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**NASA TECHNICAL  
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NASA TM-78891

NASA TM-78891

(NASA-TM-78891) GENERAL AVIATION  
INTERNAL-COMBUSTION ENGINE RESEARCH PROGRAMS  
AT NASA-LEWIS RESEARCH CENTER (NASA) 23 p  
HC A02/MF A01 CSCL 21A

N78-24139

G3/07

Unclas  
16806

**GENERAL AVIATION INTERNAL-COMBUSTION ENGINE RESEARCH  
PROGRAMS AT NASA-LEWIS RESEARCH CENTER**

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TECHNICAL PAPER to be presented at the  
Fourteenth Propulsion Conference  
cosponsored by the American Institute of Aeronautics  
and Astronautics and the Society of Automotive Engineers  
Las Vegas, Nevada, July 25-27, 1978



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### Abstract

An update 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. Its three major thrusts are: (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 life cycle fuel costs are 30 to 50% lower than today's conventional engines.

### Introduction

Many believe that the world of flying is made up almost entirely of airlines and military aircraft with a sprinkling of light planes belonging to a privileged few. In reality, about three-fourths of the miles flown and a great majority of the aircraft in service today are involved with branches of flying known collectively as "general aviation." This includes not only private ownership for travel or sport but also air taxi and commuter operations, agricultural flying, prospecting and exploration, law enforcement, fire fighting, air ambulance, pilot training and many other vital tasks. These activities are carried out by about 230,000 aircraft of varied types in the Free World. More than 90% of these are U.S. made. In 1977, these airplanes provided transportation for over 100 million Americans and carried one-third of all intercity air passengers, while using only about 8% of all aviation fuel. They serve ALL of the nations 13,200 airports (compared to the airlines' 425), thus comprising not only an important and much needed public transportation mode but a vital link in American business operations as well.

Figure 1 illustrates some of these statistics. It also shows growth trends (as predicted by the FAA) to the year 1980, indicating an increasing general aviation share in such indices as numbers of airplanes, flight hours and fuel used. When viewed as economic performer, general aviation, as an industry during 1977:

- Provided jobs for over a quarter million Americans in the manufacture, sales and service of its products.
- Grossed about \$1.5 billion in new aircraft sales.
- Exported about 30% of its total production, contributing more than \$500 million to the U.S. balance of trade.

\* based on oil companies statements at the "First National Conference on Energy Conservation in General Aviation," Western Michigan University, Kalamazoo, MI, Oct. 10-11, 1977.

Based on the same growth trends, we would expect these figures to increase to 400,000 jobs, a \$2.3 billion gross and a \$750 million balance of trade contribution by 1988 (1977 dollars).

### Impact of the Energy Shortage

But while this important part of our economy has been growing steadily in the past, it is faced today with new problems and challenges for the future in such areas as environmental concerns and particularly the energy shortage. In brief, the time is fast approaching when world demand for oil will exceed the available supplies. An extensive study on oil supply and demand, supported by the 15 major oil producing or consuming countries in the Free World, has very recently been summarized in the literature<sup>1</sup>. The excerpt shown as Figure 2 compares demand (the thick line) with supplies expected to be available, for several economic and political scenarios. A chronic and progressively worsening shortage (demand > supply) could appear as early as 1981 or as late as 1997; but in any case it is inevitable. This doesn't necessarily mean that avgas or other specific products will become instantly or completely unavailable when a "day of reckoning" arrives. Certain consequences however are inescapable (see figure 3).

- Higher prices due to increased economic competition for the remaining supplies.
- Fuel conservation measures will increasingly be expected from all user groups; in some cases there will be statutory requirements.
- Broad-specification fuels will become prominent. The oil industry will be urged to extract only the most energy-efficient selection of products out of each barrel of crude. For the transportation sector, this implies a greatly increased emphasis on broad-specification gasoline-type and diesel-type fuels, in proportions designed to minimize overall energy consumption.

Availability is potentially a serious problem for the piston-engine segment of the general aviation fleet, because these engines reflect WW II technology and require very specific grades of gasoline. As pointed out above, specialized, low-volume fuels may someday become unavailable, or available only at unreasonable prices. It should be noted that avgas has already increased from about 40 cents to 80 cents a gallon since 1973, and is expected to reach the level of about \$1.50/gallon\* even before the chronic shortage occurs. For comparison, a broad-cut diesel type fuel would be expected to be at least 10% cheaper or about \$1.35 per gallon. In terms of \$/BTU, diesel fuel is about 20% cheaper than avgas. Clearly, there is a strong economic incentive to take advantage of this type of fuel.

## The LeRC Internal Combustion Engine Program

With this background, the LeRC General Aviation Branch's current program has been designed to create a technology base which could be used by industry to enable light planes to burn as little as possible of the cheapest and most readily available fuels of the future. The present program encompasses modest in-house and contracted efforts to improve the fuel economy, fuel tolerance, and emissions characteristics of both present and next generation engines. A proposed program augmentation to extend and intensify these efforts is under consideration in order to produce more timely results.

Specifically, the long-term objective is to lay the technology base for an efficient, reasonably-priced multifuel or broad-specifications fuel engine whose fuels costs (based on current prices) would be 30 to 50% less than present-day engines, and which would also meet previously legislated EPA emissions levels. It is anticipated that about half of the fuel economy improvement will come from reduced SFC's and the rest from the ability to use cheaper fuels. Assuming substantial and increasing follow-on participation by industry, the expected outcome would be efficient, reasonably-priced multifuel engines that can use the cheapest fuel available. Using these goals, a program to upgrade the piston-engine fleet could commence at about the time the chronic oil shortage is most likely to arrive. Figure 4 suggests a possible schedule of events.

General aviation airplanes last for many years and are produced at relatively low rates. This means that the benefits of use of any next-generation multi-fuel engine, although valuable to the individual owner or operator, would require a period of years to noticeably impact the overall fleet. Hence the program also includes technology for current-production type engines as well as the longer-term prospects. The goal for this nearer-term technology is to reduce SFC's by 10% from current performance and meet the previously legislated EPA emission levels, while burning non-premium gasoline. We would prefer, however, to leave any detailed discussion of near-term developments to the respective engine companies. This discussion will primarily address the longer-term prospects -- 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 5 indicates the capabilities and leading features of the currently-operational cells. Figure 6(a) is a view inside the aircraft engine test cell, with the engine (a TCM TSI0-360) 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 6(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 7 which illustrates in bar-chart format, the IMEP measured for 100 successive cycles of one cylinder on a Chevrolet automotive engine for convenience in testing. 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. At right, the engine was 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 possible 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 data taking can be an order of magnitude more productive than a conventional test 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<sup>2</sup>; effect of temperature, humidity and lean operation on fuel economy, emissions and cooling requirements<sup>3</sup>; hydrogen enrichment of fuel<sup>4</sup>; and theoretical analyses of cooling fins<sup>5</sup>. Also, progress has been made toward the development of advanced analytical tools such as an Otto Cycle performance and emissions prediction computer code<sup>6</sup>.

The results from these efforts 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 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 8(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 8(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, would improve both fuel economy and emissions.

The hydrogen injection program is another case in point. In both our own programs<sup>4</sup> and a parallel JPL effort<sup>7</sup>, 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 9, 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. 10) 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 using gasoline 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 foreseen 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 possibly enable the engine to burn lower octane fuel. Figure 11 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 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 improved combustion

geometries coupled with vapor-phase or other fuel injection schemes, 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 those 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 University of Michigan<sup>8</sup> of a dieselized aircraft cylinder mounted on a single-cylinder crank-case showed unexpectedly high SFC due to poor combustion (Fig. 12). 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 comparatively high combustion volume with associated cooling losses. The latter normally has a high turbulence design with a compact combustion volume intended to keep the heat in. The work however is being continued to improve the combustion process to reach the indicated BSFC level of about 0.42.

Figure 13 illustrates a turbocharged diesel concept in which an auxiliary combustor fed by a 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. A similar concept has been under study and development for some time by the Hyperbar Diesel Co. in France. The French results<sup>9</sup> indicated that SFC's at least as low as 0.38 can be obtained at cruise type 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 (Fig. 14) is presently being checked out and should be operating productively by mid-1978.

