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The Rotary Combustion Engine - a Candidate for General Aviation

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A symposium held at
Lewis Research Center
Cleveland, Ohio
February 28, 1978

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FOREWORD

NASA is engaged in a program to evaluate the potential of several alternative engines for use as general aviation powerplants. The rotary engine is one of the potential candidates. It is of interest because of its relatively low weight, simplicity, compactness, low vibration, low octane fuel requirement, and possible multifuel capability. A 1-day symposium on rotary engines was held at the NASA Lewis Research Center, Cleveland, Ohio, to provide those interested with an update on the state of development of these engines as potential powerplants in both aircraft and automobiles. This proceedings of the symposium includes the seven papers presented at the symposium.

The symposium was coordinated by Phillip R. Meng of the Lewis Research Center.

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OVERVIEW OF NASA GENERAL AVIATION PROGRAM

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N79-15962

During the past five years, the NASA efforts devoted to new technology for general aviation have grown steadily. As described in previous statements, and as illustrated in Figure 1, our efforts have been focused in three areas: (1) improved safety through improved crashworthy structural design, spin resistance, and improved operations around uncontrolled airports; (2) reduced environmental impact for both reciprocating and turbine engines; and (3) research for improvement in the performance of both aerodynamic and system components. Figure 2, illustrates a few of the 14 production and prototype aircraft developed by industry that employ new technology generated by this program.

While our current and past efforts have been productive in terms of providing new technology for improved capability in general aviation aircraft, the critical needs of the future will require a shift of emphasis as illustrated by Figure 3.

While no abrupt change is envisioned, much of the current activity shown on the left will, over the next several years, become more directly aimed at technology for increased utility and energy efficiency while maintaining a significant emphasis on improved safety.

The R&T program planned for Fiscal Year 1979, while comprised to a large extent of continuing activities, does contain some elements relating to the new areas of emphasis.

Continuing programs in technology for improved safety are illustrated in Figure 4. The principal effort devoted to uncontrolled airport traffic involve the demonstration of an automatic pilot advisory system to provide pilots near nontower-equipped airports with up-to-date airport and traffic information. Since our hearings last September, we have been working with the FAA to develop a formal interagency agreement on a cooperative program that insures compatibility of this concept with the automated terminal service project underway in the FAA. By the end of FY 1978, both concepts will be in operational demonstration and evaluation status. At that point, data from the evaluations will be used by the FAA to identify the most effective system concepts as a function of airport activity. In FY 1979 and beyond, NASA efforts in the evaluation will be in direct support of the FAA.

Improved crashworthiness through new structural design techniques is the objective of a continuing joint effort with the FAA. In FY 1979, the series of impact tests with standard general aviation aircraft will be completed by conducting a limited number of tests with a velocity augmentation system utilizing small rockets to increase the impact velocity up to 90 miles per hour (mph)--30 mph over the maximum free-fall speed. This rocket system was evaluated in a recent test at 75 mph. The higher velocity tests will duplicate some of the impact angles in earlier lower velocity tests to provide comparative data on the effects of higher speeds. In addition, two energy-absorbing seats will be tested in the full-scale impact tests. These seats are being evaluated in sled tests at the FAA Civil Air Aeromedical Institute (CAMI) in Oklahoma City in FY 1978. The FY 1979 tests of the two seat concepts will verify their performance and their suitability for application by the general aviation industry. In another important area, structural concepts capable of substantially increasing the energy-absorbing capability of a fuselage will be fabricated and components will be impact tested during FY 1979. A significant increase in the efforts devoted to improved stall/spin characteristics was implemented in FY 1978 and will continue in FY 1979. The augmented efforts have a considerably broader scope than was possible in the past and are now addressing three additional critical factors.

Determination of aerodynamic characteristics at high angles of attack, stall/spin-prevention concepts and the development of criteria for emergency spin recovery systems are areas of research now being pursued in addition to the previous efforts in developing test techniques, defining normal spin recovery design criteria and consulting with the industry on specific problems. Following the FY 1978 flight evaluation of a modified high-wing aircraft, the FY 1979 program will include a T-tail configuration and begin the study of light twin-engined aircraft.

As illustrated in Figure 5, ongoing efforts in the development of more efficient aerodynamic components, such as airfoils and high lift devices, will continue in FY 1979. The concentration on drag reduction techniques is intended to provide a generalized design procedure that will reduce the need for the current cut-and-try flight test approach to drag clean-up. In addition, results of ongoing work in the Conventional-takeoff-and-landing (CTOL) area to develop low drag coatings for aerodynamic surfaces will be examined for applicability to light aircraft.

Benefits from a particular aerodynamic improvement, such as a high-lift airfoil or reduced drag through the use of winglets, will not necessarily be achieved when integrated into an aircraft as a modification. Beginning in FY 1978, and continuing, is an effort to provide guidelines for optimum integration of new aerodynamic capabilities into current configurations. A similar effort will explore potential efficiency improvements from new or novel configurations.

Illustrated in Figure 6, are several areas that are being investigated in an effort to provide greater propulsive efficiency. Turbine engines, both fan and shaft versions, appear to be gaining acceptance across a wider spectrum of aircraft types. Less maintenance, lower cost of turbine fuel, broader tolerance to fuels, and high combustion efficiency make these engines potentially viable alternatives to reciprocating engines in the above-400-horsepower class.

The Quiet, Clean, General Aviation Turbofan (QCGAT) engine will be completed in FY 1979. Following the evaluation tests by the two contractors, the engines will be delivered to NASA. Subsequent efforts beyond FY 1979 will concentrate on in-house verification testing and performance evaluation at the Lewis Research Center.

Existing turbine engines are too large for application to all but the largest general aviation aircraft. In FY 1978, four contractors have undertaken preliminary definition studies of small, 400-horsepower, 800-pound-thrust turbine engines. In FY 1979, detailed definition studies will be initiated including a careful evaluation of the airframe requirements to properly incorporate such an engine into the aircraft.

Significant losses are encountered during the installation of reciprocating engines. Drag generated by cooling requirements, cowling drag and adverse interactions between the propeller and the nacelle are estimated to be from 5 to 20 percent of the cruise drag of current aircraft. Ongoing studies in each of these areas will provide design procedures and data for optimizing engine installations.

Closely coupled to these tasks are the efforts in propeller optimization. During FY 1979, design and fabrication of model hardware for propeller/nacelle flow field investigations will be underway, as will research on advanced blade sections.

More basic studies of fuel tolerance and cycle efficiency, including evaluation of diesel and rotary engines, will continue during FY 1979.

As illustrated in Figure 7, the utility of light aircraft as a mode of transportation is heavily dependent upon the ability to operate in adverse weather and a complex air traffic system. While accomplished routinely by the airlines, the differences in airborne equipment, operational requirements, ground facilities and flight crew make general aviation instrument operations considerably more challenging. Continuing research on advanced integrated avionics, studies of advanced navigation concepts and previous work on stability, control and handling qualities for general aviation represent a technology base that is available for improving the safety and reliability of instrument flight.

Information available to us through the Aviation Safety Reporting System (ASRS) and other sources indicates a number of problems exist with single-pilot instrument-flight-rule (IFR) operations. During FY 1979, we will be initiating efforts to isolate the most critical problems so that we may begin, in consultation with users and FAA, to explore concepts for resolving them.

Our approach will be to establish realistic operating scenarios and, through simulation, identify the operating and procedural conditions adversely affecting the single pilot's flying task. Although premature to speak about specific areas we would investigate to resolve problems, we envision that we may be looking into such matters as charting, training requirements, and air traffic control (ATC) procedures. In addition to the work outlined here, we also will be defining plans for examining single-pilot IFR issues within the context of the cockpit-displayed traffic information program described earlier in the testimony.

A symposium on Short-Haul, Small Community Air Service was held at the Ames Research Center in early FY 1978. Participants represented all facets of the industry providing small community air service, including researchers, regulators, manufacturers and operators.

In general, the purpose was to identify what, if any, technologies should be developed to enhance this very vital segment of civil air transportation.

Current airline service and future prospects were examined as were the results of past studies. Aircraft design and operating system requirements were reviewed in terms of technology opportunities and some related NASA research programs.

Conclusions resulting from these deliberations were that there is a lack of an appropriate sized and performing modern aircraft available to the commuter market and that, in general, shrinking of current transport technology much below 50-60 passengers would not be economically viable.

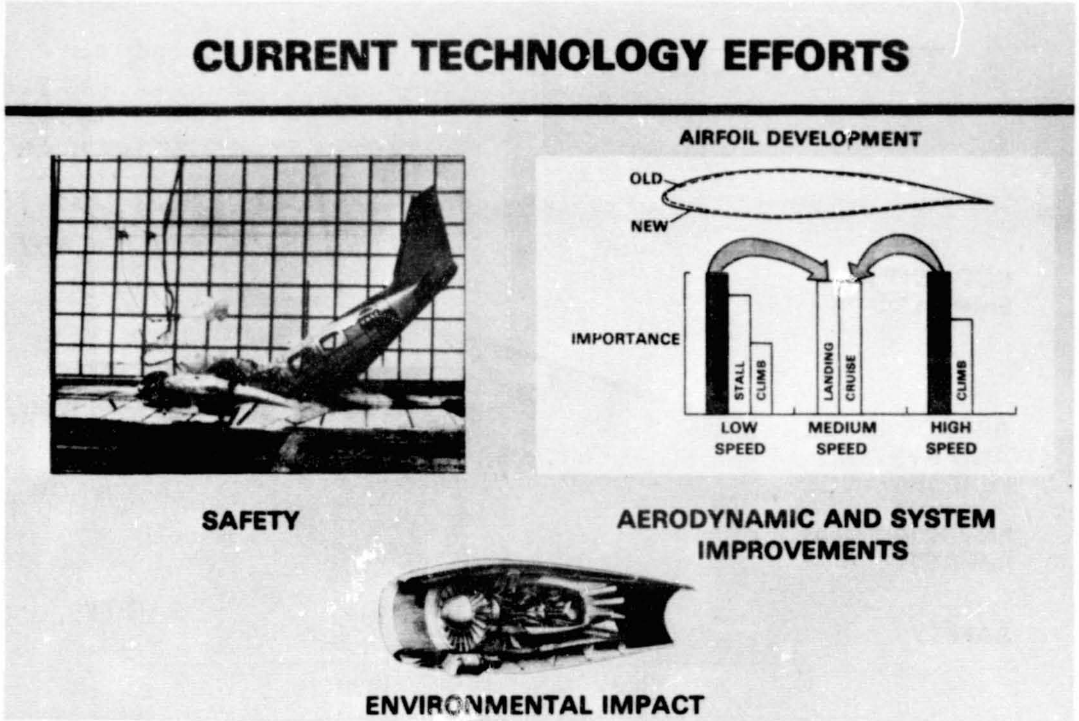
As illustrated in Figure 8, a study was initiated in FY 1978 to explore what, if any, technology limits exist that preclude the general aviation industry's development of a larger aircraft matched to the commuter airline requirements. FY 1979 activities will continue these studies, concentrating on definition of the appropriate NASA role in resolving any problems identified in the current study.

The utility and productivity of aircraft dedicated to the performance of a special mission can be enhanced if the aircraft is specifically tailored to the requirements of the task. Such is the situation with aircraft used to apply agricultural materials.

Since the primary transport mechanism for the materials, once ejected from the aircraft, is wake generated by the aircraft, the width of the pattern and its evenness are directly influenced by the uniformity of the downwash. As illustrated in Figure 9, the wake of the aircraft and the propeller slipstream seriously detract from the ability to apply a uniform layer of material.

Relying on facilities and techniques developed in the study of trailing vortices, model tests and analytical studies will be carried out to define acceptable modifications to current aircraft that will improve the uniformity of the pattern by tailoring the wake characteristics. While a relatively low-level effort, it does capitalize on a unique area of expertise within NASA and does hold the promise of significant return if successful.

In summary the general aviation research and technology program planned for FY 1979 is well balanced and is addressing the most critical problems identified as future limits to growth. This shift in emphasis away from the near-term problems to a next generation timeframe in aerodynamics, propulsion and avionics is compatible with the time required for the evaluation and incorporation of new technology by the industry.



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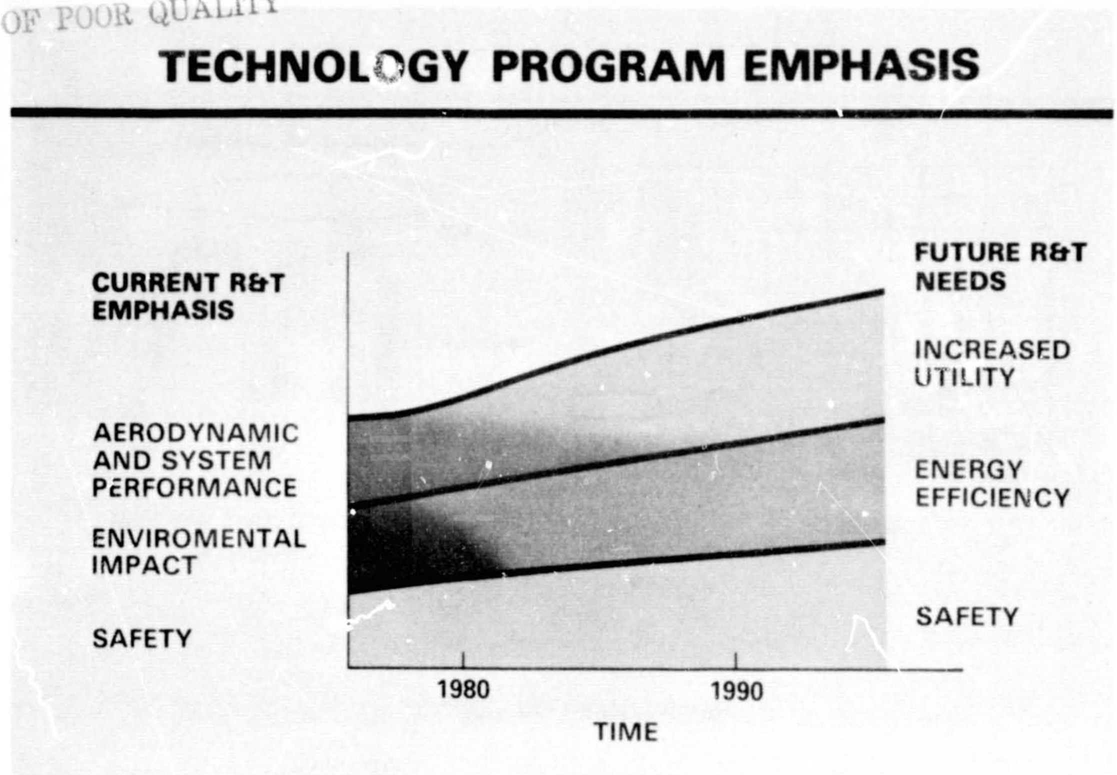

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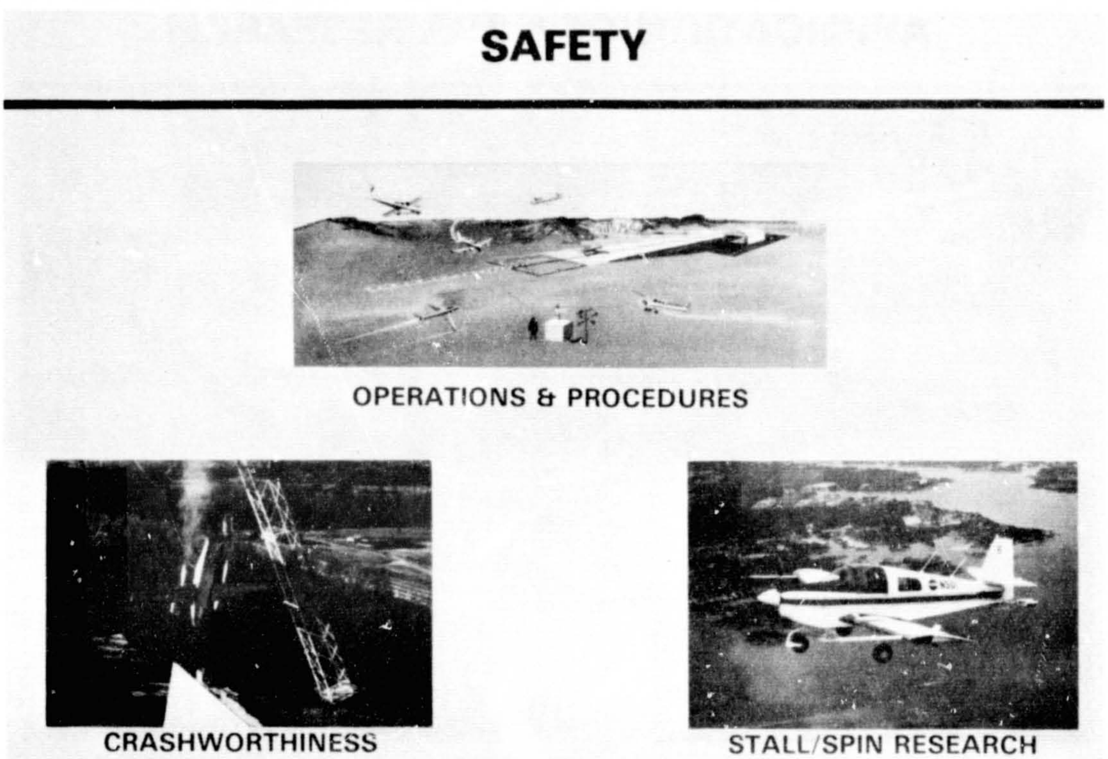

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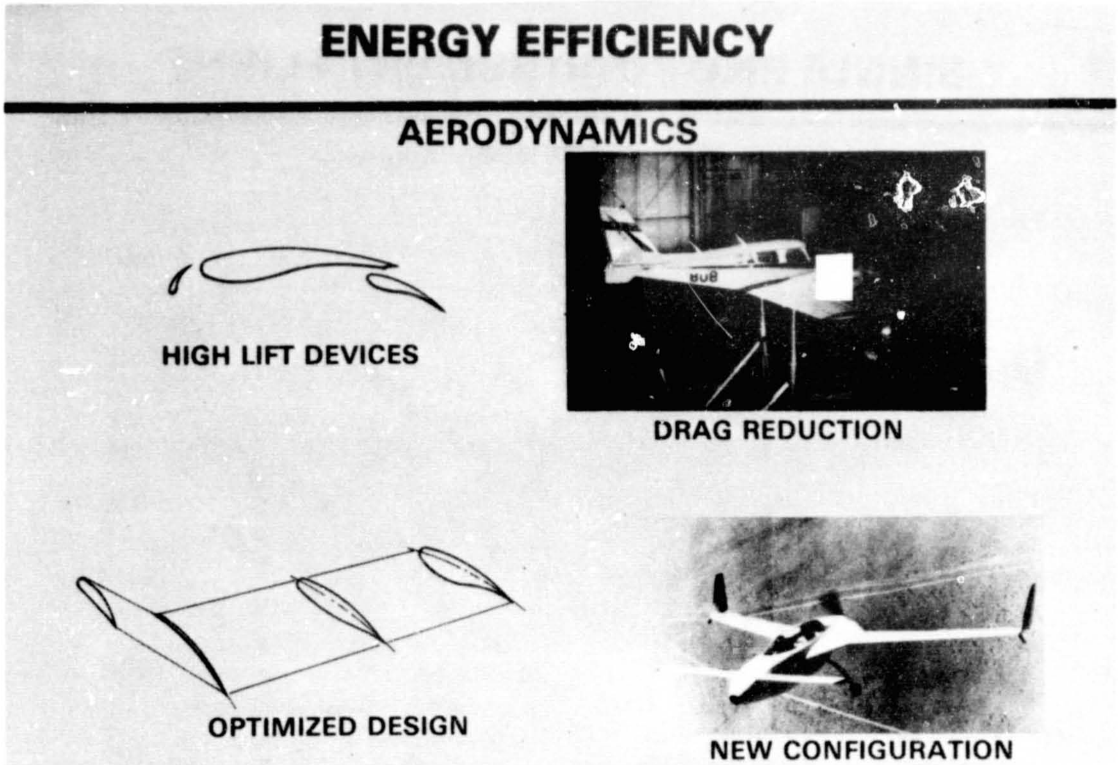

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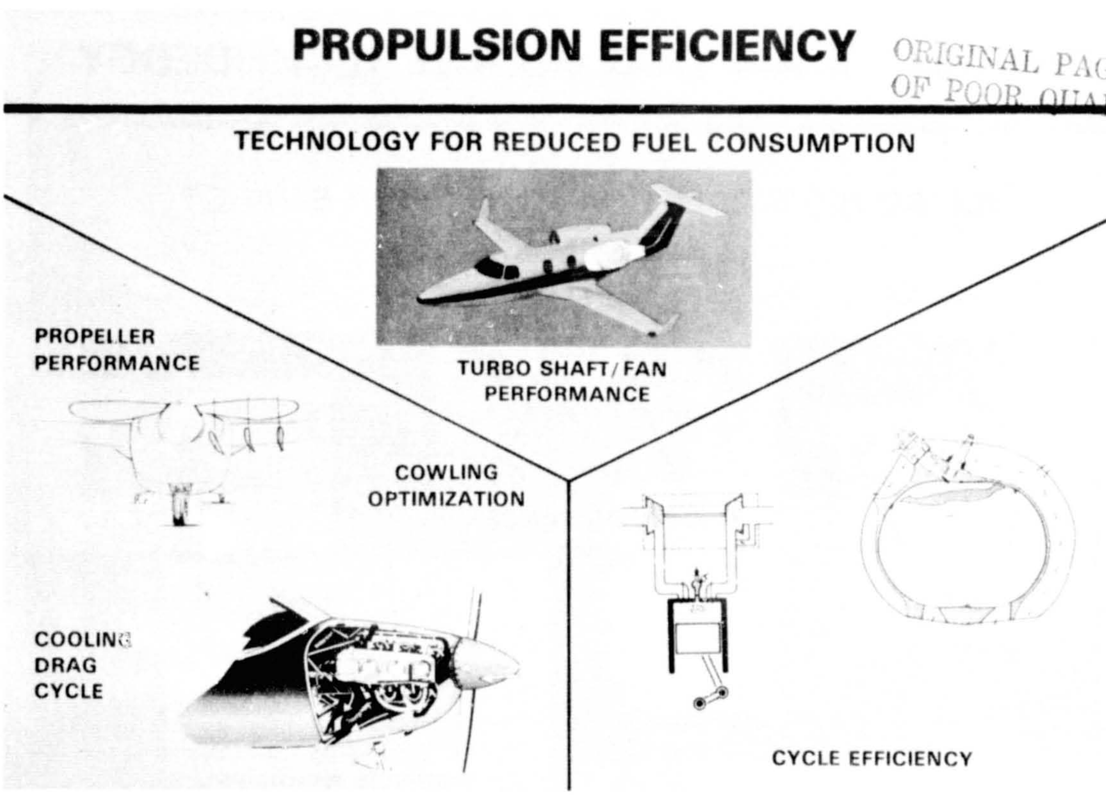

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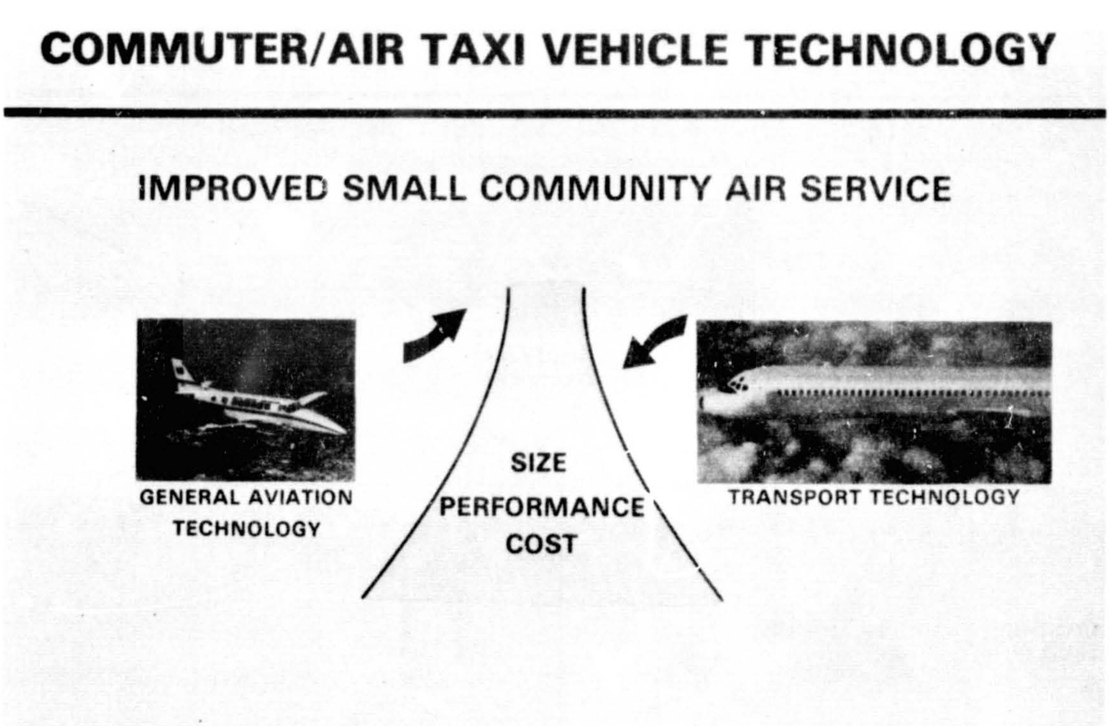
Figure 6

Figure 7



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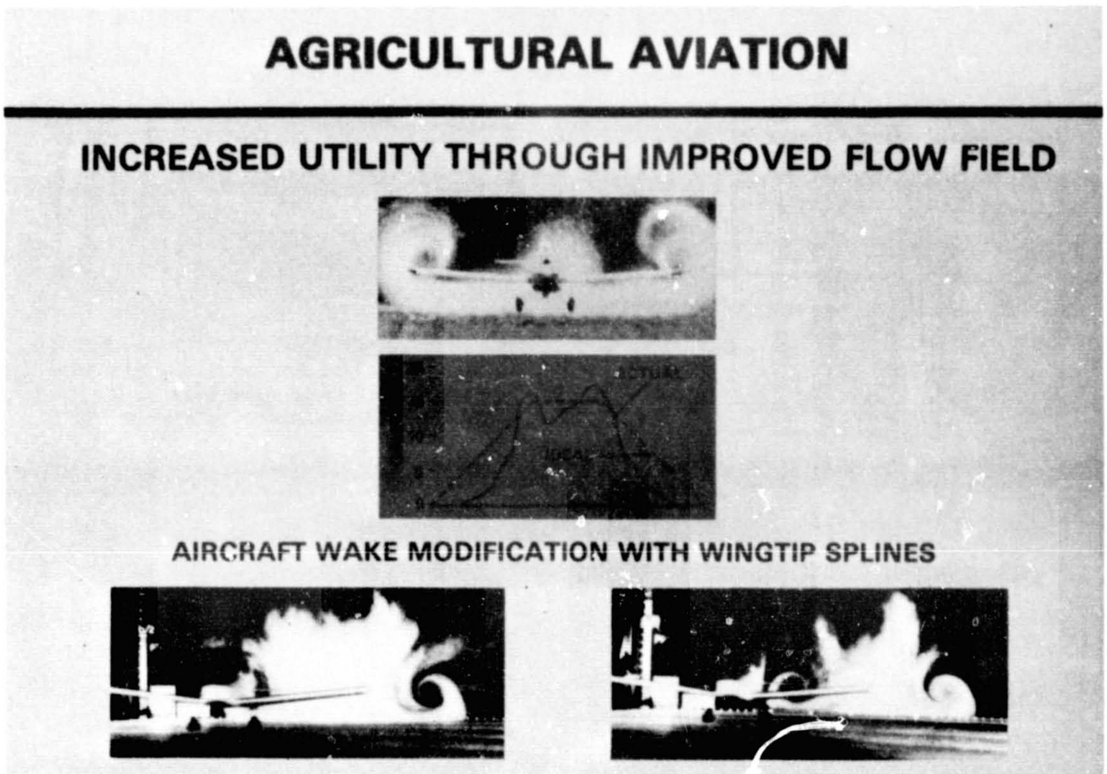

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GENERAL AVIATION ENERGY-CONSERVATION RESEARCH PROGRAMS AT NASA LEWIS RESEARCH CENTER

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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. Its 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.

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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 <u>have</u> 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 l/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 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 system.

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

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ENERGY PROGRAMS DIRECTORATE (G. M. AULT)

RECIPROCATING ENGINES ROTARY ENGINES	(UP TO 800 SHP)	GENERAL AVIATION BRANCH

AERONAUTICS DIRECTORATE (W. L. STEWART)

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.

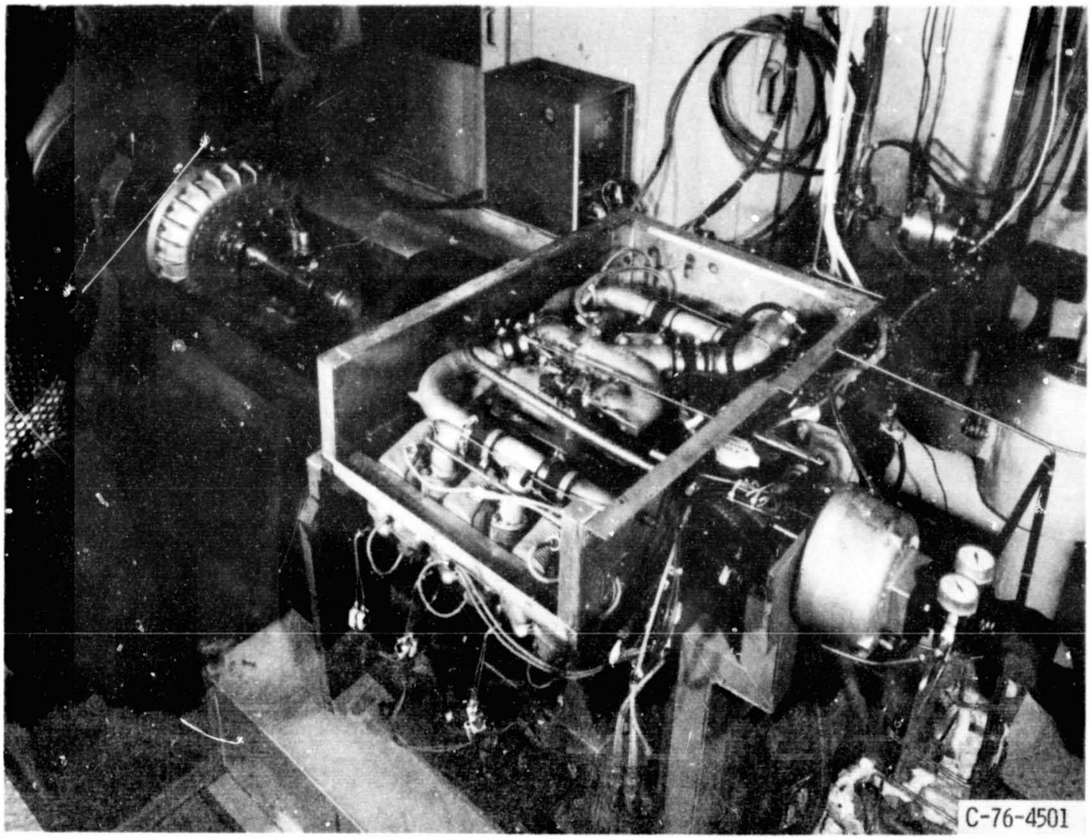

Figure 3(a). - View of aircraft engine test cell.

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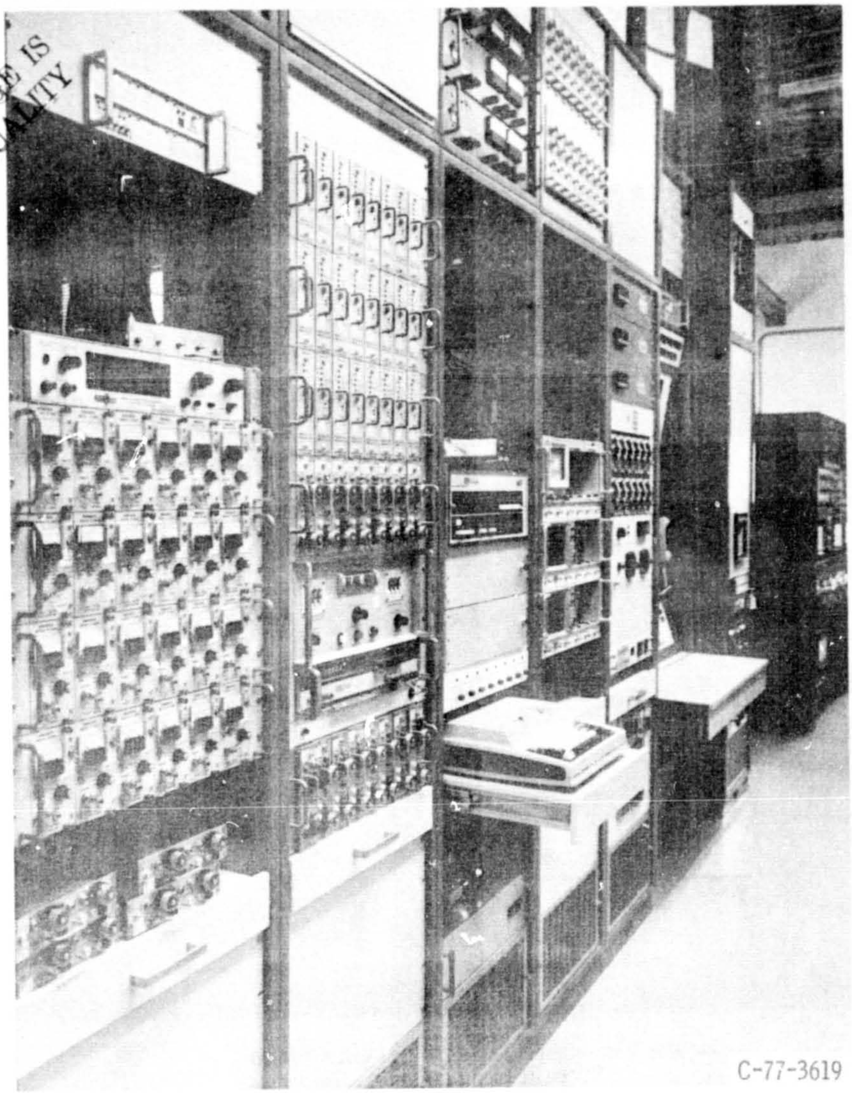

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Figure 3(b). - View of control room.

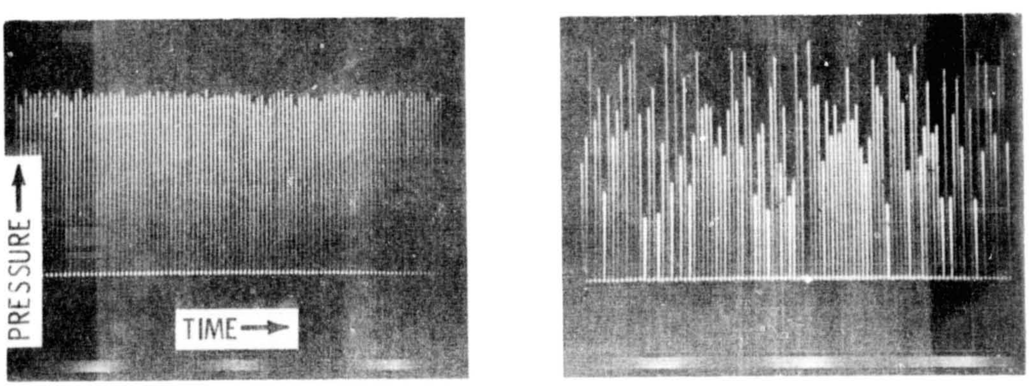

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Figure 4. - IMEP instrumentation - 100 cycle bar-chart displays. CS-78-381

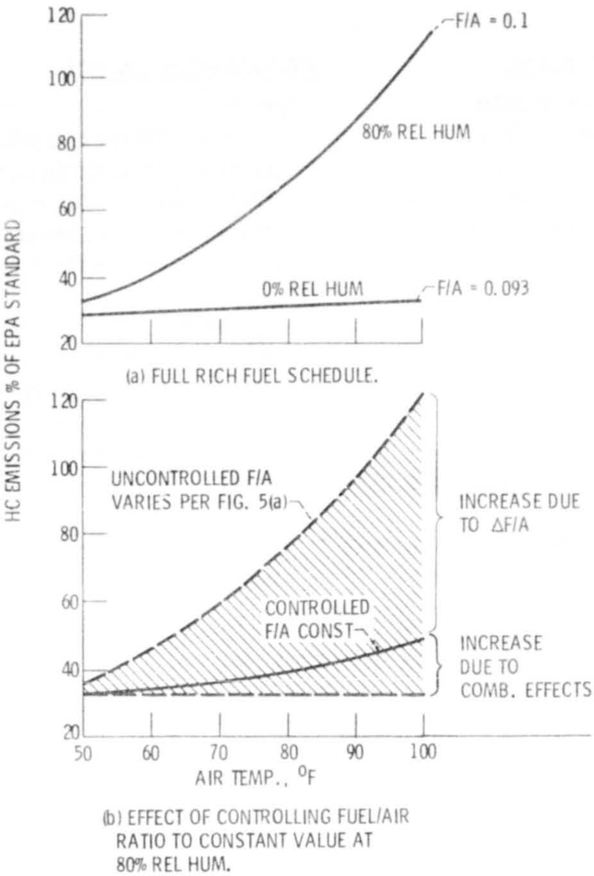

Figure 5. - Taxi mode HC emis... ns.

