be fuel-conservative accomplishments as well. For example, large amounts of scatter observed in prior emissions data prompted us to include the effects of atmospheric temperature and humidity in our own program. Typical results obtained in the aircraft engine test cell with conventional mixture control are shown in Figure 5(a). The HC emissions level is plotted vs. temperature for relative humidities of 0 and 80%. The level increased by a factor of about 4 between "cool, dry" and "hot, humid" conditions. The fuel/air ratio increased by about 20% at the same time due to the decreased air density and displacement of air by water vapor. Since the engine was run at constant speed/load conditions, fuel consumption suffered by the same amount. A second series of tests, illustrated in Figure 5(b) was run to evaluate the situation when the fuel/air ratio was held constant at the "cool, dry" value of 0.093. The result, as shown by the solid curve between the two shaded regions (representing 80% humidity) was a much smaller increase in HC emissions. Since fuel/air was held constant, there was no penalty in fuel consumption. The upper curve represents the 80% humidity case previously shown, where the conventional mixture control allowed fuel/air to vary. The shaded area between the two curves shows that most of the initially observed increase in HC was due to the induced change in fuel/air. The lower shaded area illustrates the smaller increase due to changes in temperature and humidity alone. From these results, it is clear that an automatic mixture control system, capable of holding a desired fuel/air ratio despite atmospheric variations, is needed to improve both fuel economy and emissions.

The hydrogen injection program is another case in point. Both in our own programs (Ref. 3) and a parallel JPL effort (Ref. 6) it was initially thought that the free hydrogen, by permitting leaner operation, would improve both economy and emissions. A considerable amount of extra spark advance was required to support lean operation, whether hydrogen was used or not. The results are illustrated in Figure 6, where SFC is plotted vs. mixture strength at typical load conditions for an automotive engine (NASA) and an aircraft engine (JPL). Operation with gasoline only is represented by the solid curves while the dashed curves denote gasoline plus the indicated amounts of hydrogen. In each case the spark advance was maintained at an optimum or near-optimum setting, typically 30° - 35° BTDC for the aircraft engine and over 40° for the auto engine. Under these conditions, the minimum SFC buckets occurred with gasoline only even though the auto engine's lean limit was noticeably extended by using hydrogen. The amount of extra spark advance required to obtain these results is incompatible with starting and high-power operation. Thus, a variable timing ignition system is desirable and perhaps an essential ingredient in realizing the indicated improvement of 5 or 10% SFC below the normal stoichiometric or slightly rich condition in the aircraft engine.

ONGOING AND FUTURE PROGRAMS

With this basic work behind us, the current program (Fig. 7) includes elements designed to achieve a technology base which will enable general aviation to live with the fuels of the future. As indicated, the program includes near-term elements which could improve the fuel economy of present-day type engines, as well as longer-term elements leading to broad-specification or true multi-fuel capability (together with further reductions in SFC). While recognizing the inherent multi-fuel capability of other candidates such as gas turbine or Stirling engines, the program discussed here is now oriented toward diesel and rotary combustion engines in addition to advanced piston engines. All of these can benefit immediately from the results of ongoing automotive diesel and stratified charge research programs and offer significant benefits without having to wait for "technology breakthroughs" in one or more areas. We are of course, monitoring ongoing turbine and automotive Stirling programs for applicable developments.

Advanced Piston Engines

Current production general aviation piston engines reflect a level of technology that existed at the end of W. W. II. It seems reasonable to expect that they could be improved substantially by incorporating applicable developments of the last 30 years. In particular, the automotive research programs that have been mounted within the past decade, would appear to be a rich source of new technology for general aviation. While the most interesting developments are proprietary and cannot be discussed at this time, it is to be hoped that arrangements beneficial to general aviation can be worked out among the companies concerned.

For conventional engines, the lean out approach should yield about a 10% improvement in basic engine SFC levels. To realize this benefit, we have initiated programs in: (1) improved fuel injection; (2) variable timing ignition systems; and (3) improved cooling.

Improved fuel injection together with even air distribution is needed to minimize the cylinder-to-cylinder variations of fuel/air ratio. More leaning can then be accomplished, since the lean limit for the engine as a whole is set by the leanest cylinder.

Variable timing ignition systems are required, because as shown by our own and JPL testing, radical spark advance is required to extend the lean limit and obtain very low SFC's on some engines. The degree of advance required is incompatible with starting and high power requirements.

In many turbocharged installations, the amount of leaning made possible by the two items above would be accompanied by excessive CHT's and detonation. This would negate the potential SFC improvement due to leaning unless better cooling is provided. Potential improvements are forseen in several areas.

Exhaust port liners and/or thermal barrier coatings will decrease the heat load into the cylinder head by as much as 35%. Advanced designed cooling fins and passages can more effectively dissipate the remainder of the heat load. The resulting lower CHT's and elimination of hot spots will enable the engine to run leaner and/or at a higher compression ratio without detonating. For turbocharged engines, a 5 to 10% reduction in SFC is anticipated from these improvements. Alternatively, the lower CHT's could enable the engine to burn lower octane fuel. Figure 8 illustrates a hypothetical cylinder head design that incorporates the port liners, improved fuel injection and other advancements into a well-integrated package.

More efficient inlets, baffles, fins and exits can reduce the cooling air pressure drop for a given heat load by a factor of 2 or more. The resulting decrease in cooling drag is equivalent to a further fuel economy improvement of up to 5%. This is additive to the above and also applies to those engines that are already capable of operating lean.

In the longer term, advanced combustion research is essential to utilize cheaper, more readily available fuels. It should be noted that, based on current fuel prices, 100 octane avgas is 10 to 15% more expensive per gallon than diesel or Jet-A fuels. These fuels however, contain about 10% more BTU's per gallon than avgas because of their greater density. Thus a fuel cost saving potential of 20% or more is readily apparent, even if SFC's are not improved at all. Automotive research results indicate that novel combustion geometries coupled with vapor-phase fuel injection, may significantly broaden the fuel tolerance of an otherwise conventional engine.