**Rotary Engines** - The rotary or Wankel engine (Fig. 15) 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 with foreign companies are being considered<sup>10</sup> to establish a favorable production-volume basis. Unconfirmed reports<sup>11</sup> also suggest that General Motors may 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 16 illustrates results obtained last year in testing a Curtiss-Wright RC-2-75 engine under a NASA contract<sup>12</sup>. Its best SFC of about 0.54 might be good enough for an automotive application, but it 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. Its specific weight of about 1.25 lbs/hp is most attractive. It should be noted that the rotary, because of its different combustion chamber geometry, 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 16, a 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<sup>11</sup> 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 17 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 turbcharged 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<sup>12, 13, 14</sup> indicates that the technology is now at hand to develop a multifuel stratified charge rotary whose SFC, as projected in Figure 18, 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 of 0.38 to .040.

#### Economic Impact

The discussion thus far has only concerned technology, but several other considerations are also 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 definitely 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 an example to support my view.

The example concerns a hypothetical high-performance general aviation business twin. Appendix A outlines some admittedly crude, success-oriented and over-simplified calculations to compare a status-quo engine and a stratified-charge rotary 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 for ca. 1985. On this basis, the annual fuel bill for 600 hours utilization would range from about \$36,000 to \$35,000.

For the stratified-charge rotary, we chose the 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 \$10,900 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 19. 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 1-1/2 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 major respects from current practice. 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 must conduct 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?

Appendix B contains some highly simplified estimates on the economic impact of a fleet-wide upgrading program based on the anticipated levels of lightweight diesel technology. The results should be interpreted in an order-of-magnitude sense only, but also lead to some interesting conclusions:

- \* By the latter 1980's, the status-quo fleet is projected to consume avgas at the rate of about 1 billion gallons/year, at a cost of about \$1.5 billion/year and while using up about  $112 \times 10^{12}$  BTU of energy/year.
- \* Gradual introduction of next-generation engines meeting our goals could result in a savings of over \$7 billion in fuel costs alone, after 5 years of R. & D. followed by a 20-year upgrade program.
- \* The upgraded fleet would also satisfy the strictest emission levels that had been seriously proposed for light airplanes.
- \* The economic benefits justify substantial investments; e.g., a \$300 million capital outlay could be "paid back" in the sixth year of production and (with accumulated interest) would thereafter generate a \$13 billion benefit to society, by the end of the upgrade program. This is a 43/1 ROI over 25 years which averages 173%/year. Figure 20 compares the economic performance of the upgrade program with conventional investments, e.g., compound interest at 5% and 10%/year. The crossovers indicate that an investment as large as \$0.5-1.0 billion may be justifiable. The upper curve indicates the year in which the initial R&D investment, including interest charged at 10% is fully repaid. Thereafter, the annual savings accumulate interest at the same rate and rapidly mount to the final values shown. For example, even if the required capital investment were as high as \$1 billion, the program could break even in the 14th year of production and still generate an ultimate benefit of \$5.4 billion by the end of the program. This averages about 22%/year ROI which is better than some conventional investments.

In addition to this calculated direct benefit, there is the question of impact upon the U.S. balance of trade position. The domestic G/A industry is currently earning about a \$0.5 billion favorable balance of payments and, as mentioned

before, this is expected to increase substantially in the future. The upgrade program should help to preserve this valuable asset against likely foreign competition. The attractively-priced Polish PZL engines are now available in this country as well as in Europe. The German firm of Rhein-Flugzeugbau has developed an aircraft conversion of the Audi-NSU model KKM-871 automotive rotary engine. This has been successfully tested in the experimental "Fanliner" airplane, and serious marketing efforts can be expected if Audi-NSU commits the KKM-871 to full scale automotive production. There are also reports that Citroën and Comotor in Europe are developing rotary aircraft engines.

#### 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 figure 21. 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 A - SIMPLIFIED ESTIMATE OF ANNUAL FUEL COST SAVINGS

DUE TO ADVANCED ENGINES (ANTICIPATED 1985 FUEL PRICES)

Baseline Airplane

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

Utilization

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 cents/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 @ \$1.35 gal or 17.9 cents/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 l/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.

\* Includes 25 hp loss due to drag of conventional cooling systems,

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

APPENDIX B

ECONOMIC BENEFITS OF UPGRADING THE

PISTON-ENGINE G/A FLEET

Suppose that our technology programs are successful and the resulting engines are used to upgrade the fleet at the rate of 5% per year (20-year upgrade program). What are the economic implications of such activities? A gross estimate is given below.

It has been projected that by 1980, the G/A fleet will be consuming fuel at the rate of about 2400 x 10^6 gal./year, of which about 1000 x 10^6 gal. is avgas for piston engine planes. In any one year of the 20 year upgrade program, the 5% status-quo airplanes scheduled for replacement would have consumed 50 x 10^6 gal. or 302 x 10^6 lbs. of avgas. This is worth \$75 x 10^6 at the then anticipated price of \$1.50/gal, and represents about 5.6 x 10^12 BTU of energy. At a representative SFC of 0.44 lbs. hp-hr, the effort expended is 687 x 10^6 hp-hours.

For simplicity, assume that the advanced engine is a lightweight diesel that weighs the same as status-quo engines, but has a SFC of 0.35 lbs./hp-hr. and a cooling drag that is only half as much as the conventional engine's. (For comparison, the 3000 HP Napier "Nomad" engine, built and tested in England during the 1940's, demonstrated a BSFC of 0.33-0.35 lbs./hp-hr over its useful operating range and weighed about 1.1 lbs/bhp. Modern diesel technology offers BSFC's significantly less than 0.30 lbs/bhp-hr together with a major reduction in cooling heat load.) As cooling drag represents roughly 10% of cruise thrust hp for most present airplanes, the diesel powered upgraded airplanes would only need to supply 0.95 x 687 x 10^6 or 652 x 10^6 hp-hrs. for the year. At the diesel's SFC of 0.35, this translates to 228 x 10^6 lbs. or about 30 x 10^6 gal. of diesel fuel (density = 7.544 lbs./gal.). At \$1.35/gal., this is worth about \$41 x 10^6, a savings of about \$34 x 10^6 per year.

That is, in the first year the upgraded 5% of the fleet will in effect "earn" \$34 x 10^6 for its owners. The second year the upgraded 10% "earns" \$68 x 10^6. The third year the upgraded 15% earn \$102 x 10^6, and by now the cumulative saving is \$204 x 10^6, i.e. \$(34 + 68 + 102) x 10^6. By the end of the 20-year upgrade program, this process has accumulated a total benefit of \$(1 + 2 + 3 + ..... + 19 + 20) x 34 x 10^6 or \$7.14 x 10^9, as was illustrated in figure 5.

The magnitude of this potential benefit would appear to warrant a sizeable investment of capital to finance the R&D, design work, certification programs, re-tooling, and other activities needed to make it happen. It is difficult today to estimate how large an investment might actually be required. It is possible, however, to estimate, in a gross sense, how large of an investment might be economically justifiable.

Consider the following, highly simplified economic model. The overall program is to consist of a 5-year R&D effort to define and tool up for a

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comprehensive family of new-generation engines. It is recognized that the costs and benefits must be apportioned so that the program represents an attractive investment to the financial, manufacturing and user groups concerned. But for simplicity, it is treated here as a single trust fund, the ultimate proceeds of which must be divided between various interests. The entire capital investment is to be in place at the beginning of the R&D period and is assumed to be committed immediately. During the initial 5-year R&D period there is no return on this investment; interest accumulates until the entire debt is retired. In the first year of production (6th program year) the entire savings from the first upgraded 5% of the fleet is applied against the debt. In succeeding years the savings from the by then-upgraded portion of the fleet is similarly applied, before interest is charged. Eventually the entire debt is thus repaid. The time at which this occurs will be termed the breakeven year. Thereafter, the account, which now represents a net savings to society, is credited with interest instead of being charged.

Table 1 summarizes these calculations for a sample case in which the initial investment is \$300M and interest at 10% (compounded annually) is charged against the unpaid balance or added to the accumulated net savings. As may be seen, the debt increases initially but is retired after 10.7 years. Thereafter the savings mount rapidly to \$1.3 Billion as shown. (For reference, the same \$300M, invested conventionally at 10% compounded annually, would increase to \$3.25 Billion after 25 years.)