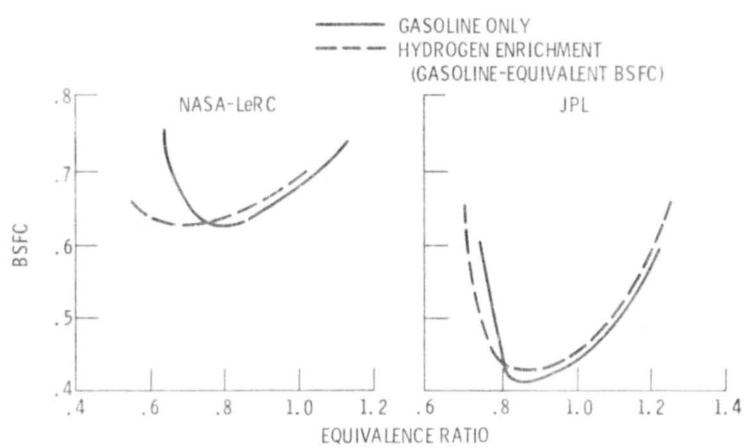

Figure 6. - Effect of hydrogen enrichment on fuel consumption.

CONVENTIONAL ENGINES	ADVANCED ENGINE CONCEPTS
JOINT NASA/FAA PROGRAM	CONTRACT
AVCO-LYCOMING CONTRACT	LIGHTWEIGHT DIESEL CYLINDER (U. MICH)
VARIABLE VALVE TIMING	LIGHTWEIGHT DIESEL DESIGN STUDY (TGPD)
ULTRASONIC FUEL VAPORIZATION	ROTARY ENGINE (CUTRISS-WRIGHT)
ADVANCED IGNITION CONCEPTS	STRATIFIED CHARGE ROTARY DESIGN STUDY
TCM CONTRACT	ADVANCED SPARK IGNITION ENGINE STUDIES
AIR INJECTION	IN-HOUSE
PULSED FUEL INJECTION	LIGHTWEIGHT DIESEL OR STRATIFIED-CHARGE ENGINE WITH SEMI-INDEPENDENT TURBOCHARGER
IMPROVED COOLING COMB. CHAMBER	ROTARY ENGINE WITH SIMPLIFIED CHARGE STRATIFICATION SCHEMES
CONTRACT	COOLING FINS STUDY FOR ADVANCED CYL. HEADS
FUEL TOLERANCE TESTS	CONTINUING OTTO PROGRAM DEVELOPMENT
IN-HOUSE	CONTINUING DEVELOPMENT OF INSTRUMENTATION AND CELLS
TEMPERATURE/HUMIDITY CORRELATION FOR EMISSIONS	
LEAN OPERATION (HEI, FUEL INJECTION)	

Figure 7. - Current programs.

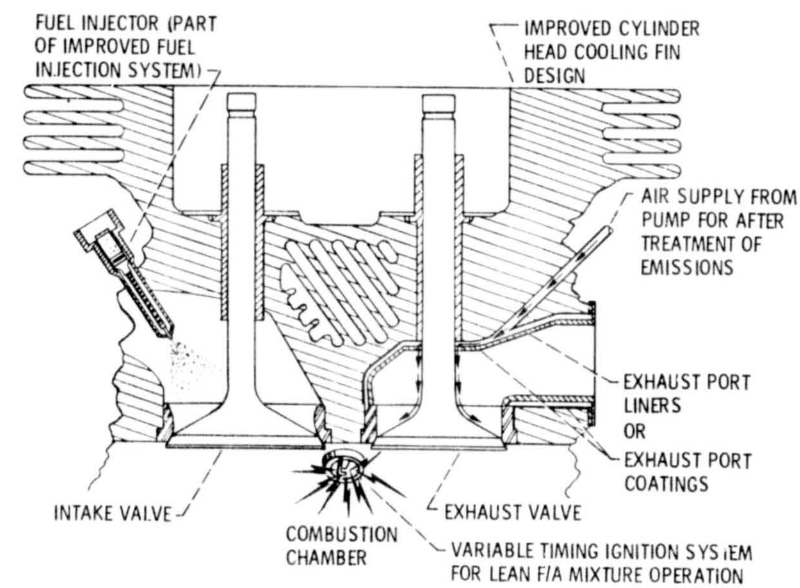

Figure 8. - Advanced cylinder head concept integration.

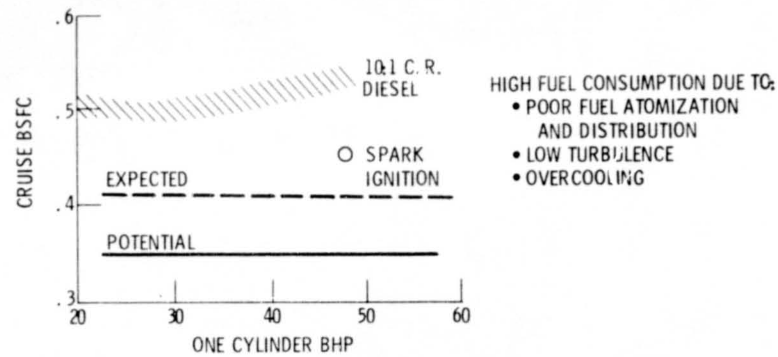

Figure 9. - Initial test results on cylinder low compression ratio aircraft diesel at the University of Michigan.

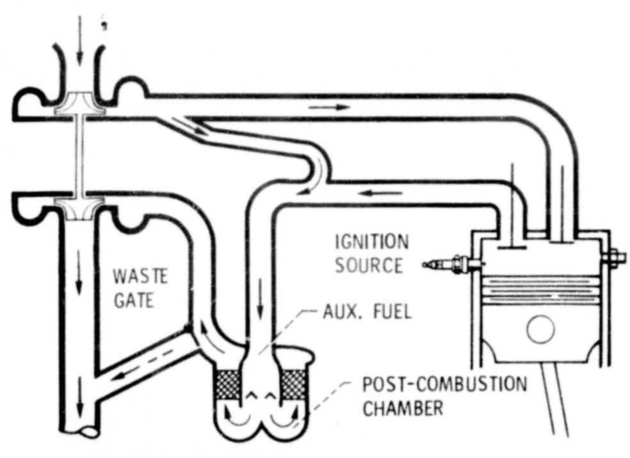

Figure 10. - Lightweight diesel or stratified-charge engine (semi-independent turbocharger).

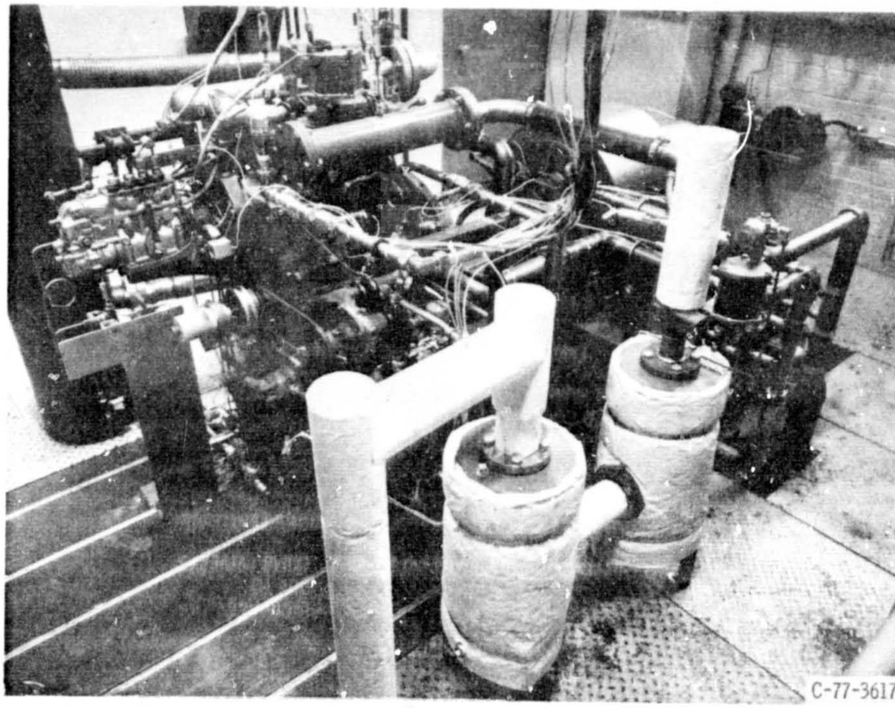

Figure 11(a). - View of diesel engine test cell.

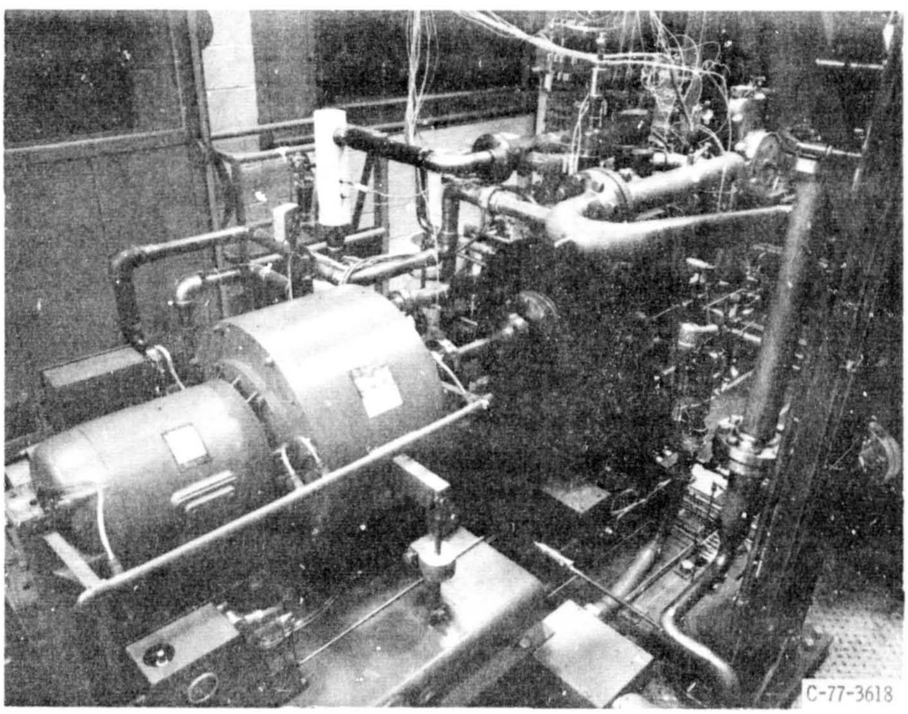

Figure 11(b). - View of dynamometer and AVL research diesel.

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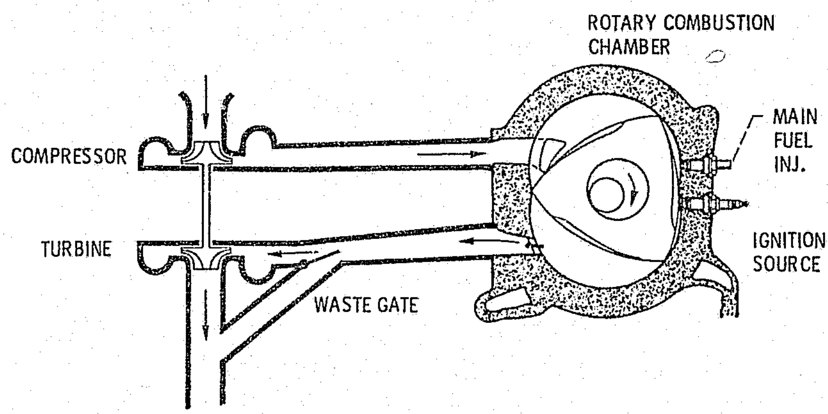

Figure 12. - Stratified charge rotary multi-fuel engine (conventional turbocharger).

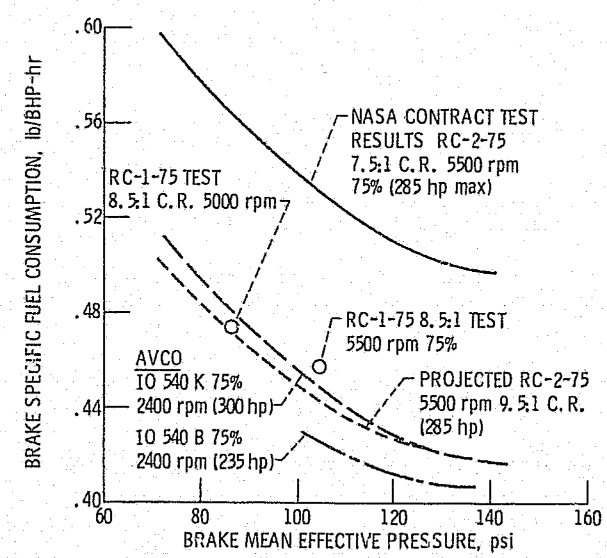

Figure 13. - Rotary engine fuel consumption trends.

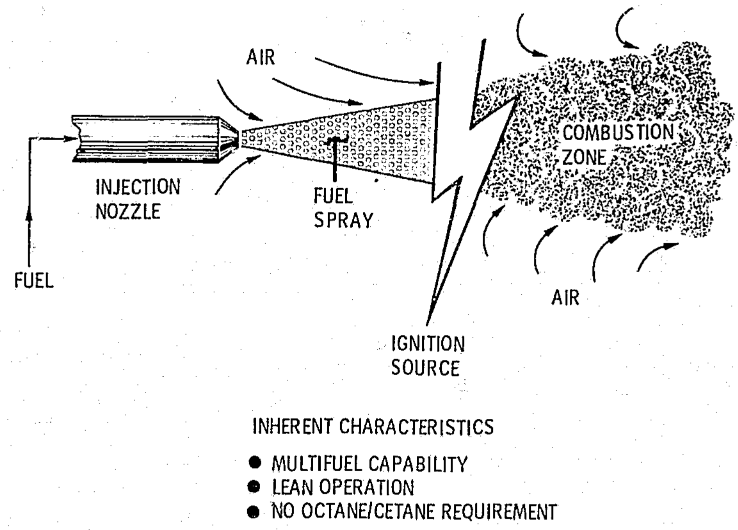

Figure 14. - Stratified-charge principle.

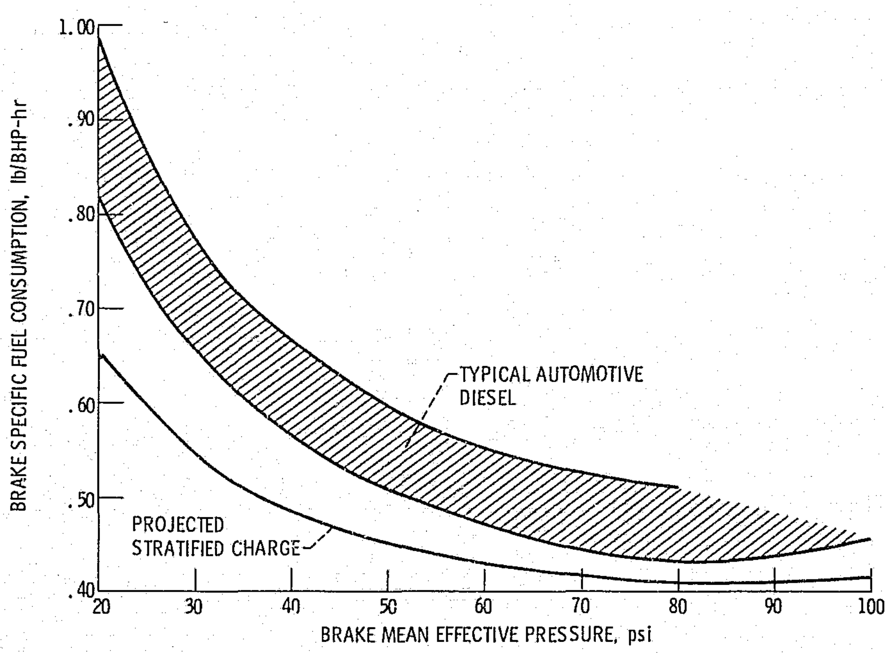

Figure 15. - Rotary engine fuel consumption trends.

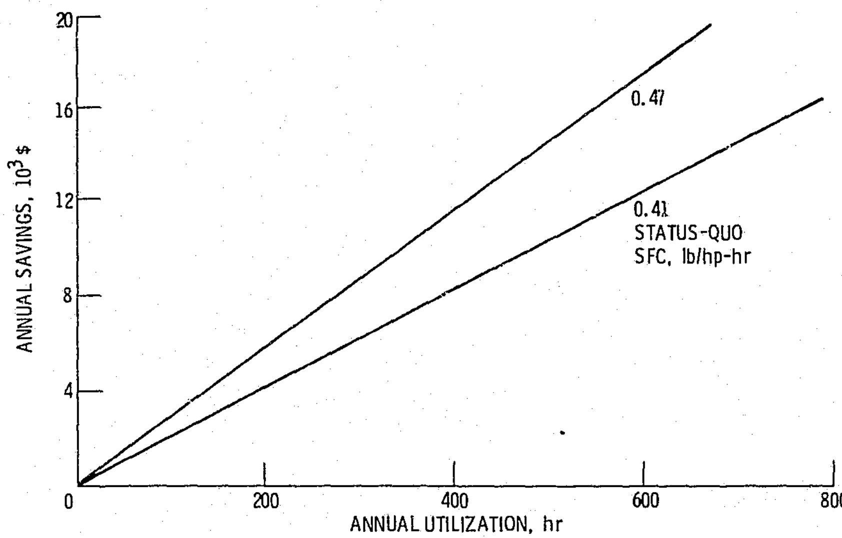

Figure 16. - Annual fuel cost savings due to advanced technology engine in 6-place business twin.

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

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

D3

N79-15964

DEVELOPMENT STATUS OF ROTARY ENGINE AT TOYO KOGYO

Kenichi Yamamoto
Toyo Kogyo Company, Ltd.

Current Production Engine

(Table 1)

Currently, as shown in Table 1, we are producing two types of rotary engines; the 12 A and 13 B. Both use a thermal reactor as the primary part of the exhaust emission control system.

(Fig. 1)

Fig. 1 shows a 12 A engine construction.

New Technologies Applied to Main Component

(Fig. 2)

A two-piece type metallic apex seal is shown in Fig. 2. Originally, a special carbon material had been used for the apex seal, but now it has been replaced by acicular iron based metal.

The top portion of this metallic seal is crystallized in the form of carbides, a so-called "chilled layer" by the electron beam process. This treatment contributes to improving the anti-wear characteristics and has made it

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possible to adopt a two-piece type apex seal with a reduced width, which results in the improvement in gas sealing.

(Fig. 3)

The rotor housing is made by aluminum pressure die-casting with a carbon steel-sprayed inner core as shown in the upper sketch in Fig. 3. We call it TCP(Transplant Coating Process). This method contributes to a significant improvement in adhesiveness of the chromium plating as compared with that of direct chromium plating on to the aluminum alloy, resulting in easier quality control.
From 1974 model, a new process, SIP(Sheet-metal Insert Process), has been adopted for increasing the strength of the trochoidal surface and obtaining higher productivity.

In this process, the aluminum alloy rotor housing is die-cast to a thin sheet-metal with a jagged surface and the chrome plating is applied onto the flat surface of the sheet metal as shown in the lower sketch in Fig. 3.

This process has enabled to achieve better bonding of the aluminum and the sheet metal, as well as better adhesion of the chrome plating.

(Fig. 4)

Fig. 4 shows the sheet-metal formed in a trochoidal shape. The outer side of it is the jagged surface.

(Fig. 5)

As shown in Fig. 5, a pin-point porous chrome plating has been applied onto the trochoidal surface to maintain the oil film effectively and to improve anti-wear characteristics of the apex seals and the chrome plating.

(Fig. 6)

The special surface treatment which we call a gas-nitrizing is applied onto the side housing as shown in Fig. 6. Anti-wear characteristics of the sealing elements such as oil seals and gas seals have been greatly improved due to this surface treatment, which is newly applied to the RX-7 engine.

(Fig. 7)

The 2-electrode spark plug has been replaced by a 3-electrode plug from the 1976 model as shown in Fig. 7.

The spark plug gap has been increased from 0.65mm (0.026 in.) to 1.05 mm(0.04 in.) in order to obtain more stable ignition.

Development on the Exhaust Emission and Fuel Economy of the Rotary Engine at Toyo Kogyo

Now I would like to explain our "Development on the Exhaust Emission and Fuel Economy of the Rotary Engine at Toyo Kogyo"

The discussion will cover two main areas; "Improvements of Current Production Engine", and "Development in Advance Programs".

Toyo Kogyo began manufacturing rotary engines in 1967 and we have produced some 930,000 rotaries to date.

As you may already know, we made substantial improvements in fuel economy on our 1976 rotary engine models. These improvements were achieved through various modifications of the engine and the thermal reactor system. Details of this are discussed in the paper, and I will now touch briefly on the main items.

(Fig. 8)

Fig. 8 shows a friction loss analysis on the 1975 model 13 B engine. It is clear that the gas sealing is one of the major factors of the total friction loss in the Wankel type rotary engine. In order to reduce gas leakage, we incorporated various improvements in the gas seal elements.

(Fig. 9)

We adopted a two-piece metal apex seal from the 1974 models, but on 1976 models we reduced gas leakage substantially by lowering the end height ΔM of the apex seal as shown in Fig. 9. We also adopted a

10 - 30μ crowning to improve the conformability of the apex seal to the trochoidal surface.

We also increased the elasticity of the corner seal from the 1976 models to minimize the clearance ΔC between the corner seal and the seal bore.

(Fig. 10)

The effect of improved gas sealing is shown in Fig. 10. A 2 - 9% Brake Mean Effective Pressure improvement was achieved in the low and medium engine speed ranges, and in Brake Specific Fuel Consumption, a 3 - 8% improvement was achieved at 1500 rpm.

(Fig. 11)

Next, we have made an extensive study on the combustion chamber recess in order to increase combustion speed and we have adopted the Leading Deep Recess (LDR) type combustion chamber as shown in Fig. 11 in the 12 A engine from 1976 models. This type of combustion chamber shifts its recess to the leading side of the rotor.

(Fig. 12)

As a result, a 3 - 4% improvement in fuel economy was attained by the leading spark plug alone as shown in Fig. 12. However, we had to suspend the adoption of the Leading Deep Recess combustion chamber in the 13 B engine -which has a larger displacement - because it aggravated the tendency to misfire.

As you know, reduction in the final gear ratio is also effective in improving fuel economy but, to do this, improvements in low-speed torque are required.

(Fig. 13)

This figure shows the effect of inlet close timing on Brake Mean Effective Pressure. On the 1976 models, inlet close timing was changed to 40 degrees from 50 degrees After Bottom Dead Center.

Based on this increase in low-speed torque, we reduced the final gear ratio from 3.900 : 1 to 3.636 : 1 on the 13 B engine and to 3.727 : 1 on the 12 A engine. In addition to this, on the 1976 model, we adopted the 5 speed manual transmission with an overdrive gear ratio of 0.862 : 1.

Simultaneously with these modifications, we also improved the thermal reactor system.

(Fig. 14)

Modification of the exhaust port insert is shown in Fig. 14.

After testing many types of inserts, we chose the one shown in the right sketch. Its decreased heat loss and increased port insert capacity from 33 cc to 55 cc enhanced pre-reaction in the port insert area.

(Fig. 15)

Fig. 15 shows the effect of secondary air temperature on thermal reaction limit at a certain engine load. As the secondary air temperature goes up, thermal reaction becomes possible at a leaner air-fuel ratio.

(Fig. 16)

This is the heat exchanger for pre-heating secondary air which was adopted from the 1976 models. The heat exchanger is integrated with the exhaust pipe behind the thermal reactor, and raises secondary air temperature approximately 200 degrees centigrade, for example, in the light load range at 1500 rpm.

This pre-heating of secondary air and the modified exhaust port insert allowed the adoption of a leaner air-fuel ratio and more advanced ignition timing.

(Fig. 17)

This figure is the comparison of Brake Specific Fuel Consumption between 1975 and 1976 models. The dotted line is for the 1975 model and the solid line is for the 1976 model, both conforming with the required emission standards without an EGR system.

(Table 2)

This table shows the emission and fuel economy data of the 1975 and 1976 models as published by the EPA. In the combined fuel economy, the 1976 model 12 A engine in the 2750 lb inertia weight class made an improvement of approximately 43 percent over the 1975 model.

There was an approximate 38 percent improvement in the 13 B engine in the 3000 lb inertia weight class.

All these improvements in the engine and thermal reactor system have been applied to the current engines.

(Table 3)

Now, I will move on to the second heading, "Development in Advance programs". The basic target in our advance programs is to pursue better fuel economy, higher performance and better drivability, while of course meeting the stringent exhaust emission standards. Of these, needless to say, fuel economy improvement is the most important. Our basic thinking on the subject of fuel economy improvement is discussed in the paper, and I will give you an outline of the main items.

First, I would like to explain our experiments on spark plugs and the combustion chamber recess.

(Fig. 18)

These are comparison test results of the dual spark plugs (trailing and leading), and the single spark plug (leading spark plug alone) with regard to fuel economy, exhaust emission and exhaust gas temperatures at 1500 rpm and 3 kg/cm^2 Brake Mean Effective Pressure. The engine is a 13 B with MDR - Medium Deep Recess - combustion chamber.

A leading spark plug alone appers to be more desirable than dual spark plugs for the after-treatment device which requires a higher exhaust gas temperature and less base exhaust emissions. However, the dual park plugs are better in terms of fuel economy than the single spark plug.

(Fig. 19)

This is a comparison of the fuel flow requirements obtained by the leading spark plug alone and the dual spark plugs while thermal reaction is taking place in the reactor. This shows, when the thermal reactor is used, the single spark plug gives better fuel economy than the dual spark plugs.

As a next step, we carried out a series of tests on the combustion chamber with the leading spark plug alone.

(Fig. 20)

For example, this is the comparison of combustion speed at idling. The dotted line is for the Medium Deep Recess design, and the solid line is for the Leading Deep Recess, both with the leading spark plug alone.

The axis of abscissa is the eccentric shaft angle and the axis of ordinate is the mass burning rate, or combustion speed. The combustion speed of the LDR is faster than that of the MDR.

(Fig. 21)

The effect of the combustion chamber on Brake Specific Fuel Comsumption is shown in Fig. 21. In the case of the leading spark plug alone, the LDR gives less fuel consumption than the MDR, as shown in the lower figure. The upper figure is the comparison in Brake Mean Effective Pressure at Wide Open Throttle when both leading and trailing spark plugs are ignited.

Here again, the LDR shows slightly better results than the MDR.

(Fig. 22)

Next, we made various studies on the influence of the compression ratio in the LDR type combustion chamber. This is the relationship between the compression ratio and the octane number requirement. The dotted line is for the dual spark plugs and the solid line is for the leading spark plug alone, both with the LDR type combustion chamber.

The octane number requirement for a single spark plug is relatively low compared with that of the dual spark plugs. For example, the octane number requirement for the leading spark plug alone at a compression ratio of 10.0 : 1 is nearly equivalent to that for the dual spark plugs at a compression ratio of 9.2 : 1.

(Fig. 23)

Fig. 23 shows the effect of the compression ratio. It is natural that Brake Specific Fuel Consumption improves as the compression ratio increases, but it is rather interesting to know that Brake Mean Effective Pressure at a compression ratio of 10.0 : 1 with the leading spark plug alone is better than that at a compression ratio of 9.2 : 1 with dual spark plugs.

(Fig. 24)

This is a comparison of fuel economy, exhaust emissions and exhaust gas temperature between the LDR with a compression ratio of 10.0 : 1 and the leading spark plug alone, and the MDR with a compression ratio of 9.2 : 1 and the dual spark plugs.

From the foregoing comparison, it can be said that the LDR with a compression ratio of 10.0 : 1 and the leading spark plug alone is better.

(Fig. 25)

Now I will continue with "Modifications to the Gas Seals". Fig. 25 shows a trial for improvement in the gas sealing elements in our advance program. We changed the position where the apex seal is split, filled the corner seal hole with a heat-resisting elastic material and made the side seal spring pitch variable.

These modifications are aimed at reducing gas leakage from the apex seal end and from the lower portion of the apex seal inside the corner seal hole, and also at decreasing the friction of the side seal.

(Fig. 26)

This is the effect of these modifications applied to the advance engines. For example, we obtained about a 5% increase in low speed torque and about a 4 - 5% improvement in fuel economy at 1500 rpm.

Increasing the thermal efficiency through the improvements in the combustion chamber and gas seals resulted in a decrease in the throttle valve opening during low speed light load conditions, and the misfiring characteristics became worse because of an increase in exhaust gas dilution.

In our development program for improvements in fuel economy, one of the major objectives was to develop a highly misfiring-resistant engine. The semi-surface discharge spark plug for improvement in ignition performance is one of the measures we developed.

(Fig. 27)

This semi-surface discharge spark plug, which we call the SSD spark plug, is a combination of a surface gap and air gap, and this SSD spark plug is activated by the High Energy Ignition system.

(Fig. 28)

Fig. 28 shows a remarkable improvement in misfiring characteristics at idling. The dotted line is for the engine with the aforementioned engine modifications and the conventional ignition system, and the misfiring is not on an acceptable level. The solid line is for the same engine with the High Energy Ignition system and Semi-Surface Discharge spark plug.

When EGR becomes necessary in the future to reduce NOx, a powerful ignition system like this will definitely be one of the prerequisites.

We have incorporated all the modifications mentioned so far into our advance engine which we call the P-3 engine.

(Fig. 29)

This is a comparison of fuel economy between the P-3 engine and the current production engines.

A 6 - 10% improvement in Brake Specific Fuel Consumption at 1500 rpm was achieved in the P-3 engine over the current production engine.

(Fig. 30)

A further rotary advancement is our new intake system which we call CISC, for Compound Inductions Step Control.

The CISC is a combination of a peripheral port and side ports and is aimed at supplying the air-fuel mixture toward the center of the width of the combustion chamber, utilizing the rotary engine's inherent characteristic of the mixture flowing in one direction.

The slit shape peripheral port is fitted with a reed valve to minimize the side-effects of overlapping, and the mixture from this port speeds up the total air-fuel mixture flow. As a result, the fuel is atomized more effectively and the distribution of the mixture in the combustion chamber becomes more uniform. In the CISC system, only the peripheral port functions during light loads; the dual side ports additionally function for heavy loads. The peripheral port shares about 26% of the load.

(Fig. 31)

This figure shows an effect of the CISC system on peak pressure fluctuation rate when the peripheral port functioned alone. The CISC was superior in combustion stability - particularly in the leaner air-fuel mixture zone - and as shown in Fig. 32, the fuel economy improved by 4 - 6% at a low speed and a light load. (Fig. 32)

Additionally, we have developed an engine with full-direct fuel injection.

(Fig. 33)

This is our ROtating Stratified COmbustion engine, which we call ROSCO.

In the ROSCO engine, a fuel injection nozzle is located in the cold zone of the trochoidal surface where the thermal load is low. Injected fuel is well atomized by the air flowing in at a high speed from the peripheral port, which also has a reed valve like the CISC. Then, the atomized fuel is stratified in the combustion chamber on the leading side of the rotor. Although the mixture moves to some extent toward the trailing side with the rotation of the rotor, more desirable distribution of the mixture around the leading spark plug is obtained than in the case of the conventional carburetor system.

(Fig. 34)

As you see from this figure of the peak pressure fluctuation, the ROSCO offers much more stable combustion, particularly in the lean mixture range, compared with the carbureted engine.

(Fig. 35)

This is the effect of the EGR ratio on the peak pressure fluctuation in caburetor and ROSCO systems, which represents combustion stability. Even at the higher EGR ratio, drivability was not sacrificed in the ROSCO system as much as in the carburetor system, and this indicates the ROSCO has a higher potential for the reduction of NOx emissions.

(Fig. 36)

In order to achieve not only improved fuel economy but also higher performance we have been developing a manifold injection by EFI (Electronic Fuel Injection). One nozzle type and dual nozzle type are shown in Fig. 36.

The advantage of this system is the capability of maintaining a constant air-fuel ratio and the elimination of a narrow passage like a carburetor venturi.

(Table 4)

I have mentioned our approaches to the advance engine. One of the most important considerations is the use of leaner air-fuel mixtures for better fuel economy. However, beyond a certain point of leanness we cannot maintain efficient thermal reaction in the reactor. Therefore, a catalytic converter will become necessary for our advance engine in the future.

It was thought that application of a catalytic converter to the rotary engine would in practice be very difficult because the high HC emission level of the engine would affect the durability of the catalytic converter. However, the recent developmental progress of both the rotary engine and catalytic converter has changed the situation.

First of all, the base HC level of our advance engine, which had been a 10 g/mile in the FTP mode, has been reduced to a 7 g/mile before the catalytic converter by supplying the secondary air.

Although this reduced level has been increased to about a 8 g/mile with an EGR for a 1.0 g/mile NOx, such figures will be reduced by further engine modifications such as a cooling control of the engine.

In addition, optimization of the catalytic converter system, including control of the exhaust gas temperature and air-fuel ratio, has become promising with the development of durable catalysts.

With these developments, we believe that the adoption of a catalytic converter to the rotary engine will become possible.

(Table 5)

This table is one of our test results on exhaust emissions and fuel economy of the P-3 engine combined with the catalytic converter, although this P-3 engine does not incorporate all of the engine optimization programs we have in mind. As you can see from this table, 25 miles per gallon combined fuel economy has been obtained, which of course surpasses the target set by the EPA for the 1981 model year while meeting the 1981 Federal Emissions Standards. In this P-3 engine, the fuel flow at idling is remarkably reduced to 0.9 - 1.1 liters/hour, while the current production engine requires 1.5 - 1.7 liters/hour. And, the average air-fuel ratio used for this engine was 16 - 17 : 1.

(Fig. 37)

Also we tested the road load fuel economy on the advance engine with the catalyst system. The test result has shown that the fuel economy improvement by the advance program is more noticeable in the lower engine speed ranges. We will be able to obtain nearly 25 - 30% improvement at 30 km/h over the current production engines.

(Fig. 38)

It is too early to draw conclusions about the durability of the catalytic converter in the rotary engine, but, according to our on-going test results, we believe there is a potential to meet the 50,000 mile durability requirement. As shown in this figure, our advanced rotary engine with the catalytic converter will be expected to meet the HC emission standard on the FTP test mode even after 50,000 miles, based on the estimated deterioration factor of about 1.5.

Among the many methods and approaches to improve rotary engine fuel economy while meeting the more stringent emission standards, we believe the most realistic approach at present is to combine a catalyst with an engine which is highly EGR-resistant in a lean air-fuel ratio.

With respect to the 0.4 grams per mile NOx requirement, we are not yet in a position to discuss the prospect of satisfactory attainment.

For the target fuel economy of 27.5 miles per gallon for the 1985 model year, further engine improvements and more reduction in the final gear ratio will be required.

Finally, as mentioned, the progress obtained in our advance development both on the engine and the exhaust emission control system has indicated possibilities of further improvements in fuel economy of our rotary engine in the future.

Other Applications

We have also been studying possible applications of the current production rotary engines without major modifications to other areas than automobiles. The most promising area is a boat engine.

(Fig. 39)

Fig. 39 shows one example of the prototype engine for boats.

(Fig. 40)

As a measure to increase power of the boat engine, tune-up techniques accomplished through motor sports experience will be a big help.

Fig. 40 shows one of the examples. The housing on the right is the standard one with a side intake port and the one on the left is the housing with a bridge type side port being added.

(Fig. 41)

Fig. 41 shows the performance of the marinized 13 B engine. An approximately 50 PS increase will be gained over the current production engine.

Rotary Engine in Motor Sports

(Fig. 42)

In Japan, the enthusiast's interest in motor sports has shifted from the touring class races to the ones for the 2-seater class which belongs to FIA group 6.

Fig. 42 shows the rotary March powered by this 13 B racing engine made its debut, September 1976 and triumphed over the previously unrivaled BMW.

(Fig. 43)

The 13 B racing engine developed for the 2-seater racing machine is basically the same as the 12 A racing engine except it has a newly adopted dry sump as shown in Fig. 43 to lower the center of gravity. The metallic apex seals are installed on this 13 B racing engine.

(Fig. 44)

As shown Fig. 44, the rotor housing with the peripheral intake port used for the racing engine is shown on the right side in comparison with the one on the left side with the side intake port for the production engine. The peripheral type intake port results in an outstanding volumetric efficiency at high speeds.

(Fig. 45)

It seems necessary to incorporate the special oil supply system as shown in Fig. 45 to improve lubricating performance at high engine speeds when adopting the metallic apex seals.

(Fig. 46)

We have been developing the rotary engine to make it more powerful by utilizing fuel injection, among other things.

Fig. 46 shows the testing of the Lucas type fuel injection system being carried out in our laboratory.