Diesel Engines

Diesel engines are of interest because of their well-known potential for low SFC. They can also burn kerosine-type jet fuels with little difficulty. These types of fuel are generally cheaper than avgas. Since the diesel is not detonation-limited, it can run at high compression ratios and/or can be turbocharged to exceptionally high power densities. The problem with diesels is weight. A normally aspirated diesel suffers an immediate specific power penalty of about 15% compared to a gasoline engine because only about 85% of the theoretically-available air per cycle can be burned efficiently. At typically high diesel compression ratios, the high peak firing pressures result in major structural weight penalties in addition. Based on these considerations, it was felt that a low compression, turbocharged diesel concept might offer the best trade-off between weight and performance.

Initial efforts, however, showed that it is no simple matter to obtain good diesel combustion at low compression ratios. Tests at the U. of Michigan (Ref. 7) of a dieselized aircraft cylinder mounted on a single-cylinder crank-case showed unexpectedly high SFC due to poor combustion (Fig. 10). The problems are ultimately due to the major geometrical differences between an aircraft gasoline engine's combustion chamber and the typical diesel's. The former has low turbulence and a high surface-to-volume ratio to promote cooling. The latter normally would be a high turbulence design with a compact combustion volume intended to keep the heat in. The work however is being continued to optimize the combustion chamber geometry and we expect to reach the indicated BSFC level of about 0.42 after another years' effort.

Figure 10 illustrates a turbocharged diesel concept in which an auxiliary combustor fed by compressor air is used to provide additional power to the turbine. In this concept the power output is limited only by cooling and structural consideration. The turbomachinery can be started and run independently of the diesel cylinders to provide hot compressed air for starting and low power operation. This concept has been under study and development for some time by the Hyperbar Diesel Co. in France. The French results (Ref. 8) indicated that SFC's at least as low as 0.38 can be obtained at cruise to rated power conditions. At Lewis, we are initiating a research program on this concept, using a single-cylinder research engine, with which we hope to further improve this figure. Our diesel test cell (Figure 11) is presently being checked out, is scheduled for start up in December 1977 and should be operating productively by early 1978.

Rotary Engines

The rotary or Wankel engine (Figure 12) is of great interest because of its established advantages of simplicity, light weight, compactness, clean low-drag installation features, low vibration and reduced cabin noise. Its reputed disadvantages of high fuel consumption and emissions, have been largely overcome by continued research, some in this country and some by foreign automotive companies. For example, according to EPA "city cycle" driving test results, the 1973 Mazda gave 10.6 mpg while the 1977 version showed nearly a 100% improvement to 20 mpg. The detailed SFC and raw-emissions data are proprietary at this time, but it can be stated that the best of the late-model automotive rotaries are becoming competitive with their piston-powered counterparts.

The price situation for rotaries is uncertain at this time. The parts are few and simple but require high-grade materials and very close-tolerance machining. On the other hand, the concept clearly lends itself to high-volume automated producibility. Co-production arrangements among foreign companies are being considered (Ref. 9 and 10) to establish a favorable production-volume basis. Unconfirmed reports (Ref. 10) also suggest that General Motors will re-enter the rotary field in the early 1980's. If this occurs, a volume production basis would be established in this country as well.

These potential developments are highly significant, because the same tooling might also be used to manufacture derivative aircraft engines or key components thereof at reasonable cost.

For aircraft applications, two distinct versions of the rotary engine are of interest and they will be separately discussed. A naturally aspirated, spark ignited version appears to be most attractive for lower-power applications and whenever turbocharging would not be desirable. Figure 13 illustrates results obtained last year in testing a Curtiss-Wright RC-2-75 engine under a NASA contract (Ref. 11). It's best SFC of about 0.54 might be good enough for an automotive application, but is not competitive with even a current production normally aspirated aircraft engine. On the other hand, it met the EPA NOx and CO standards, and was only slightly above the HC standard. It's specific weight of about 1.25 lbs/hp is most attractive. It should be noted that the rotary, because of heat losses from its high surface to volume combustion chamber, is less subject to detonation and has a lower octane requirement than a piston engine. Also, it is insensitive to lead in the fuel due to self-cleaning internal surfaces and having no valves to stick. At a given compression ratio, therefore, the rotary is more fuel-tolerant than a piston engine. Alternatively, the rotary can run a higher compression ratio on the same fuel. Returning to Figure 13, single rotor tests at an increased compression ratio (to 8.5:1) with other minor changes, showed significantly better SFC's coupled with acceptable HC emissions.

The Polish PZL Franklin engines currently run a 9.5:1 compression ratio on 100/130 octane avgas, according to the manufacturers' literature. Based on the above arguments, we would expect that the rotary could run at least that high. On that rationale, we have projected the 8.5:1 rotary test points to 9.5:1 and expect to be at the more competitive level shown in about a year. Based on unconfirmed reports concerning the new Toyota rotary (Ref. 10) we anticipate that the results shown can be further improved by employing a comparatively simple, partial charge-stratification scheme. This may also improve the engine's fuel-tolerance and emissions characteristics.

Attempts to further improve the rotary's SFC by going to diesel operation have thus far proven discouraging. Considering the effects of heat losses, seal leakage and manufacturing tolerances, it appears impracticable to obtain a high enough compression ratio. On the other hand, much the same result can be obtained via stratified charge operation. As Figure 14 suggests, the principle is that fuel is injected directly into the combustion chamber via a high pressure injector, as in a diesel. But instead of depending on compression heat to ignite the fuel spray, this is accomplished by a separate means such as an arc or a timed high-energy spark. The rotary is uniquely well adaptable to this approach for two reasons. First, the elongated rotary combustion chamber, in its natural sweeping motion past fixed injection and ignition points yields inherent charge-stratification. No power-robbing pre-chamber is needed; in effect, the combustion volume is moved through a stationary flame front. This keeps fuel out of the rotor trailing-edge region where poor combustion is apparently responsible for part of the rotary's past SFC and HC emissions problems.