The results of these and similar calculation for smaller and larger investments were already presented in Figure 20. The net savings and break-even years are shown as functions of the initial investment, assuming interest payments or credits at 10% compounded annually. The three curves shown on the "savings" chart compare the economic performance of the G/A upgrade program with that of a conventional investment (0.5% and 10%) as described above. The G/A program pay-off, of course, declines as the initial investment increases in size, while the pay-off from an equal-sized conventional investment is simply proportional to the original amount. The crossover suggests that about \$750M initial investment is the largest that could be considered economically attractive if conventional investments at 10% were also available.

TABLE 1 - SAMPLE CALCULATION OF ECONOMIC BENEFIT

Program Year	Amount Owed/Saved Incl. Interest \$M	Fuel Cost Savings \$M	Years-end Balance before Interest \$M
0	- 300		(initial investment)
1	- 330		
2	- 363		
3	- 399		
4	- 439		
5	- 483		
6	- 494	34.35	- 449
7	- 468	60.7	- 425
8	- 400	103.7	- 364
9	- 289	137.4	- 263
10	- 129	172	- 117
10.7	0		Break-Even Year
11	+ 85	206	+ 77
12	+ 358	240	+ 325
13	+ 696	275	+ 633
14	1105	309	1005
15	1594	344	1449
16	2169	378	1972
17	2839	412	2581
18	3614	447	3286
19	4505	481	4095
20	5522	515	5020
21	6680	550	6070
22	7990	583	7260
23	+ 9460	618	+ 8610
24	+11130	653	+10120
25	+13000	687	+11820

(\$13 billion)

#### ASSUMPTIONS

##### 1. Economic

- Trust Fund Model
- Savings applied to balance before interest is figured.
- Interest @ 10%, compounded annually, begins immediately.
- \$300M initial investment is committed immediately.

##### 2. Engines

- Status-quo engines use avgas @ 0.44 lbs/hp-hr.
- Diesel engine weighs same as status-quo but uses diesel fuel @ 0.35 lbs/hp-hr, and has half the cooling drag.

##### 3. Fuels

- Avgas: \$1.50/gal; 6.014 lbs/gal; 18600 Btu/lb.
- Diesel: \$1.35/gal; 7.544 lbs/gal; 18600 Btu/lb.

## REFERENCES

1. Flower, A. R.: "World Oil Production." Scientific American, Vol. 238, No. 3, March 1978. Note: Figure 2 excerpted from Ref. 1, Copyright 1978 by Scientific American, Inc. All rights reserved.
2. Anon: "Aircraft Piston Engine Exhaust Emissions Symposium, Lewis Research Center, September 14-15, 1976". NASA CP-2005.
3. Meng, P. R.; Cosgrove, D.; Skorobatchyi, M.; and Kempke, E. E.: "Performance and Emissions of an AVCO-Lycoming U-320-DIAD Air-Cooled Light Aircraft Engine". NASA TMX-73500, August 1976.
4. Cassidy, J. F.: "Emissions and Total Energy Consumption of a Multicylinder Piston Engine Running on Gasoline and a Hydrogen Gasoline Mixture". NASA TND-8487, May 1977.
5. Siegel, R. and Graham, R. W.: "Effect of Finned Passage Length on Optimization of Cylinder Head Cooling Fins". NASA TP-1054, in press.
6. Zeleznik, F. J. and McBride, B. J.: "Modeling the Complete Otto Cycle-Preliminary Version". SAE Paper 770191, March 1977.
7. Chirivella, J. E.; Duke, L. A.; and Menard, W. A.: "High Fuel Economy in an Aircraft Piston Engine When Operating Ultralean". SAE Paper 770488, April 1977.
8. Kroeger, R. A.; Bottrell, M. S.; Gaynor, T. L.; and Bachle, C. F.: "Lightweight Low Compression Aircraft Diesel Engine". University of Michigan/NASA final report in progress.
9. Melchior, J. and Andre-Talamon, T.: "Hyperbar System of High Supercharging". SAE Paper 740723, 1974.
10. Anon: "Toyo Kogyo & Audi NSU Discuss Production Sharing". The Japan Economic Journal, November 1, 1977.
11. Anon: "Toyota Unveils Stratified-Charge Rotary, Car It Could Power Audi, Toyo Kogyo Share Wankel Parts, Technology". Gordon Reports & Auto World, Volume XIII, No. 21, November 25, 1977.
12. Berkowitz, M.; Hermes, W. L.; Mount, R. E.; and Meyers, D.: "Performance, Emissions and Physical Characteristics of a Rotating Combustion Aircraft Engine", Curtiss-Wright/NASA CR-135119, December 1976.
13. Jones, C.; Lamping, H. D.; Mount, R. E.; and Meyers, D. M.: "An Update of the Direct-Injected Stratified Charge Rotary Combustion Engine Developments at Curtiss-Wright". SAE Paper 770044, 1977.
14. Bracco, F. V.: "Theoretical Analysis of Stratified, Two-Phase Wankel Engine Combustion", Combustion and Science Technology, Vol. 8, No. 1-2, September/October 1973, pp. 69-84.
15. Reitz, R. D. and Bracco, F. V.: "Studies Toward Optimal Charge Stratification in a Rotary Engine", Combustion Science and Technology, Vol. 12, No. 1-3, Jan. 1976, pp. 63-74.
16. Sammons, H. and Chatterton, E.: "Napier Nomad Aircraft Engine" SAE J Vol. 63, 1955, pp. 107-131.
17. Kamo, R. and Bryzik, W.: "Adiabatic Turbocompound Engine Performance Prediction." SAE Paper No. 780068, 1978.