Table 1

ENGINE SPECIFICATIONS

ENGINE	12A	13B
GENERATING RADIUS (MM)	105	105
ECCENTRICITY (MM)	15	15
HOUSING WIDTH (MM)	70	80
SINGLE CHAMBER DISPLACEMENT × NUMBER OF ROTORS (CC)	573×2	654×2
MAX. POWER SAE gross (HP/RPM)	120/7000	135/6500
MAX. TORQUE SAE gross (LB-FT/RPM)	110/4000	128/4000

Table 2

FUEL ECONOMY AND EXHAUST EMISSIONS OF '75 AND '76 MODELS (EPA TEST RESULTS)

		'75 MODEL		'76 MODEL	
ENGINE		12A	13B	12A	13B
TRANSMISSION (MANUAL)		4-SPEED	4-SPEED	5-SPEED	5-SPEED
VEHICLE		RX-3	RX-4	RX-3	RX-4 & COSMO
INERTIA WEIGHT (LB)		2750	3000	2750	3000
FUEL ECONOMY (MPG)	CITY	13.8	13.4	19.3	18.4
	HWY	20.0	20.5	29.6	28.8
	COMB.	16.0	15.9	22.9	22.0
EXHAUST EMISSIONS (G/MILE)	HC	0.42	0.40	0.95	0.81
	CO	3.92	5.39	7.44	4.98
	NOx	1.16	1.09	1.60	1.68

Table 3

DEVELOPMENT IN ADVANCE PROGRAMS

- SPARK PLUGS
- COMBUSTION CHAMBER
- GAS SEALS
- AIR-FUEL SUPPLY SYSTEM

Table 4

DEVELOPMENT OF CATALYTIC CONVERTER

- OPTIMIZATION OF ENGINE AND ITS CONTROL
- REDUCTION OF BASE HC
- OPTIMIZATION OF CATALYTIC CONVERTER SYSTEM
- DEVELOPMENT OF CATALYST

Table 5

EXHAUST EMISSIONS AND FUEL ECONOMY OF ADVANCE ENGINE WITH CATALYTIC CONVERTER

ENGINE:12A(P-3), WITH EGR
CATALYST:OXIDATION CATALYST(PELLET TYPE)
TRANSMISSION:5-SPEED MANUAL TRANSMISSION
INERTIA WEIGHT:2750 LB

EXHAUST EMISSIONS

	FTP (G/MILE)	10 MODE (G/KM)	11 MODE (G/TEST)
HC	0.13~0.15	0.03~0.04	4.0~6.0
CO	0.5~1.2	0.2~0.3	10.0~15.0
NOx	0.80~0.93	0.19~0.22	2.7~4.0

FUEL ECONOMY

FTP (MPG)		10 MODE (KM/L)	11 MODE (KM/L)
CITY	22.0~23.0	8.7~9.0	9.3~9.5
HWY	29.0~30.0		
COMB.	24.7~25.7		

12A ENGINE 35x2 CID

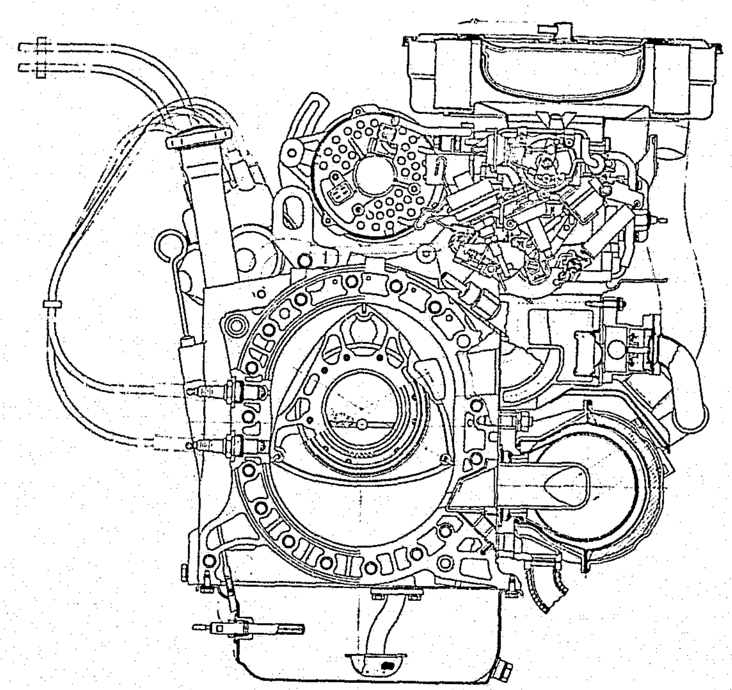

Figure 1

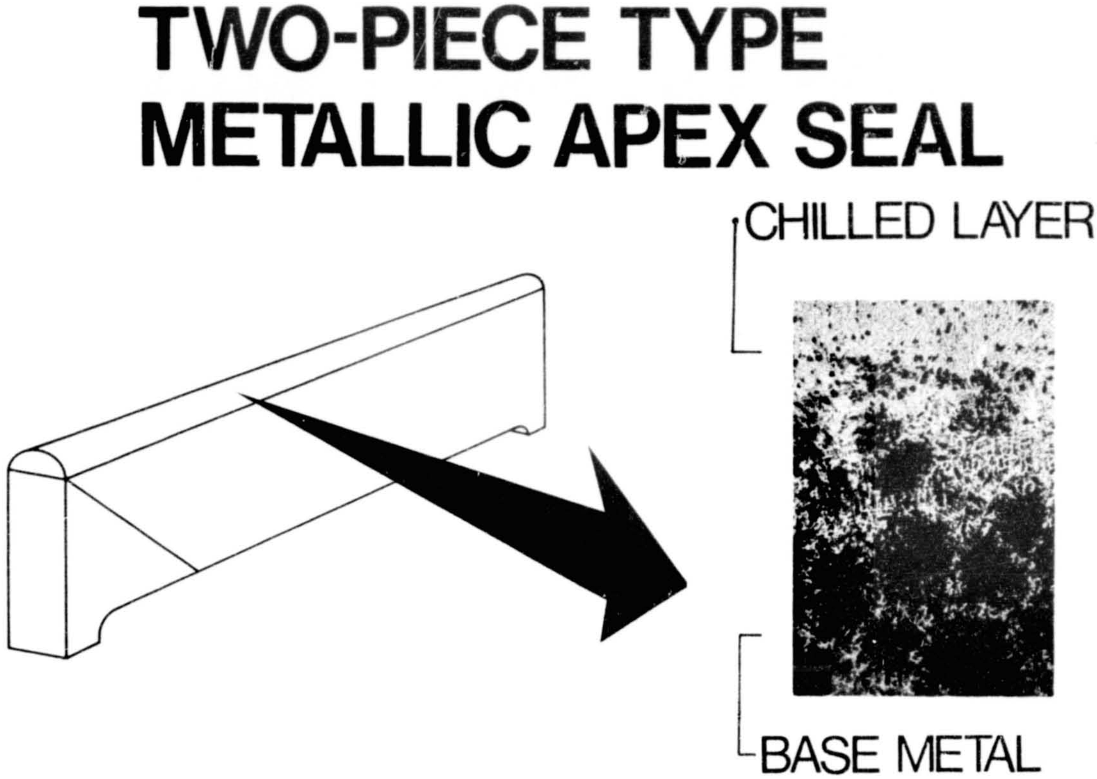

Figure 2

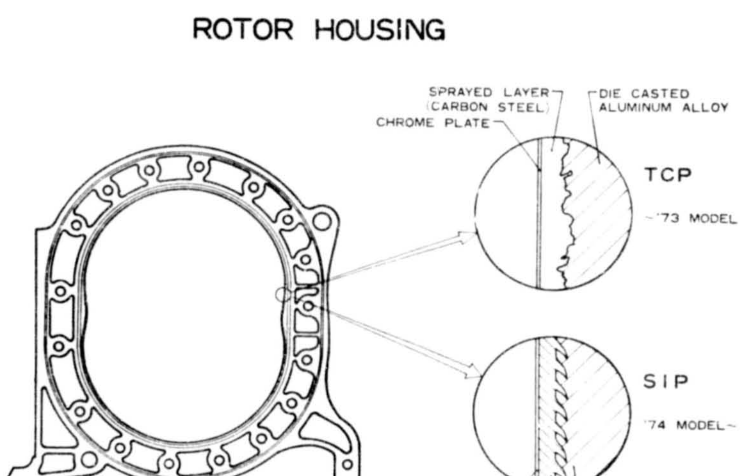

Figure 3

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SHEET—METAL

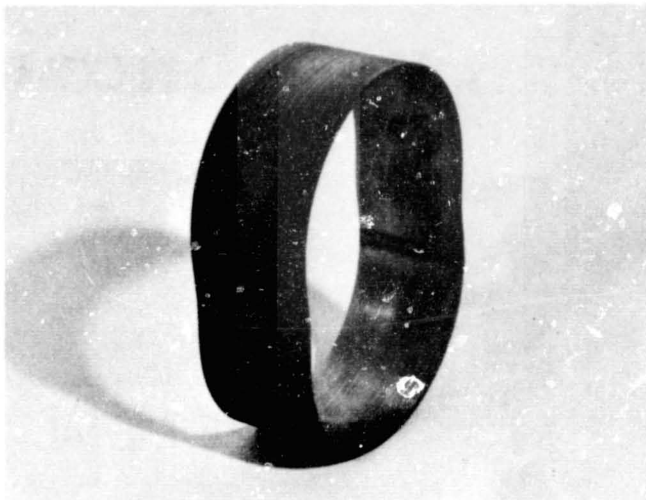

Figure 4

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PIN-POINT POROUS CHROME PLATED ROTOR HOUSING

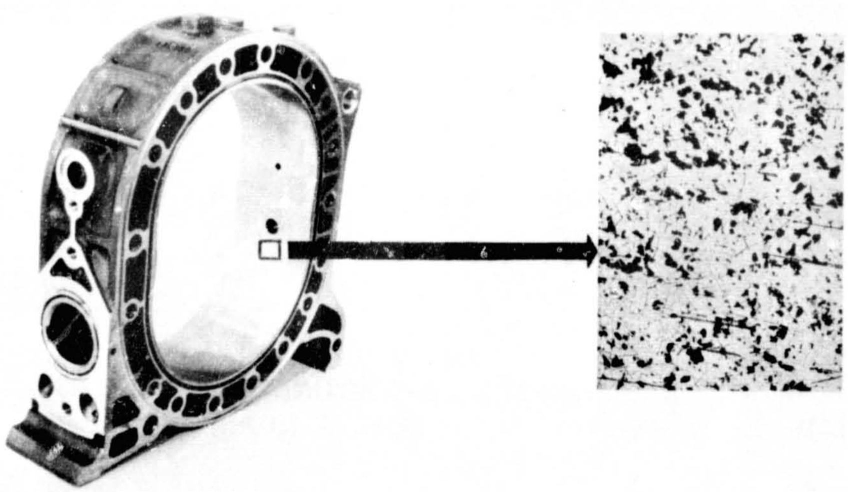

Figure 5

SPECIALLY SURFACE TREATED SIDE HOUSING

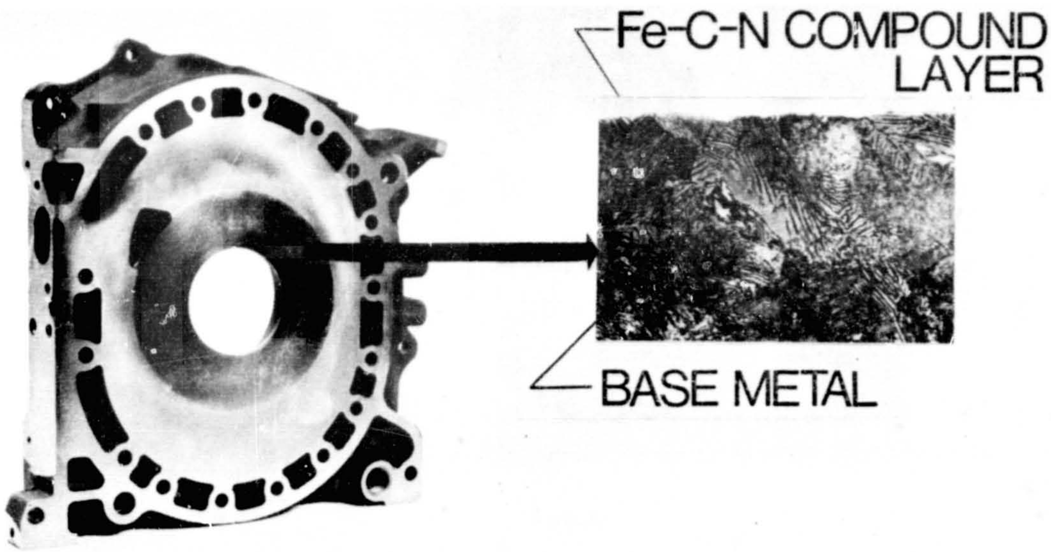

Figure 6

SPARK PLUG

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'75 MODEL

'76 MODEL

2-GROUND ELECTRODES
GAP : 0.65 MM

3-GROUND ELECTRODES
GAP : 1.05 MM

Figure 7

FRICTION LOSS ANALYSIS

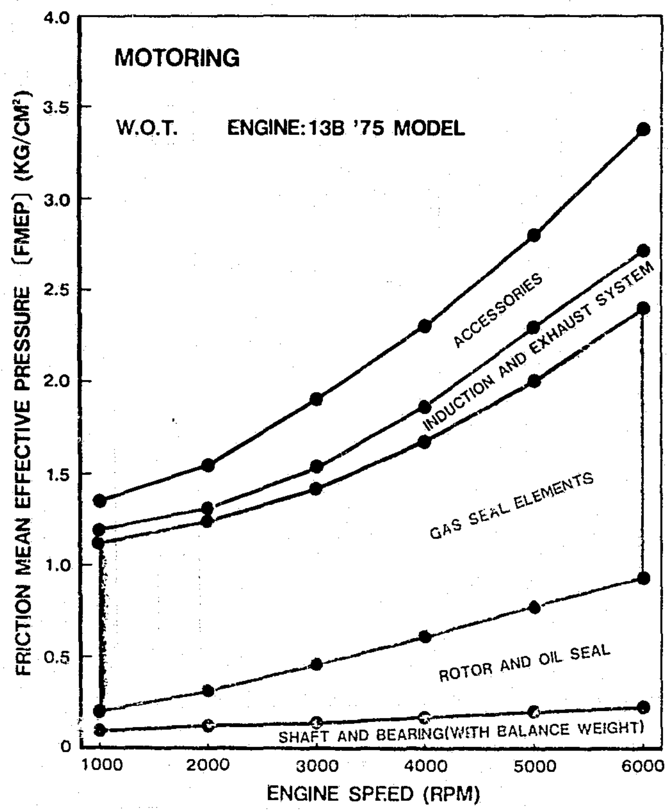

Figure 8

MODIFICATION OF GAS SEAL ELEMENTS

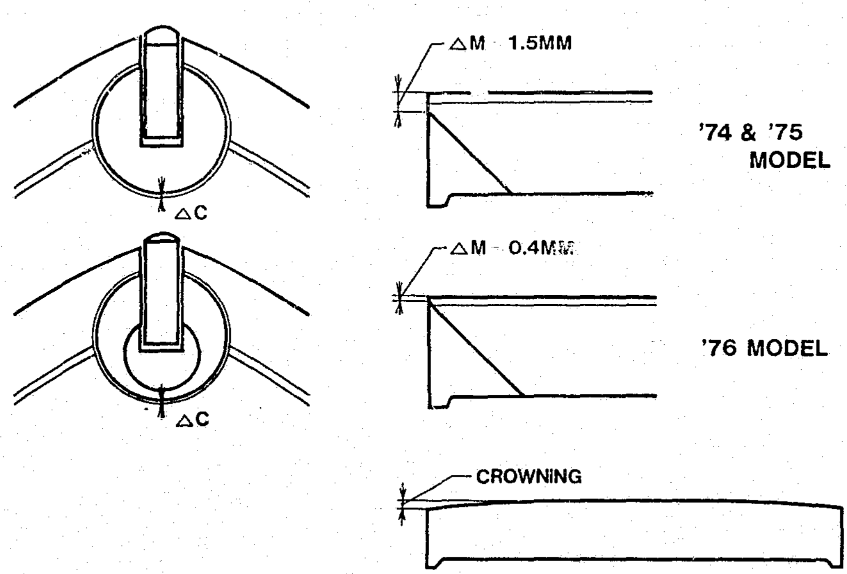

Figure 9

EFFECT OF MODIFIED GAS SEAL ELEMENTS

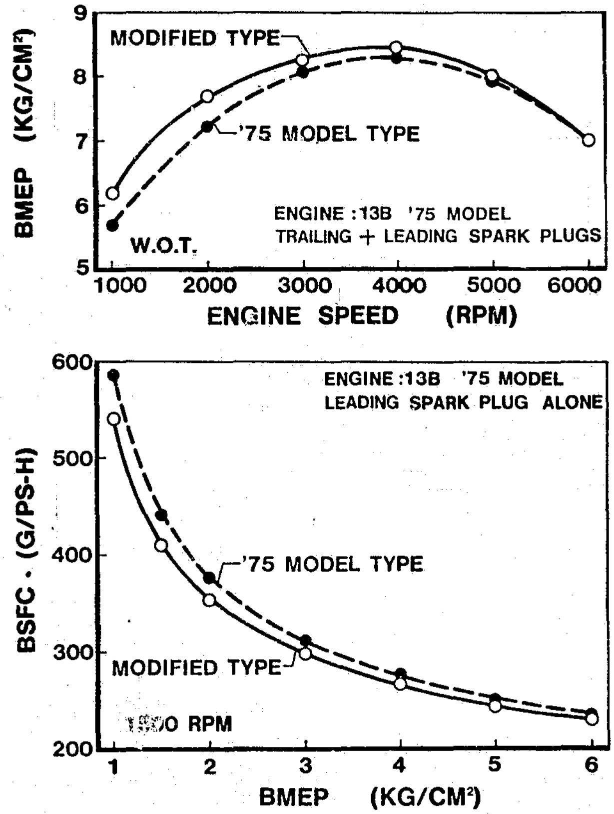

Figure 10

MODIFICATION OF COMBUSTION RECESS AND SPARK PLUG LOCATION

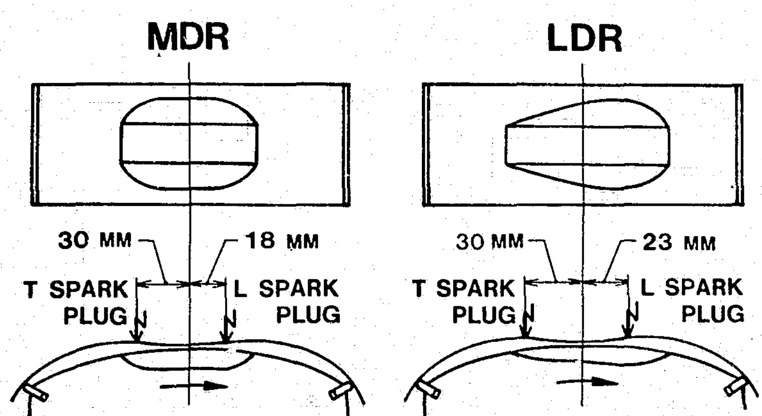

Figure 11

EFFECT OF COMBUSTION RECESS ON BSFC

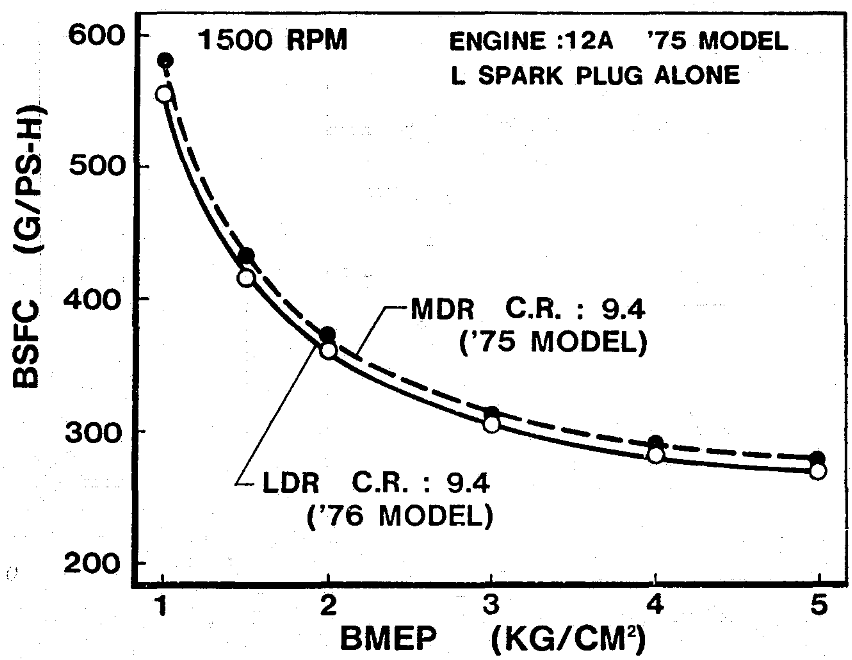

Figure 12

EFFECT OF INLET CLOSING TIMING ON BMEP

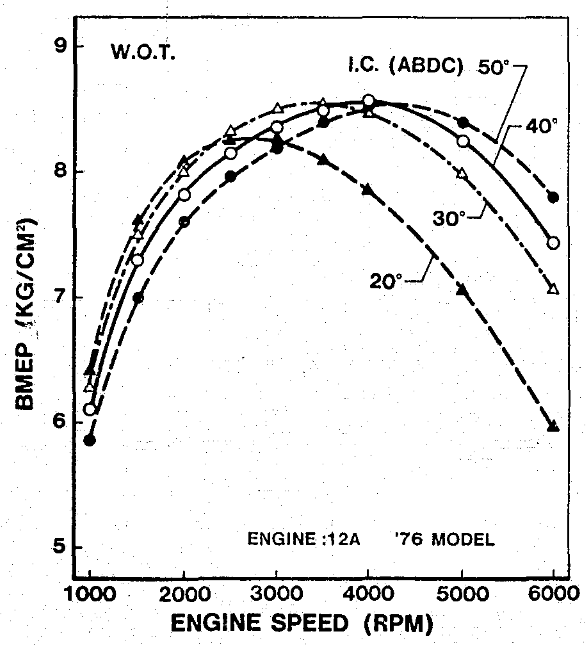

Figure 13

MODIFICATION OF EXHAUST PORT INSERT

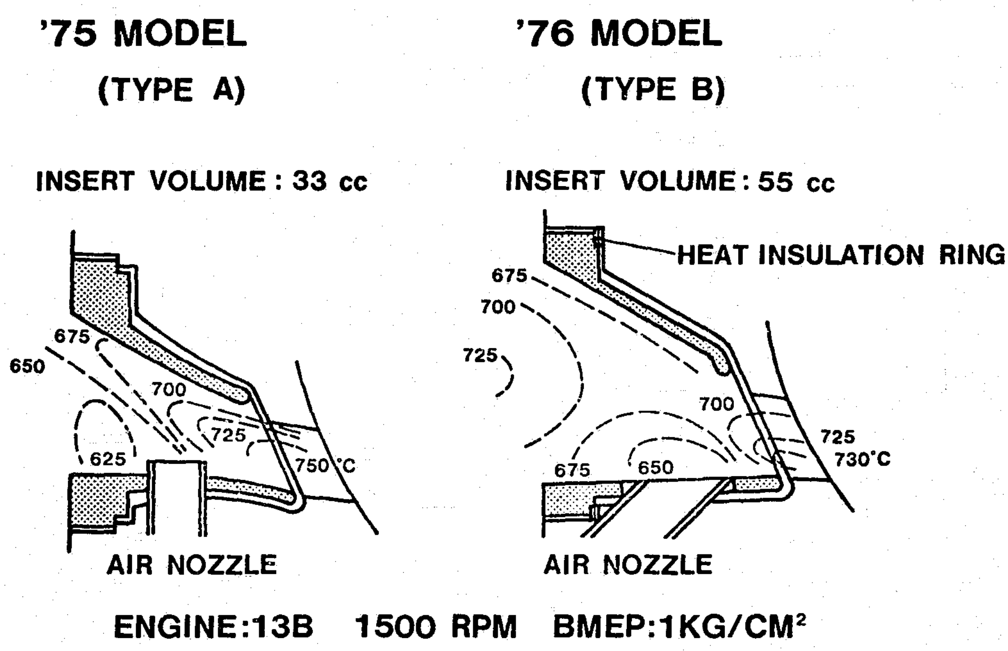

Figure 14

EFFECT OF SECONDARY AIR TEMPERATURE ON THERMAL REACTION LIMIT

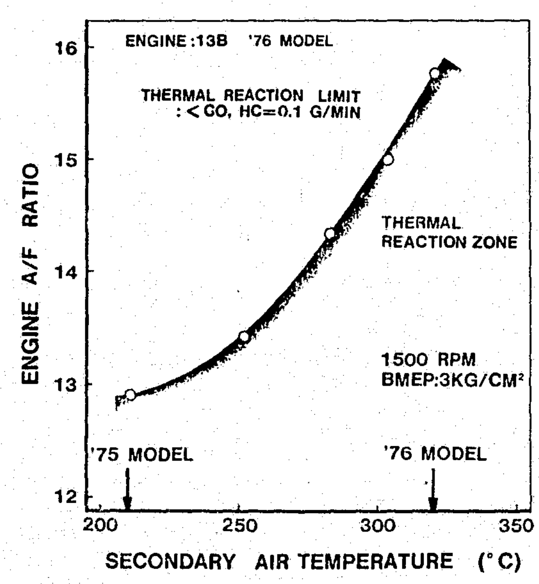

Figure 15

SECONDARY AIR PRE-HEATING SYSTEM

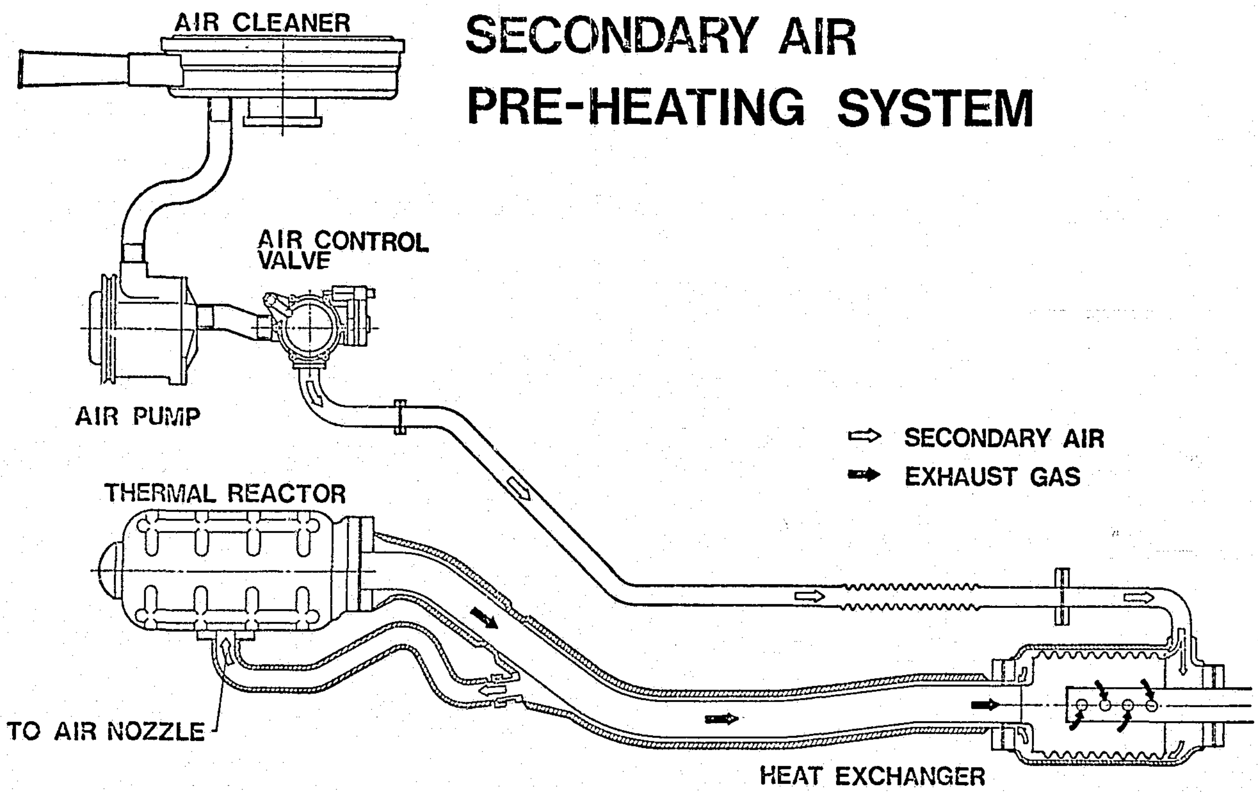

Figure 16

COMPARISON OF BSFC BETWEEN '75 AND '76 MODELS

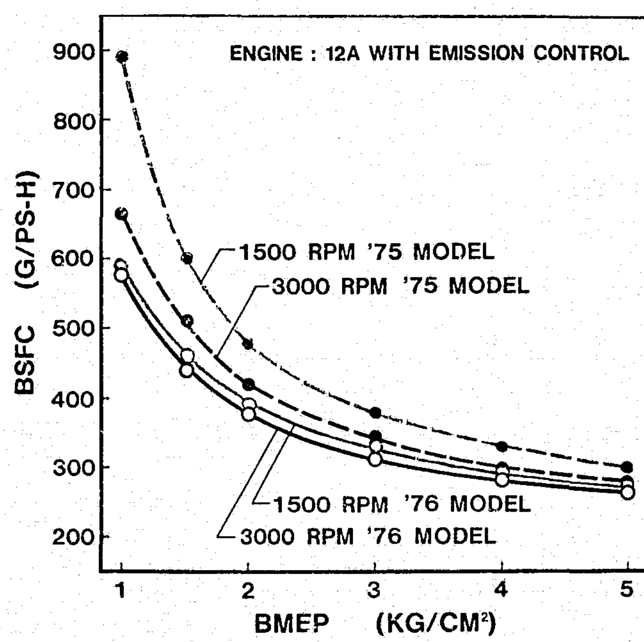

Figure 17

EFFECT OF COMBUSTION RECESS AND SPARK PLUG NUMBER ON BSFC, EXHAUST EMISSION AND EXHAUST GAS TEMPERATURE

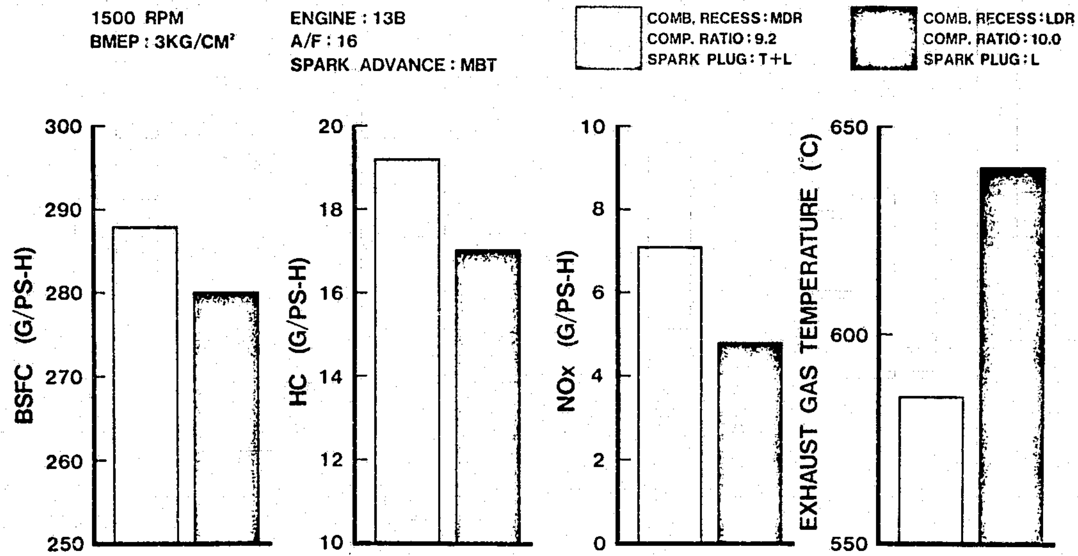

Figure 18

EFFECT OF SPARK PLUG NUMBER ON THERMAL REACTION

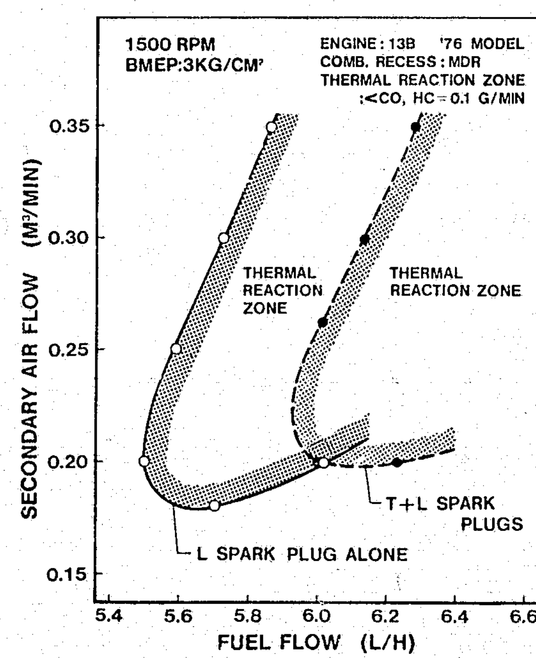

Figure 19

EFFECT OF COMBUSTION RECESS ON COMBUSTION SPEED

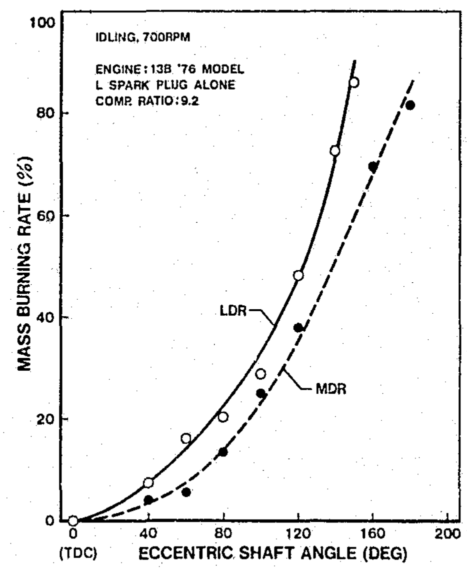

Figure 20

EFFECT OF COMBUSTION RECESS ON BMEP AND BSFC

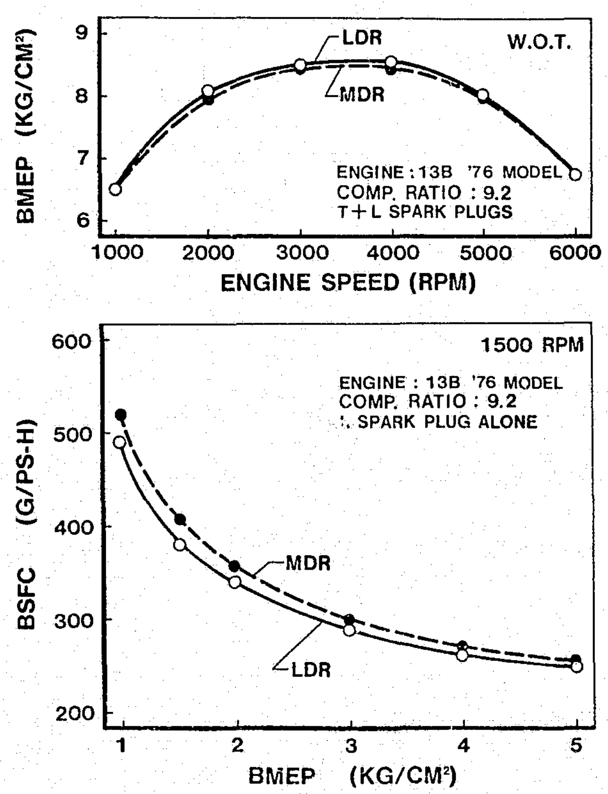

Figure 21

EFFECT OF SPARK PLUG NUMBER ON O.N.R.