Secondly, the firing impulses of a two rotor Wankel engine are as smooth as those of a 6-cylinder piston engine. Thus, it needs only 1/3 as many high pressure injectors as a comparable diesel or stratified charge piston engine; and hence is much better able to absorb the cost and weight penalties of this sophisticated and typically expensive equipment.

The resulting engine would potentially have a true multifuel capability in that it has neither octane nor cetane requirements. Like the diesel, it can be turbocharged to very high power densities. Although presumably designed for optimum performance and efficiency on a fuel of choice -- such as diesel or Jet fuel -- it should have "keep flying" capability on gasoline in case of shortage or unavailability. Operations at a small FBO may be a case in point. Such advantages have not gone unnoticed by other investigators. A perusal of fundamental and applied research in the recent literature (Refs. 12 through 14) indicates that the technology is now at hand to develop a multifuel stratified charge rotary whose SFC, as projected in Figure 15, is at least comparable to that of the best current production aircraft engines. And all the while it is using a cheap and very available fuel.

The results shown are for a naturally aspirated engine with a specific weight of about 1.25. Our goal for 1985 is to improve these figures to a specific weight of less than 1.0 and a SFC under 0.40.

ECONOMIC IMPACT

The discussion thus far has only concerned technology, but several other considerations are also most important. They all relate, directly or indirectly, to the issue of cost. It already costs money to maintain the industry's excellent present standards of safety, reliability, etc. Will advanced technology add more to the bill? If so, who pays and where does the money come from? These very legitimate questions cannot be definitively answered now, but neither can they be avoided. Extensive studies will be needed to fully assess the economic impact of advanced technology on general aviation. I disagree however, with the notion that high-technology products are necessarily complicated and expensive; and would like to cite two examples to support my view.

The Diesel Rabbit automobile introduced this year is being profitably sold for about $170 more than its gasoline counterpart -- a premium of only 3-4% of the usual retail price range. Without attempting to account for the economic value of diesel durability, this premium will be recovered in fuel cost savings* alone in about 2 years of average driving. Thereafter, this automobile will in effect be making money for its owner. So technology doesn't have to be expensive or unprofitable if it is properly combined with value engineering.

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* Based on EPA mileage estimates and late 1977 motor fuel retail prices.

The second example concerns a hypothetical high-performance general aviation business twin. The Appendix outlines some admittedly crude, success-oriented and over-simplified calculations to compare a status-quo engine and an advanced engine in the same airplane. For the one model considered, this provides a preliminary estimate of the annual fuel-cost savings that might be expected from advanced propulsion technology.

The numbers representing the baseline airplane and engine are not specific to any current models but are thought to be representative. The maximum cruise SFC is installation dependent and varies with the amount of fuel required to cool the engine; the spread of 0.47 to 0.41 covers most installations. Fuel prices were established for this exercise by extrapolating the late 1977 pricing structure to the levels predicted at this Conference for about 1982. On this basis, the annual fuel bill for 600 hours utilization would range from about $35,000 to $30,000.

For the advanced engine, presumably a lightweight diesel or stratified-charge rotary, we chose the most optimistic numbers from the context of the present discussions: SFC = 0.38 lb/hp-hr; specific weight = 1 lb/hp; and a cooling drag reduction equivalent to 4% of the cruise thrust hp. This results in an annual fuel bill of about $19,600 -- a savings of $12,800 to $15,400 -- if it is assumed that the weight saved in engine and fuel is added to the payload. In this case we achieve a 36-44% fuel cost savings coupled with a 55% increase in payload.

Alternatively, if the airplane is simply flown lighter, the engine may be throttled back to cruise at the same speed; the fuel bill is then about $17,700 which represents a savings of nearly 50%.

The above results vary linearly with the annual utilization rate of the airplane, as shown in Figure 16. For the nominal 600 hr. rate, the maximum savings of about $17,300 probably represents 5 to 7% of the airplane's base price. Thus, a premium of 10% of the selling price could be recovered in 1½ to 2 years. Thereafter, within its expected lifetime, the airplane would probably repay its original base purchase price in fuel savings alone.

The above results assume that the best of the anticipated developments occur simultaneously and are in that sense optimistic. On the other hand, no effort has been made here to estimate the possibly significant added benefits that could be expected from re-sizing and otherwise re-optimizing the airplane to better match the new engine. This would be especially important for the rotary engine since it differs in several major respects from current practice. No economic credit was estimated for the better durability and reliability anticipated of an advanced diesel or rotary engine. As these same factors also influence safety, the ultimate benefit may be very significant. Considering these factors, even a 50% savings may be conservative.

As mentioned, extensive studies will be necessary to evaluate the economic impact of advanced technology on all types, classes and uses of general aviation. In the end, the more conservative fuel cost savings of

30% mentioned before may prove to be more representative. But even that is enough to eventually amortize half the base price of many general aviation airplanes. This should prove most attractive to owners and manufacturers alike.

A sizeable investment will be required, however, to realize this very desirable state of affairs. The Government research programs I described are not cheap and the industry is conducting additional work on its own. When the technology base has been laid, the industry will then have to develop, certify and tool up for the new designs. How is all this to be paid for?

An extension of the preceding business-twin example suggests that the eventual benefit to the economy as a whole could be surprisingly large and of a sufficient order of magnitude to justify a respectable investment. Assume that an annual production of 100 advanced propulsion airplanes is established to upgrade a static, 2000 airplane fleet on a 20-year life cycle. The airplanes, engines and utilization are as described in Appendix A, except that the more conservative 30% annual fuel cost savings is assumed. Each new airplane then would "earn" on the order of $10,000 per year. The first year, 100 upgraded airplanes replace 100 retiring status-quo airplanes and collectively "earn" $1M. The second year, the 200 new airplanes "earn" $2M, and so forth. By the tenth year, 1000 upgraded airplanes are earning $10M. This when added to the sum of all prior year savings ($1M + $2M . . . + $9M + $10M) yields an accumulated total benefit to the economy of $55M, compared to prolonging the status quo. By the end of the 20-year life cycle, the now-upgraded fleet has produced a total benefit of $210M to the economy and the benefit is increasing at the rate of $20M/year. Recall that this is for one airplane model only, which represents less than 1/10 of the total general aviation fleet and a modest fraction of the industry's dollar volume. If all elements of the piston-engine fleet were similarly upgraded, the total benefit after 20 or 25 years may approach the $1 Billion order of magnitude. This would appear to justify a sizeable initial investment.