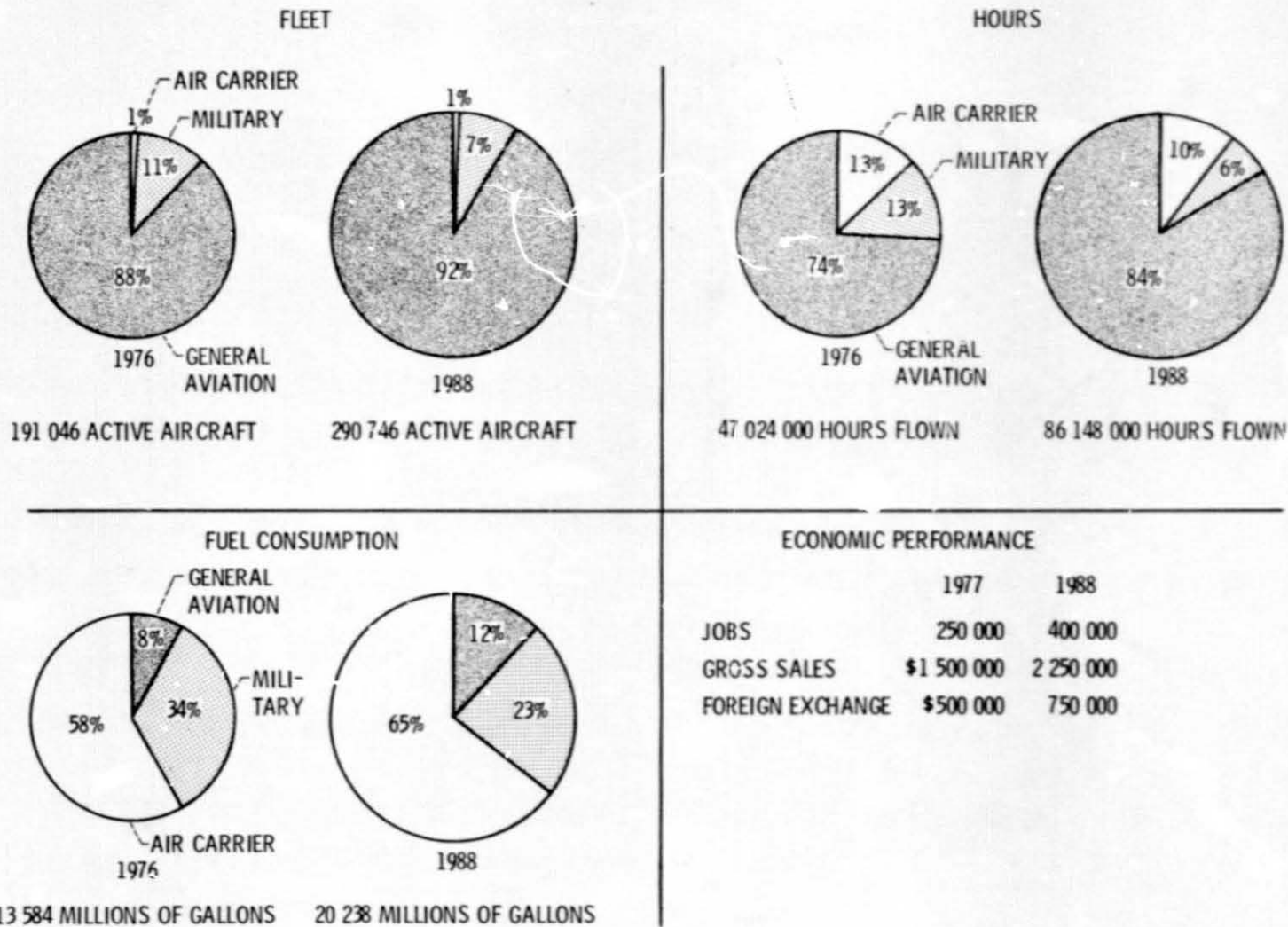
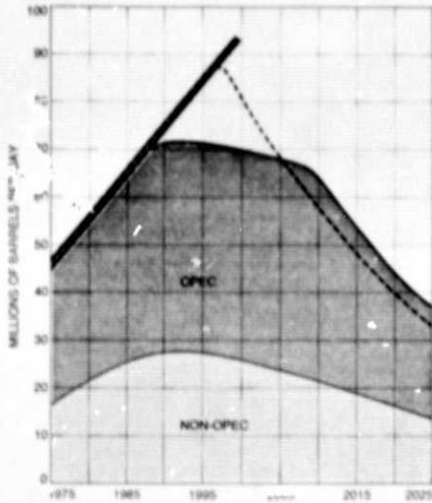
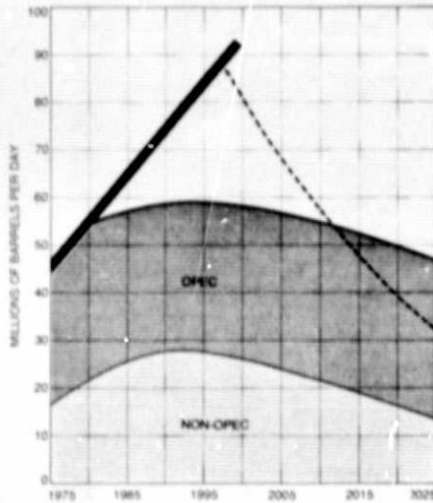


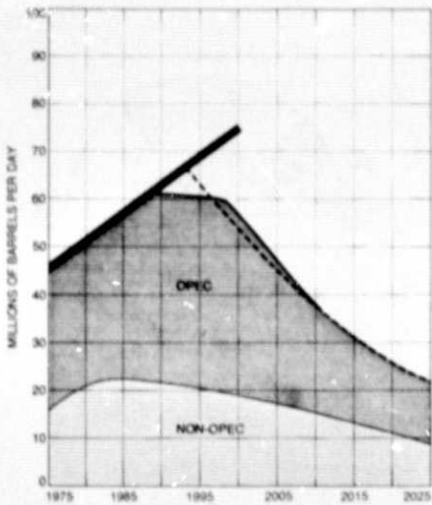
Figure 1. - Some general aviation statistics and forecasts.



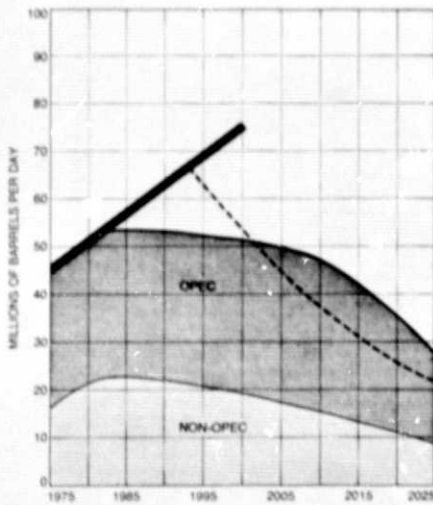
**MORE REALISTIC PROFILES** take into account government limits. These curves are for the high-growth, high-price scenario and a high rate of additions to reserves. Here non-OPEC production is shown combined with OPEC production that is limited to 45 million barrels per day (left) and to 33 million barrels per day (right) to give



total production in the non-Communist areas of the world (heavy colored line). In both cases a comparison with the unconstrained total (broken colored line) shows that the imposition of government limits would cut supply below demand (gap line) sooner (as early as 1981) but that the subsequent fall in oil supply would be less precipitate.



**REALISTIC PROFILE** for the low-growth, constant-price scenario and a low rate of additions to reserves shows similar effects. With OPEC production limited to 40 million barrels per day (left) or to 33



million barrels per day (right), production fails to meet demand sooner than in the unconstrained case, but later production of reserves that have been conserved keeps supply fairly steady for some time.

Figure 2. - Excerpt from March, 1978 Scientific American; A. R. Flower, "World Oil Production."

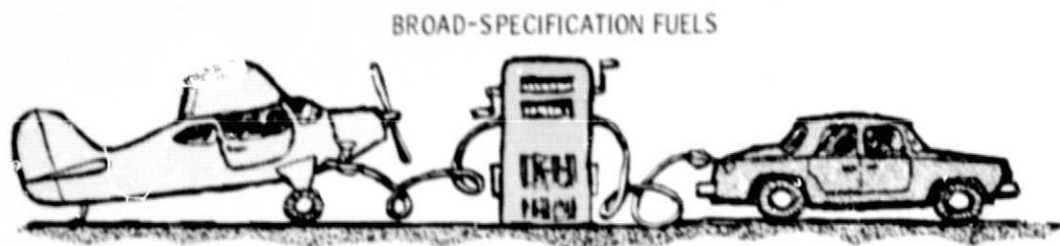
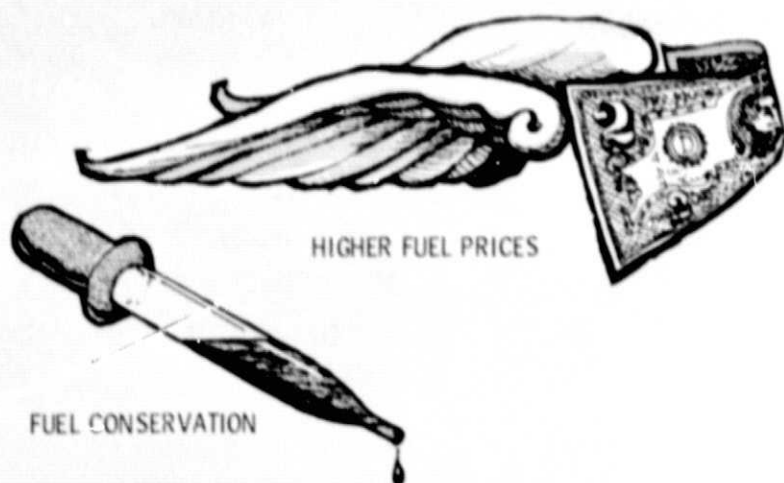


Figure 3. - Consequences of the oil shortage.