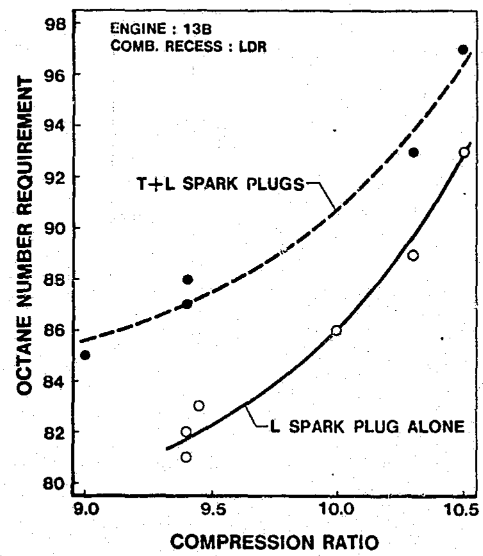

Figure 22

EFFECT OF COMPRESSION RATIO ON BMEP AND BSFC

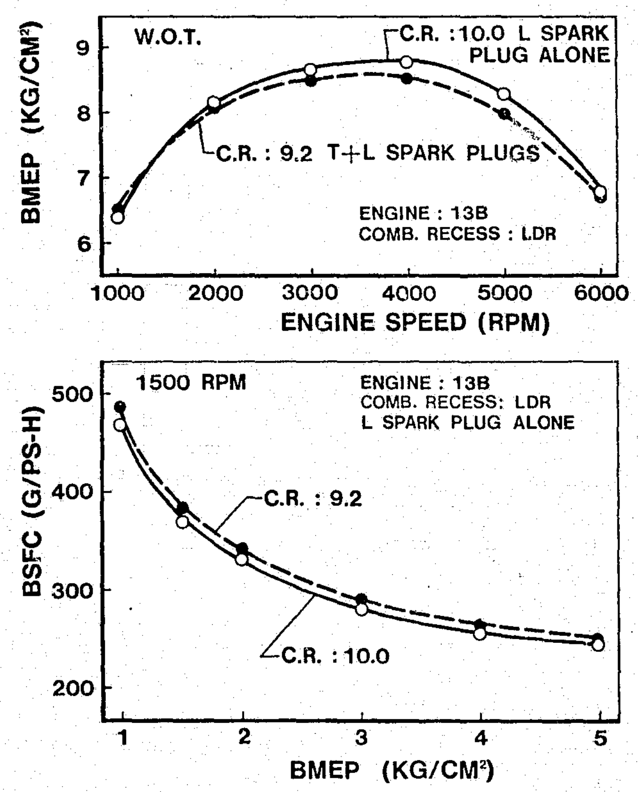

Figure 23

EFFECT OF SPARK PLUG NUMBER ON BSFC, EXHAUST EMISSION AND EXHAUST GAS TEMPERATURE

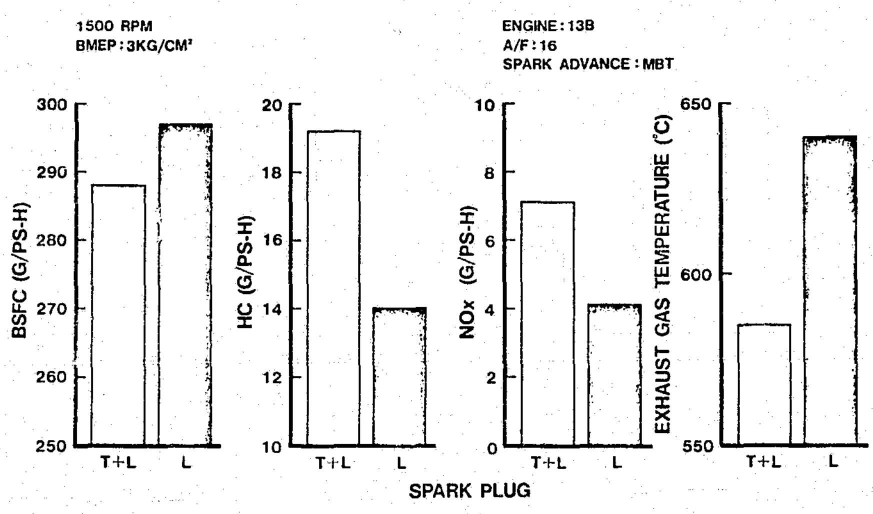

Figure 24

MODIFICATION OF GAS SEAL ELEMENTS

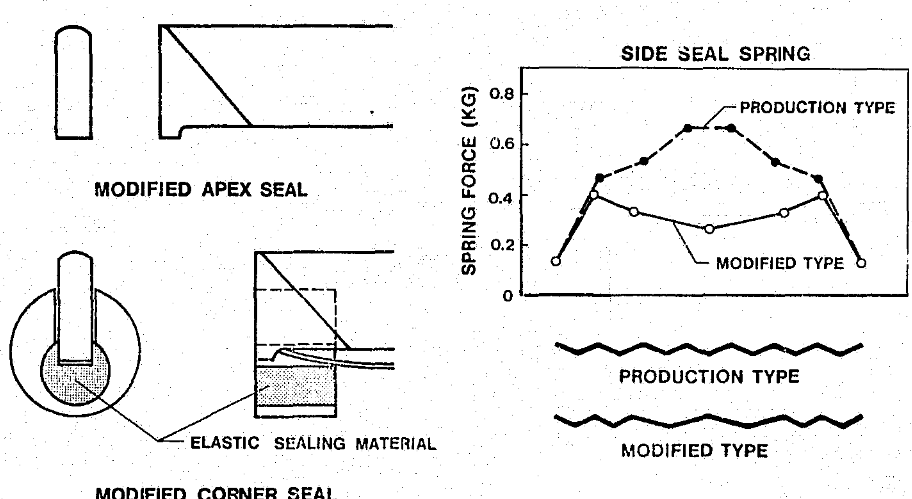

Figure 25

EFFECT OF MODIFIED GAS SEAL ELEMENTS

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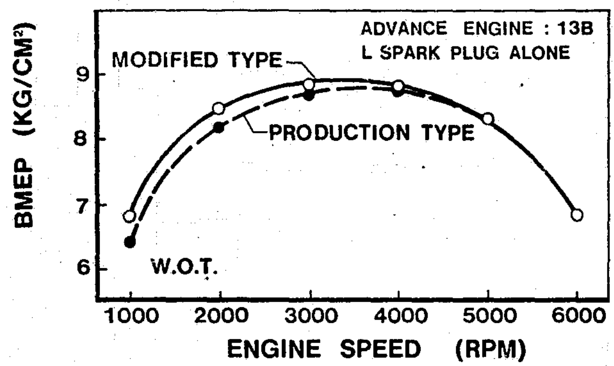


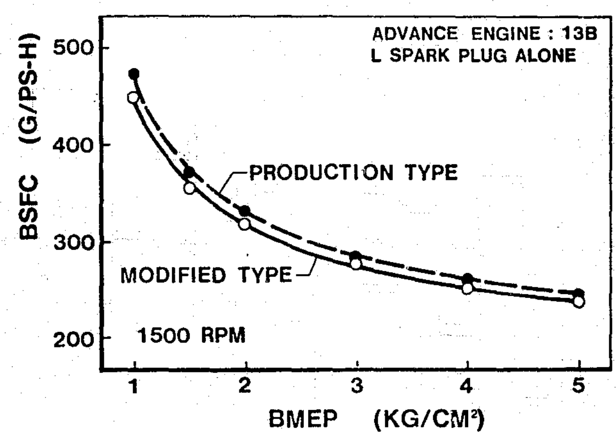
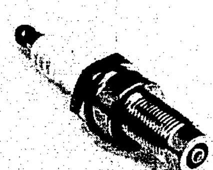


Figure 26

NEWLY DEVELOPED SPARK PLUG



SEMI-SURFACE DISCHARGE SPARK PLUG

Figure 27

EFFECT OF H.E.I. SYSTEM AND S.S.D. SPARK PLUG ON MISFIRE

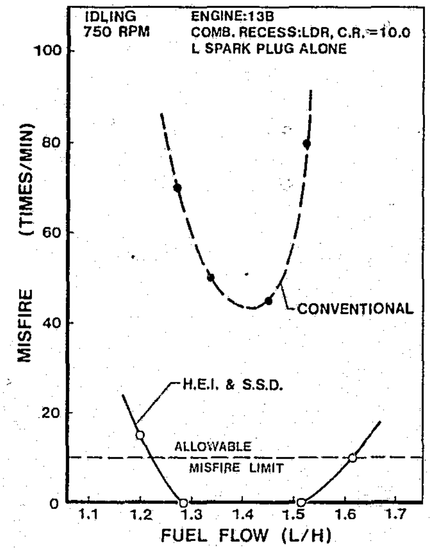
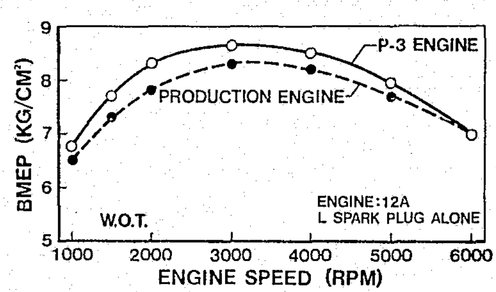


Figure 28

COMPARISON OF BMEP AND BSFC BETWEEN PRODUCTION AND ADVANCE ENGINE (P-3)



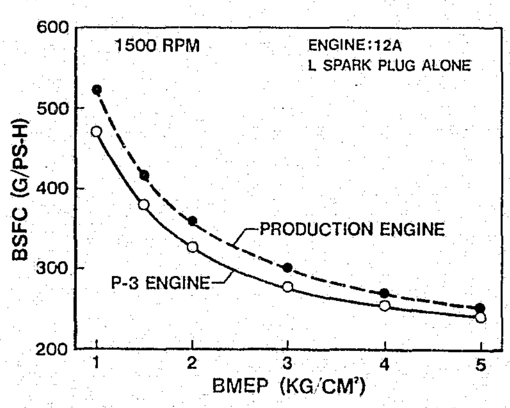


Figure 29

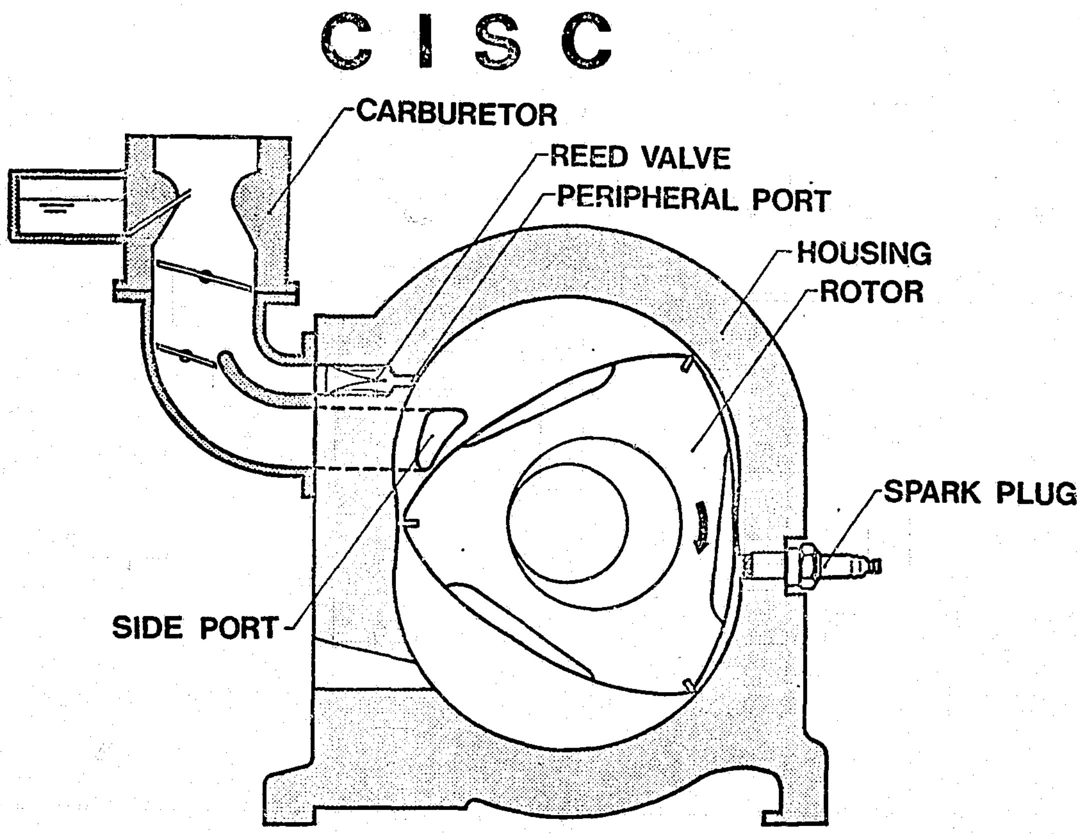


Figure 30

EFFECT OF CISC ON COMBUSTION STABILITY

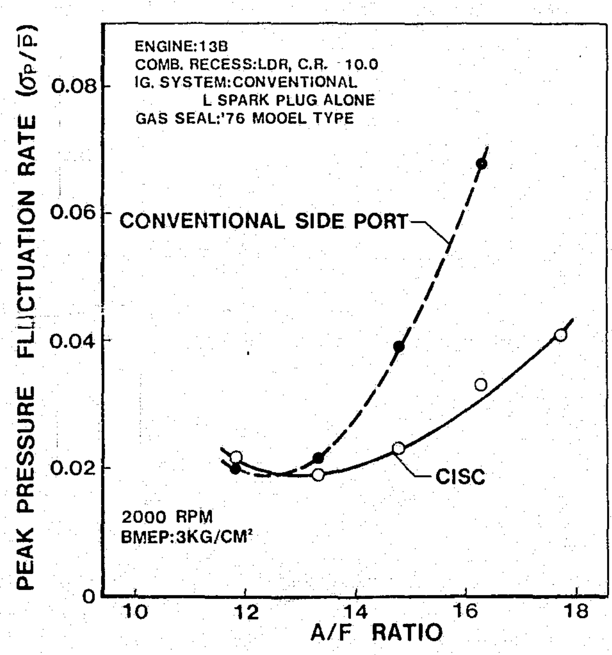


Figure 31

EFFECT OF CISC ON BSFC

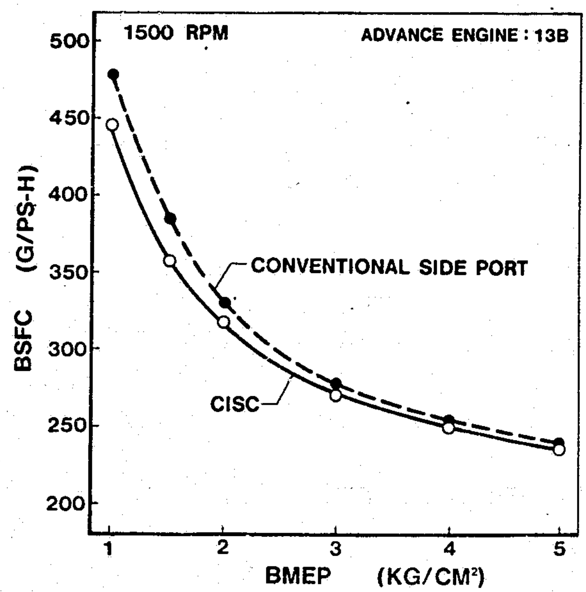


Figure 32

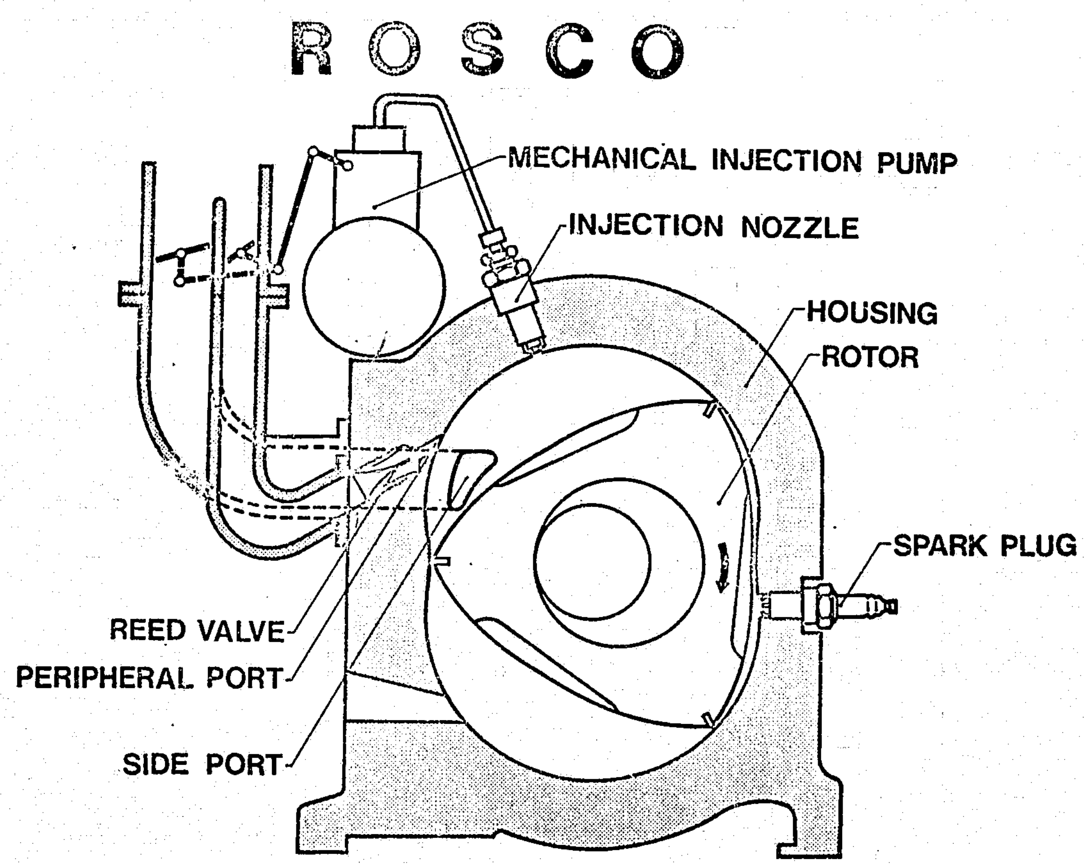


Figure 33

EFFECT OF ROSCO ON COMBUSTION STABILITY

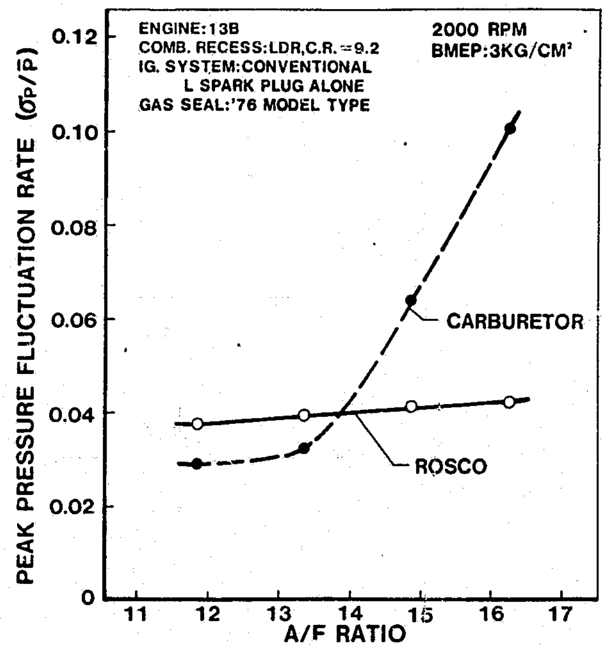


Figure 34

EFFECT OF ROSCO ON COMBUSTION STABILITY

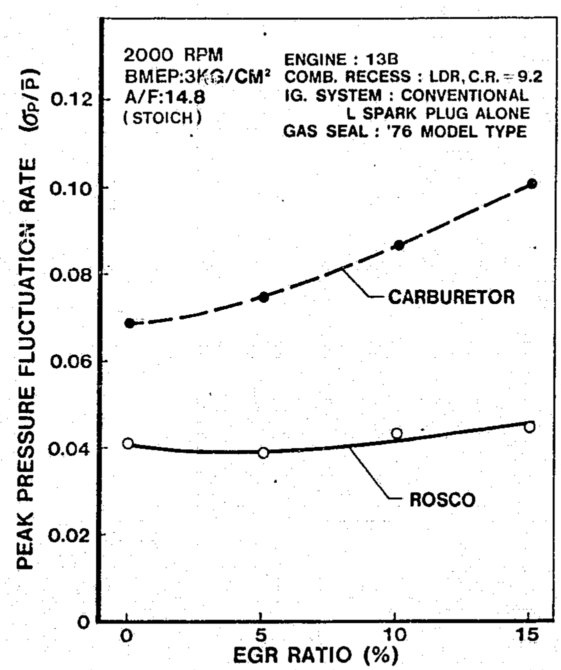


Figure 35

ELECTRONIC FUEL INJECTION

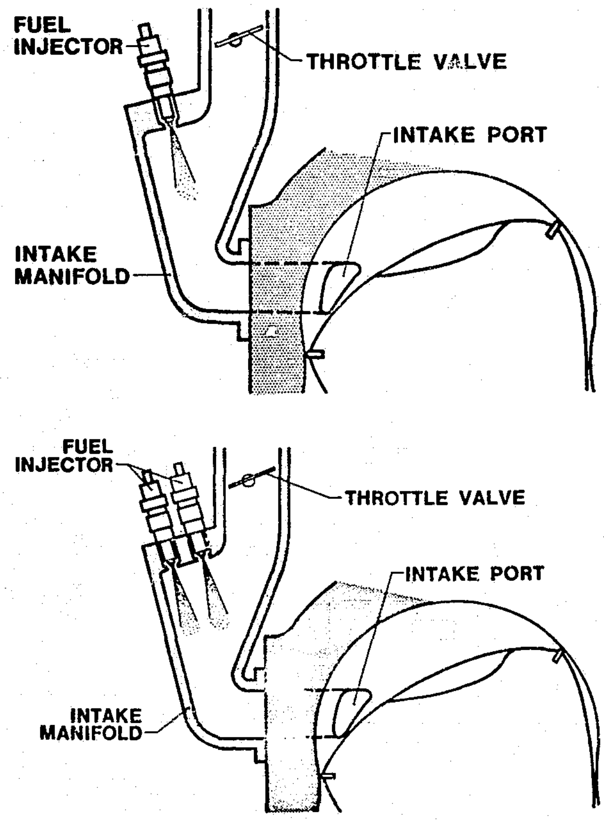
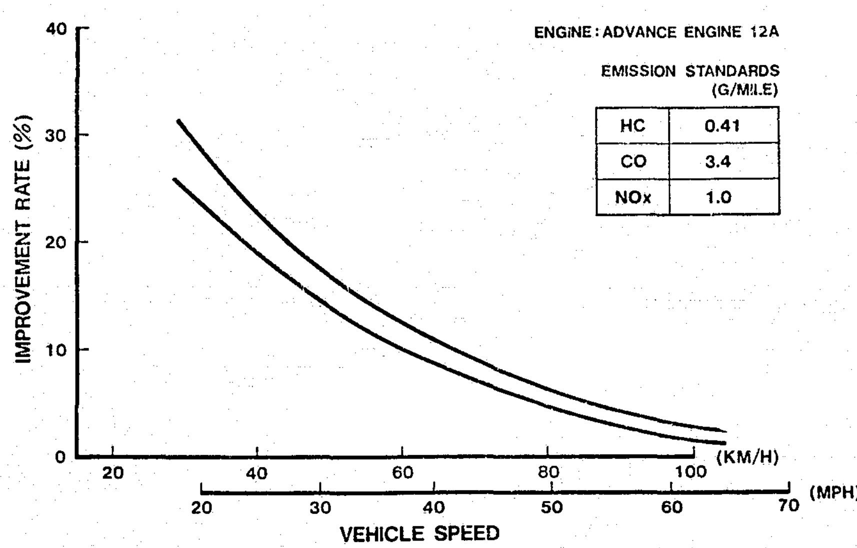


Figure 36

IMPROVEMENT RATE OF FUEL ECONOMY



HC	0.41
CO	3.4
NOx	1.0

Figure 37

VEHICLE DURABILITY TEST

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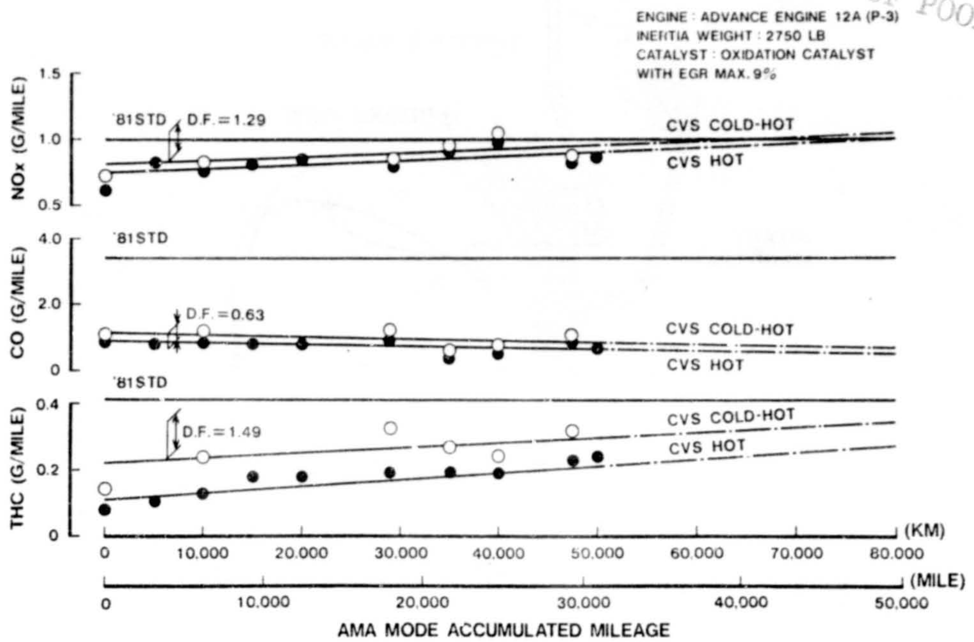

Figure 38

MARINIZED 13B ENGINE

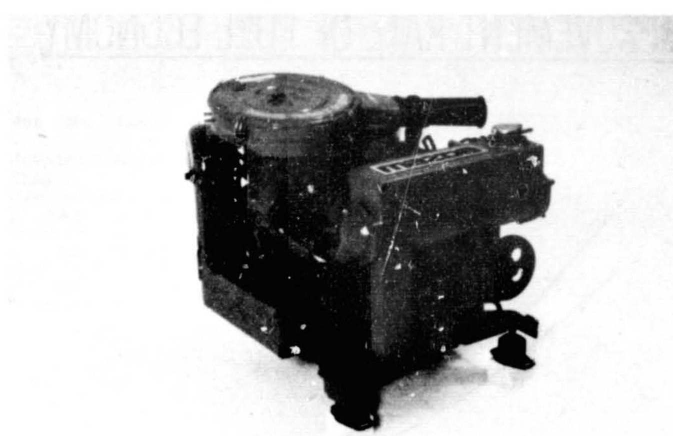

Figure 39

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BRIDGE TYPE & STANDARD INTAKE PORTS

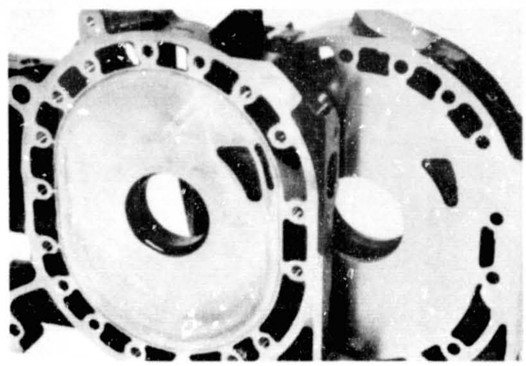

Figure 40

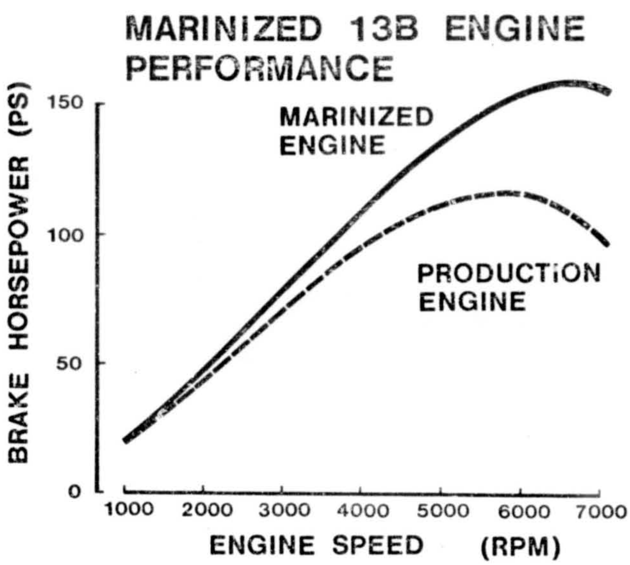

Figure 41

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ROTARY MARCH

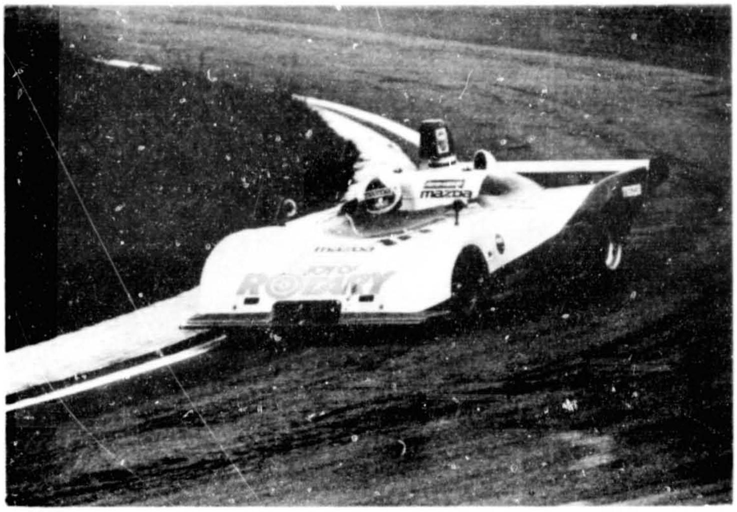

Figure 42

13B RACING ENGINE

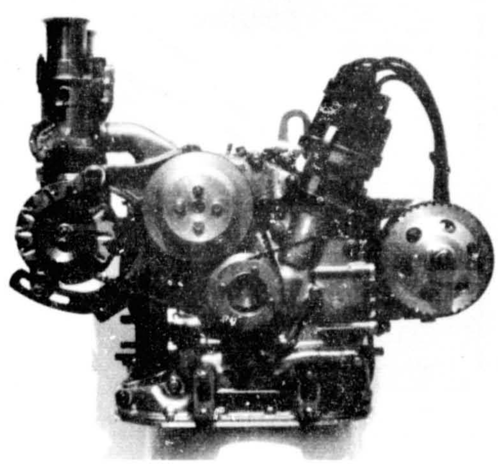

Figure 43

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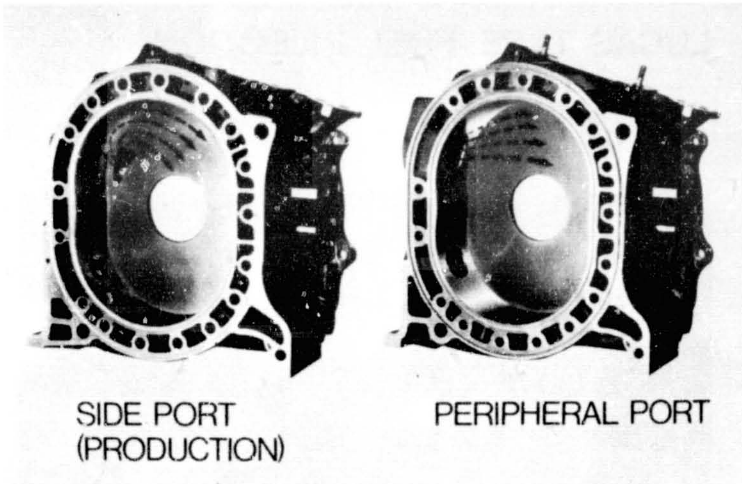

Figure 44

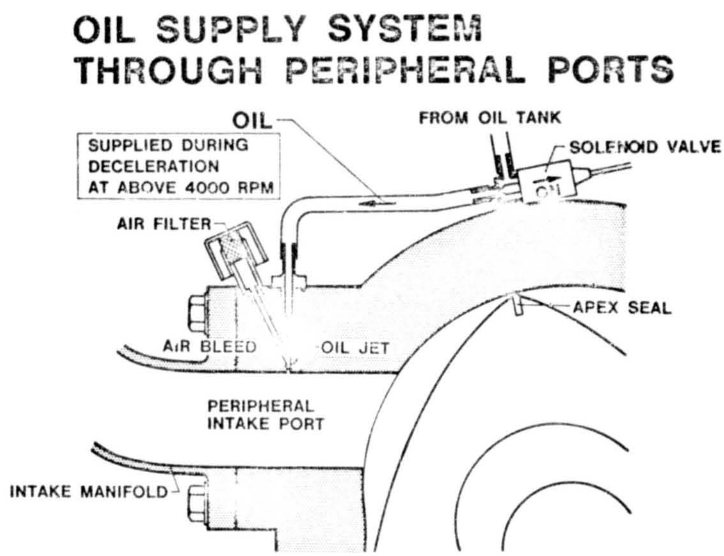

Figure 45

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LUCAS TYPE FUEL INJECTION

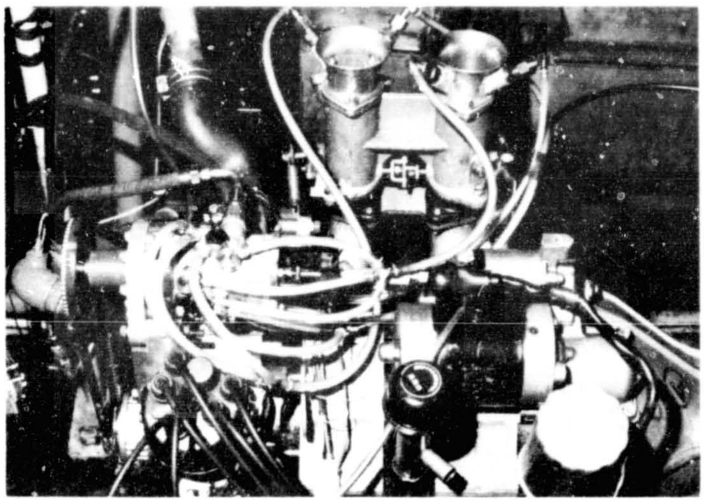

Figure 46

D4

UPDATE OF DEVELOPMENT ON THE NEW AUDI NSU ROTARY ENGINE GENERATION

N79-15965

Richard van Basshuysen
Audi NSU Auto Union

Since 1971, AUDI NSU has developed a new generation of rotary engines with a chamber volume of 750 cc as a two rotor automotive powerplant, called KKM 871. This engine can be compared to a 3 liter or 183 cubic inch, six-cylinder reciprocating engine.

In the following, the development and the current status will be presented.

1. GENERAL LAYOUT

The general layout of the new rotary engine generation resulted out of the target to develop a comfort powerplant for passenger cars with front wheel drive.
The geometric layout has been optimized by analytical and empirical investigations. Fig. 1 is a graph of this optimizing study showing the eccentricity as axis of ordinate, rotor radius as abscissa coordinate and rotor width as parameter lines g. The additional lines of parameter f represent constant specific intake port areas, only valid for an engine with side intake port. For the desired chamber volume a zone is defined, in which the most favourable range of engine geometry in respect to strength and structure is marked by the limitation lines a, b, c, d and e. Within this area of favourable engine design the KKM 871 has been selected with 17 mm eccentricity, 122,5 mm rotor radius and 69 mm rotor width. This results in sufficient safety margins to all limitation lines under consideration of an engine size as small as possible. This geometric layout was accompanied by thermodynamic calculations and investigations using simulation models.

2. ENGINE STRUCTURE

Based on the preliminary examinations the engine has been developed up to the current status as shown in Fig. 2 with the following characteristic features:

- water cooling for engine housings
- oil cooling for rotor, thermostatically controlled
- dual side intake port, peripheral exhaust port
- mixture preparation by Bosch-K-Jetronic-fuel injection system
- two fuel injection nozzles per bank
- direct lubrication of the gas sealing

- dual ignition with two separate ignition systems
- dual scraper ring oil seal
- exhaust emission control system with catalytic converter

Fig. 3 shows a picture of a prototype experimental engine with the intake manifold for the K-Jetronic.

In the following various items of the structural configuration mentioned will be further explained.

2.1. Intake and exhaust system

In the beginning of the development extensive comparison tests have been conducted between the same engine with peripheral and side intake port to find the most suitable intake system. The decision was made in favour of the double side port configuration that had already shown operational advantages in earlier NSU-experimental engines. The major factors that applied in this decision were:

- far less sensitivity to the tuning of the exhaust system with aftertreatment devices
- less influence to the tuning of the intake system
- lower induction noise
- possibility of port timing of intake and exhaust with nearly no overlap
- and by favourable selection of engine geometry roughly the same performance as with the peripheral port configuration

2.2. Fuel injection system

To realize a lean burn concept and according to basic investigations a standard Bosch-K-Jetronic, used for production 6-cylinder reciprocating engines has been selected.
Fig. 4 shows the complete mixture supply system. The intake air quantity is metered by an air flow sensor installed in the mixture control unit. According to the volume of air metered, a fuel distributor apportions a specific fuel quantity via the injection nozzles into the combustion chamber. Since a fuel distributor with 6 exits is used both injection nozzles per chamber will be supplied with different fuel quantities:

- the rotor housing injection nozzle with two thirds of the total fuel per chamber, by connection of two exits.
- the intake manifold injection nozzle with one third of the fuel quantity per chamber by one distributor exit.

An electromagnetic start valve, placed at the common intake manifold, is under certain conditions injecting an additional quantity of fuel in case of engine starting. During the warm-up period an increased fuel quantity will be provided via a warm-up control.
If, under this condition, the throttle valve is closed, supplementary air is inducted via the additional-air-valve for stabilization respectively increase of idling speed. The intake manifold shows a design, in which downstream of the common part each intake channel has a separate air supply.
The two outer intake pipes, connected to the front and rear side housings are equipped with one intake manifold nozzle each, whereas the two pipes of the intermediate housing are without injection nozzles and therefore feeding air only.
The coasting valve shown in Fig. 4 has the function to cut off the air under coasting condition, which is defined by closed throttle valve, gear and clutch engaged and engine speed above idling. By air-cut-off, the air-flow sensor in the mixture control is not operating and thus the fuel supply is interrupted.
A more detailed illustration of the rotor housing injection nozzle is shown in Fig. 5. In difference to a standard fuel injection, this nozzle is provided with an air jacket. The air, selfinducted by such a configuration, is directed radially onto the fuel jet via a narrow gap at the tip of the nozzle.

2.3. Gas sealing lubrication system

By using fuel injection it is no more possible to apply a lubrication system based on oil/fuel mixture. Consequently a new direct lubrication system for the gas sealing as shown in Fig. 5 has been developed. In this system oil and air as shown in section A-A will be supplied via channels in the rotor housing to small recesses in the side housing. The lubrication oil thus entering the combustion chamber will be distributed to the trochoid surface as well as to the side housing surfaces.