CONCLUDING REMARKS

In conclusion, I would like to offer some comments that primarily reflect my own viewpoint rather than matters of policy or settled opinion within NASA. Regardless of one's views on the real nature of the "energy crisis", it does appear that conservation and energy efficiency will be part of the scene for as far as we can see into the future. What does this mean to general aviation? My personal views on the subject are expressed on the last figure. Sooner or later -- perhaps by the early to middle 80's, some customary grades of fuel may simply become unavailable. Or, they may remain available, but at what price? Clearly, it will be economically desirable to take advantage of the broad-specification, high volume fuels of the future. As indicated, several work areas must be addressed to approach this goal in either a long-term or short-term sense. It is equally desirable to use less of those fuels, if only to keep from going broke.

I have now indicated the main technological steps along the path I think we must follow, although only the longer-term aspects were discussed in this presentation. The ultimate benefits are indicated at the bottom. Our earlier work shows that economy and emissions are interlocked to such an extent that the former EPA standards will probably be met anyway, in the due course of events. Not by 1980, but eventually. Much work remains to demonstrate that some of the advanced engine's anticipated advantages, in such areas as durability and reliability, are in fact real. Extensive studies will be needed to more accurately evaluate the economic impact of these developments, and it is hoped that all segments of the industry will contribute to these studies. My own highly preliminary assessment should be taken as indicating an order-of-magnitude potential only. But the potential appears to be there. If the research programs turn out as expected, the benefits are large enough to be compelling.

APPENDIX - SIMPLIFIED ESTIMATE OF ANNUAL FUEL COST SAVINGS DUE TO ADVANCED ENGINES (ANTICIPATED 1982 FUEL PRICES)

Baseline Airplane: 6-place pressurized business twin, turbocharged 750 lb payload class, 200+ kt. max. cruise @ 20,000 ft and 1/d = 8.5

Utilization: 600 hrs/year @ max. cruise

Baseline Engine:
Rating/weight: 333 hp/500 lbs
Max. cruise power/SFC: 250 hp*; 0.47 to (0.41) lbs/hp-hr
Fuel flow: 235 lbs/hr (2-engines) (205 @ 0.41 SFC)
Annual fuel use: 141000 lbs
Fuel: 100 octane avgas @ \$1.50/gal or 24.8¢/lb
Density/heating value: 6.042 lbs/gal; 18600 BTU/lb
Annual fuel bill: \$34968 (\$30504 @ 0.41 SFC)

Advanced Engine:
Rating/weight: 333 hp/333 lbs
Max. cruise power/SFC: 240 hp**; 0.38
Fuel flow: 184.2 lbs/hr (2-engines)
Annual fuel use: 109440 lbs/year
Fuel: Diesel 2 @ \$1.35/gal or 17.9¢/lb
Density/heating value: 7.544 lb/gal; 18600 BTU/lb
Annual fuel bill: \$19590

Annual Saving: \$15378 to \$10914 or 36-44%, of which about half is due to direct SFC improvement, plus reduced cooling drag; and the remainder is due to lower fuel price/BTU

In Addition: Payload may be increased by over 400 lbs (55%) due to the lighter engine and the 200 lb. fuel savings recorded over a typical 4-hour mission.

Alternatively: The airplane may be flown throttled-back since it is lighter (assuming the 1/d ratio stays constant at about 8.5). This results in another fuel savings of about 72 lbs. over the same 4-hour mission, and brings the annual fuel cost down to \$17667. The savings is then 49.5%. (\$12873 and 42% @ 0.41 SFC).

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* Includes 25 hp loss due to drag of conventional cooling system.

** Includes 15 hp loss due to drag of improved cooling system.

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ENERGY PROGRAMS DIRECTORATE (G. M. AULT)

RECIPROCATING ENGINES (UP TO
ROTARY ENGINES 800 SHP)

GENERAL
AVIATION
BRANCH

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COMMERCIAL TURBOFANS, TURBOPROPS
QCGAT-LARGE G. A. TURBOFANS (1500 lb F_N)
GATE - SMALL G. A. TURBINES (150 - 1000 SHP)
GAP - G. A. PROPELLER TECHNOLOGY

GOALS

REDUCED A/C PRICE AND OPERATING COST
REDUCED FUEL USE
LOW NOISE AND EMISSIONS

Figure 1. - LeRC general aviation programs.

FACILITY	ENGINE TYPE	INTAKE & COOLING	DYNAMOMETER, hp/rpm
SE-17	AIRCRAFT (4 & 6 CYL)	TEMPERATURE/HUMIDITY CONTROLLED	300/5000
SE-11	AUTOMOTIVE (CHEV. V-8 & ROTARY)	AMBIENT INTAKE WATER-COOLED	250/4500
SE-6	SINGLE-CYLINDER RESEARCH (DIESEL)	AMBIENT/HEATED INTAKE WATER-COOLED	125/5000

Figure 2. - General aviation reciprocating engine test facilities.