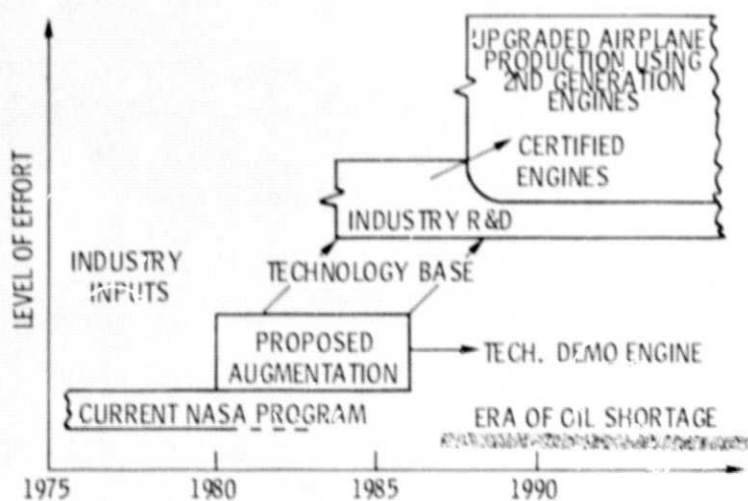


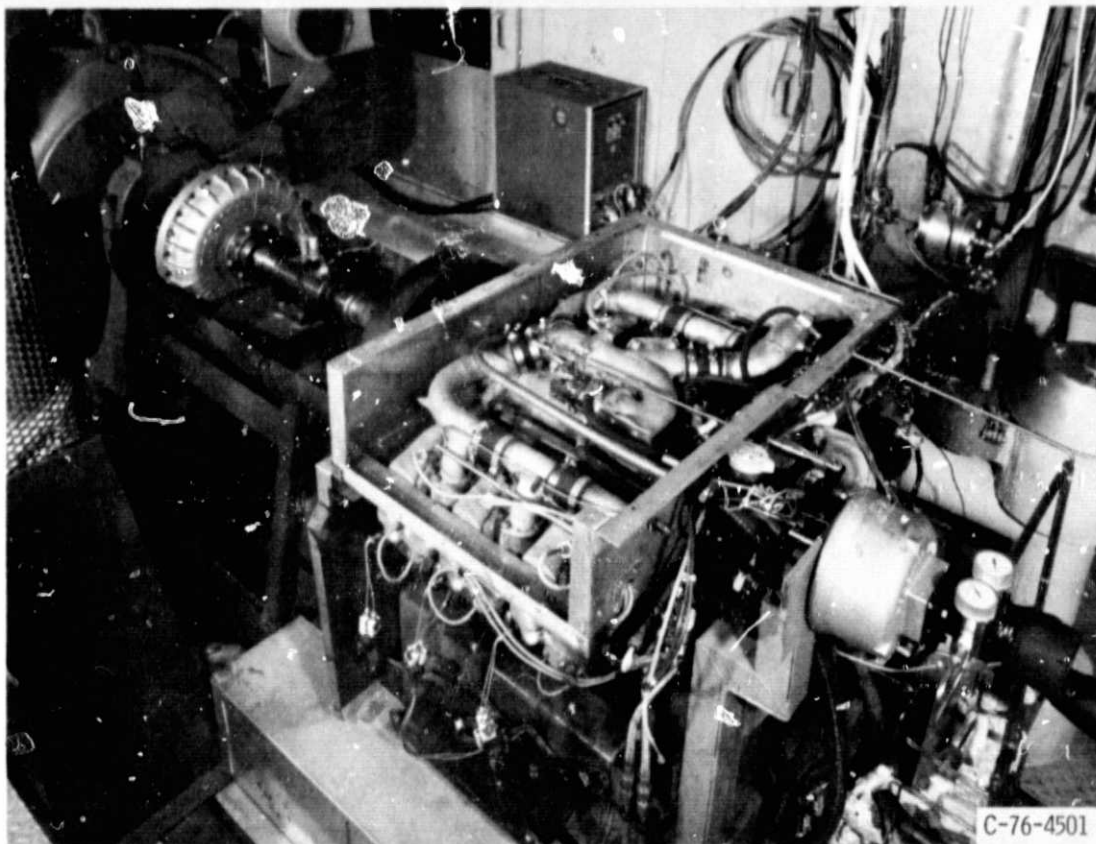
Figure 4. - Steps in the upgrading process.

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

Figure 5. - General aviation reciprocating engine test facilities.

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Figure 6(a). - View of aircraft engine test cell.



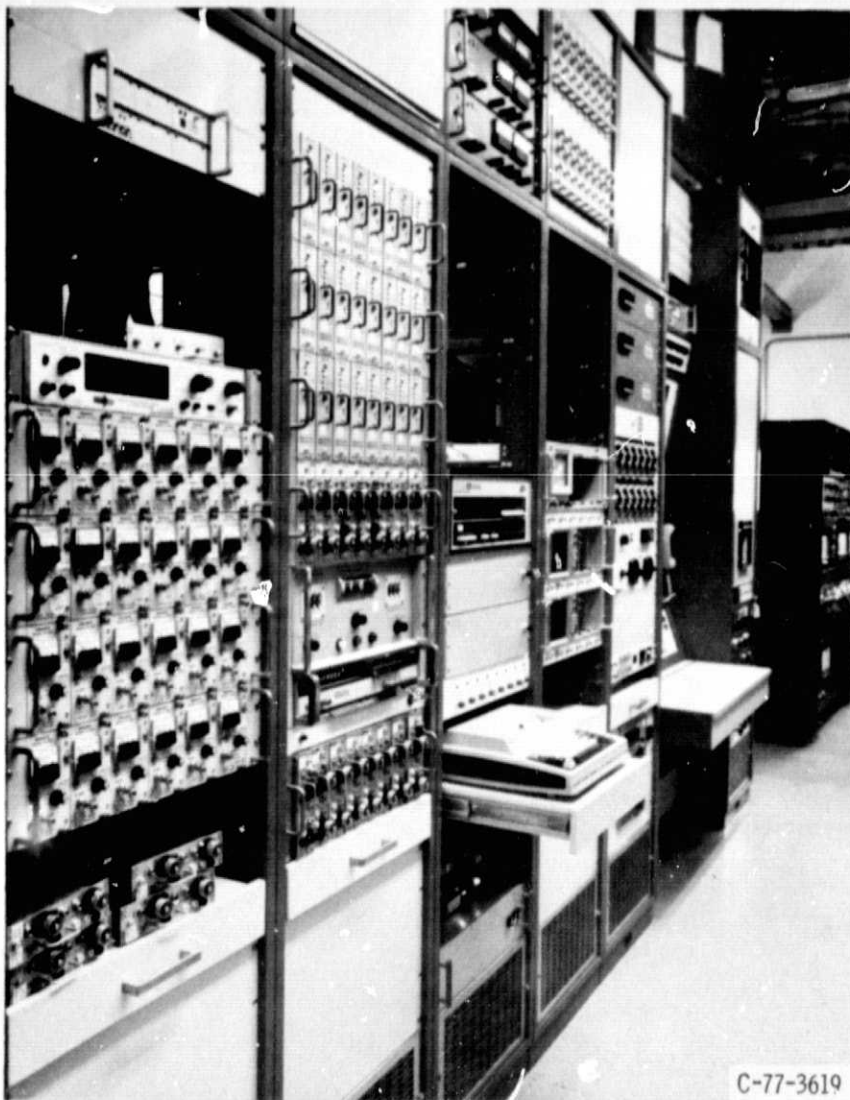
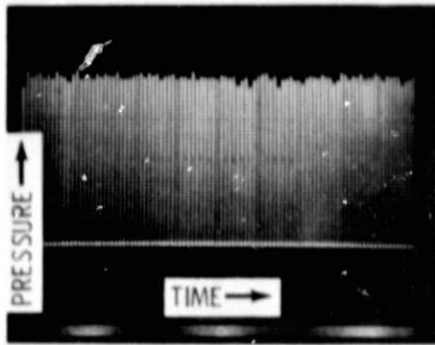


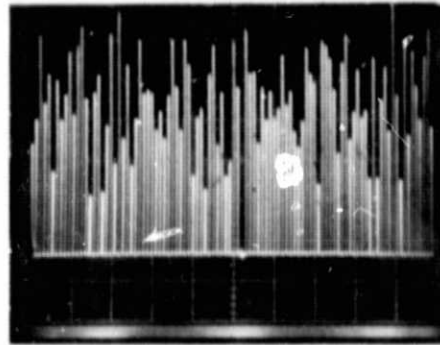
Figure 6(b). - View of control room.

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Figure 7. - IMEP Instrumentation - 100 cycle Barchart displays.