2.4. Ignition System

The ignition system used is a transistorized coil ignition system with a considerably decreased inner resistance resulting in a steeper increase of voltage and less shunting effect.
The energy storage becomes nearly independant from engine speed and by this the drop of ignition voltage capability at high speeds will be reduced.
Fig. 6 shows the ignition voltage capability of a conventional and a transistorized coil ignition system in comparison to the range of the voltage requirement between a new and a used spark plug indicated by the cross hatched area. It is obvious that the transistorized ignition system offers a considerable higher safety margin.
The two distributors, which are of conventional type, allow different ignition timings to be set for the leading and for the trailing spark plug. An inductive ignition timing control guarantees an accurate and free-of-maintenance operation.
Fig. 7 shows the position and design of the spark plugs as well as the configuration of the shooting holes.

The trailing spark plug is provided with a narrow shooting hole by reason of reducing the blow back across the apex seal tip. The center of this shooting hole is dislocated eccentrically to the opposite direction of rotor rotation. This results in a purposefully scavenging of the spark plug pre-chamber by fresh mixture and at the same time in a purification of this pre-chamber from deposites, that can be responsible for preignition. This effect is additionally supported by a conical recess in the spark plug face as it can be seen in the drawn up detail. Both spark plugs are of the surface gap type with an additional ground electrode.

2.5. Rotor cooling and rotor design

The KKM 871 is provided with a thermostatically controlled rotor cooling for faster warm-up and for maintaining a higher temperature level on the rotor flank respectively rotor recess. This is a measure to improve the mixture preparation in the combustion chamber and to decrease the friction losses.
Fig. 8 indicates the effect of this control. The graph shows the different areas in which the oil jet will be open, closed. or regulating depending on engine speed and load.
The design of the inner structure of the rotor has been modified to realize a directed cooling oil flow as shown in principle in Fig. 9. The cooling oil is injected into the rotor on the left side by the oil jet. In the areas below the apex seal groove the oil will flow over to the other side and than will be forced out of the rotor by way of ribs. By such an oil flow system, the oil will pass mainly the areas of the sealing elements and by this the cooling effect is concentrated on the critical places.
Fig. 10 shows the reduction of friction mean effective pressure with this new rotor, called thin film, type in comparison to the rotor with an interior cell structure used so far.

2.6. Exhaust emission control

In respect to exhaust emission control for compliance with the US and Japanese requirements, systems with catalytic converters have been selected.
Fig. 11 shows the principles of these systems differentiated into the United States version which includes a so called starting catalytic converter, and the Japanese version with one converter only. Looking at the US-system, the starting catalytic converter is located close to the engine exhaust port to reach as fast as possible the reaction temperature needed.
Currently this converter consists out of one catalyst per exhaust port and is provided with a bypass. controlled by a flap. Under cold starting condition, the exhaust gas is directed through the starting converter and when engine oil and catalyst temperature reach a certain value, this converter will be bypassed and only the main converter will remain in function.
The latter converter contains two catalysts located in-line with a short spacing in between. The separation into two segments serves for generating a more turbulent exhaust gas flow through the catalyst as well as for a faster warm-up. Presently used are metal support catalysts with platinum coating from the German Company Degussa.

Due to the richer air/fuel mixture under cold start condition it is still of an advantage and for the stringent US-standards necessary, to use an air pump for secondary air injection. This air, however, will be cut off, if the water temperature exceeds 68 degree centigrade.

3. TEST RESULTS

The following items present test results with the KKM 871, related mainly to the engine configuration described so far. The results also include some data of the different engine development stages and are explained by means of fuel consumption, exhaust emission, noise emission and durability.

3.1. Engine Performance

The performance at wide open throttle is shown in Fig. 12 indicating the maximum output at 6500 rpm of 165 horse power, a maximum BMEP of 130 PSI and a minimum specific fuel consumption of .51 lbs/HP-HR.

3.2. Fuel Consumption

Concerning fuel consumption one of the main targets was to reach the level of comparable European reciprocating engines. This has been realized by improvements in the fields of:

- mixture preparation
- gas sealing system
- friction losses
- ignition
- combustion

3.2.1 Ideal mixture

In respect to mixture preparation a principle investigation with a so called "ideal mixture" has been conducted to find out, to what extent the lean out ability and the fuel consumption can be improved only by a perfect preparation of the air-fuel mixture. For this purpose a special test arrangement for ideal mixture formation as schematically shown in Fig. 13 was used. Hereby, the intake air as well as the fuel delivered by a fuel injection system, will be heated up sufficiently before both are forming an ideal mixture in a heated reservoir.
Out of this reservoir a homogeneous charge of 70 degree centigrade will be inducted by the engine. Due to the homogenization, the cyclic variations of the air-fuel ratio are omitted. The high mixture temperature prevents a condensation of the fuel in the intake passage, which guarantees a uniform composition of the charge inducted. The test results with this system are shown in Fig. 14. At four characteristic points of the engine operating range, the specific fuel consumption is plotted over the excess air ratio. The engine with ideal mixture is compared with carburetted engines.

The measurements show a significant improvement of lean out ability up to excess air ratios of 1.4 and a reduction of the minimum specific fuel consumption.

3.2.2. Engine operation with K-Jetronic

The investigation with the ideal mixture has indicated, that a lean burn concept can be realized which now should be attained with a standard mixture preparation device. For this purpose the carburetor used so far has been replaced by the Bosch K-Jetronic. Experiments have shown, that with this fuel injection system the best results so far in respect to mixture preparation and driveability have been gained with the injection nozzles location shown already. It was also found, that an improvement of atomization of the fuel jet, and by that, a lower penetrating depth could be realized with the annular air jacket of the rotor housing nozzle. As the nozzle is located close to the intake ports, where vacuum is always present, the air is self-inducted via this air jacket and is reducing the fuel droplet size obviously. Fig. 15 shows the average test results with this system in comparison to engines with carburetor. The curves are very similar to those with the ideal mixture. This means nearly same lean out ability and a displacement of the minimum specific fuel consumption to higher excess air ratios, both requirements for a lean burn concept. Another comparison, shown in Fig. 16, where SFC is plotted versus BMEP at 2000 rpm, demonstrates the improvement in SFC related to the different development stages. The curves of the prototypes originate from engine versions without exhaust emission control systems. How the improvements in mixture preparation affect the fuel economy on the road shows a comparison test in Fig. 17. An increase of fuel economy under transient driving condition between 8 and 11 percent could be gained with the K-Jetronic compared with the same engine equipped with carburetor. Fuel economy at constant speed in comparison to European cars with 6-cylinder reciprocating engines are shown in Fig. 18. Whereas the reciprocating engines, however, are only complying with the present European exhaust emission standards, the KKM 871 is equipped with an exhaust emission control system for future stringent US-standards.

As shown by these results the target of fuel consumption equal to that of reciprocating engines has been realized by the measures applied so far.

3.3. Exhaust Emission and fuel economy

In the following, exhaust emission test results and the corresponding fuel economy data will be covered . The current disadvantage of rotary engines in respect to exhaust emissions is still the higher base emission of unburned hydrocarbons. Fig. 19 shows, that in the course of improvement of fuel consumption, the base emissions of hydrocarbons and carbon monoxides have been reduced considerably. Here the base emissions in the CVS test cycle of the different prototypes II and III with carburetor and prototype IV with K-Jetronic are compared.

By comparing prototype II and III in respect to NO_x the increase was a result of improved combustion. The reduction reached again with prototype IV was gained by the lean burn concept.
Although a remarkable reduction of the exhaust emissions has been obtained so far, the use of an aftertreatment system is still necessary.

With the emission control system for USA the test data as shown in Fig. 20 have been measured. All test data are below the Federal emission standards of 1981.
In respect to CO the emission is far below the standards, so that no further problems should be expected. However it has still to be proven, that the HC-emissions will comply with the standards after the 50 000 miles endurance test. These endurance tests are still running at the time of this presentation.
Concerning NO_x, the data represent a status of the engine without any special measure for reduction.

Integrated in this diagram are average values of measurements conducted by an US-automobile company in the United States with an engine and exhaust emission control system of the current development status.
The test data from these measurements are within the range of the data specified by Audi NSU. For completion the corresponding values of the city fuel economy are added.
In Fig. 21 the ranges of fuel economy in the City- and Highway-test and the combined fuel economy are shown. Indicated additionally are the measurements of the US-automobile company confirming again our test data.
For further information fuel economy data should be mentioned resulting out of a trip through the United States with two Audi NSU cars. The driving conditions over a total distance of approximately 2800 miles for each car includes city, highway and test driving. The average fuel economy was 20.8 mpg with automatic transmission and 22.9 mpg with a 5-speed manual transmission. Measurements on highway driving only. have shown 24.4 mpg for the automatic and 27.6 mpg for the manual transmission car.

With the exhaust emission control system for Japan, the ranges of test results in the 10-Mode test gained so far are shown in Fig. 22. In this diagram results of measurements conducted by a Japanese automobile company in Japan with an Audi NSU test vehicle are included. These data, however, show a somewhat higher NO_x-emission. Since the NO_x data represent values without exhaust gas recirculation, additional investigations will be performed with EGR as well as with oxygen sensor control and three-way-catalysts to comply with the stringent 78 standards with a sufficient safety margine for production engines.
Fig. 23 demonstrates, that in the Japanese 11-mode test the results are sufficiently below the standards of 1978. By this reason no further reduction, for instance by using a starting catalytic converter. is necessary.

The fuel economy measured during a trip through Japan with the Audi NSU test vehicle equipped with a 5-speed manual transmission has shown the following average values over a total distance of approximately 1440 miles:

19.5 mpg or 8,3 km/l including test driving and emission tests

and 22,3 mpg or 9.5 km/l excluding test driving and emission tests.

3.4. Noise Emission

Since the noise emission becomes more and more important, the rotary engine should also be evaluated under this aspect. As already known, the rotary engine is advantageous in respect to low vibration and low mechanical noise. The latter becomes especially evident under road driving condition at higher engine speeds. Noise comparison tests have been conducted with a reciprocating engine and the KKM 871 both installed in the same car.
Fig. 24 shows the test results due to the test requirements of the German Certification Authority, recorded under no load condition over the whole engine speed range from a point 7 meters sideways of the vehicle. It is obvious, that evaluating the dB(A) level, the rotary engine is lower in noise compared to the reciprocating engine due to its lower mechanical noise emission.
Looking at the dB(B) level, which in difference to the dB (A) evaluates preferably the bass frequences, the lower mechanical noise level of the rotary engine comes into effect again at higher engine speeds.

3.5 Durability and wear

Experiences with former production engines of Audi NSU in respect to durability and wear have led to a very thorough testing of the new engine. Fig. 25 shows the wear results out of numerous durability tests conducted with experimental engines of the different prototype versions. Since the wear data over 62 000 miles shown can be related directly to the life time of the engine, equivalent durability as with reciprocating engines can be expected.

4. Conclusion

The present development status of the KKM 871 at Audi NSU has shown, that in respect to fuel economy the level of comparable reciprocating engines was reached. Exhaust emission test data give the expectation to comply with future US-Standards also after 50 000 miles. However, this has to be approved by means of actual endurance test results. In respect to the Japanese requirements further reduction of NO_x is necessary. The mechanical noise emission of the rotary engine demonstrates the advantage in respect to possible future restrictions.
Results of comprehensive durability tests indicate engine life time equal to that of reciprocating engines.

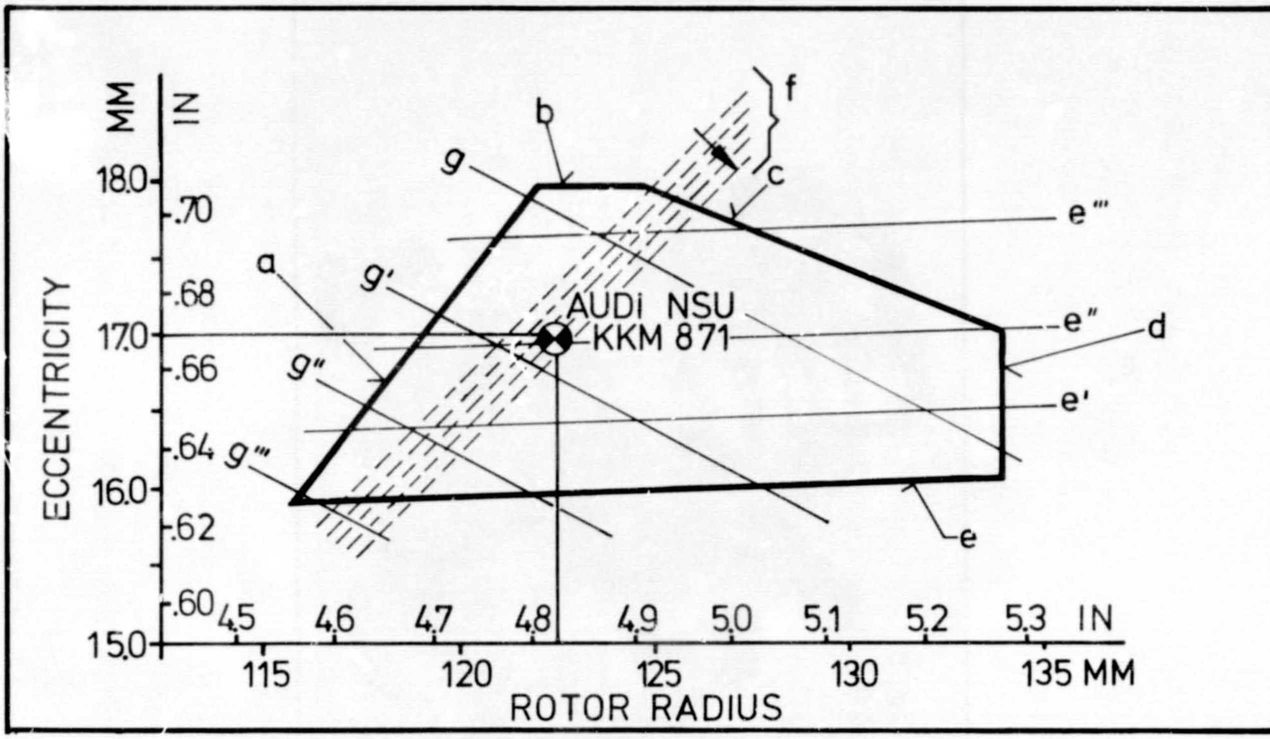

Figure 1. - Design range for R. E. with 750 cc chamber volume.

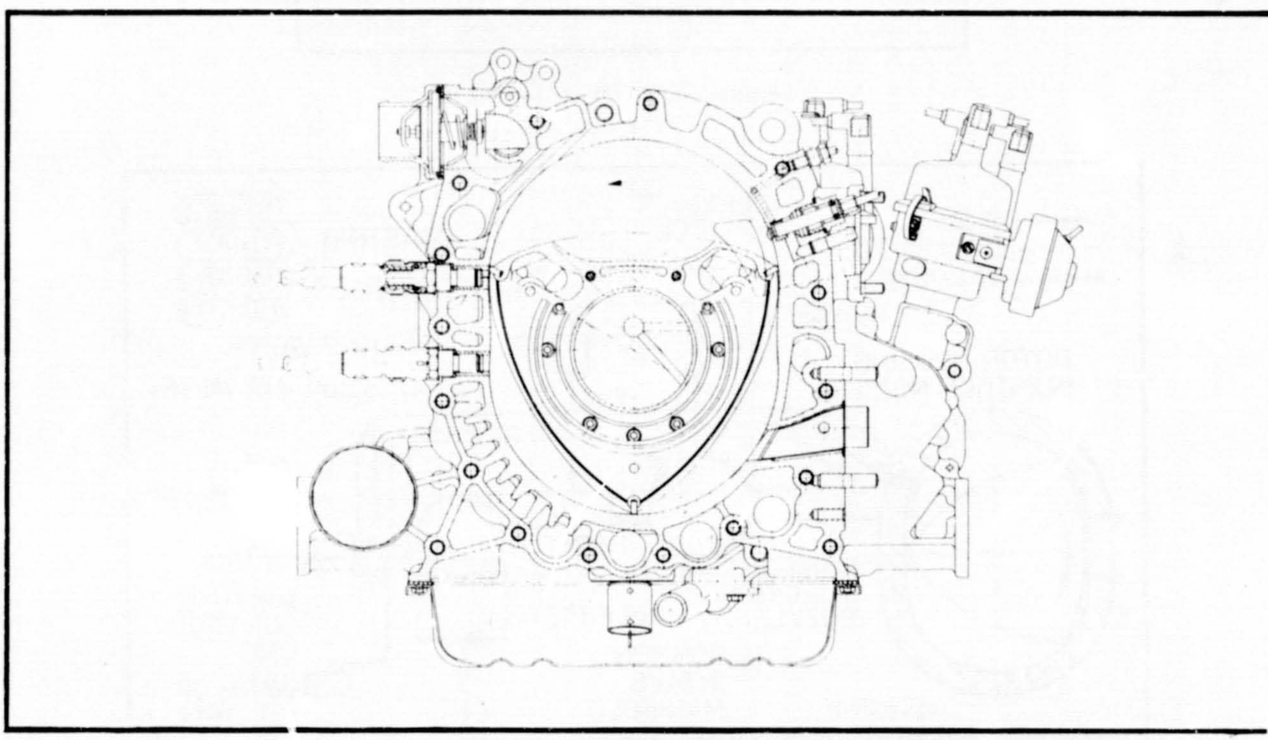

Figure 2. - KKM 871 - cross section.

C-2

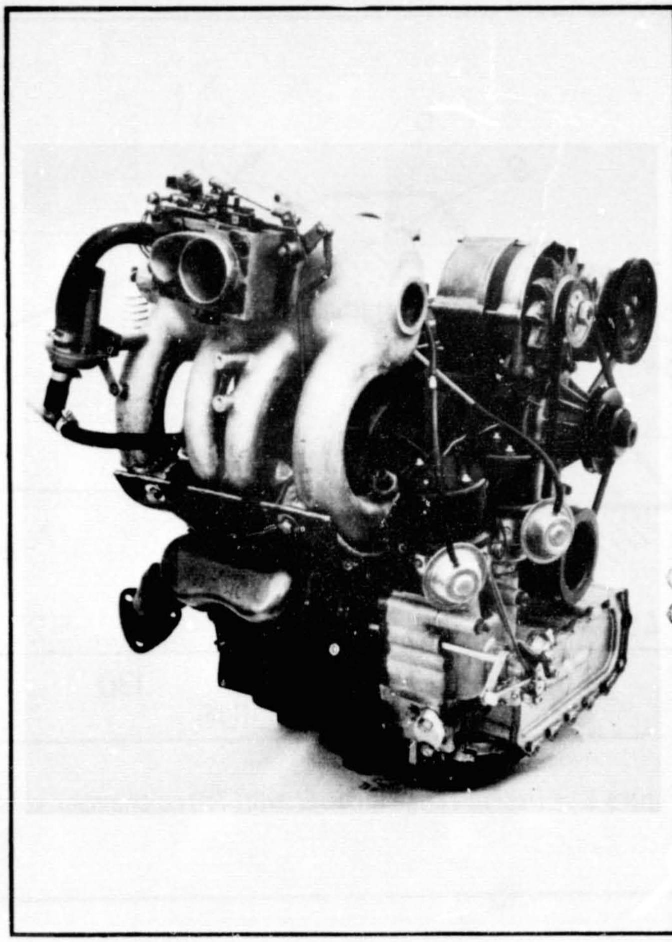

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Figure 3. - KKM 871 - test engine.

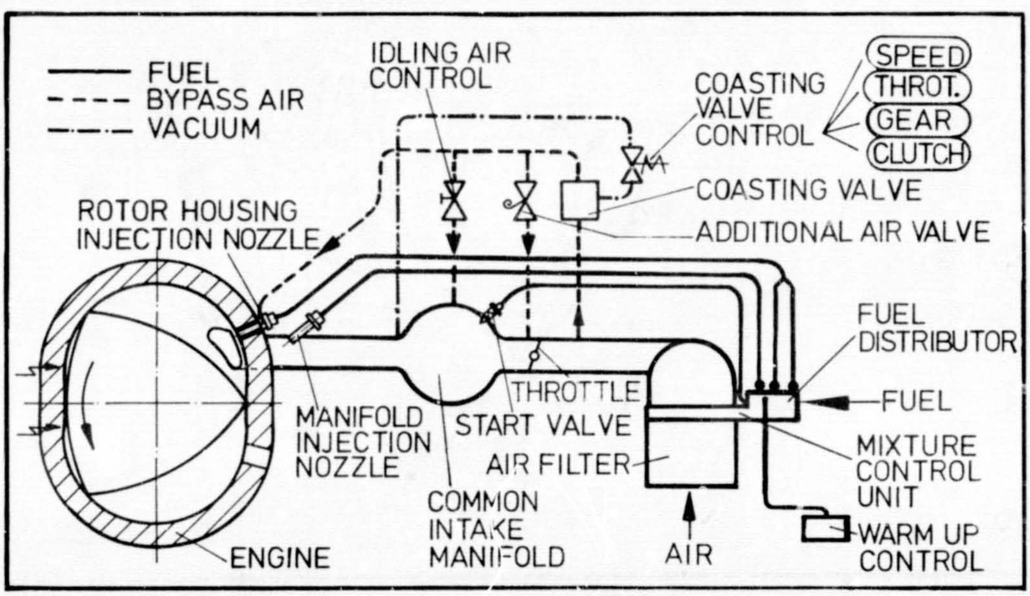

Figure 4. - Fuel and air supply system with K-jetronic.

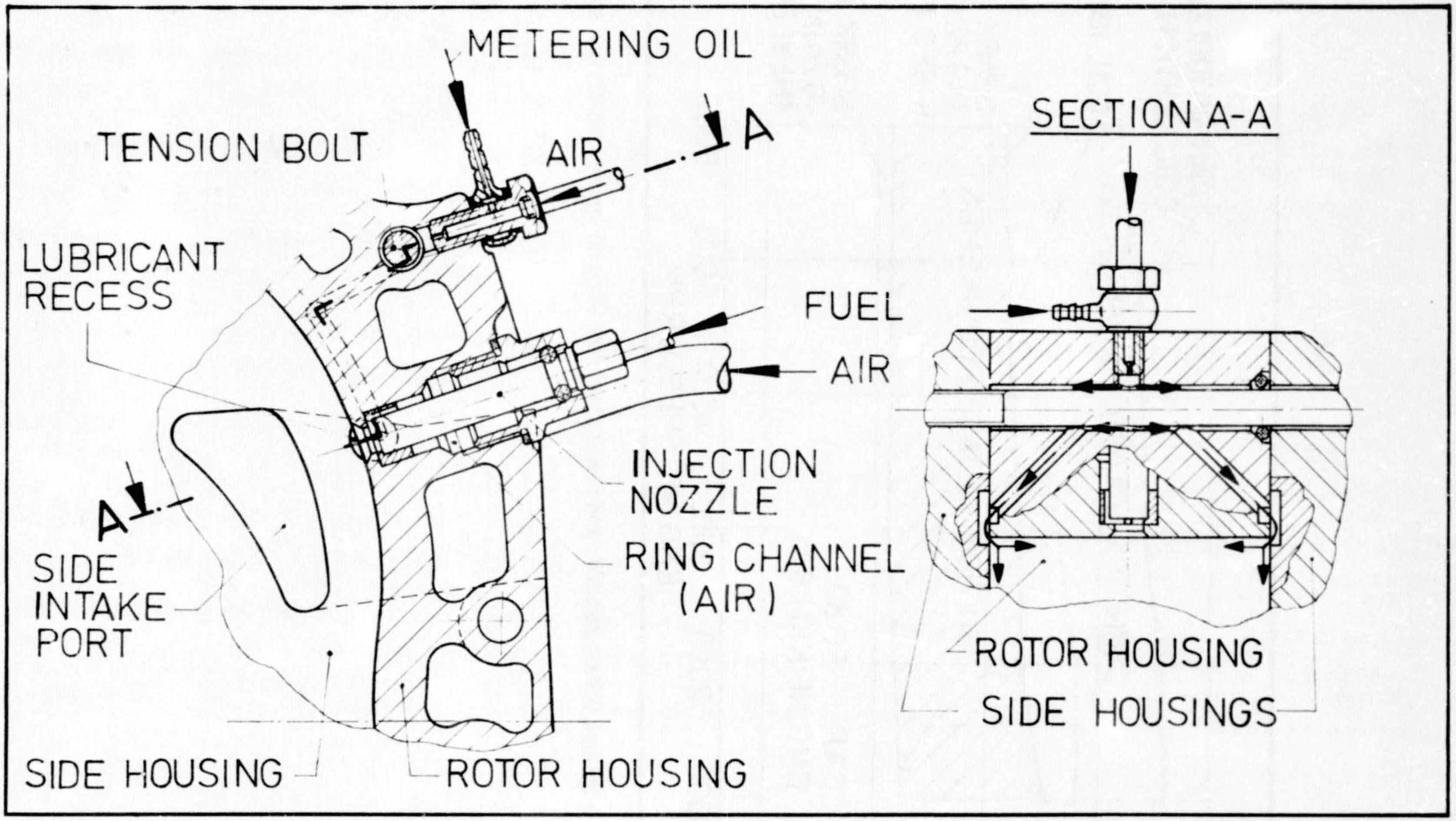

Figure 5. - Fuel injection and gas sealing-lubrication system.

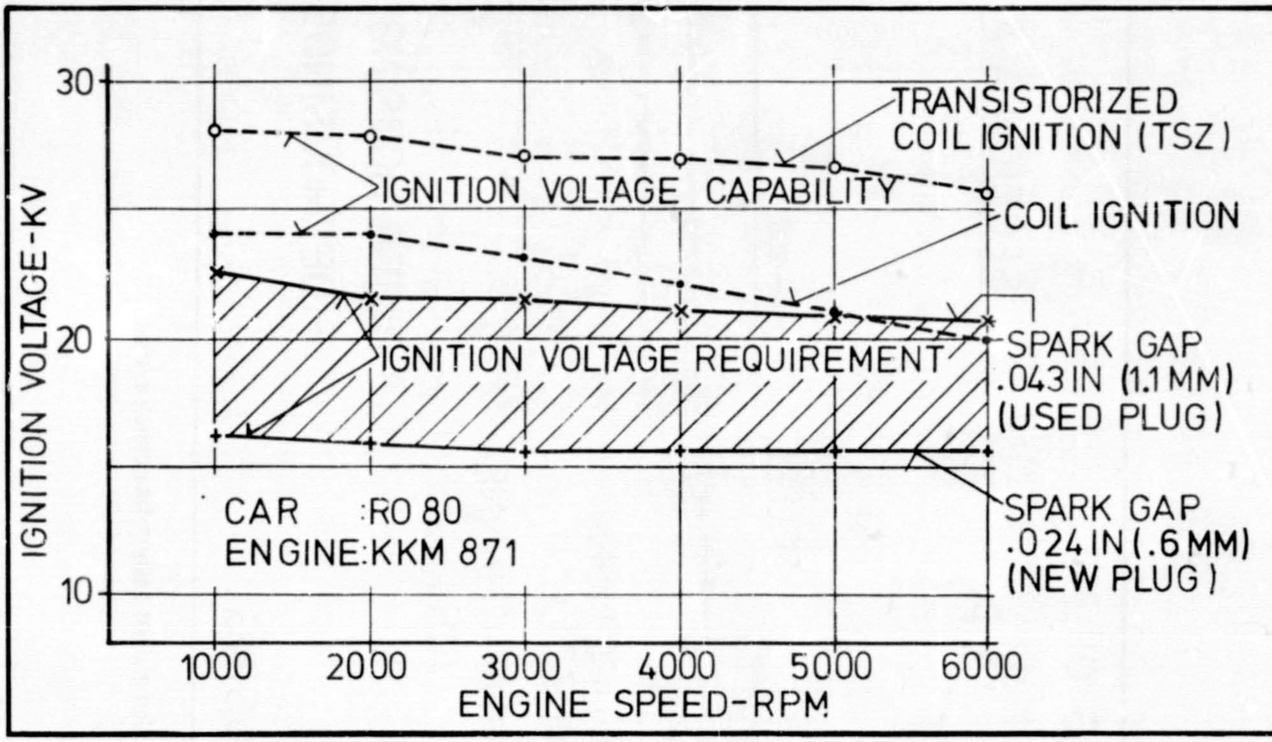

Figure 6. - Ignition voltage capability and requirement depending on ignition system and spark gap.

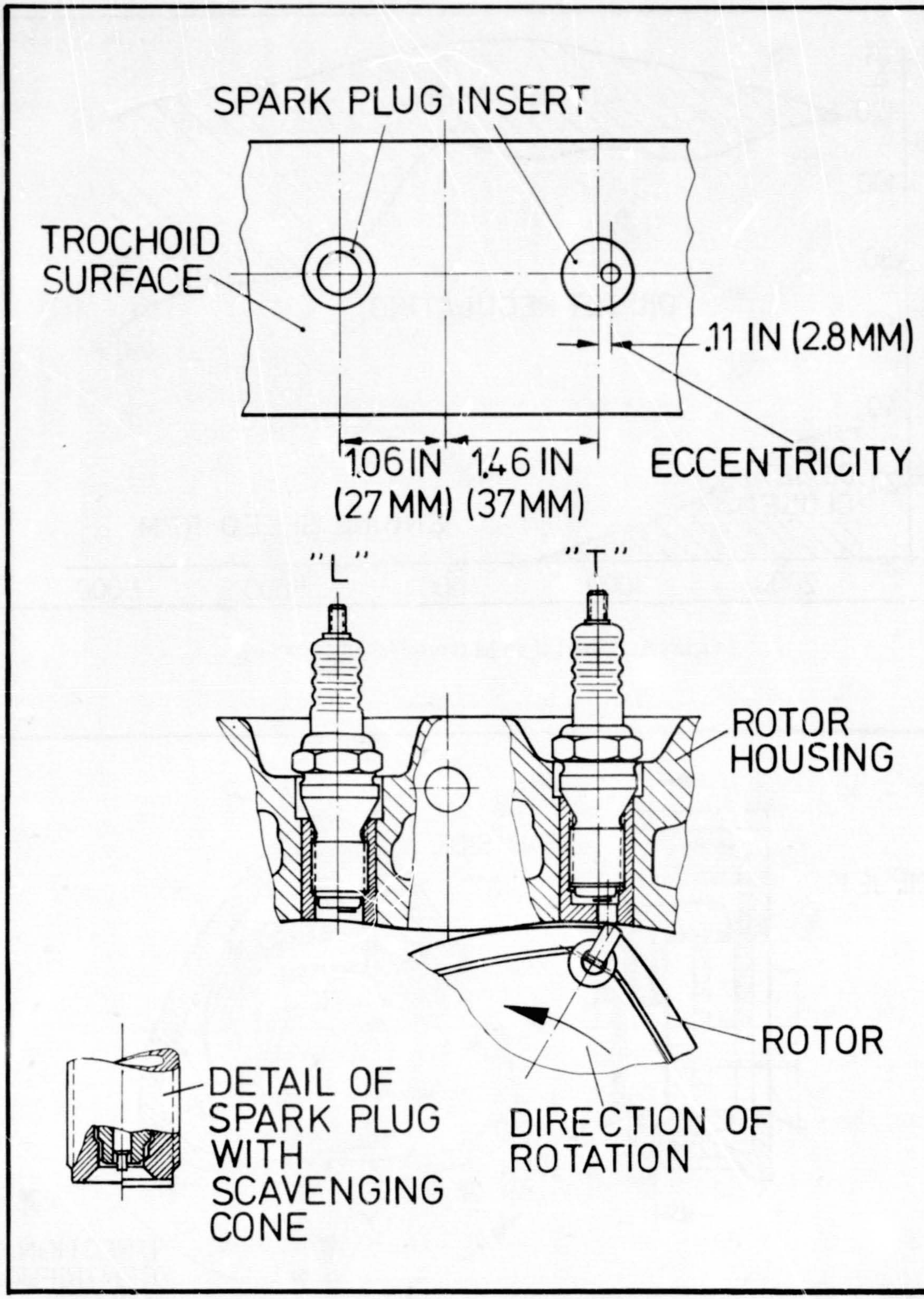

Figure 7. - Arrangement of spark plugs.

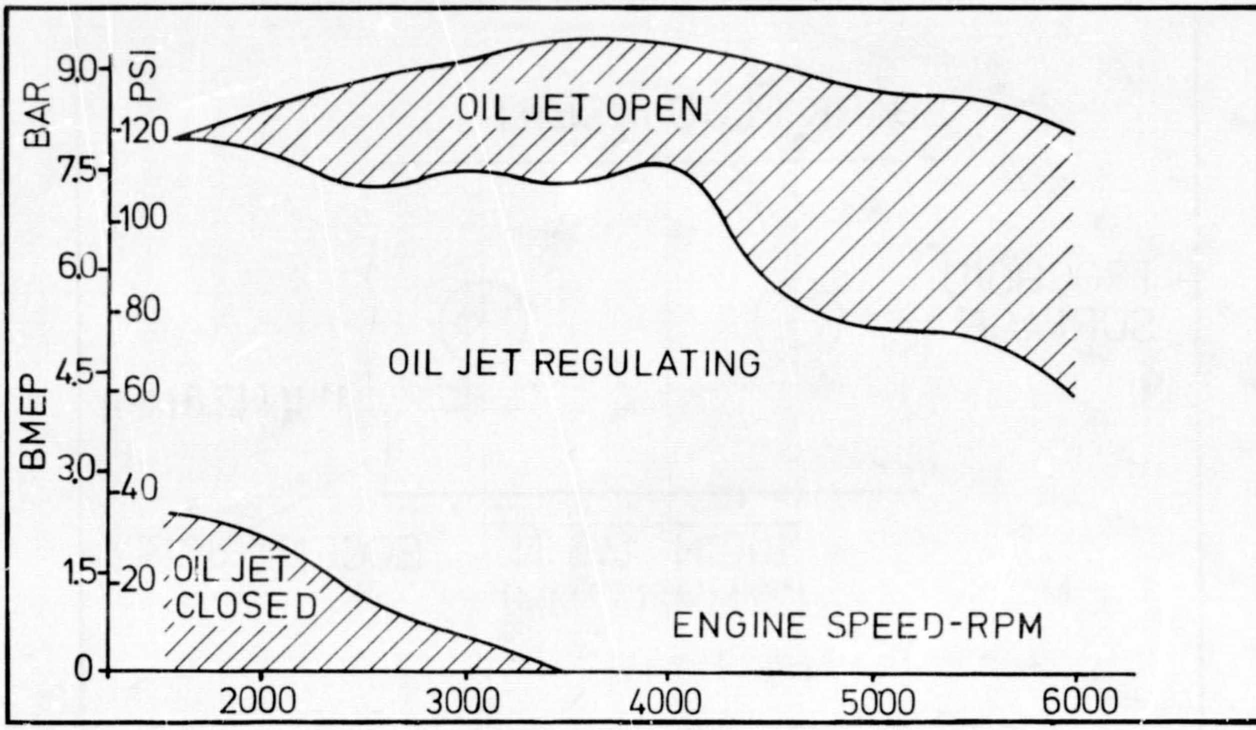

Figure 8. - Chart of oil jet control for rotor cooling.

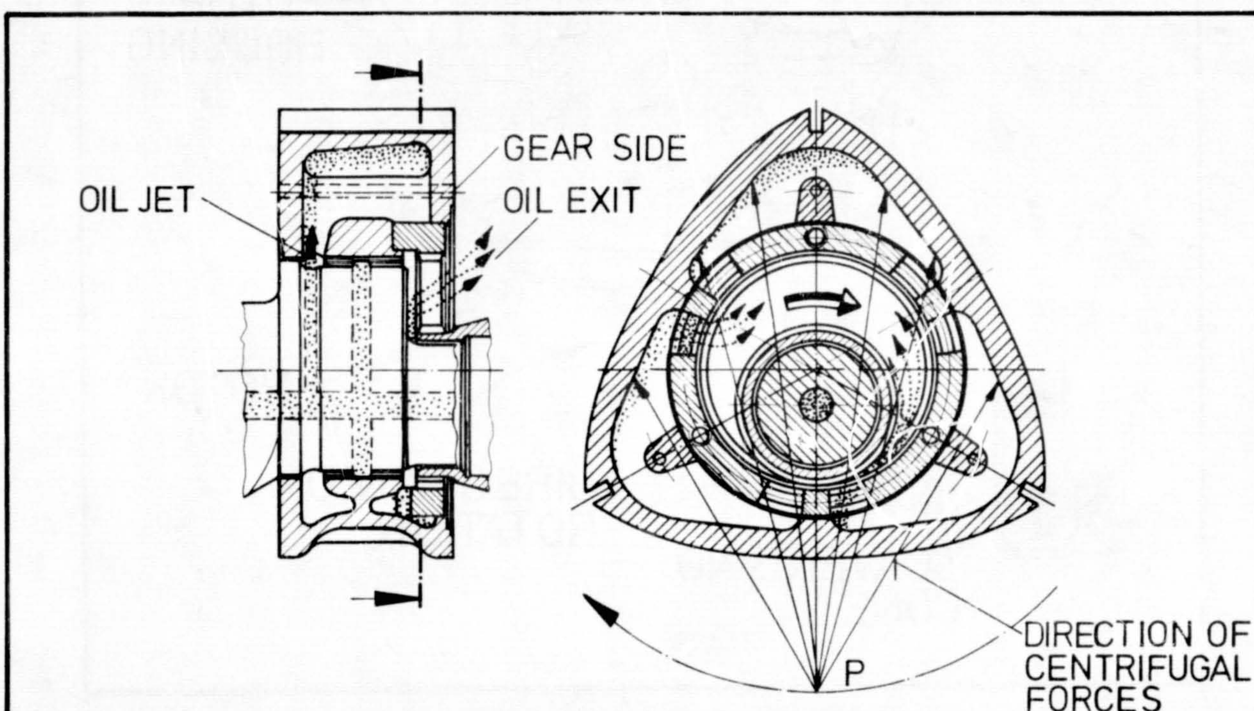

Figure 9. - Principle of cooling oil flow.