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

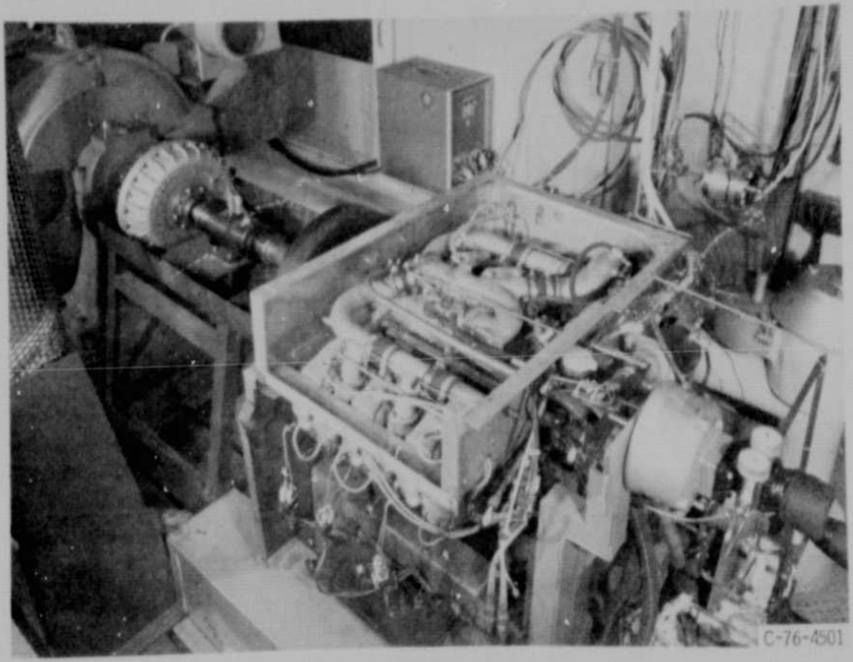

Figure 3(a). - View of aircraft engine test cell.

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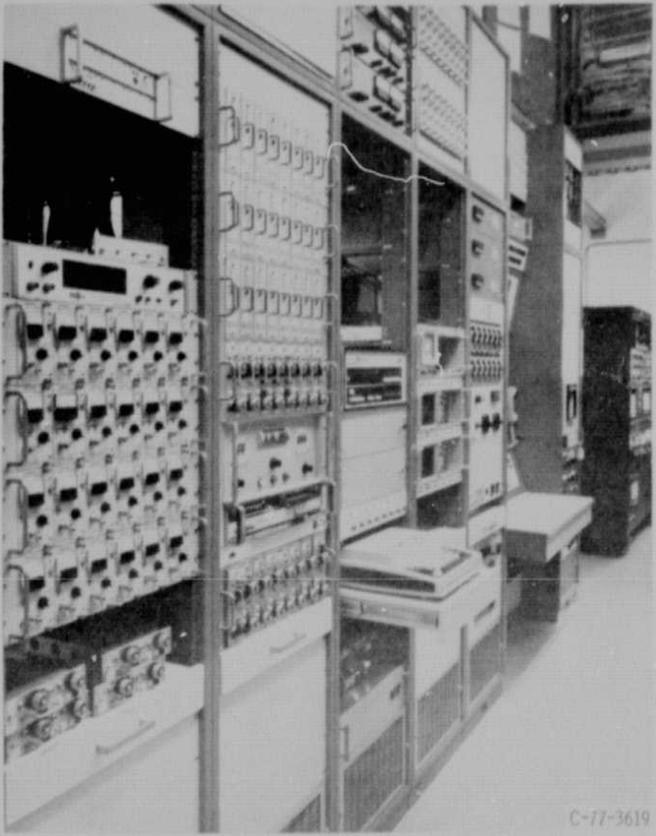

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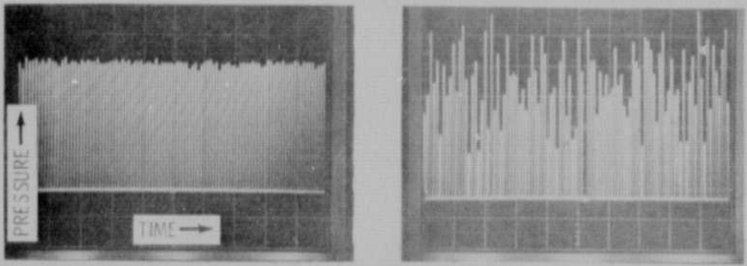
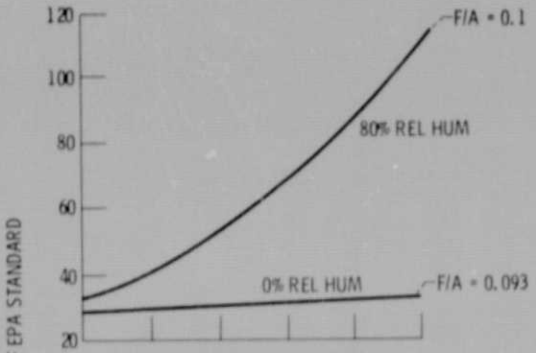
Figure 3(b). - View of control room.



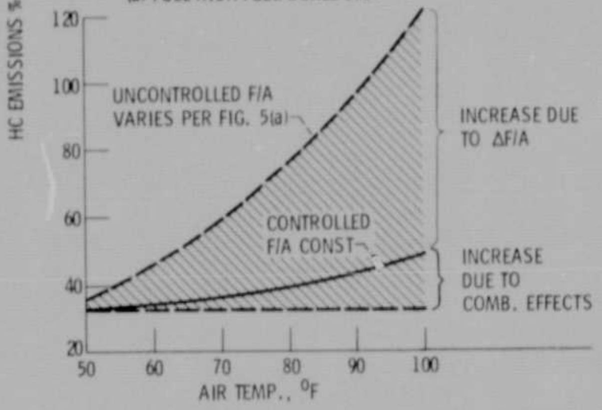
STOICHIOMETRIC

LEANED-OUT

Figure 4. - IMEP instrumentation - 100 cycle Barchart displays.



(a) FULL RICH FUEL SCHEDULE.



(b) EFFECT OF CONTROLLING FUEL/AIR RATIO TO CONSTANT VALUE AT 80% REL HUM.

Figure 5. - Taxi mode HC emissions.