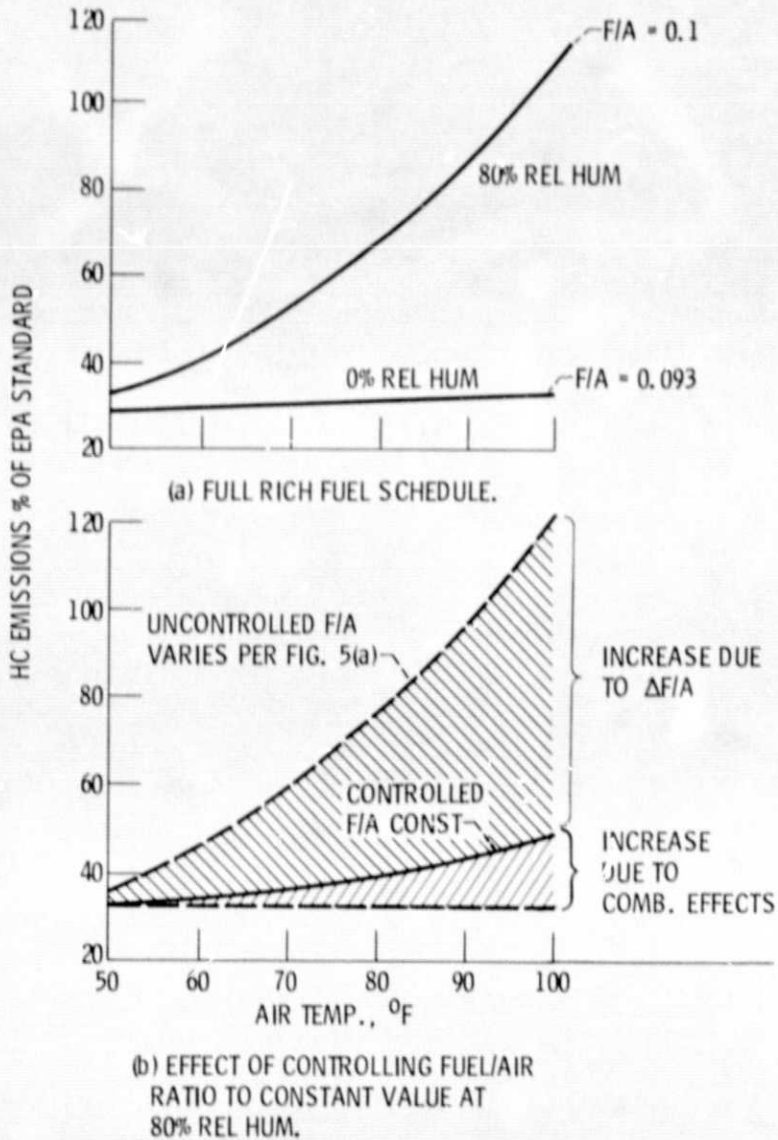


Figure 8. - Taxi mode HC emissions.

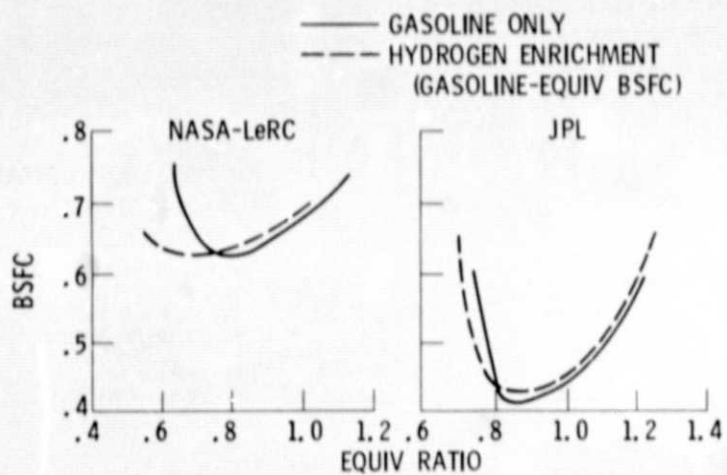


Figure 9. - Effect of hydrogen enrichment on fuel consumption.

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 (TGD)
  - 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 10. - Current programs.

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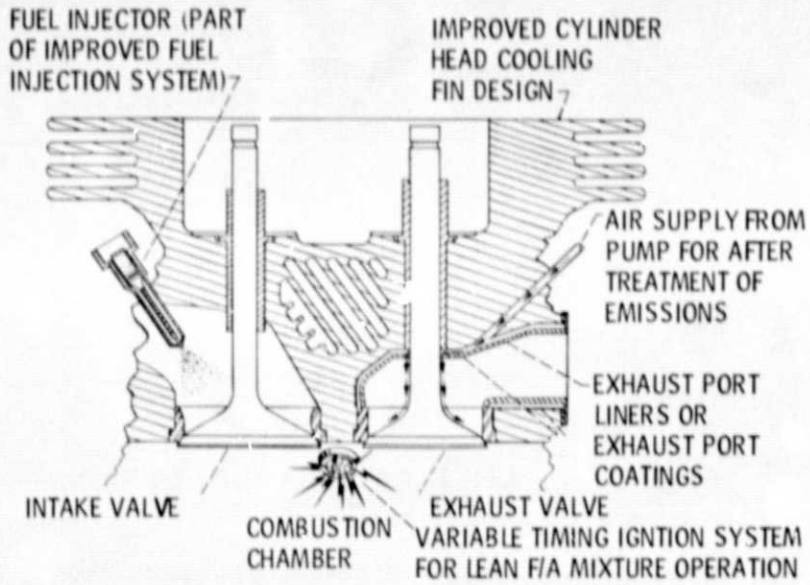


Figure 11. - Advanced cylinder head concept integration.

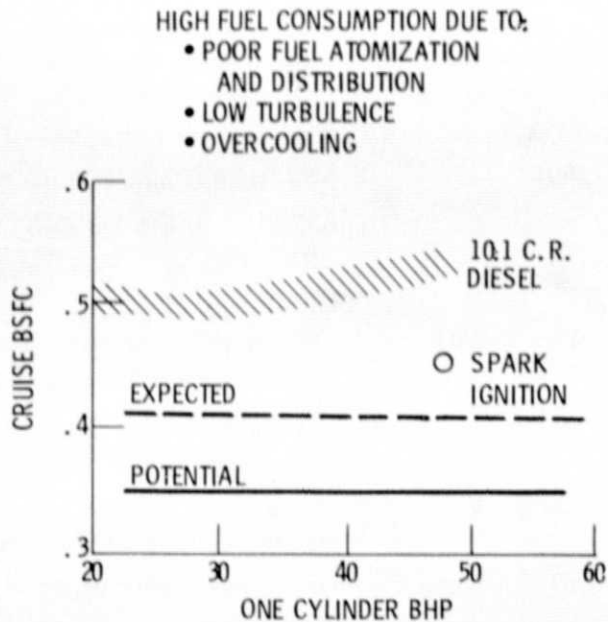


Figure 12. - Initial test results on cylinder low compression ratio aircraft diesel at the University of Michigan.