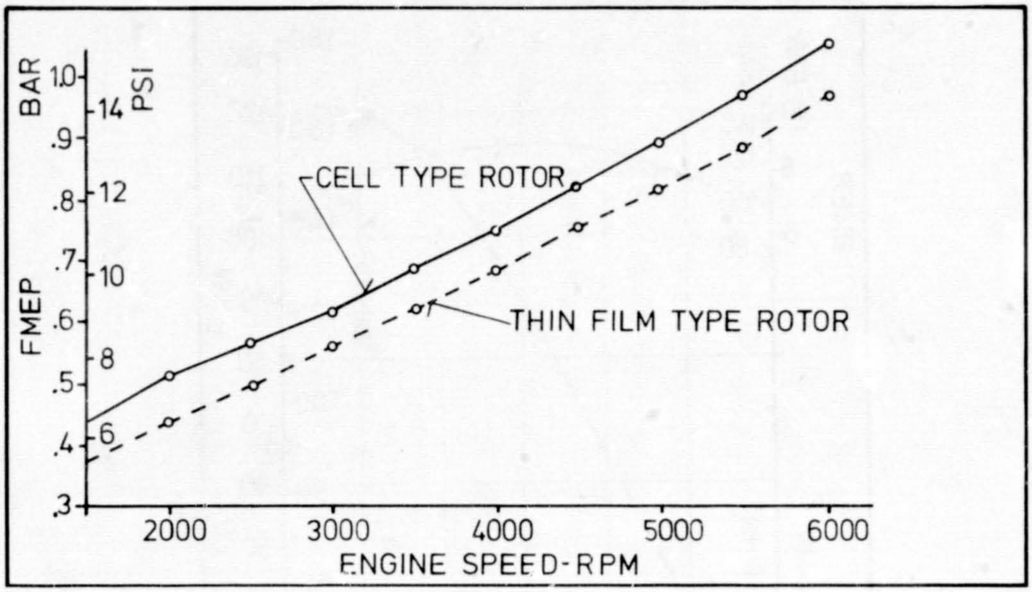

Figure 10. - Comparison of friction-MEP.

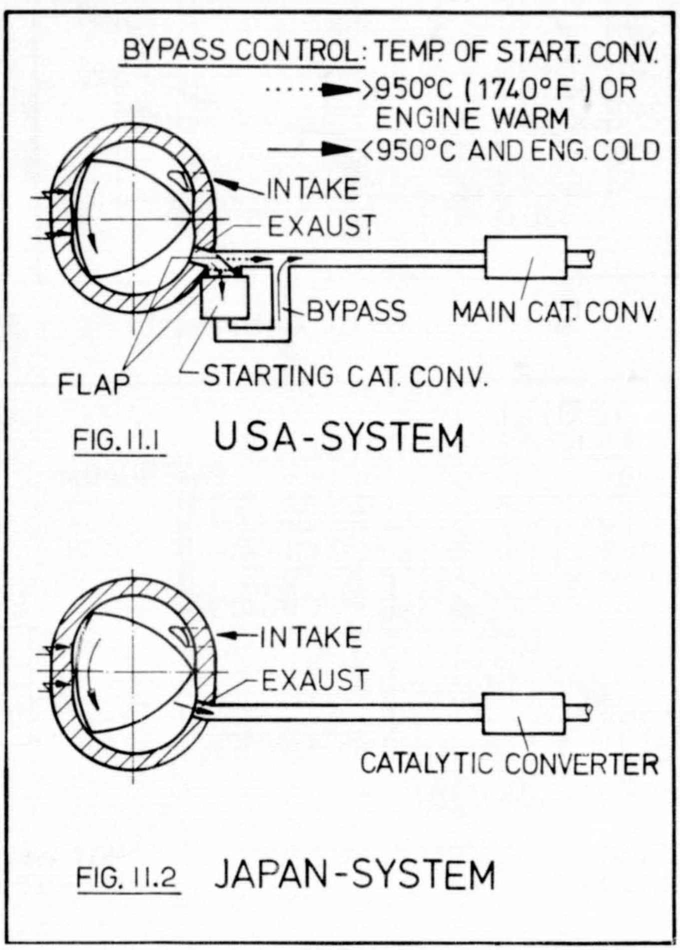

Figure 11. - Exhaust emission control system.

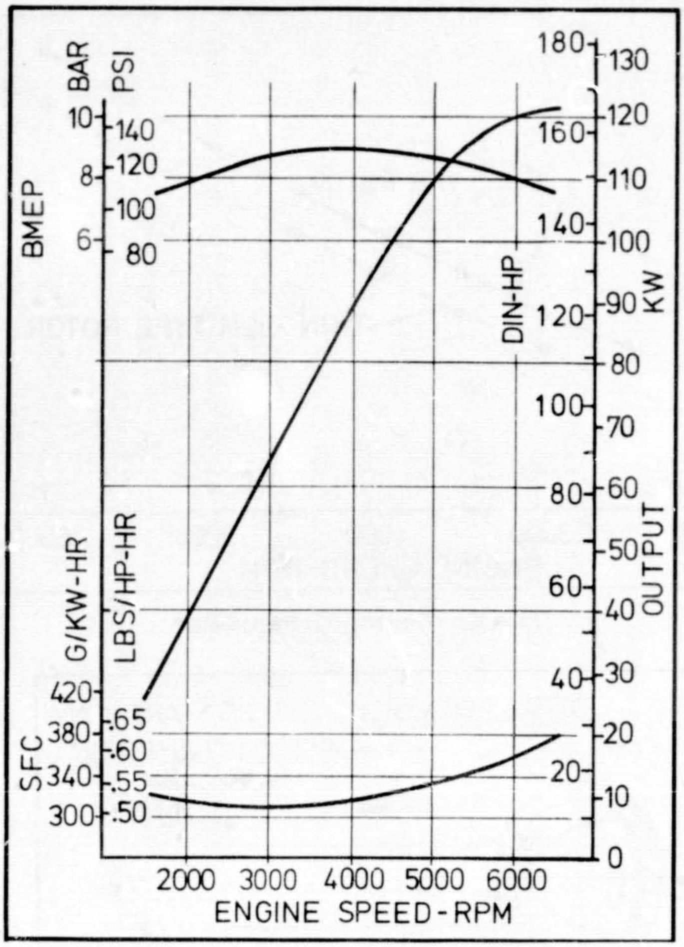

Figure 12. - Performance of KKM 871 at WOT.

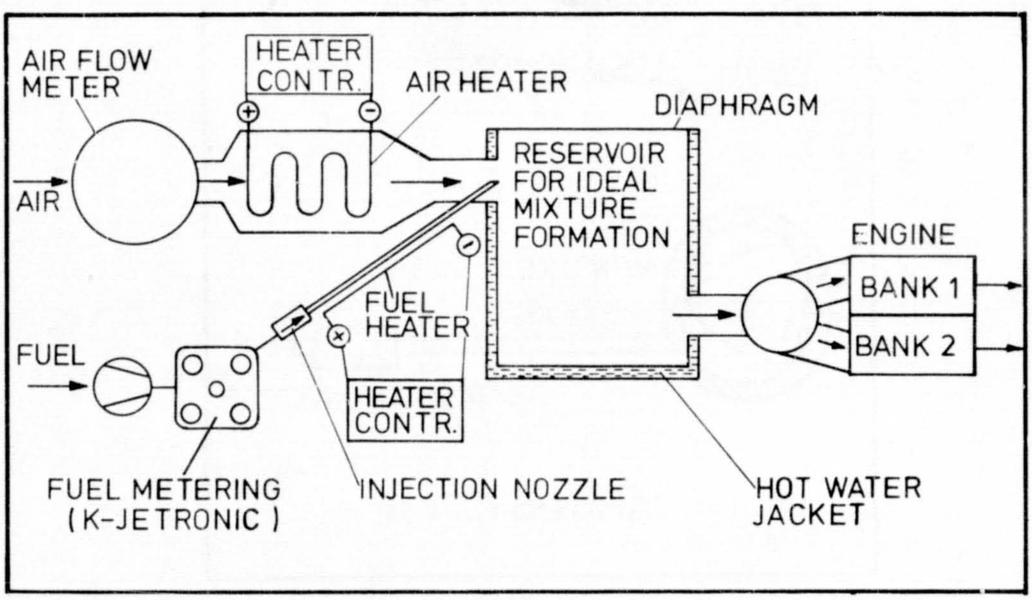

Figure 13. - Arrangement of ideal mixture formation system.

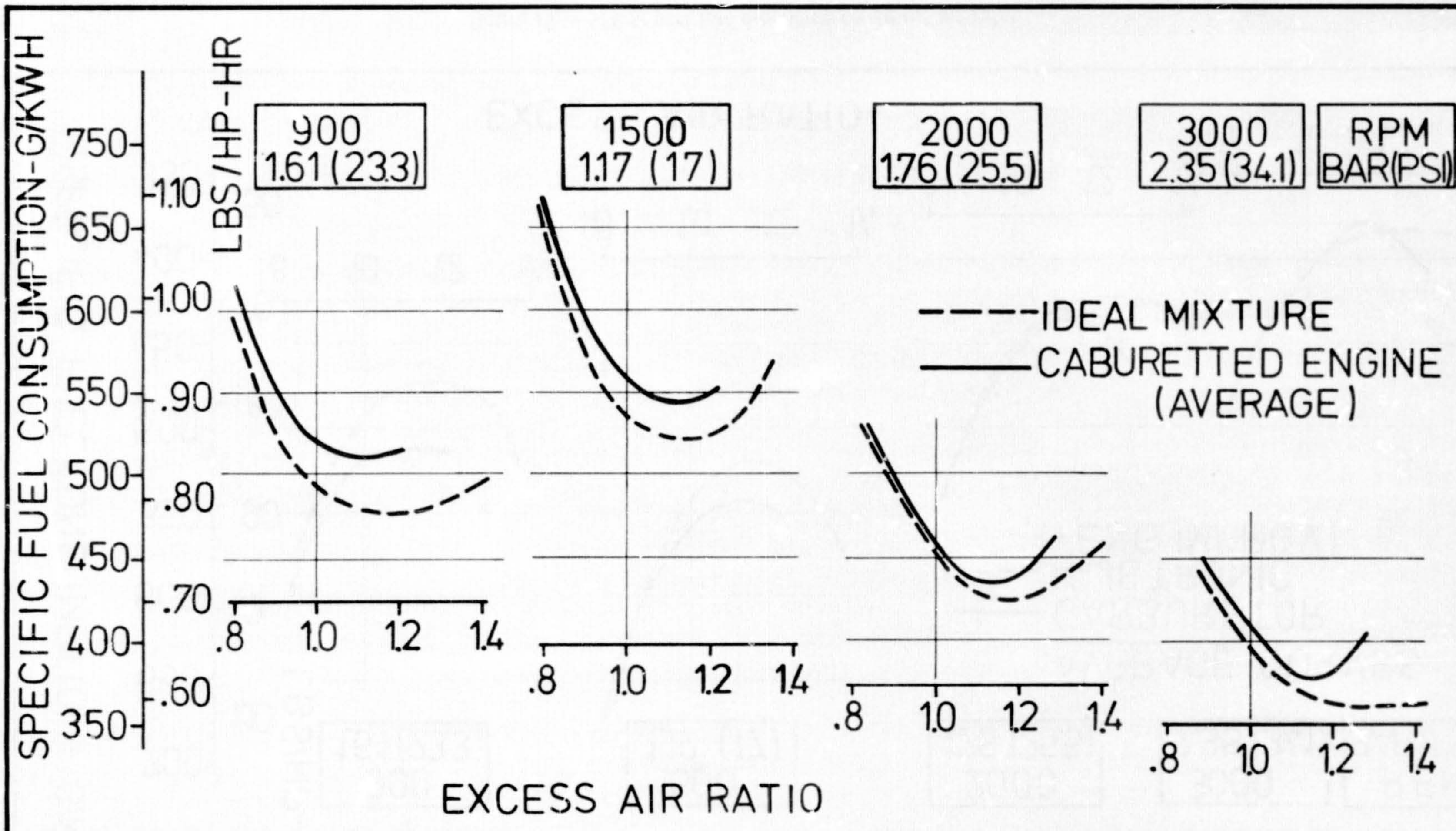

Figure 14. - SFC at part load of R. E. with ideal mixture.

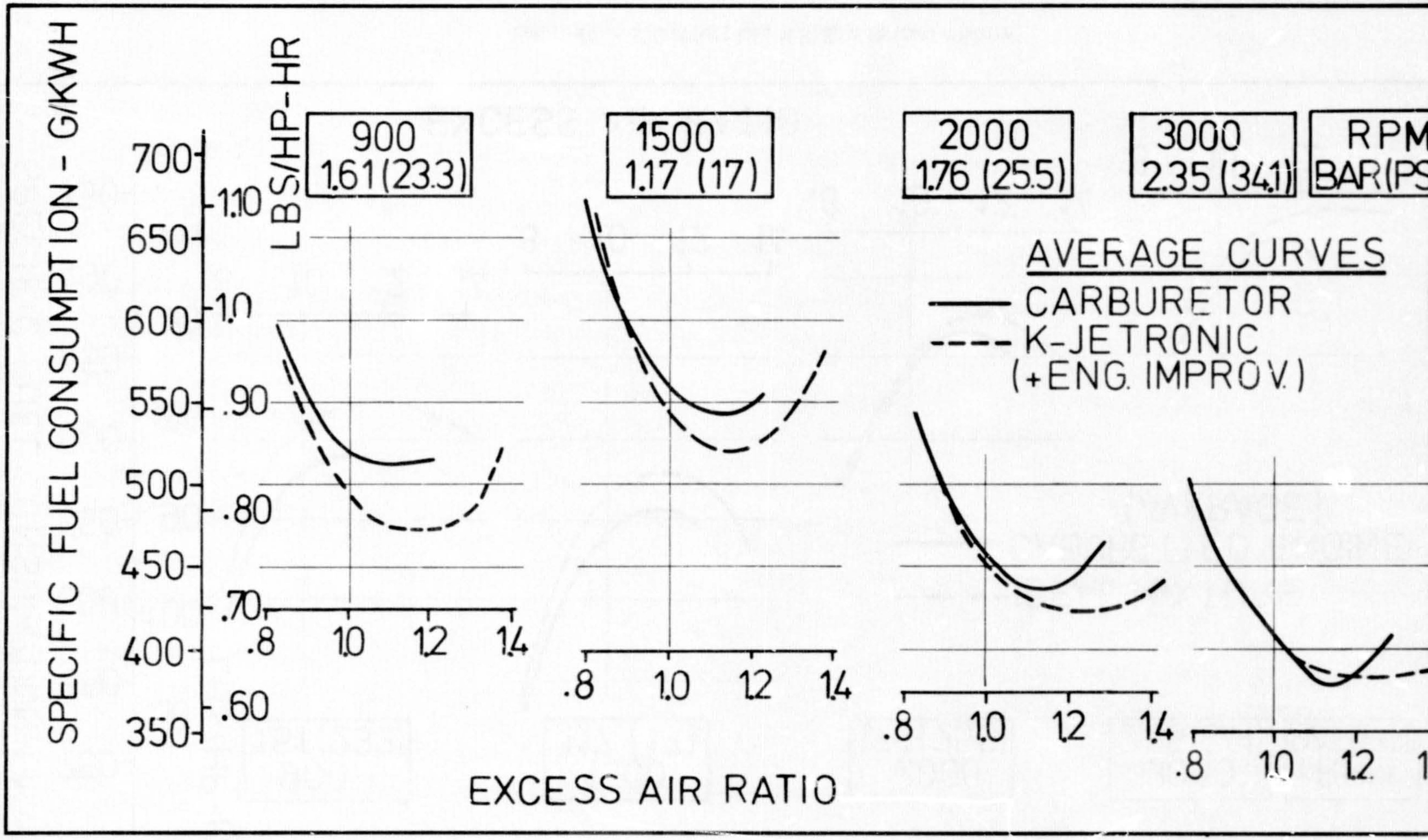

Figure 15. - SFC at part load depending on excess air ratio.

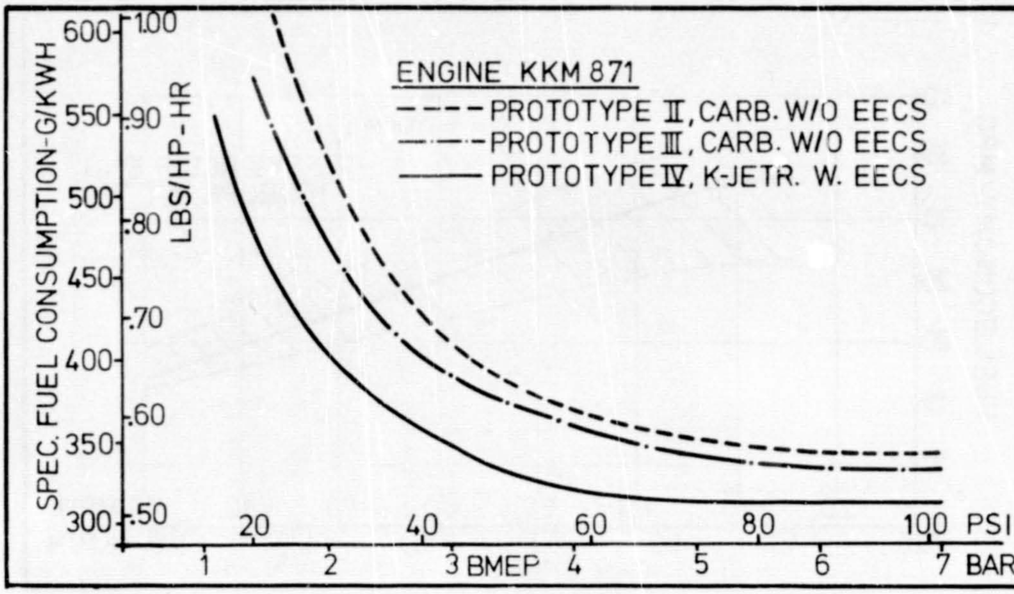

Figure 16. - Specific fuel consumption at 2000 rpm.

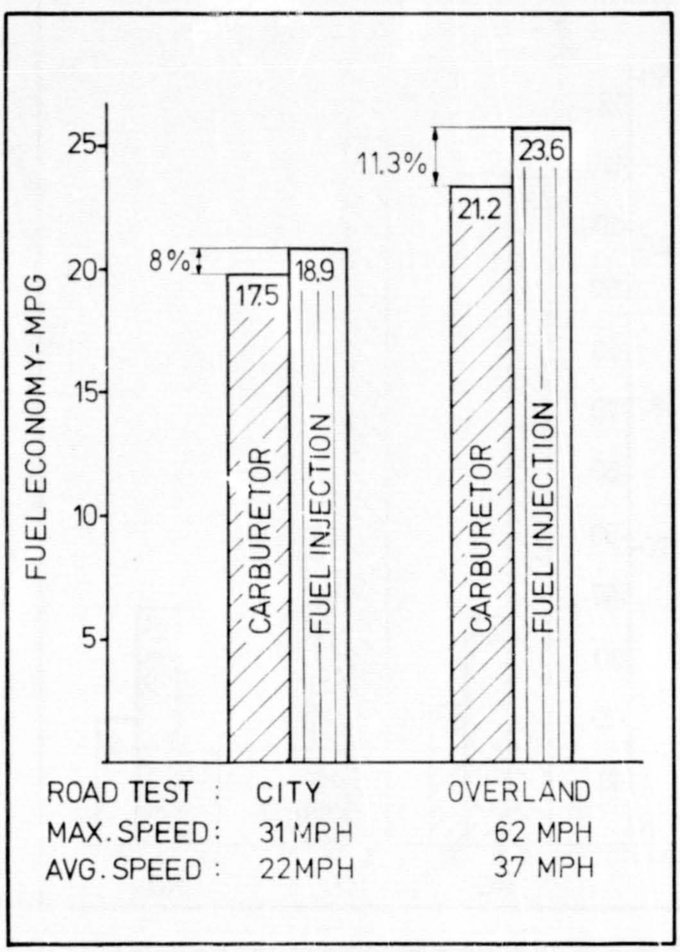

Figure 17. - Comparison of fuel economy.

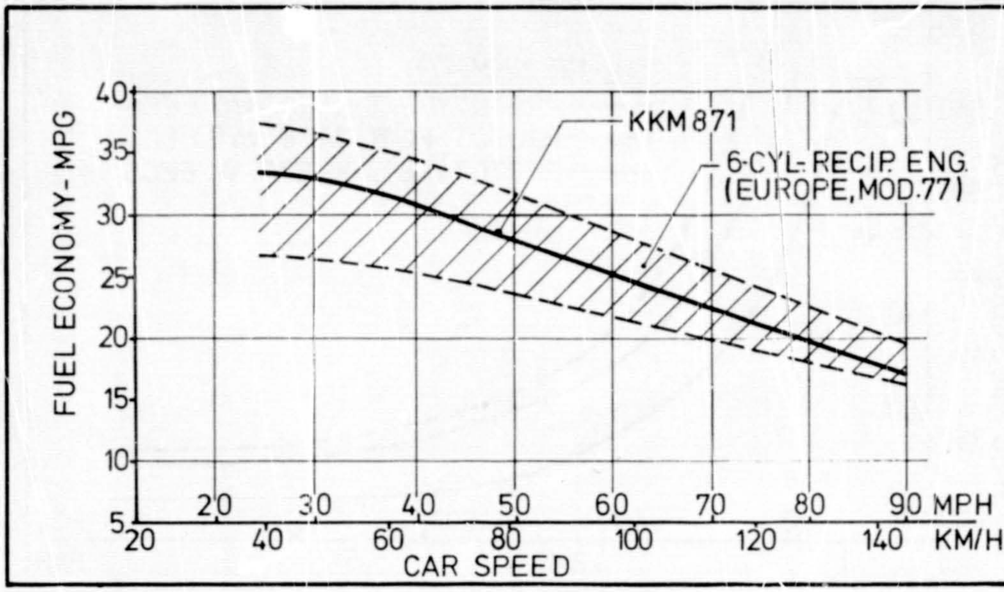

Figure 18. - Fuel economy depending on car speed.

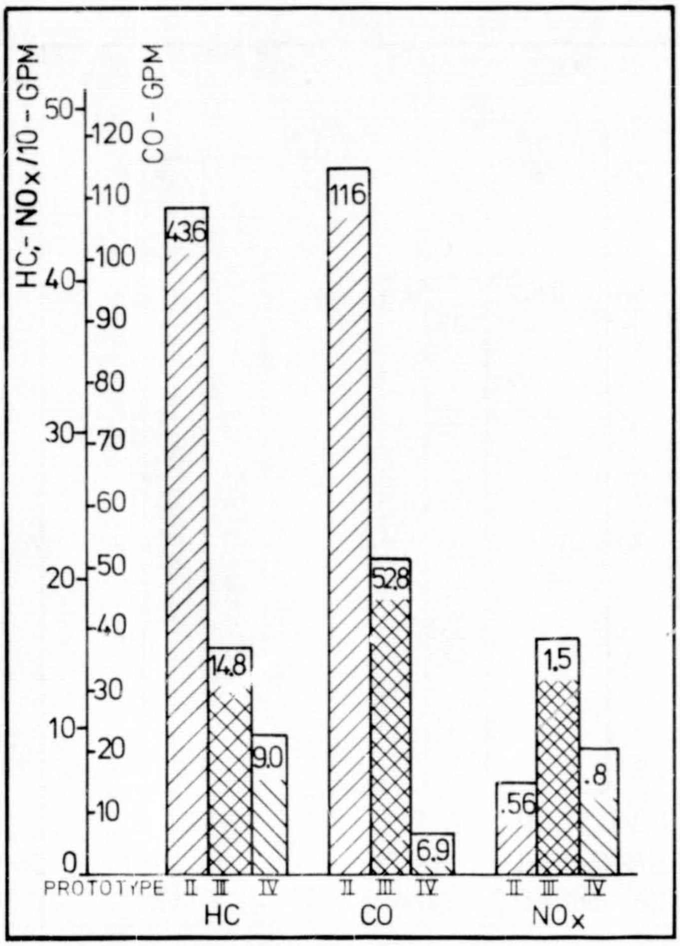

Figure 19. - Reduction of base emissions (CVS-test results).

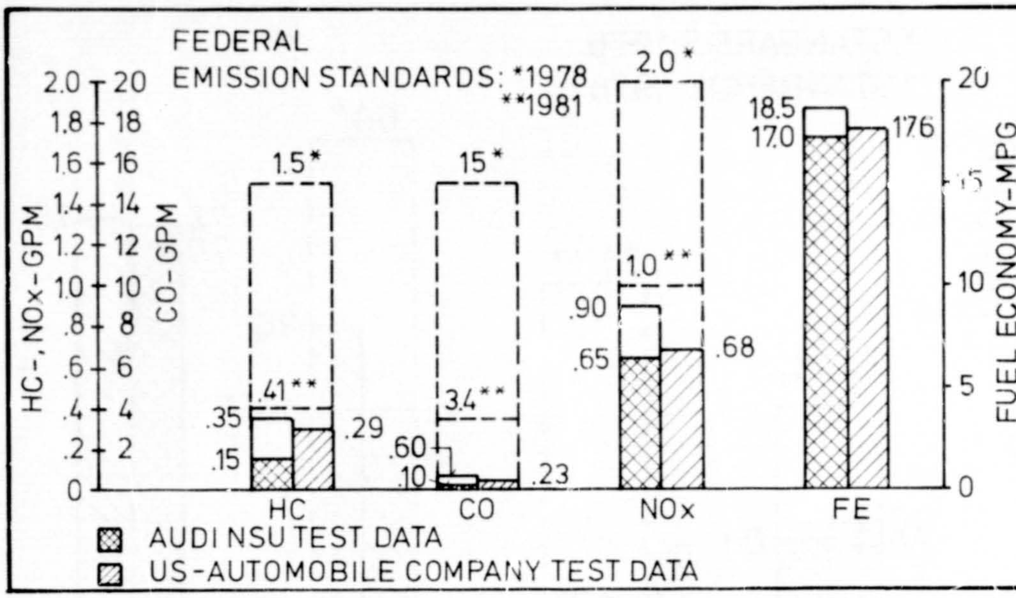

Figure 20. - CVS-test exhaust emission data and fuel economy.

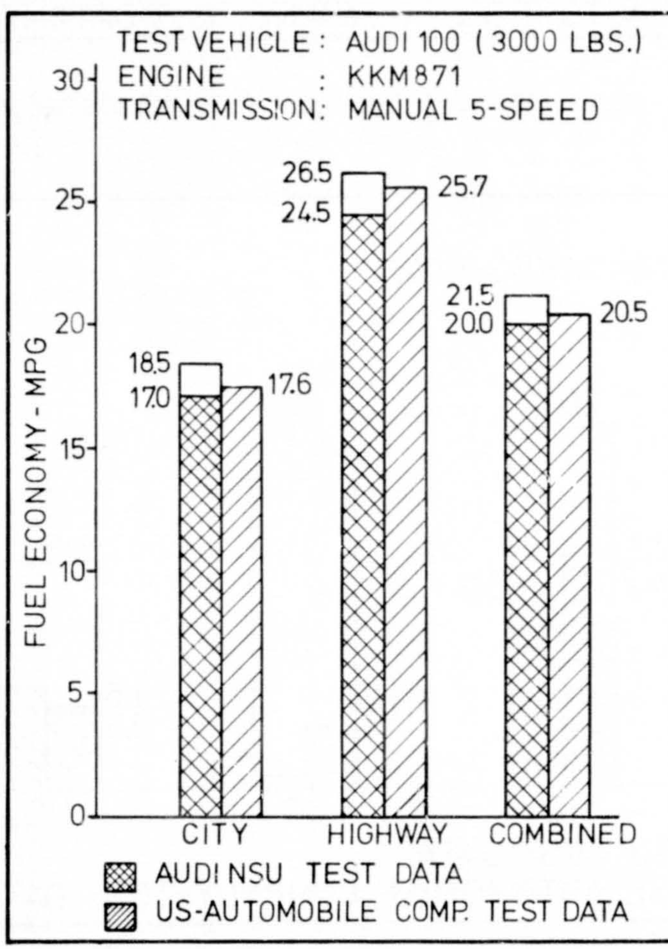

Figure 21. - FTP-fuel economy test data.

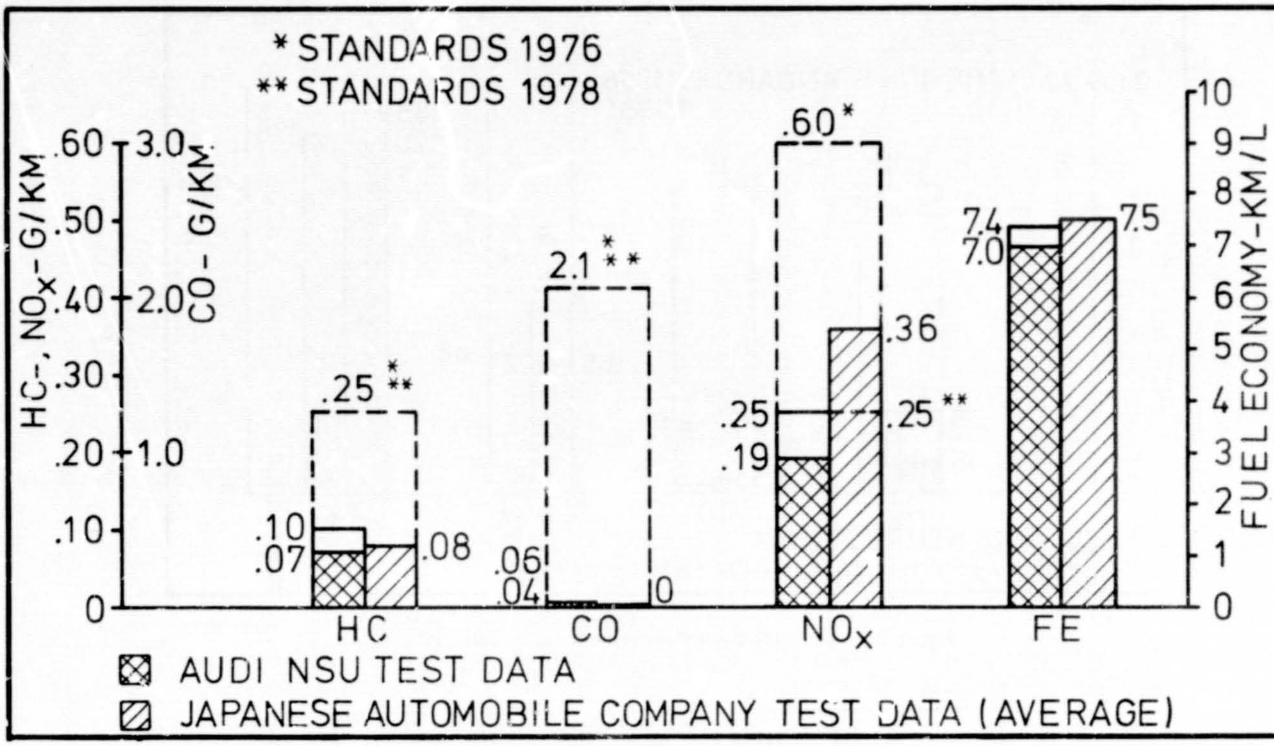

Figure 22. - Japanese 10-mode test exhaust emission data and fuel economy.

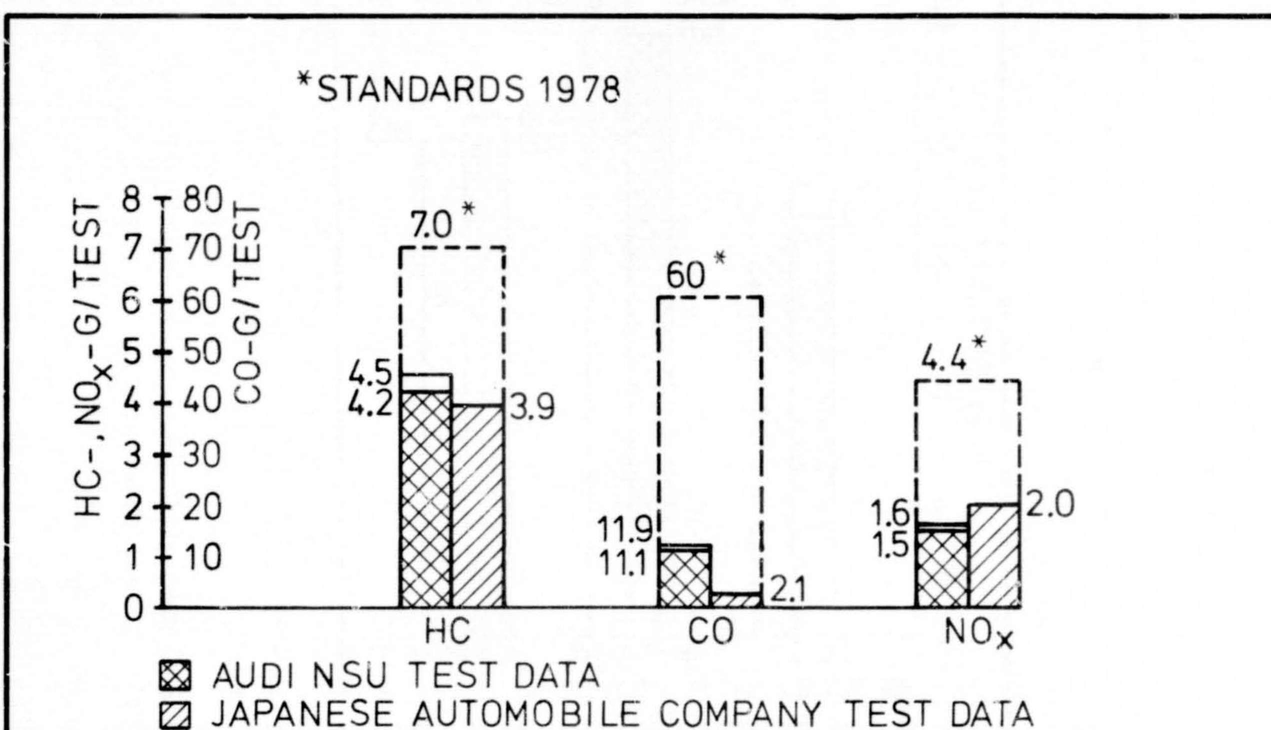

Figure 23. - Japanese 11-mode test exhaust emission data.

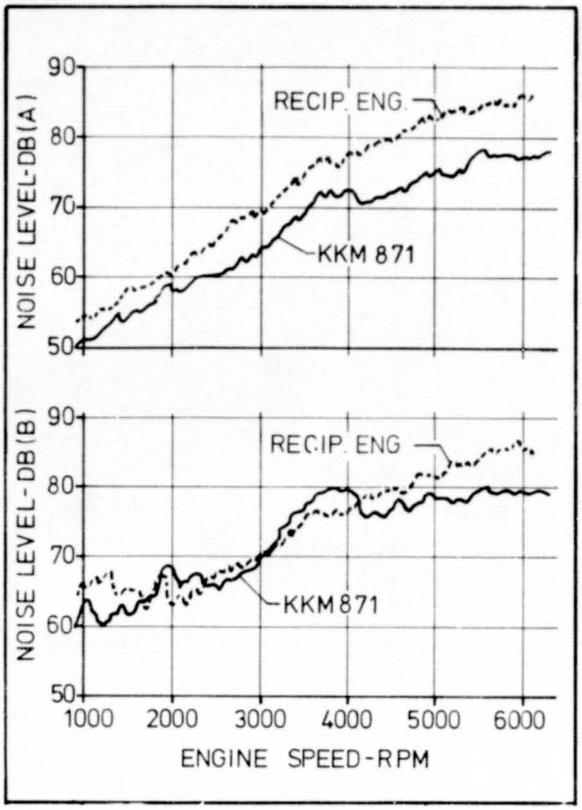

Figure 24. - Comparison of noise level.

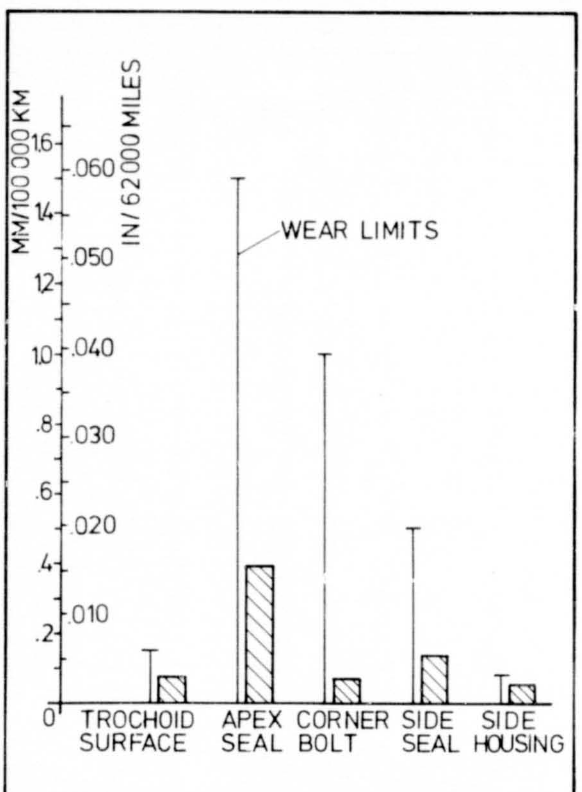

Figure 25. - Average wear data of durability tests.