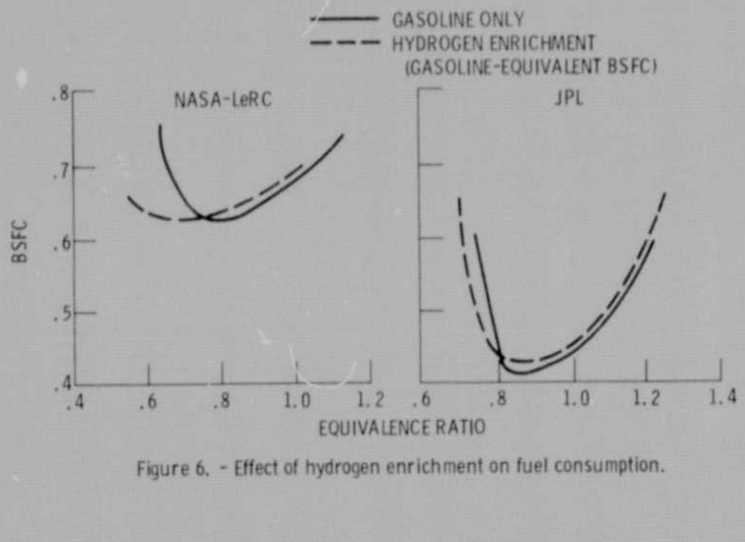


Figure 6. - Effect of hydrogen enrichment on fuel consumption.

CONVENTIONAL ENGINES

- JOINT NASA/FAA PROGRAM
- AVCO-LYCOMING CONTRACT
  - VARIABLE VALVE TIMING
  - ULTRASONIC FUEL VAPORIZATION
  - ADVANCED IGNITION CONCEPTS
- TCM CONTRACT
  - AIR INJECTION
  - PULSED FUEL INJECTION
  - IMPROVED COOLING COMB. CHAMBER
- CONTRACT
  - FUEL TOLERANCE TESTS
- IN-HOUSE
  - TEMPERATURE/HUMIDITY CORRELATION FOR EMISSIONS
  - LEAN OPERATION (HEI, FUEL INJECTION)

ADVANCED ENGINE CONCEPTS

- CONTRACT
  - LIGHTWEIGHT DIESEL CYLINDER (U. MICH)
  - LIGHTWEIGHT DIESEL DESIGN STUDY (TGPD)
  - ROTARY ENGINE (CUTRISS-WRIGHT)
  - STRATIFIED CHARGE ROTARY DESIGN STUDY
  - ADVANCED SPARK IGNITION ENGINE STUDIES
- IN-HOUSE
  - LIGHTWEIGHT DIESEL OR STRATIFIED-CHARGE ENGINE WITH SEMI-INDEPENDENT TURBOCHARGER
  - ROTARY ENGINE WITH SIMPLIFIED CHARGE STRATIFICATION SCHEMES
  - COOLING FINS STUDY FOR ADVANCED CYL. HEADS
  - CONTINUING OTTO PROGRAM DEVELOPMENT
  - CONTINUING DEVELOPMENT OF INSTRUMENTATION AND CELLS

Figure 7. - Current programs.

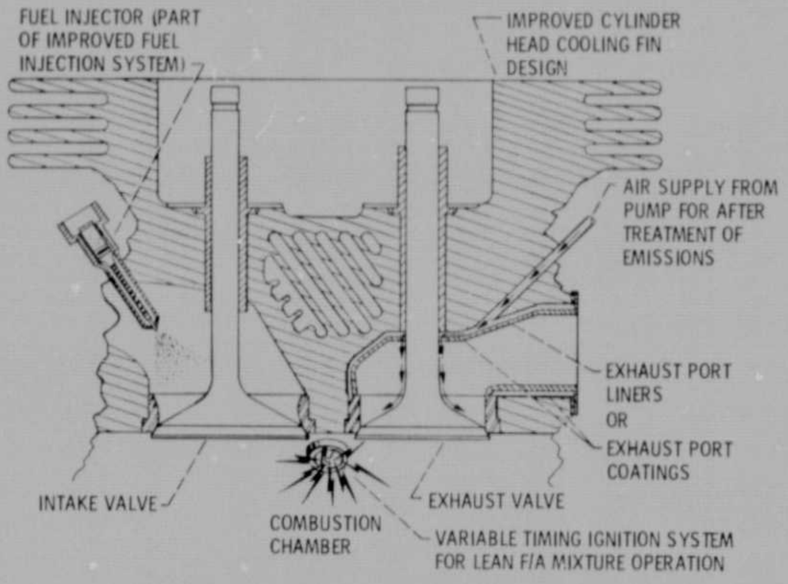
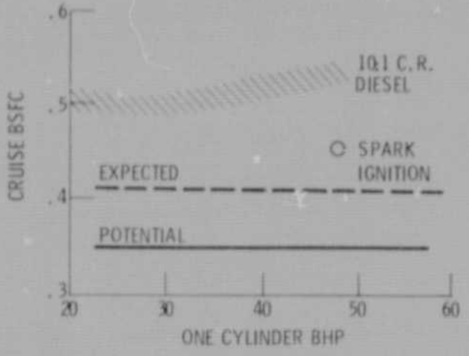


Figure 8. - Advanced cylinder head concept integration.



HIGH FUEL CONSUMPTION DUE TO:
- POOR FUEL ATOMIZATION AND DISTRIBUTION
- LOW TURBULENCE
- OVERCOOLING

Figure 9. - Initial test results on cylinder low compression ratio aircraft diesel at the University of Michigan.

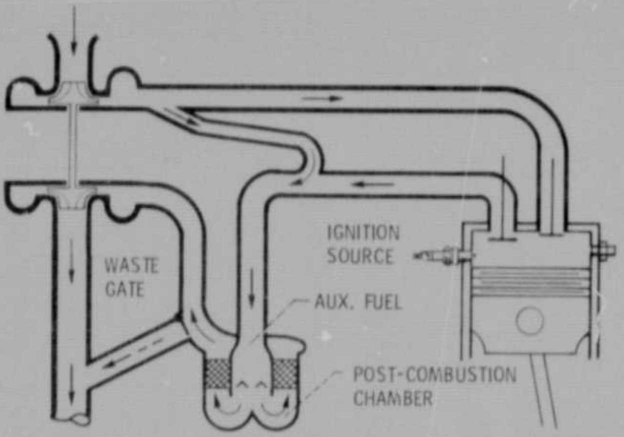


Figure 10. - Lightweight diesel or stratified-charge engine (semi-independent turbocharger).