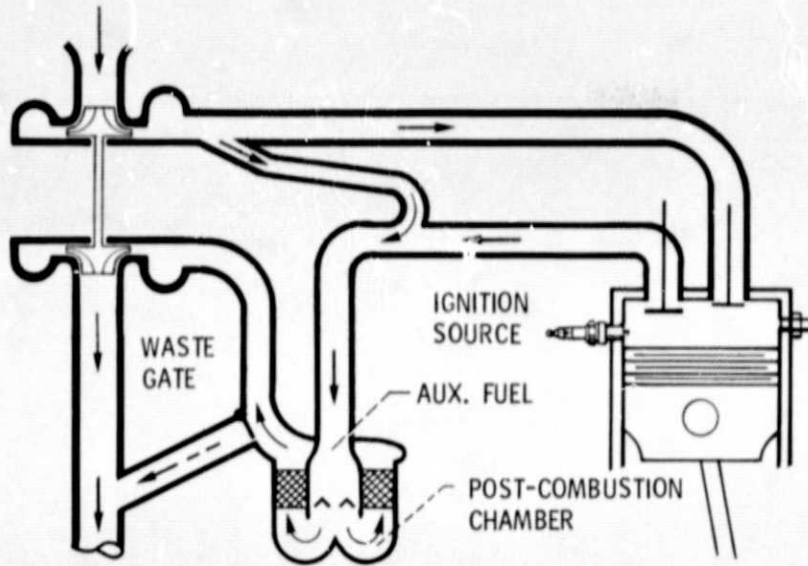
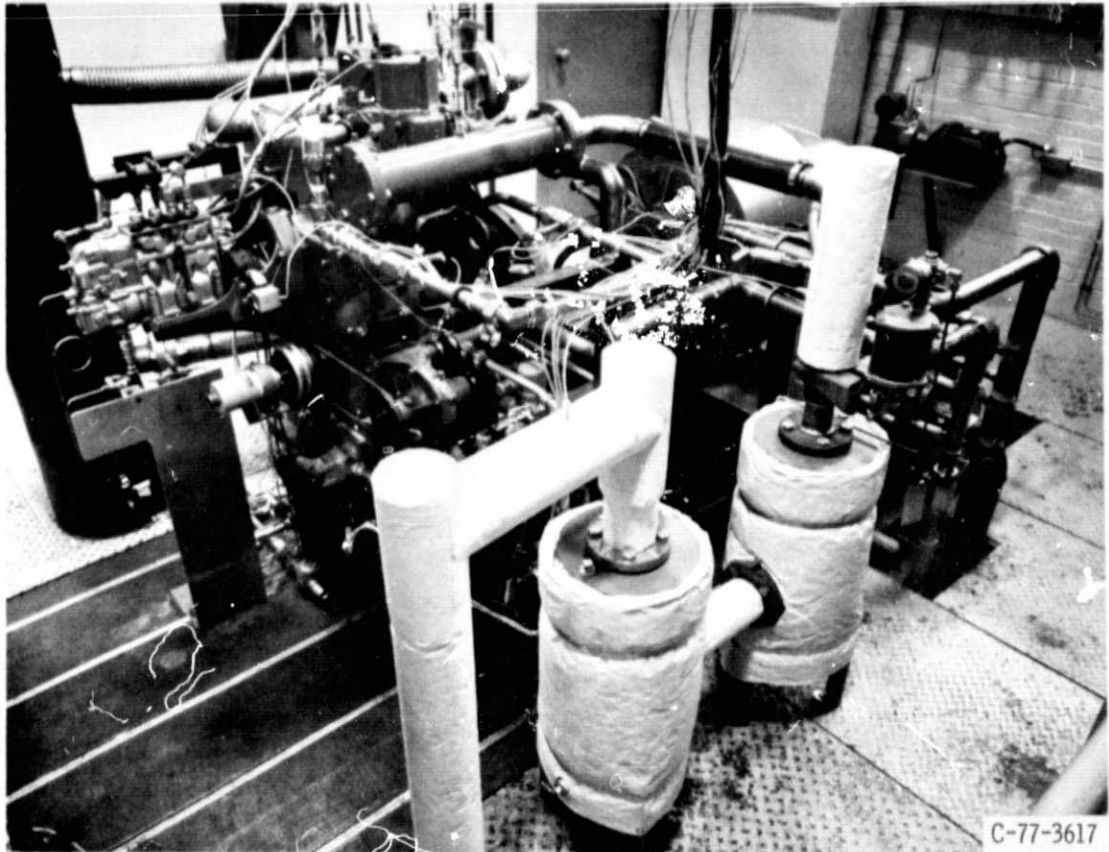


Figure 13. - Lightweight diesel or stratified-charge engine (semi-independent turbocharger).



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Figure 14(a). - View of diesel engine test cell.

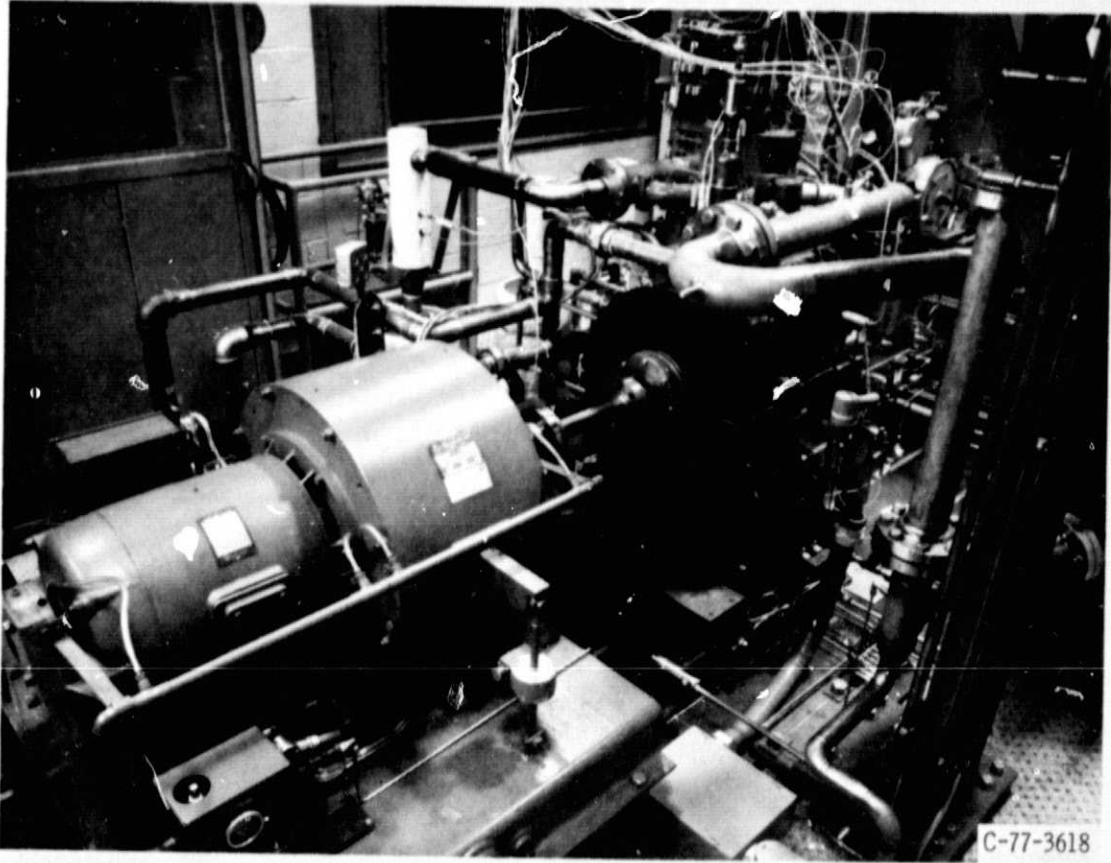


Figure 14(b). - View of dynamometer and AVL research diesel.

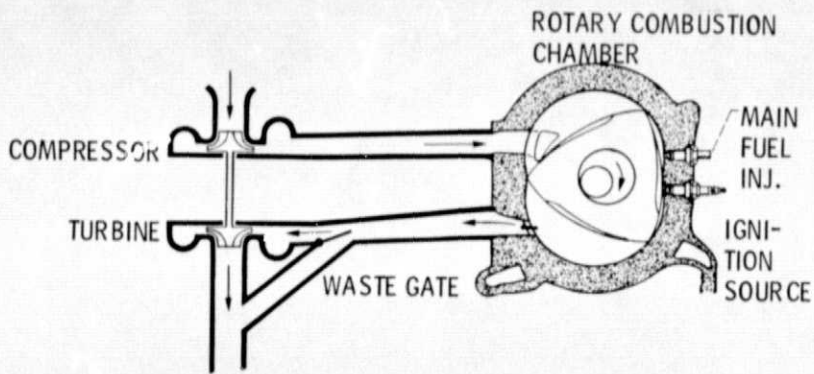


Figure 15. - Stratified charge rotary multi-fuel engine (conventional turbocharger).