D5

REVIEW OF THE RHEIN-FLUGZEUGBAU WANKEL POWERED AIRCRAFT PROGRAM

Manfred Riethmüller
Audi NSU Auto Union

N79-15966

1.) Introduction:

The Rhein-Flugzeugbau GmbH hereinafter called RFB founded in 1956 is a division of the VFW-Fokker Aerospace Industries and their program includes among others the development of light aircraft with special emphasis on modern propulsion systems and production.
Since 1971, RFB is working on the application of rotary engines to their aircraft program.
Fig. 1 shows different types of aircrafts under the development of which the most interesting projects are the Fanliner and the Fantrainer. For both, the heart of the concept is the integrated ducted-fan propulsion system using rotary engines.

The decision for the application of rotary engines based on the general opinion, that only high rotating fans could be used as integrated ducted-fans. Therefore RFB looked for engines with the capability to run at high revolutions. On the other hand, the powerplant should feature smaller space requirements than currently available conventional reciprocating engines, which were not modified in this respect since many years.

The reason for the need of smaller engines was the installation of the powerplant behind the cockpit and to reduce the loss of some area in the hub region of the ducted-fan necessary for ventilation purposes of the engine compartment. Another reason was, that by using a rotary engine based on an automotive production version, the initial price would be low.

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2. Fanliner

Fig. 2 shows the Fanliner on the ground. The first Fanliner, that started flying in October 1973, was equipped with an Audi NSU two-rotor production rotary engine available as an automotive configuration with 115 Horsepower at 6000 rpm driving an RFB three-bladed fan at full engine speed. In 1974 RFB fitted a 150 horsepower prototype engine from Audi NSU to the Fanliner. This engine was a former prototype version of the current KKM 871. The powerplant based on an automotive engine was progressively modified by RFB resulting in a second aircraft prototype rotary engine which took his first flight in 1975.

At the beginning of flight testing it was found, however, that although the engine performance has shown very good results, the noise level of the whole propulsion system was too high, caused by the ducted-fan. For this reason RFB conducted several fan speed tests in flight and on the test bench with the result, that the high revolution of the ducted-fan can be lowered by means of a reduction gearbox without any loss of performance, but resulting in a much lower noise level that can comply with the limits of the German Federal Aviation Association called LBA.

Present measured in flight noise at the rotary engines permitted full-throttle cruise during horizontal overflight at 1000 feet is 65 dB(A). That is about 7 dB(A) below the current German light-aircraft limit. With the new propulsion configuration about 440 flights with a total flying time of 220 hours have been conducted.

The present engine installed in the Fanliner and shown in the Fig. 3 delivers between 150 and 160 horsepower and has a wet engine weight of 159 kg or approximately 350 pounds. It has to be mentioned, however, that this engine weight includes cast iron side housings as used for the automotive application. By changing these parts to aluminum material the weight can be reduced by approx. 20 kg respectively 45 pounds. On the other hand, since the engine is running at 6000 rpm and the ducted fan with 3000 rpm, there will be an additional weight for the reduction gearbox.

For the modification of the automotive prototype engine as supplied by AUDI NSU into an aircraft engine the following items were changed.

a) The carburetor was replaced by a Bendix fuel injection system together with a new intake manifold shown in the picture.

b) Several accessories such as generator, starter, fuel pump and some parts of the ignition system into parts with LBA certification

c) dual v-belt-drive

d) and finally the flywheel with gear

Fig. 4 shows the engine from the spark plug side with the mounted reduction gear box. Since the engine is initially designed with two spark plugs per bank and two independant ignition circuits there is no necessity for additional spark plugs or a second ignition circuit for safety reasons.

Experiences out of the flight tests have shown several advantages in respect to the rotary engine:

- <u>smooth running characteristic</u>

  The lack of vibration translates into less fatigue for the occupants and less stress on the many connections holding the airplane together.

- safer flying
  In contrast to the conventional engine there is no problem of engine blockage due to piston seizure. This reduces the possibility of engine failure in flight.

- highly effective mixture control versus altitude
  The lean out ability without powerloss is much better than with reciprocating engines and there is no problem of overheating under this condition. The engine runs at full throttle also under cruise speed without any harm to the engine.

- no warm up time is necessary which means little wasted fuel and no delays in taxiing out to a take-off point and resulting in less wear on the engine itself.

Although the fuel consumption of the KKM 871 aircraft engine with approx. 235 grams or .51 pounds per horse power and hour under 75 % WOT condition, is not as good as with reciprocating engines of similar output, this disadvantage will be compensated by better performance. In respect to fuel consumption it has to be mentioned, that this proto-tpye engine does not represent the updated features of the current Audi NSU KKM 871 automotive engine which includes further measures for fuel consumption reduction.
Since the decision for a production of the automotive engine has been delayed by Audi NSU, it became necessary for RFB to look out for alternative powerplants.
It was found that for an installation in the Fanliner the following engines could be used which are listed with some data in Fig. 5:

in the reciprocating engine field the
Lycoming - 360 A3A and -320-H
and in the rotary engine field the
Mazda 13 B, but this engine only
in connection with turbocharging up to 180 horsepower
and the Citroën rotary engine.

Although a final decision has not yet been made, the Citroën rotary engine will be the most promising alternative in the moment taking also into consideration that Citroën has tested the engine for about 800 hours already in respect to the FAA Part 33 for the purpose to obtain the certification of the engine as an aircraft propulsion system.

The lycoming reciprocating engines have the disadvantage, that the installation space needed will result in a considerably decreased area for the fan respectively fan blade length. A general comparison of the space and frontal area requirement between the rotary engines and reciprocating engines mentioned without the reduction gear box, show the following figures:

in space

approx. 14 cu ft will be needed
for reciprocating engines compared to
approx. 5 cu ft for the rotary engines

This means the reciprocating engine would require roughly 3 times more space than the rotary engines.
in respect to the frontal area:

approx. 820 sq in compared to approx.
460 sq in for the rotary engine

which means roughly twice as much area needed for the reciprocating engine.
This comparison indicates, that the rotary engine offers much more freedom in the layout of small air planes and especially for the design of the Fanliner chances are not good to apply a current reciprocating engine.

3. Fantrainer:

Most of the items covered so far will also apply to the Fantrainer concept.
The Fantrainer as shown in Fig. 6 in flight represents a two-seater utility trainer.

The development and testing is sponsered by the German Minister of Defense. The target of this program is the introduction of the novel fan-propulsion in connection with rotary engines and turbines for the task of an advanced and cost saving training of jet pilots.

The Fantrainer was initially designed for the installation of the 4-rotor rotary engine with 300 horsepower developed by Mercedes-Benz and tested in their sports car called C 111. Since the production of this engine was cancelled and Audi NSU prototype rotary engines were available it was decided to use 2 of these engines with 150 Horsepower each, instead. The first flight with this configuration took place in October 1977.

The arrangement of the two engines in the engine compartment is shown in principle in Fig. 7.

The rotary engines are coupled via the gearbox unit, driving the integrated ducted-fan. In case of failure of one engine, the disengagement automatically occurs by the free wheel clutch between the engines and gear box and the flight mission can be completed with the running engine.

The investigation of the Twin-Engine Gearbox system as well as the development and production of the gear box will be performed by the Klöckner-Humboldt-Deutz Company.

Fig. 8 shows a Fantrainer mock-up with the actual installation of the propulsion system behind the cockpit and the configuration of the exhaust pipes. The complete powerplant is shown in Fig. 9.

The two rotary engines are mounted one upon another and are connected by the reduction gear-box. The view from the intake and exhaust side indicates the intake manifold, fuel injection nozzle location and the shape of the exhaust pipes which are partially shielded. One engine has 4 injection nozzles located on each of the separate manifold tubes close to the rotor housing intake port.

Fig. 10 shows the powerplant from the spark plug side. This whole unit has a weight of approx. 300 kg or 660 pounds.

With an output of 300 Horsepower, the Fantrainer reaches a cruise speed of approx. 200 mph. The flight performance drawn up in Fig. 11 shows the flight envelope, take-off and landing performance, climb performance, endurance, maximum range and thrust versus speed. These diagrams however show only theoretical values.
Due to actual flight analysis it was found, that with the rotary engines KKM 871 in connection with the current ducted-fan an 8 to 10 percent better flight performance was obtained, which would not be possible at present by using reciprocating engines.
In Fig. 12 a table is shown with different alternative powerplants for the Fantrainer concept, including several turbines, which, as indicated by the prices are much more expensive than reciprocating engines or modified rotary engines.

For further development and testing of the Fantrainer the situation has changed in the meantime differently to that of the Fanliner.
The comparison of different alternative powerplant becomes less interesting since the German minister of defence decided to use the turbine version of the Fantrainer with the Allison 250 C 20 turbine giving approx. 420 horsepower. RFB will in future apply only this powerplant to the Fantrainer.

4. Summary:

The test hours conducted so far by RFB with the Audi NSU rotary engine KKM 871 in the Fanliner and Fantrainer amounts to a total of 423 hours. The number of actual flights amounts to a total of 707 flights.

Due to the experience of RFB, the rotary engine has proved its capability as an engine for aircraft application with very good results and with the advantages of

- smooth running characteristic
- no sudden engine failure
- high effective mixture control versus altitude and no overheating by lean mixture.
- good performance compensating the presently higher fuel consumption
- low initial price by mass production of the basic engine for automotive application.

Although the situation has changed for the Fantrainer in respect to rotary engine application, the Fanliner still will be equipped with rotary engines and the tests continue. However, what type of rotary engine will be finally used is not decided yet.
Furthermore it has to be mentioned, that the engines applied and tested so far are modified automotive rotary engines, which are not optimized in lay out and design as an aircraft engine.

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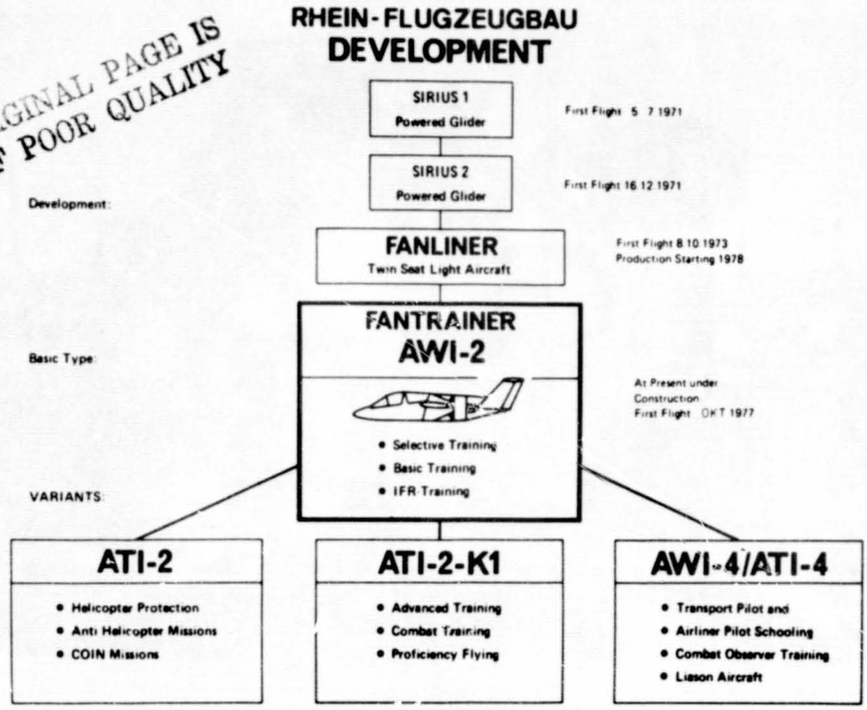

Figure 1

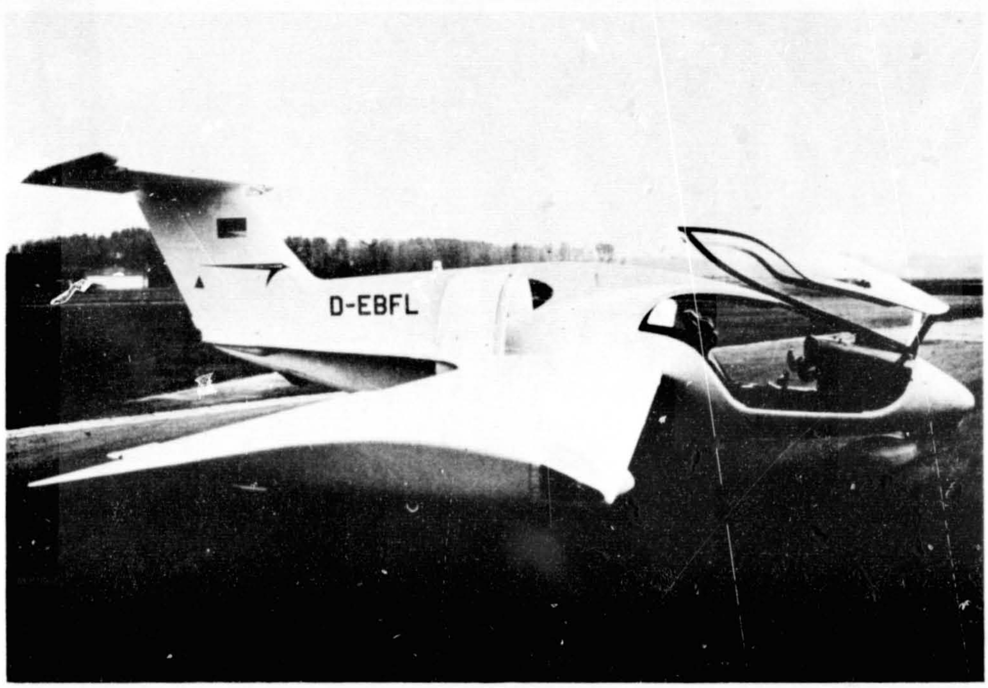

Figure 2

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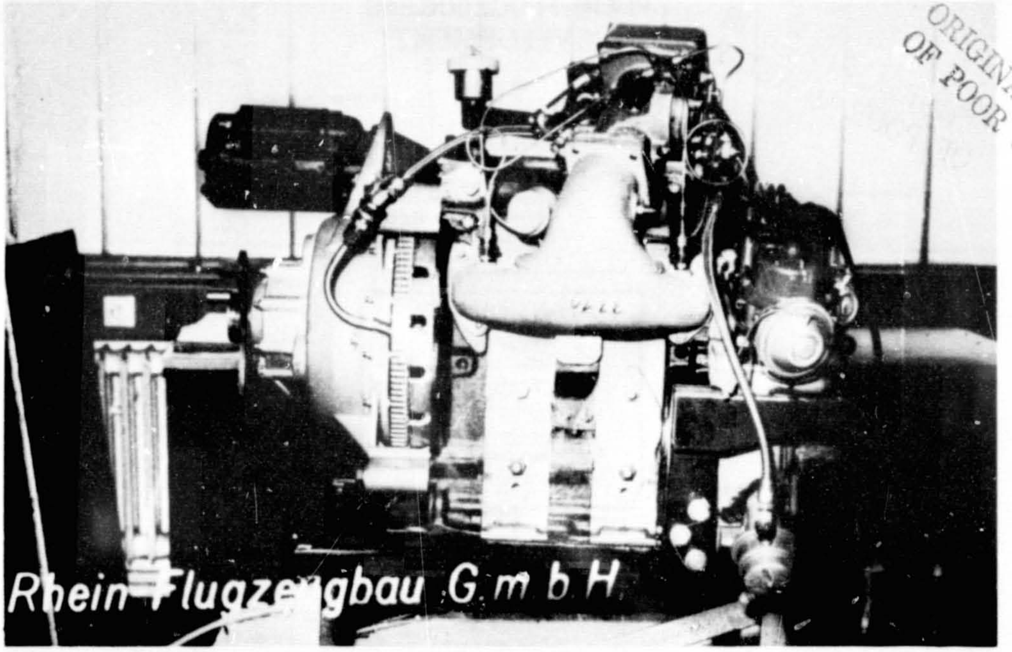

Figure 3

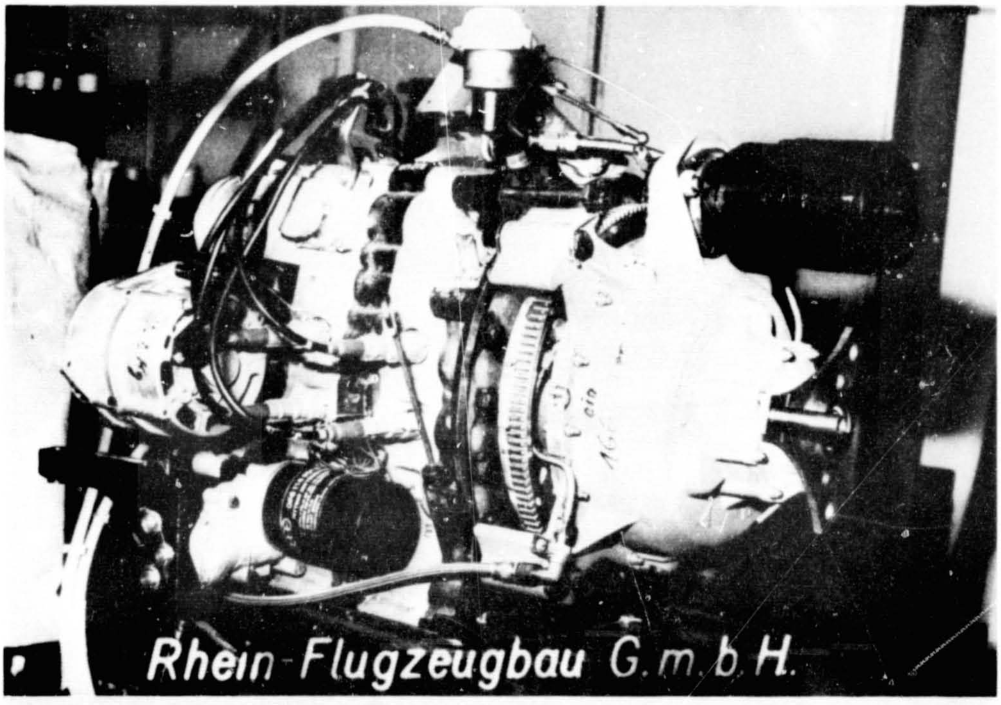

Figure 4

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FANLINER mit Triebwerk / with engine type		Audi NSU EA 871	Mazda 13 B turbocharged	Citroën	Lycoming 0-360 A 3 A	Lycoming 0-320 - E
Wellenleistung / shaft horsepower	PS	160	180	180	180	160
Startleistung / take-off-power	PS	-.-	-.-	190	-.-	-.-
Standschub / static thrust	kp	285	309	320	296	273
Rollstrecke / ground run	m	190	175	165	180	200
Steiggeschwindigkeit / ROC	m/sec	5,5	6,6	7,2	6,0	5,2
max. Geschwindigkeit / max. level speed	mph	157	174	174 (180PS)	166	153
Reisegeschwindigkeit / cruise						
sea level	mph	157	174	170		
2500 ft	mph	157	180	170	152 (75%)	145 (75 %)
8500 ft	mph	154	185	166	156 (75%)	150 (75 %)
Reichweite opt. / opt. range	km	1020	-.-*)	-.-*)	1160	1100
bei v_{max}	km	670	-.-*)	-.-*)	650	700

*) sufficient data not yet available.

TE-SST Nov. 76	FANLINER Triebwerksvergleich Comparison of engine - types	RHEIN-FLUGZEUGBAU GMBH

Figure 5

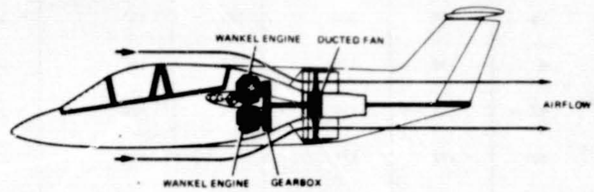
Figure 6

RHEIN-FLUGZEUGBAU
THE FANTRAINER CONCEPT

The heart of the Fantrainer concept is the integrated ducted-fan propulsion system. This system is made up of two 150 hp Wankel engines coupled by a gearbox and connected to a ducted-fan which is an integrated part of the fuselage. Instead of the two Wankel engines one turboshaft engine (from 400 eshp upwards) can also be used.

The characteristics of this propulsion system are very similar to jet engines thus providing an excellent platform for fighter type cockpits.

By changing the wing area of the Fantrainer, different wing-loadings are achievable. The following table describes the possible engine-wing combinations.



VERSIONS	Normal Wing	Smaller Wing	Larger Wing
2 Wankel Engines	AWI-2		AWI-4
1 Turboshaft Engine	ATI-2	ATI-2-K1	ATI-4

Figure 7

Figure 8

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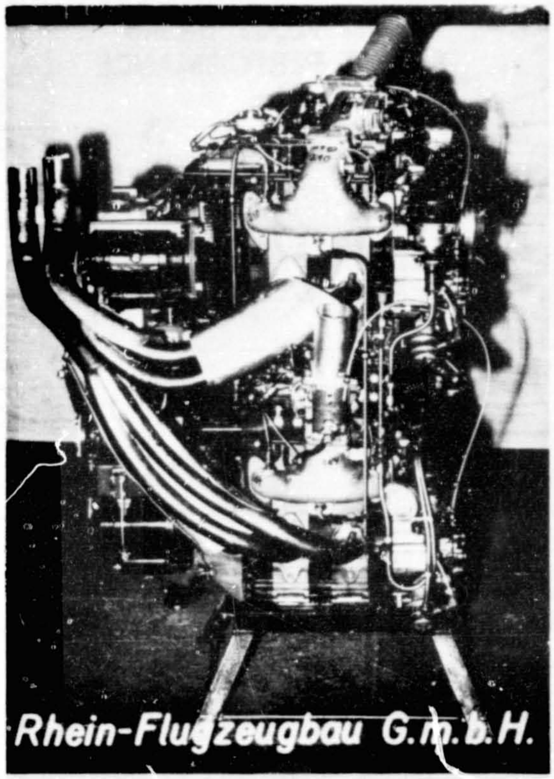


Figure 9

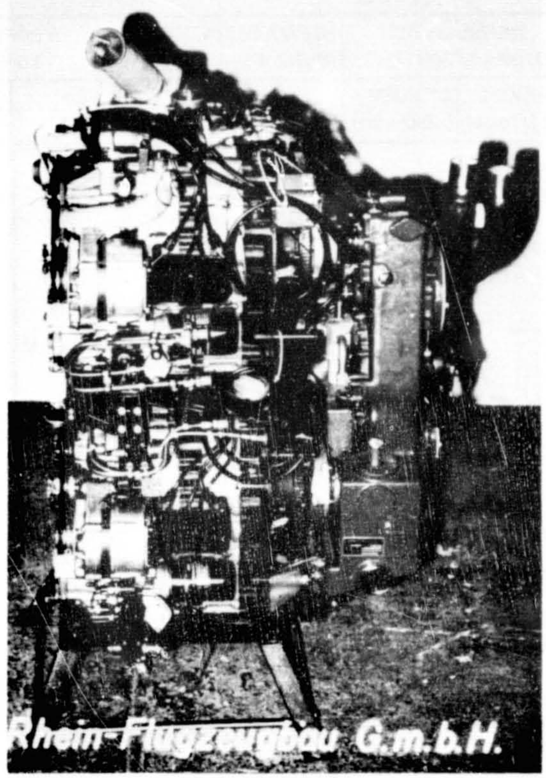
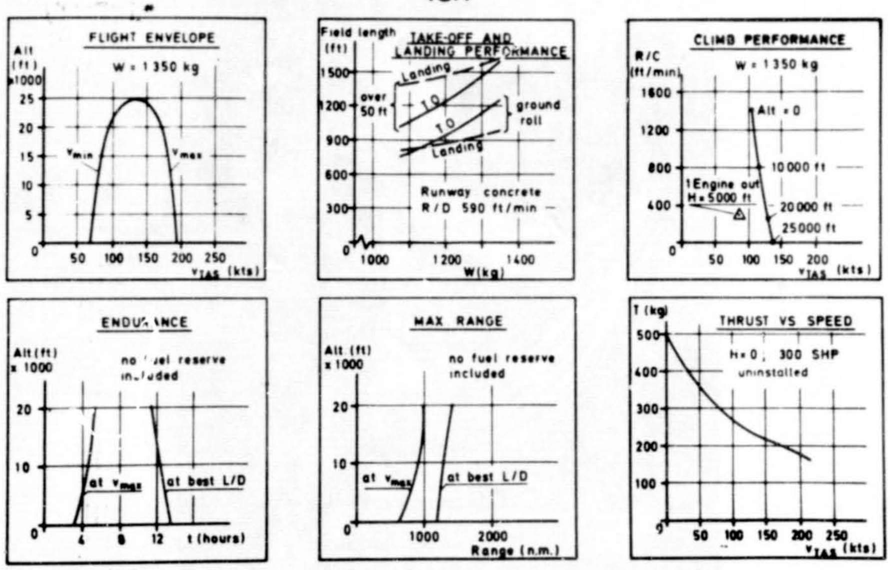


Figure 10

RHEIN-FLUGZEUGBAU
FLIGHT PERFORMANCE
ISA



FANTRAINER AWI-2

Figure 11

TRIEBWERK ENGINE	WANKELMOTOR WANKEL ROTARY ENG.		HUBKOLBENMOTOR PISTON ENGINE	PROPELLERTURBINE TURBOPROP		
	AUDI NSU 2×2 Scheiben	CITROËN 2×2Scheiben	LYC IO-540	ALLISON 250 C 20	PT6 B-16	LYCOMING LTS 101
PS/ U/Min PS/ RRM	2×150/6000	190/6000	300/2700	410/6000	732/6230	595/6000
Verbrauch kp/PSh Consumption	0,235	0,212	0,230	0,277	0,240	0,260
*Gewicht kp Weight	270	290	230	80	150	120
Preis DM Price	~16000,-	?	20000 -	80 000,-	170 000,-	90 000
*Wasserkühlung kp Watercooling	20	?	-	-	-	-
Getriebe kp Gearbox	31	20	-	~16	~20	~20
*Einbaugewichte						3/77

AWI-2	TRIEBWERK ENGINE	RHEIN- FLUGZEUGBAU GMBH

Figure 12

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ROTARY ENGINE DEVELOPMENTS AT CURTISS-WRIGHT OVER THE PAST 20 YEARS AND REVIEW OF GENERAL AVIATION ENGINE POTENTIAL

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This paper will very briefly cover the range of Rotary Engine development work at Curtiss-Wright since 1958, review highlights of recent direct injected stratified results accomplished in the last few years, and discuss several aviation related engine trials, tests, and possible growth directions. The earlier technical material is drawn from more detailed SAE publications.

Background, Development History, and Popular Misconceptions

The baseline standard has changed since Rotary Engine development activity started in this country twenty years ago. Energy and raw material conservation have taken on new import and cast the size and weight advantages of the Rotary Engine, for any application, in a new light. Figure 1 shows the relative weight picture in the engine size range applicable to General Aviation.

The Rotary Engine is inherently a high power density machine because the ratio of working volume to total power section volume is high and the kinematics permit high speed. This speed capability derives from unrestricted intake and exhaust porting, absence of valve and drive system dynamics, complete balance with any number of rotors, non-reversal of the sealing element path, and a low rise of friction power with speed.

Of course, smaller engine size and commensurate weight only translate into fuel consumption advantages in transport use if the engine has comparable efficiency. In addition, the engine must be durable and producible.

The simplicity of the engine also introduces obstacles to attainment of the technical goals. The line-contact of the apex seals with the trochoid surface and the localization of heat input in the combustion zone require fundamentally sound design approaches to realize the full potential of the geometry.

I will briefly cover durability and economy developments at Curtiss-Wright and let the fact of over a million rotary automobiles address directly to the producibility issue.

Taking the durability aspects first, it is true that when we ran our first engine in 1959, where the seals were scaled from the NSU-Wankel dual rotating machine which was the starting point for all of these developments, seal life-spans were best measured in minutes. We were able, however, to design sealing elements by mid 1959 which would wear out before they failed mechanically, although the "wear-out life" at high power was only a matter of hours until 1960. All of the various wear solutions--and there are several--were achieved on the basis of finding a metallurgically compatible combination, rather than by basic design changes. The particular resolution which we adopted at Curtiss-Wright in 1962 has been proven to have acceptable high speed and high power capability, as shown in Figure 2, which provides growth margin for future higher engine ratings. The trochoid coating itself shows virtually no wear in up to 2000 hours continuous testing, as well as cumulative totals much higher. This material combination consists of detonation gun applied tungsten carbide - cobalt on the trochoid surface with alloy cast iron apex seals. This approach is acceptable for aircraft or military engines but is too expensive, and unnecessarily durable, for the less stringent operating cycle requirements of an automotive engine; however, lower cost plasma sprayed carbides have been used commercially in OMC's snowmobile engines and promising new variations are under development. The current materials used in Toyo Kogyo and NSU automobiles, which were either developed or refined during this decade, provide an engine life that is at least competitive with reciprocating engines. Since NSU's, Toyo-Kogyo's and Curtiss-Wright engines are all capable of WOT, full speed operation for significantly longer sustained periods than production reciprocating automotive engines, it is probable that trochoid coatings other than metal-sprayed carbides will prove adequate in high output aircraft engines as well. The point is that, as of this time, there are a number of technically satisfactory solutions to seal wear and only test results can decide which of these is most cost-effective for a particular application and at a given facility.

Another area where the out-of-time-phase popular image dies hard is Rotary Engine fuel economy performance. Here, too, the solutions differ for the particular application. The American automobile engine of the past, with its power reserve, large displacement, and low BMEP normal road-load operation, was a very different animal than the European high output machine which normally operated closer to the bottom hook of its BSFC vs. BMEP curve. Perhaps we were insufficiently automotive-oriented at Curtiss-Wright, but our early preoccupation with high power density resulted in some rude awakenings when American automotive companies compared our 20-30 BMEP fuel consumption data with the engines they were then using. Chrysler expressed interest, in late 1962, in road testing an engine provided we could first demonstrate a significant low end improvement to bring our data into the acceptable automotive range. By the end of 1962, we had succeeded in reducing the SFC at the more difficult low speed and low power end, as shown in Figure 3. A number of items were tried on the RC1-60 Rig Engine, Figure 4, but the most significant were:

1. Two or three piece apex seals, where the moveable triangular corner reduces end leakage which is particularly damaging at low engine speeds.

2. Relocation of the spark plug electrodes as close as possible to the trochoid surface, which promotes consistent firing, particularly at high manifold vacuum (closed throttle).

3. Change from peripheral (radial) to side ports.

The latter is a particularly meaningful change because peripheral intake ports can admit about 20% more air, with zero back pressure, but the geometry will not permit low exhaust and inlet event overlap. When the throttle is closed for low power, the intake manifold vacuum will encourage exhaust gas to flow across to the intake during the long period that both ports are simultaneously open and this excess of EGR, at power levels when it is not needed, adversely affects combustion regularity and, in turn, fuel consumption. For this reason, we have since regarded controlled overlap side inlet ports as the best choice for an automotive normally carbureted Rotary Engine, whereas we still favor peripheral ports for most high speed and output applications.

Having demonstrated acceptable levels of fuel economy, design of a two rotor automotive prototype, Figure 5, was initiated in early 1963 and was on the Detroit free ways, in a 1964 Dodge Dart, by that fall. The two rotor fuel consumption data, Figure 6, was consistent with the comparable single rotor results. The automobile tests, Figure 7, in a vehicle which had not been fully optimized for the RC2-60, confirmed the SFC comparison and showed equivalent performance. Similar tests run elsewhere over the next few years came to similar conclusions and no further development activity on this engine has been pursued since the mid 1960's.

Although the performance of the RC2-60 had been proven, the engine subsequently served as an excellent vehicle to test system durability in a number of diverse applications such as generator sets, single and twin-screw boats, military fighting vehicles, trucks and aircraft. The latter tests are shown in Figures 8, 9, and 10. For reasons which will be amplified later, an engine configured for American automobile trials could not be an attractive aircraft engine, but these installations did demonstrate the sustained high power capability, smoothness, reduced noise, and basic mechanical reliability of the Rotary. Weight advantages were not fully exploited because the side ports limited output and the belt reduction systems with the fixed wing aircraft were heavy.

The work-horse engine since 1959, the RC1-60, Figure 4, is still a useful tool, most recently serving as the Stratified Charge research rig. However, about ten different sized experimental engines and twice that many model variations were designed and built at Curtiss-Wright. They are of interest now because they illustrate the scaling possibilities, particularly with respect to size and number of rotors. These engines ranged in size from the 3 HP RC1-4.3 (one rotor of 4.3 cubic inches swept volume), Figure 11, to the RC1-1920, Figure 12, scaled from the RC1-60 basic rig by a factor of the $\sqrt{10}$ to provide 1000 HP/rotor. The trochoid form of this engine is the same as the wider rotor 2500 cubic inch Ingersoll-Rand gas engine introduced on field trials in 1976 (90,000 total hours on 13 units) and to production earlier this month. The Ingersoll-Rand single and twin rotor engines, which are rated at lower speeds dictated by driven equipment, develop 550 and 1100 horsepower, respectively. The 4 rotor RC4-60 400 HP marine engine derivative, Figure 13, was the world's first multi-rotor Wankel type engine when it ran in 1960. An air-cooled RC2-90 engine, where the RC-60 rotor width was increased by 50%, was built and tested in 1966. The RC2-75, Figure 14, a liquid-cooled general aviation engine prototype, was derived from the RC2-60 by, among other apparent changes, widening the rotor by 25% and changing to peripheral intake ports for increased power. Figure 15 shows the scaling factor influence by comparing rotor sizes. This range helps put the sizing flexibility of the rotor in better perspective.

From this survey, it is apparent that the rotor can be scaled up or down proportionately, its width can be varied, and multi-rotor engines can be built.

Similar to the piston engine, which also follows the square-cube laws of scaling, the smallest and lightest engine will always be the one with the largest number of small power units. However, since the Rotary is not constrained to specific discreet power section combinations for balance purposes and since it is inherently small to begin with, the trade-offs have a different impact.

The thrust of many of these diverse developments was to demonstrate application feasibility and technical capabilities in those areas, generally high volume, where the vehicle OEM historically produced his own engine. This was compatible with our role as a licensor of technology. However, R&D efforts were also directed towards our own traditional engine fields, high output aircraft and military engines. In the case of Stratified Charge, our development efforts started in 1962 in response to the military's interest in multi-fuel engines. However, after the 1973 energy crisis, we recognized much broader advantages for unthrottled direct injected Stratified Charge in the larger sense of all commercial transport engines because of the fuel economy potential and because the approach could theoretically reduce the Rotary's higher levels of raw hydrocarbons at low output. Although this priority redirection to R&D efforts supporting our technology licensor position partially diverted our own aircraft engine R&D efforts, it was pivotal in leading to a 49 month USMC development contract last year for a Stratified Charge LVA (Landing Vehicle Assault) engine which is expected to lead to Curtiss-Wright production. This 4 rotor 1500 HP engine is about the size of an office desk and expected to be lighter than the military gas turbine in the XM-1 main battle tank. We are now ready to test the first 350 cubic inch single rotor engine in a matter of days, and are beginning to look more carefully at commercial vehicular possibilities of the same technology in engines closer to the size of our

60 cubic inch research rig.

Accordingly, since our recent Stratified Charge research results have important implications in a number of fields, we will examine them in somewhat more detail than our earlier developments.

Stratified Charge

It is well known that the stratified charge engine operates at overall lean mixtures beyond the spark ignition flammability point by exploiting "lightoff" from a richer pilot zone. The primary incentive, over the past few years, for developing automotive engines of this type has been lower emissions, but the promise of improved fuel economy with the leaner burning variations is generating extensive and increasing interest; wider range fuel capability is also expected to be important in the future.

The two best developed approaches have been either formation of the spark-ignitable zone by direct injection in the vicinity of the plug or else use of a pre-chamber containing the relatively rich mixture, a spark plug, and means for discharging the torch-like ignited mixture into the main (leaner) combustion chamber.

Both methods are adaptable to Rotary engines. Since we believe that the direct chamber injection holds more long-term promise for low emissions with the lowest possible fuel consumption, primarily because the combustible zone can, at least in the ideal case, be better confined by surrounding air to give less wall effects, Curtiss-Wright has concentrated on this approach. This direction has also demonstrated potential for detonation-free operation on low octane "heavier" fuels, as well as a reduction in pumping losses by operation with a non-throttled intake On the other hand, the dual chamber technique, or its Rotary Engine counterpart, is simpler and promising for that reason. The technical success of any of these systems will be related to the extent that they can achieve operation at overall lean mixtures.

Where does the Rotary, Figure 16, fit in? If one accepts the premise stated earlier that direct injection offers the best long-term potential, we should compare operating principles of the Rotary stratified charge basic approach with the Ford PROCO and Texaco TCCS reciprocating stratfied charge engines. Although there are differences in detail between these two reciprocating engines, both develop an air swirl to stratify the fuel-air mixture strengths at appropriate locations within the combustion chamber and both use conventional reciprocating engine valving. Production of this induced turbulence, which is part of the key to solving the difficult problem of having the mixtures properly distributed at all loads and speeds, requires some combination of shrouded intake valves, piston and head shapes, and nozzle injection angle in the reciprocating engine, but in the Rotary, the required air motion is an outright "gift" deriving from the basic engine geometry.