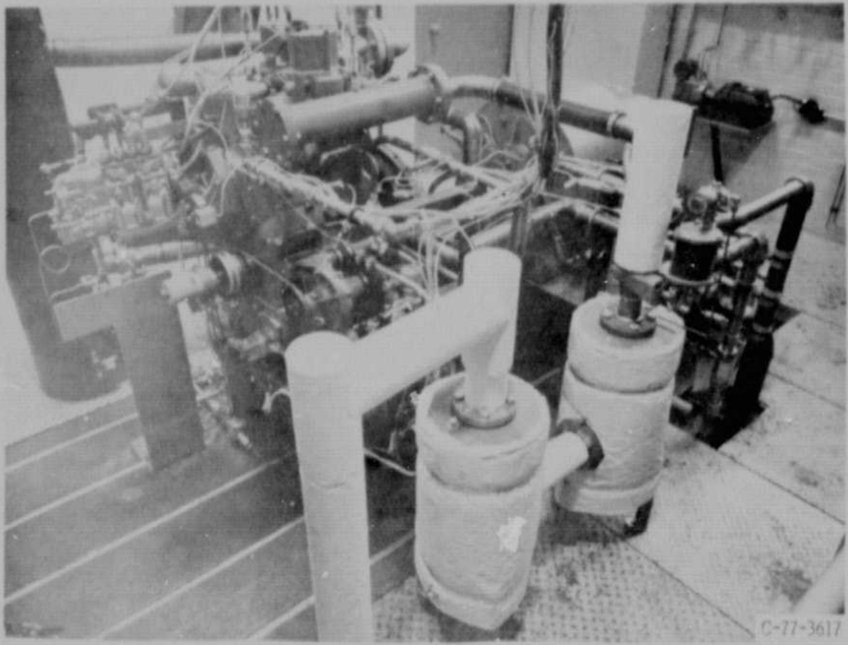


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Figure 11(a). - View of diesel engine test cell.

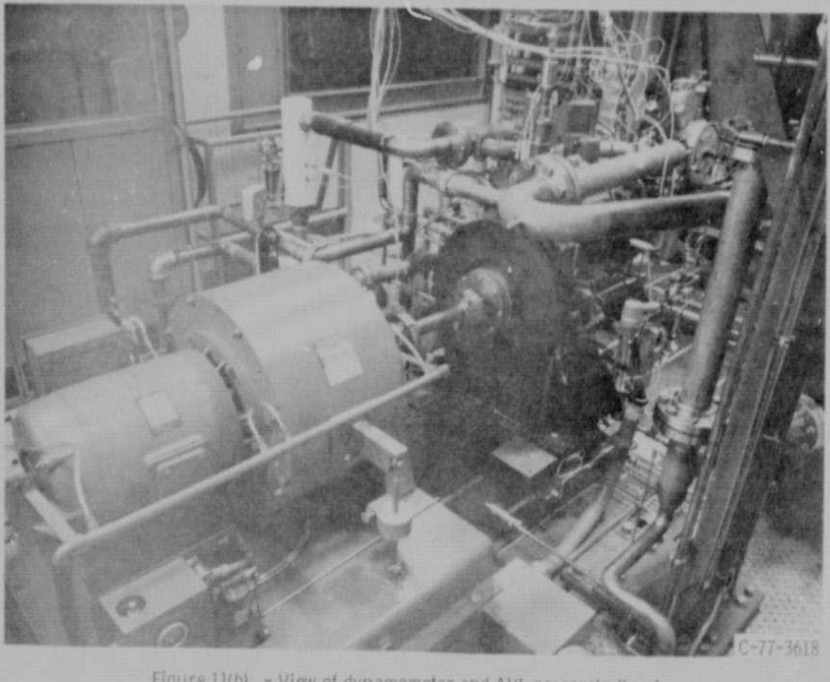

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Figure 11(b). - View of dynamometer and AVL research diesel.

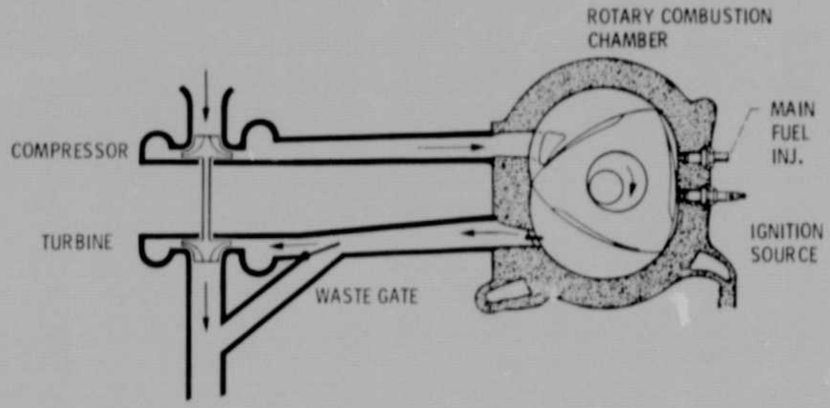


Figure 12. - Stratified charge rotary multi-fuel engine (conventional turbocharger).

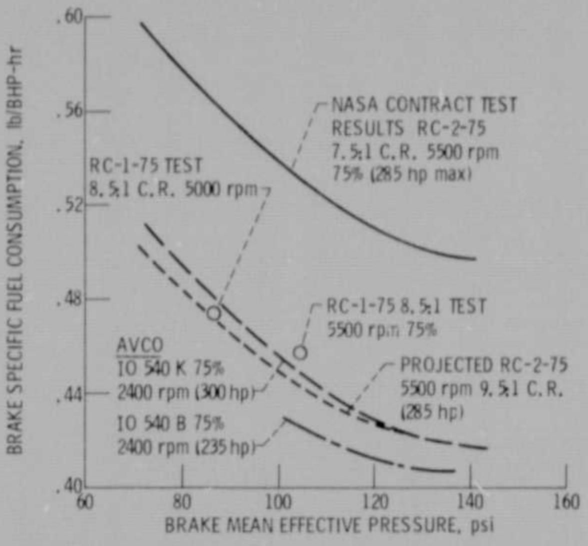
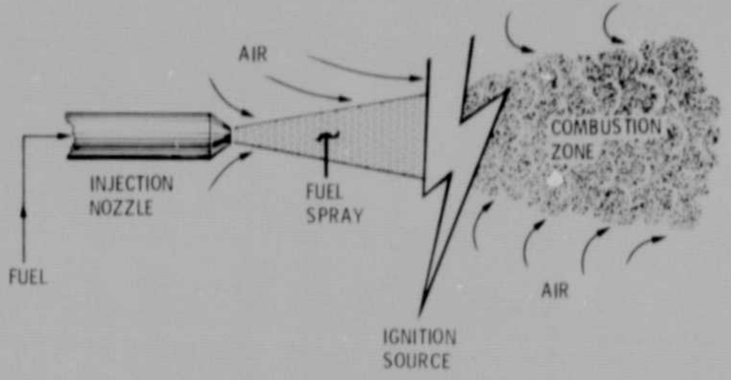