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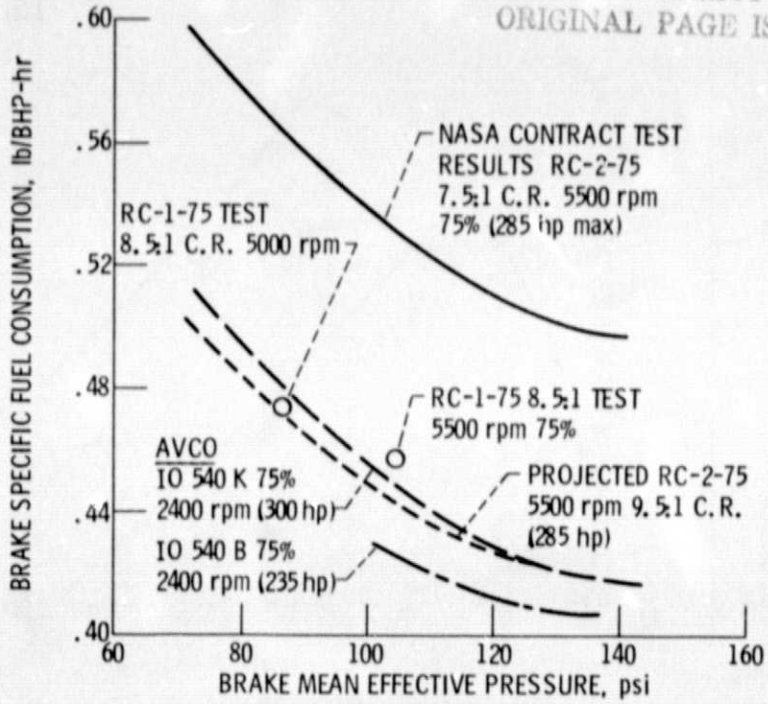


Figure 16. - Rotary engine fuel consumption trends.

INHERENT CHARACTERISTICS  
MULTIFUEL CAPABILITY  
LEAN OPERATION  
NO OCTANE/CETANE REQUIREMENT

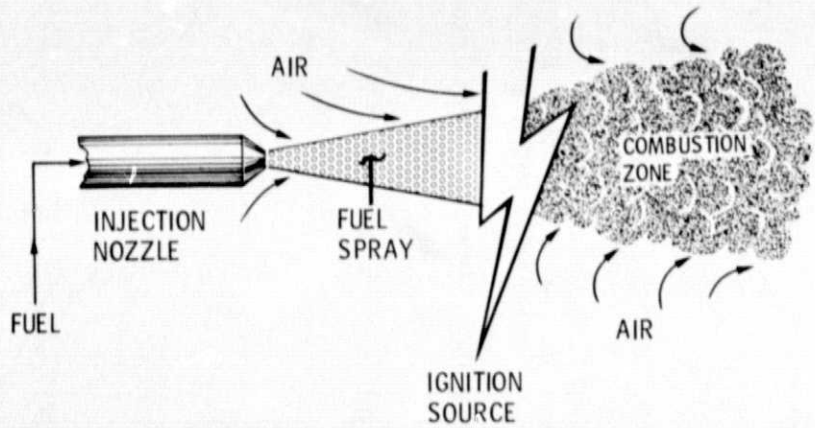


Figure 17. - Stratified-charge principle.

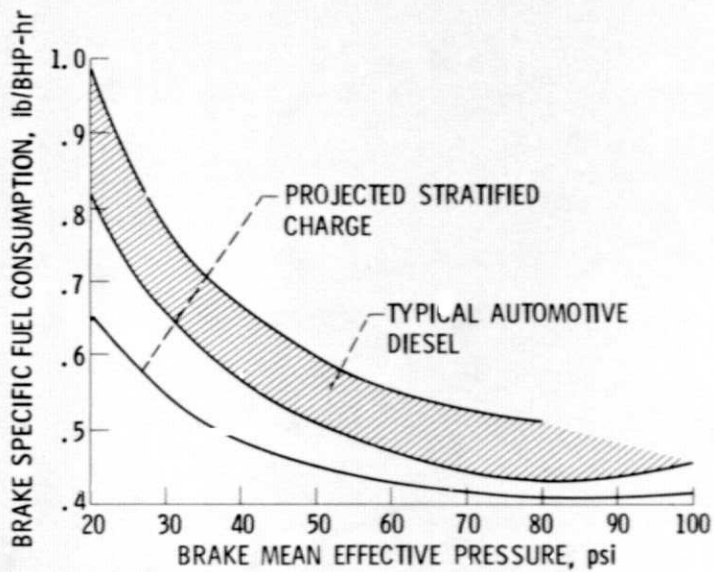


Figure 18. - Rotary engine fuel consumption trends.

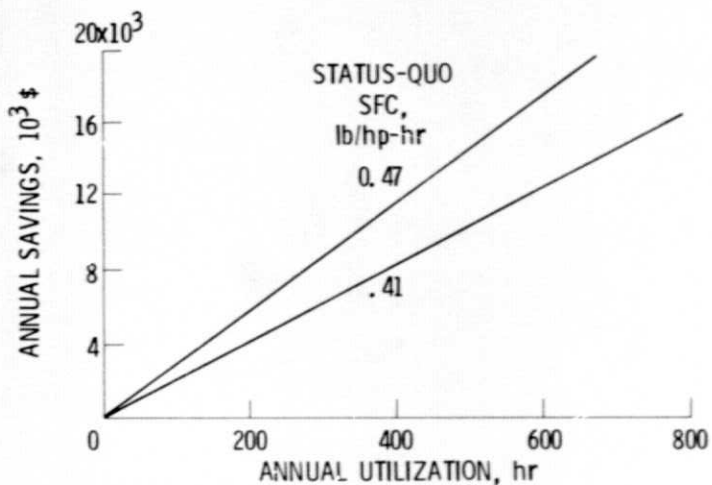


Figure 19. - Annual fuel cost savings due to advanced technology engine in 6-place business twin.

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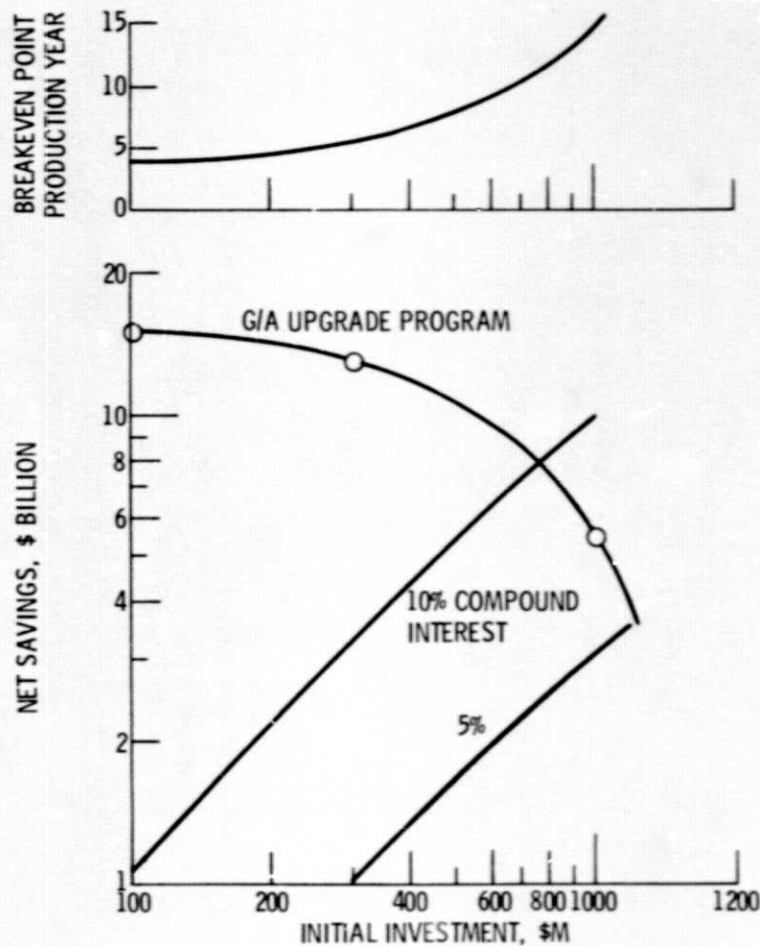


Figure 20. - Economic performance of the G/A upgrade program.

- 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 MULTIFUEL 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                      - ENVIRONMENTAL ACCEPTABILITY
  - RELIABILITY                - DURABILITY
  - COST                         - MAINTAINABILITY

Figure 21. - What does conservation mean to general aviation?

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