Figure 13. - Rotary engine fuel consumption trends.



INHERENT CHARACTERISTICS

- MULTIFUEL CAPABILITY
- LEAN OPERATION
- NO OCTANE/CETANE REQUIREMENT

Figure 14. - Stratified-charge principle.

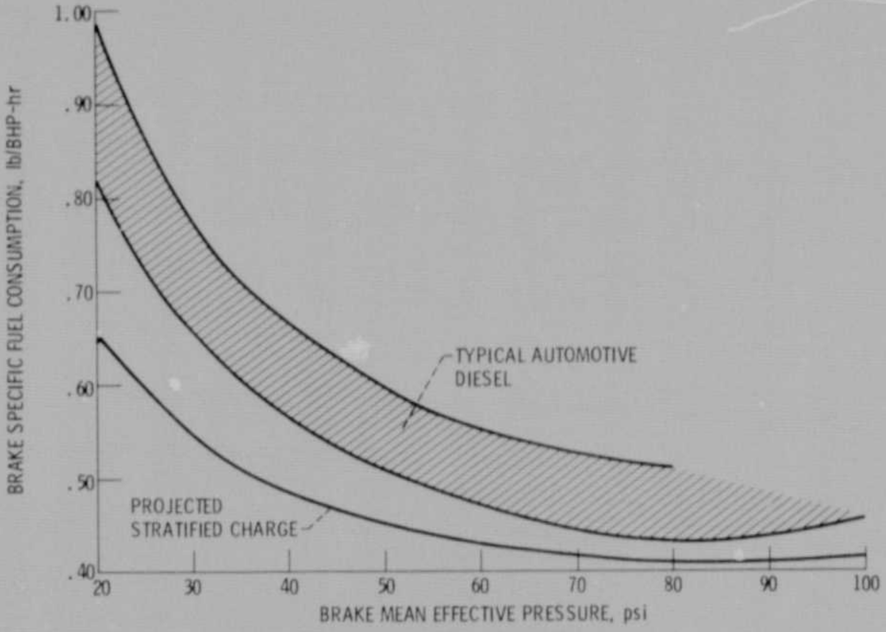


Figure 15. - Rotary engine fuel consumption trends.

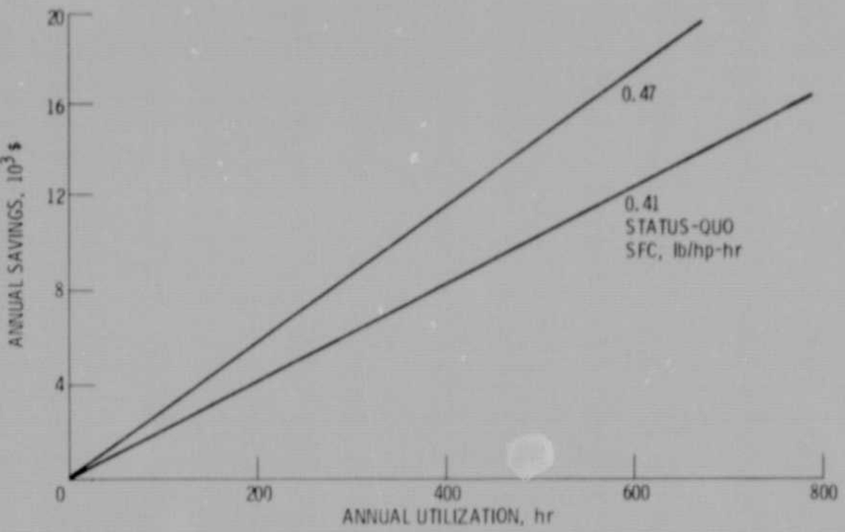


Figure 16. - Annual fuel cost savings due to advanced technology engine in 6-place business twin.

- POSSIBLE CONSTRAINTS ON FUEL AVAILABILITY/COST. USE FUELS THAT REFLECT AN "ENERGY EFFICIENT" PRODUCT SPLIT FROM AVAILABLE CRUDES AND OTHER RAW MATERIALS.
  - ALTERNATE FUELS OR MULTIFULE ENGINES VIA:
    - IMPROVED COOLING
    - IMPROVED FUEL AND IGNITION SYSTEMS
    - NOVEL COMBUSTION CHAMBERS
    - STRATIFIED-CHARGE OR DIESEL OPERATION
- USE LESS OF THOSE FUELS
  - REDUCED ENGINE SFC VIA
    - LEAN OPERATION
    - NOVEL ENGINE CYCLES
  - REDUCED COOLING & INSTALLATION DRAG VIA:
    - LOWER HEAT LOAD
    - IMPROVED AERO. INTEGRATION
    - COMPACT DESIGNS
  - LIGHTER-WEIGHT ENGINES
    - INCREASED SPECIFIC POWER
    - NOVEL STRUCTURAL CONCEPTS
    - ADVANCED MATERIALS
- AND, EXPECT BENEFITS IN TERMS OF
  - SAFETY
  - RELIABILITY
  - COST
  - ENVIRONMENTAL ACCEPTABILITY
  - DURABILITY
  - MAINTAINABILITY

Figure 17. - What does conservation mean to general aviation?