The rotor moves air past the wasp-waist of the trochoidal rotor housing once every shaft revolution, Figure 17. The degree of turbulence can be "tuned" by the shape of the rotor combustion pocket. Having established a particular pattern of air motion, the next design freedom is circumferential location of the nozzle and spark plug relative to this turbulent air. The additional key variables include nozzle and spark plug relationships and injection spray pattern relative to the rotor pocket.

The Rotary Stratified Charge Engine, unlike the Rotary carbureted engine, does not suffer at low power/low speed from high exhaust intake porting overlap since it injects fuel after the intake port closes. Accordingly, it can use peripheral (radial) intake ports with their attendant better breathing characteristics than side intake ports. The higher volumetric efficiency of peripheral intakeports can recoup loss in air utilization at the top end that all injected stratified charge engines experience because of the difficulty of having all of the fuel find the proper quantity of air at the proper time. This air-breathing advantage places the power density of radial intake ported naturally aspirated Stratified Charge Rotary Engines at the same general level as automotive side port carbureted Rotary Engines. The result is that the Stratified Charge Rotary Engine is not only smaller and lighter than the Reciprocating Stratified Charge Engine, but it has significantly higher power density than even the homogeneous charge reciprocating engine. However, both engine types have to face the problem of consistently maintaining a near-stoichiometric mixture at the spark plug, over a wide speed and load range. The development histories of Stratified Charge Engines which can operate at diesel-range mixture strengths are fraught with configurations that would run well at either end of the operating spectrum, but not the full range. Ours was no exception.

The general housing design, nozzle orientation and spray pattern, spark plug type and orientation, and rotor pocket system that was used with the RC2-60U10 engine (Figure 18), as shown in Figure 19, ran very well at the low ends (including cold-starting on JP-4 fuel down to -35°F) up through mid to moderate power. However, when this system was introduced to the higher rated RC2-90, the engine could not meet its 310 HP target, Figure 20. This air-cooled direct drive engine, designed for a remote-controlled drone helicopter, was intended to develop this output at less than one pound (dry) per horsepower. The "showerhead nozzle," Figure 21, was better able to "wet" enough of the passing air, at the right time, to demonstrate the required power output, but it lacked a protected zone to initiate and complete combustion at low loads. Development of this particular Stratified Charge Engine was never completed because of a change in military planning, but research activity continued on a water-cooled single rotor rig having the same power section (RC1-60 trochoid contour with a 50% wider rotor) and the RC1-60 until, in 1973, a combined version of both previous injector types plus a spark plug firing to the nozzle gave us our first broad-range operation and fuel consumptions better than a carbureted engine. This configuration led to the basic design (Figure 22) approach which we consider standard today. The single hole pilot nozzle fuel flow is relatively small, varying only with RPM, but it is able to maintain a consistent torch effect to ignite the main fuel charge, which is varied in rate to match load in the same manner as a Diesel engine.

The major development effort during 1975 and 1976 was directed towards finding system variations of the basic pilot and main nozzle design which would combine the advantages of economy, low emissions (in particular, HC) and not give any ground on the independence of fuel octane and cetane rating. The details of this effort are covered in SAE Paper No. 770044.

However, summarizing the fuel consumption development picture in Figure 23, the RC2-60-U5 line is comparable to the data shown in Figure 6. The "1973" line is the combination recessed and "showerhead" type nozzles, with spark plug firing to the nozzle as discussed above. The 1974 line is the dual nozzle pilot and main shown in Figure 22. The 1975 line is the same housing run with a better match of rotor pocket--in this case, a leading pocket--and main nozzle spray pattern. The 1976 line is the same basic configuration as the 1974 line, but run with higher rotor housing temperatures, facilitated in this case, but not limited to, substitution of cast iron for aluminum. An interesting finding was that raising the rotor housing temperatures improved SFC significantly but had relatively little effect on hydrocarbon (HC) emissions.

A large number of configuration variations were tested during the 1975-76 period and several interesting conclusions were drawn. One of these was that higher compression ratio not only improves SFC to a degree that would be expected with an Otto cycle engine, but that in the Stratified Charge Engine, HC is improved as well. The explanation for the HC improvement, which is also experienced with the Texaco direct injected engine, is that the negative effects of increased surface/volume ratio and quench/crevice volume for high compression ratio are minimal where the bulk F/A ratio is so low and combustion is largely surrounded by air.

The reduction of rotor combustion pocket recess volume to increase the compression ratio is illustrated in Figure 24. The effects of compression ratio, for an early configuration which was not the best, on (raw) specific HC and fuel consumption are shown in Figure 25. Unfortunately, there are a number of dependent variables involved and the increase of compression ratio has to be determined as an iterative process with the rotor pocket shape and related nozzle spray location/patterns.

Just as housing temperature had a strong influence on fuel consumption with minor HC effects, raising the rotor combustion surface temperature dramatically influenced HC and, at least so far, had little influence on fuel consumption. Heated rotor surfaces were obtained by use of air-gap insulated insert plates attached to the combustion face. A rotor designed specifically for replaceable hot inserts, referred to as the "bolt-on" hot insert design, is shown in Figure 26. Specific hydrocarbon comparisons are shown in Figure 27. The trends are qualitative in the sense that one standard rotor test had the advantage of an electronic fuel injection system which the engine "preferred" for its consistent injection characteristics, and the other had the same pilot but a different main nozzle location.

The hot rotor data is replotted in Figure 28 with our target of raw HC emissions for modern and well-designed automotive engines. Note also that the HC levels plot on the same curve for all fuels tested. This was generally the case for both emissions and fuel consumption (on weight basis; heavier fuels, including diesel, all look even more attractive on an output per gallon or other volume basis). Texaco and others have made a strong case that the miles per barrel of crude oil can be maximized by using a wide fuel tolerance engine which permits refinery optimization by use of a middle distillate.

What is shown in this illustration represents what we demonstrated in a single configuration on the test stand during this program, but is not the best that can be attained with the current technology. For example, it was shown earlier that higher compression ratio helps HC as well as SFC, but because separate investigations were proceeding in parallel, higher compression ratio was not tested on the best configuration. Other tests run concurrently showed the higher extreme low end hydrocarbons respond favorably to moderate inlet throttling, with relatively small penalty of other parameters. One of the most significant improvement trends at this low end is to be derived from nozzle orientations, particularly the pilot, which minimize spraying on the hot rotor surface.

Figure 29 indirectly indicates possible gains from use of a pilot shifted to the other side of the engine's minor axis (ATC pilot), although the balance of a "system" which is compatible with that pilot location has not yet been determined. The underlying premise is that the pilot performance (shown on "Indicated" basis to illustrate the below-idle, or coasting performance, as well) prior to the point where the main nozzle begins to inject fuel, generally determines the curve shape and location. This continuum of "pilot" and "pilot plus main" is shown, on a specific HC basis only, for both the standard BTC pilot configuration shown in Figure 22 and a modified reversed arrangement where the pilot geometry was different by virtue of recessing the nozzle/plug cavity farther back into the housing. When a similar pilot geometry is used at this reversed location, to give direct upstream injection, the "pilot only" base specific hydrocarbons are lower, presumably because direct rotor surface impingement is reduced.

The "1976" fuel consumption comparison of Figure 23 is compared with representative automotive Diesel data in Figure 30.

In conclusion, the work that has been done indicates that if the positive trends of higher compression ratio and geometry refinement are combined in one configuration and tested with a minor degree of low end inlet throttling, HC data better than existing automotive engines can be realized. Since NO_x is inherently low in all Rotary Engines, including the stratified charge version, and CO is low in this and any engine operating at diesel-range mixture strengths, the emissions potential is attractive. Combining this emission picture with light weight, compact dimensions, wide fuel range, and low fuel consumption in one engine package has to merit serious consideration for all future transport applications.

Aircraft Engines

An obvious need for small light weight, high performance engines exists for aircraft propulsion. Initial interest at Curtiss-Wright was towards propeller driven or helicopter military aircraft applications where the RC Engine could compete with small gas turbines. The rotary's superior fuel consumption characteristics, flexibility and low inertia matching advantages, reduced "hot day" power loss, ease of starting, throttle response, sound attentuation potential, and lower cost compensated for the simple (unregenerated) turboshaft gas turbine's bare engine weight differential. Furthermore, the RC Engine plus fuel weight usually proved lighter in all but very short missions as noted in the ref. 1971 NASA study.

During the course of the RC2-90 (Figure 20) stratified charge air-cooled engine development, acoustic measurements were made on our test stands. These data confirmed the potential for extreme low noise level power plants for military operations. These findings and additional theoretical studies led to a U. S. Navy sponsored acoustic test series with the RC2-60 in the Lockheed Q-Star aircraft (Figure 8). This aircraft, which, incidentally, became the first to use a Wankel-type engine for completely powered flight, demonstrated hitherto unattained levels of quiet flight (Figure 31). A large low-speed belt-driven propeller and compound muffling (Figure 32) were employed but the RC Engine's strongest virtue was its absence of valve and drive gear noise. In addition, the power was increased over the air-cooled reciprocating engine it replaced by 85% at an aircraft weight increase of only 6%.

Successful conclusion of this test led to a second quiet-airplane research contract, based on use of production aircraft, with the Cessna Cardinal (Figure 9). This test series also demonstrated capability of meeting the sound level goals established by the U. S. Navy for this airplane category (Figure 33). Since that time, the engine has been flown in a Cessna Cardinal with a single stage speed reduction at conventional propeller speeds (Figure 34) and in a Hughes model TH-55 helicopter (Figure 10).

All of these tests were performed using the same RC2-60 basic liquid-cooled engine which was designed in 1963 for automotive testing and, as pointed out earlier, not ported for aircraft. Although the tests were run for acoustic data, they indirectly demonstrated that liquid cooled RC Engines were fundamentally reliable (although we did learn that our modified automotive ignition switching unit was not) and provided a new level of smooth, vibrationless, quiet flight, combining the noise attenuation of a cooling fluid "blanket" and an "enclosable" engine with the higher efficiency and greater flexibility of liquid cooling. In addition to the breathing limitations of low-overlap side porting which restricted BMEP's and thus mechanical efficiencies, to levels inappropriate for aircraft, the propeller installations suffered both weight and efficiency disadvantages with the two stage multi-belt speed reduction.

The RC2-60 configured for flight testing, complete with aircraft carburetor, modified igntion, and appropriate manifolding, is shown in Figure 35. Our attempts to adapt an automotive C-D ignition system to dual control box reliability, via a switch, proved a mistake and the switching box itself resulted in several problems. Ironically, we have not had trouble in other field test installations with our standard automatic coil and distributor ignition system. The test stand performance is shown in Figure 36. This engine's limitations as an aircraft powerplant, aside from the obvious lack of reduction gear, are primarily due to its side porting designed for low overlap and a top speed of 5000-5500 RPM. To better illustrate the potential that a speed increase with peripheral ports can offer, Figure 37 shows data from an RC1-60 with peripheral ports and a moderate speed increase. The ports could be opened more, allowing a higher power peak. However, this test shows that over 320 HP from the RC2-60, or 400 for an RC2-75, can be achieved at 7000 RPM.

Conversion of this automotive engine to a gasoline General Aviation prototype, the RC2-75 reflected our experience with these RC2-60 tests. Propeller shaft reduction (.365:1) is by integral spur gears. The reduction drive and general configuration approach were reviewed with Piper, Cessna, Beech, the FAA, and accessory suppliers during the design process. The peripheral intake porting was a must not only for higher volumetric efficiencies which enable the initial conservative power rating of 285 HP to be attained at modest speeds but, more importantly, because it allows future growth to significantly higher ratings, with and without accompanying speed increases.

One of the reasons liquid cooling was chosen for General Aviation is that as the power output increases, air cooling becomes more difficult and the percentage of useful power that shows up as cooling power (or as parasitic drag) increases significantly; efficient liquid cooling, even, at the initial ratings of the RC2-75 in the 300 HP class, results in roughly half the cooling loss of current air-cooled reciprocating engines and also provides conservatively low metal temperatures in the highest heat zones. The liquid cooled engine can operate in an aircraft at the same specific fuel consumption figures that can be demonstrated on a test stand, whereas air-cooled reciprocating engines generally require a richer mixture to keep head temperatures to acceptable levels under certain power conditions. Other reasons include the economic differential possible with a simpler automotive engine type cooling system which can function effectively at aircraft outputs, as well as the advantages of safe cabin heat. Airframers have also pointed out that the possibility of remote location of the relatively small coolers allows packaging advantages such as airfoil surface coolers and, in other cases, thrust recovery at the heat exchanger cooling air outlet.

The basic size and weight features of the Rotary allow it to remain competitive with liquid cooling. The RC2-75 overall dimensions are 21.5 x 23.7 x 31.4 inches. The engine, shown on a propeller stand in Figure 38, weighs 280 pounds dry and 385 pounds ready to fly "wet," complete with heat exchangers. At the current stage of development, with about 1500 test hours, including 100 hours at wide open throttle and testing to 7000 rpm, the basic RC2-75 structural integrity is considered sound. Because of the 40,000 hour test background on the baseline 60 cubic inch size, relatively few durability problems are anticipated during the thousands of additional test hours we would want to run before certifying the engine--although the present design could probably pass a 150 hour qualification test at this point. However, during this reliability testing phase, finalization of compression ratio and related performance refinements would also be resolved.

The Rotary Aircraft Engine is also attractive from an exhaust emissions standpoint. Tests of the RC2-75 have been run for NASA last year. The results (Table I) show that, without exhaust after-control devices or departure from desired mixture strengths and ignition timings, the engine meets the previously proposed 1980 limits on CO and NO_x and comes very close to meeting HC. As noted, the HC excess occurs at the low power end where peripheral intake porting is at a particular disadvantage.

Curtiss-Wright is now under contract to evaluate modifications which we believe will bring all emissions within these limits. The most important changes involve adding side inlet ports which could be configured to operate alone at idle and taxi with the peripheral ports closed, and with the ignition changes mentioned earlier in this paper, which have been effective in improving low power firing regularity in our automotive prototypes.

Low hydrocarbons in an aircraft rotary may appear as a contradiction to the automotive experience but, again, performance is a function of the operating regime of the engine. The higher HC levels of the automotive rotary are an issue at the lower power and low speed end. Figure 39 compares the RC2-60U5 with an uncontrolled automotive engine of the same era, both tested at the University of Michigan, and shows the relative trends at higher powers and speeds. We theorize that the better apex sealing at high speed is a key factor but the influence of higher exhaust gas temperatures and the Rotary's close-coupling from port to exhaust manifold encourages thermal after-reaction.

The RC2-75 as tested last year had the original 7.5:1 compression ratio which was chosen at the time of design to take advantage of the less expensive 80/87 octane aviation fuel, which also contained less lead. The compression ratio is likely to increase in the final engine version, for fuel economy reasons developed in succeeding para.,although the degree has not been established at this point. The forthcoming exhaust emissions test will be run with 8.5:1 rotors for which we have test background on the single rotor rig, the RC1-75.

The wide open throttle 7.5:1 compression ratio performance of the RC2-75 is shown in Figure 40. The power drop-off above 5500 RPM is a function of port sizing; the power curve could be continued along the lower slope with slightly larger ports. The throttling restriction partially reflects conservatism and the desire to obtain user/flight experience with a moderate initial rating, although better fuel consumption can be obtained with increased power. The design decision at the time also reflected a desire to avoid the higher IMEP's and a possible dependence on the more expensive detonation gun trochoid coatings; more recent cost estimates, as well as technological advances in plasma spraying, have shown this issue to be less significant today.

The cruise fuel consumption of the single rotor RC1-75 engine, which as discussed earlier, is transferrable to the 2 rotor engine, is shown in Figure 41. The one point plotted for the RC2-75 test engine is consistent with the comparable RC1-75 curve. The other curves illustrate improvements possible with an 8.5:1 compression ratio, rotor pocket changes (symmetrical cut-out versus removal of trailing section material to reduce quench) and the strong effect of bringing the spark plug electrodes closer to the trochoid surface. The configuration represented by the lowest of these curves will be run in this year's second phase emissions test on the RC2-75.

The influence of engine rating and compression ratio upon fuel consumption has been discussed qualitatively. Figure 42 attempts to relate these issues and compare them to manufacturer's published data for engines in the same power class. The .54 BSFC point at 75% cruise represents status of the 7.5:1 compression ratio RC2-75 emissions tested last year. The drop to below .48, without a compression ratio change, by bringing the spark plug electrodes closer to the surface, is based on the test runs plotted in Figure 41. The one compression ratio increase is expected to bring this point close to the .46 line. However, the engine will still be at a relatively low BMEP point consistent with 285 HP @ 6000 RPM. If the engine rating is increased to, say 285 HP at 5500 RPM or 330 HP at 5500, both attainable naturally aspirated, the curves pass through the distribution of Lycoming IO-540 models at comparable compression ratios. Since the Rotary enjoys a detonation margin advantage over the piston engine, a 9.5:1 compression ratio is not unreasonable for 100/130 aviation fuel. The effect of engine mean effective pressure alone is shown more clearly by the curve to the right. In this case, the RC2-75 is shown only for 9.5:1 compression ratio. It can be seen that as the BMEP reaches the general level of the A, B, E and G models of the IO-540, the RC2-75 projected fuel consumptions are relatively close.

The fact that the brake specific fuel consumptions, for the same compression ratio, correspond closely at the same BMEP level implies that a comparison on an Indicated basis, reflecting only the events within the combustion chamber, is also comparable. For this to be the case, the friction horsepower (FHP) between engine types would also have to be comparable. Very little data for reciprocating aircraft engines is available, but the calculations we have made indicate that the FHP, notwithstanding higher RPM of the Rotary, is in the same range and that ISFC and Indicated Specific Air Consumption (ISAC) are also comparable.

This means that since thermal and mechanical efficiencies of both engine types are similar in the aircraft engine mode, the obvious way to improve fuel consumption is by running at higher outputs (BMEP's) if we exclude additional combustion improvements. This is not to say that future improvements in thermal efficiency and reductions in mechanical friction for the RC2-75 are ruled out, since some will occur, but a realistic appraisal says that significant additional gains in both of these areas are difficult to come by.

While the Rotary is believed to have an inherent edge over the reciprocating engine at sustained high output, any Otto cycle engine has to work at higher temperatures, pressures, and relatively higher component stresses as the BMEP, a direct index of how hard the engine is "working," rises. And there are few spark ignited engines anywhere that operate at higher BMEP's than aircraft engines. Whatever the degree, the trade-off has to be fuel consumption versus relative engine life and reliability. Since the liquid cooled rotary aircraft engine has power output capabilities beyond the air-cooled engine and the thermal efficiencies are comparable to reciprocating engines as stated above, the fuel consumption potential of the high output liquid cooled engine is clearly more favorable.

Stratified Charge Aircraft Engines

All discussion of aircraft engines to this point was for homogeneous charge machines. A direct-injected unthrottled Stratified Charge Rotary offers the advantages of safer Diesel fuel (or a middle distillate chosen to optimize refinery output) and better SFC, but performance-wise, it has a different set of characteristics and will not be power rated the same way as its mechanically very similar carbureted or low pressure injected counterpart. More work needs to be done to develop data inputs and optimize performance in this application, but the fuel economy gains will not be exactly the same as they will be in an automobile.

The gasoline Rotary Aviation Engine, such as the RC2-75, has two growth modes: higher output by allowing the engine to intake the full amount of air that it is capable of aspirating, or else higher speed. Which route, or what combination, is a function of whichever trade-offs of cruise BSFC vs. lighter engine specific weight are most attractive for a given application. However, the Stratified Charge Engine is more akin to the diesel, where the maximum power per pound of air is some 10 - 20% less than the homogeneous charge engine because efficiency is lost beyond a certain mixture strength which is generally leaner than stoichiometric. In the case of this engine, turbocharging is, therefore, not only a means of achieving the power rating of the same displacement homogeneous charge engine and the required critical altitude, but is the obvious way to improve SFC. Figure 43 illustrates the effect of reducing engine displacement, for the same power output, as the degree of turbocharging is increased. If we assume equivalent overall compression ratios and ignore the small specific friction changes with size, the decrease in BSFC with increased charging results from increasing the mechanical efficiency. This is also reflected in the operating mixture strength as can be seen from the F/A curves. The concept of increasing mechanical efficiency by upping the output is not unique to Stratified Charge but the fuel consumption limiting BMEP is lower than it is for the homogeneous charge version. Alternatively, the engine displacement can be increased to maintain the same output but either way there will be some weight penalty. The sea level blown engine will be heavier because of the slightly larger turbocharger in addition to the delta for the high pressure injection pumps, but the package can still be attractive because of the competitive margin that was available at the outset.

Insofar as turbocharging for critical altitude is concerned, both the homogeneous and stratified charge engines respond in similar fashion and are not different from conventional piston engines. The optimum degree of sea-level turbocharging for the Stratified Charge version is less apparent at this stage.

Higher Speed

Both engines have speed growth possibilities, although RPM growth for the high pressure injected engine is predicated upon continued development of any of the several electronic fuel injection techniques now in work throughout the world. While we have run Diesel jerk-pumps at 6000 RPM, this is at or close to the limit. Projections for higher speed stratified charge aircraft engines are given in referenced NASA reports by Lockheed-Georgia, but the trends are similar to the following curves for homogeneous charge engines. A possible growth scenario for the RC2-75 is shown in Figure 44. Figures 45 and 46 expand the 10,000 RPM seal speed family to other sizes. Speeds up to 10,000 RPM are considered realizable within current technology limits but do require development. Rotational speeds to 12,000 RPM are predicated upon designed but not tested apex seals which retract from trochoid contact at high speed, thus reducing friction. Since leakage is a time function, a small controlled gap is considered acceptable.

The trade-off here is somewhat different than the one discussed earlier for BSFC vs. BMEP rating. Increased rating with speed can be accomplished with only a moderate increase in component stresses if the Indicated mean effective pressure (IMEP) is held to reasonable limits. However, there is no way that the brake fuel consumption can be prevented from increasing with speed even though the rate of increase is less for the Rotary. Primary use of this capability would, therefore, be for improved take-off and climb performance of a given sized engine where cruise would then be at a lower than typical percentage of maximum speed.

Closure

The Rotary Engine has been developed to the point where it is a viable powerplant capable of a wider application range than any engine in use today. General Aviation usage is the most obvious application within this range.

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TABLE I

EPA EXHAUST EMISSIONS TEST RESULTS
285 BHP CURTISS-WRIGHT RC2-75 ENGINE NO. 7521-8
(Ignition Timing, 35° BTC)

	IDLE	TAXI	TAKE-OFF	CLIMB	APPROACH
KW	2.4	21	215	170	85
BHP	3.2	28	288	228	114
RPM	1330	2660	6000	5400	5200
Air Flow – lb/hr	142.000	406.000	2,320.000	1,840.000	1,160.000
Fuel Flow – lb/hr	10.800	29.600	169.000	134.000	85.000
Air-Fuel Ratio	13.148	13.716	13.728	13.731	13.647
CO_2, % dry	6.200	10.700	12.750	12.750	12.400
CO, % dry	4.400	3.000	2.900	2.900	3.300
THC, PPMC wet	38,571.000	10,950.000	600.000	780.000	840.000
O_2, % dry	6.750	2.400	0.000	0.000	0.000
NO_x, PPM wet	6.300	43.000	550.000	760.000	127.000
H_2O Correction	0.92037	0.89099	0.86517	0.86486	0.86301
A/F-Spindt Carbon Bal.	12.95457	13.[illegible]8732	13.34775	13.33008	13.15666
A/F-Stivender Oxygen Bal.	12.80934	13.[illegible]0191	13.21285	13.21261	13.10602
Exhaust Density, lb/ft^3	0.07374	0.07437	0.07439	0.07439	0.07430
HC, lb/hr	2.88589	2.31574	0.72492	0.74737	0.50824
CO, lb/hr	6.09172	11.36507	60.94562	48.31582	34.64385
NO_x, lb/hr	0.00155	0.02997	2.18987	2.39977	0.25323
HC, lb/Cycle	0.09620	0.54034	0.00362	0.06228	0.05082
CO, lb/Cycle	0.20306	2.65185	0.30473	4.02632	3.46439
NO_x, lb/Cycle	0.00005	0.00699	0.01095	0.19998	0.02532

	DEMONSTRATED	EPA STANDARD
HC Emissions, lb/Cycle/Rated HP	0.00264	0.0019
CO Emissions, lb/Cycle/Rated HP	0.03737	0.0420
NO_x Emissions, lb/Cycle/Rated HP	0.00085	0.0015

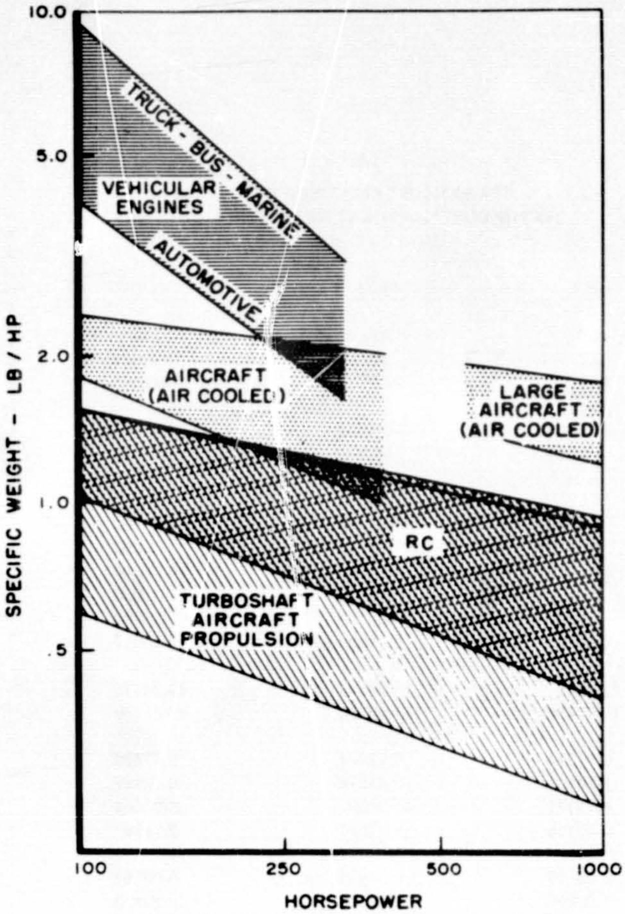

Figure 1. - Specific weight comparison with turboshaft engines and Otto cycle gasoline engines.

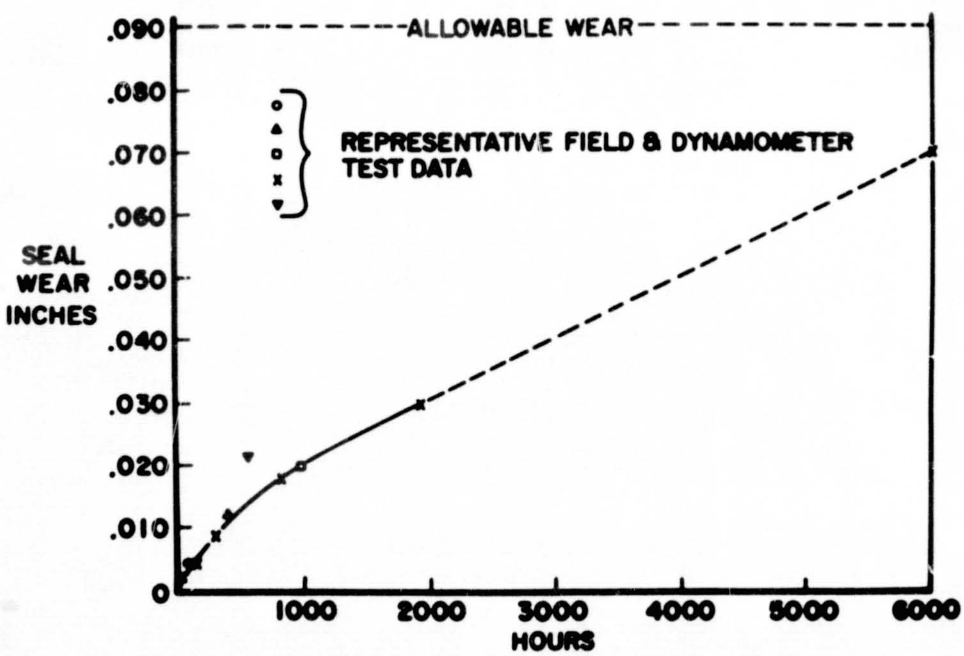

Figure 2. - Apex seal wear, RC2-60.

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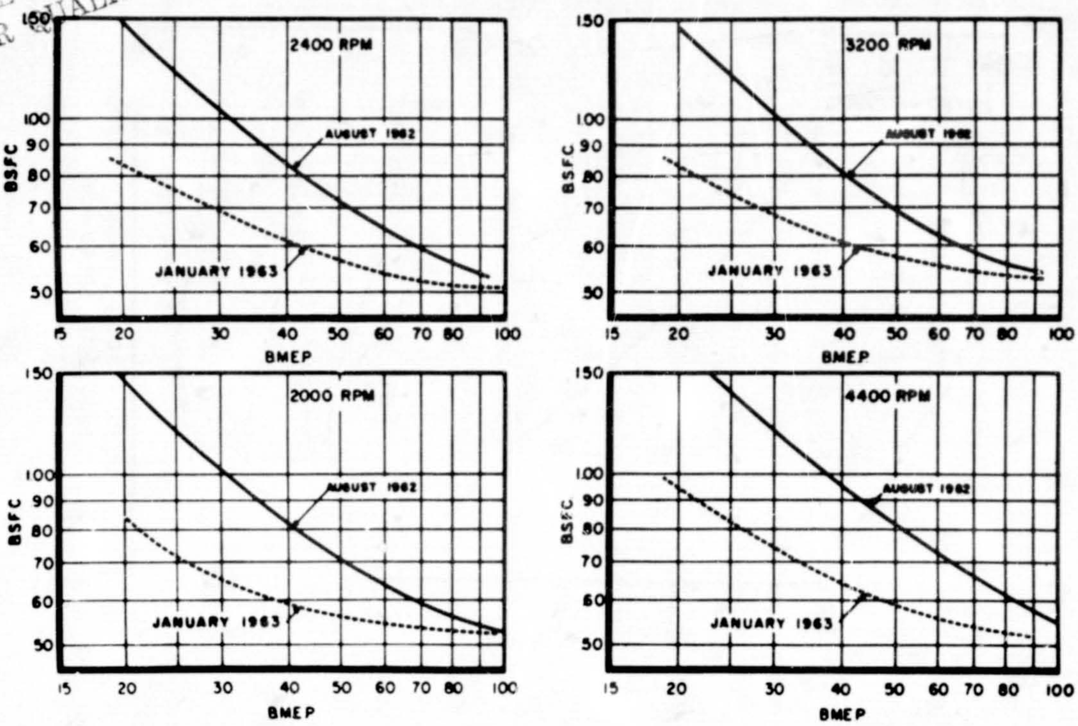

Figure 3. - SFC test results, January 1963, RC1-60.

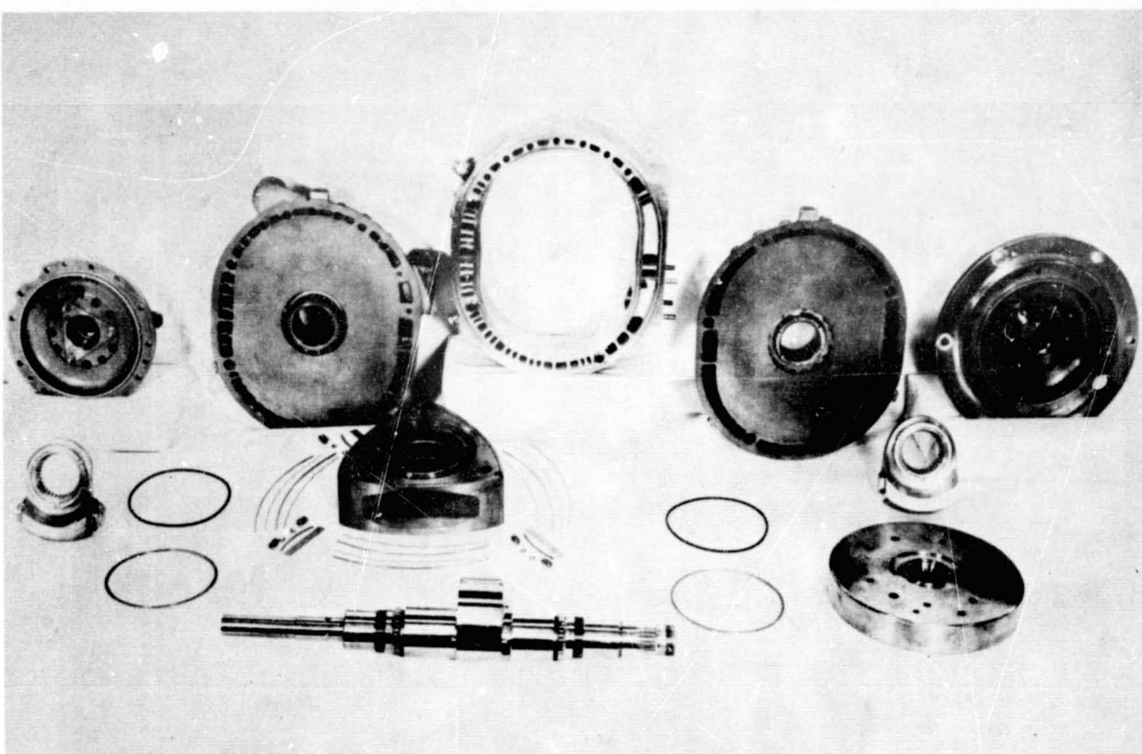

Figure 4. - Basic engine components, RC1-60.

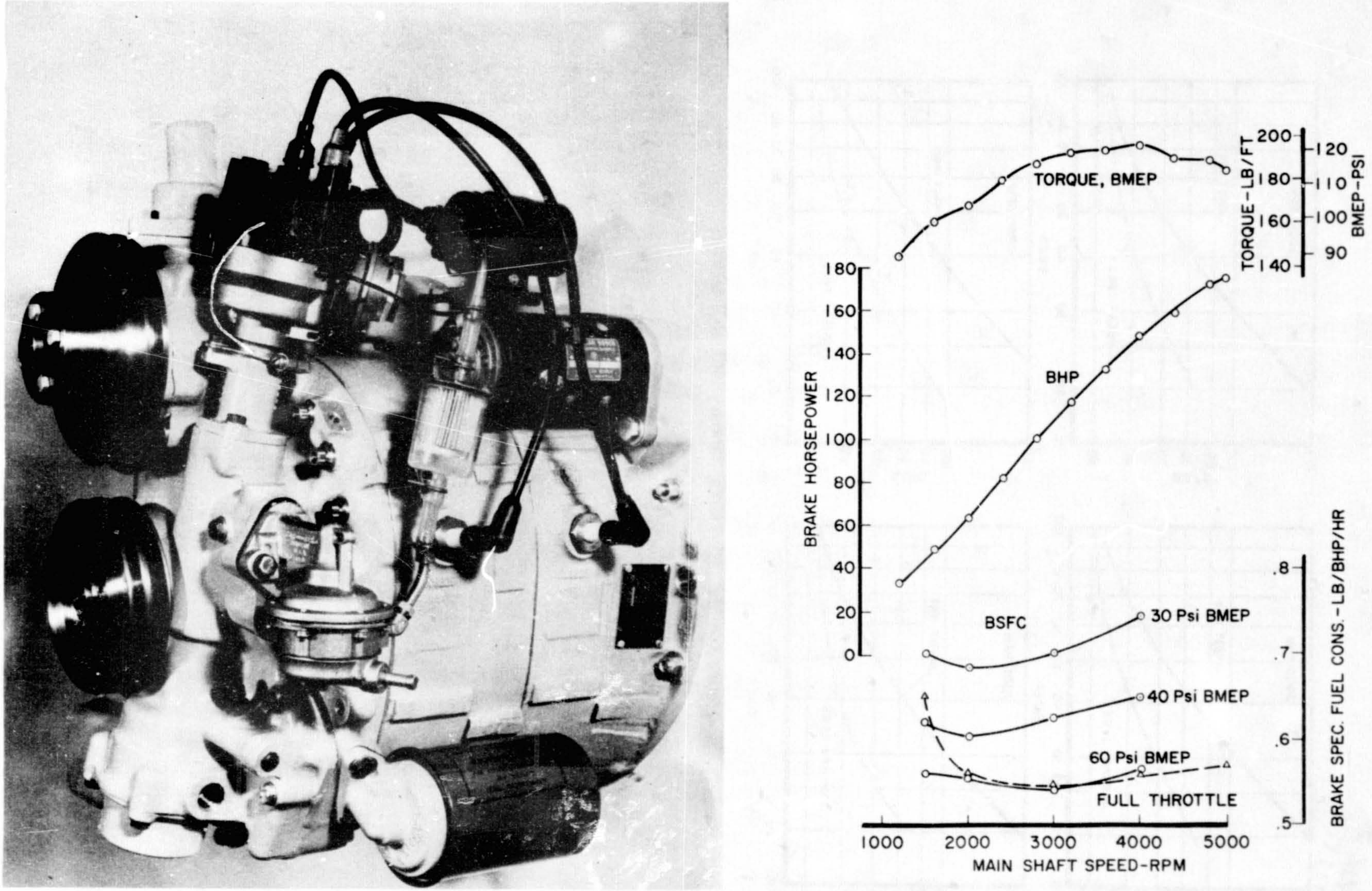

Figure 5. - RC2-60U5 automotive engine prototype.

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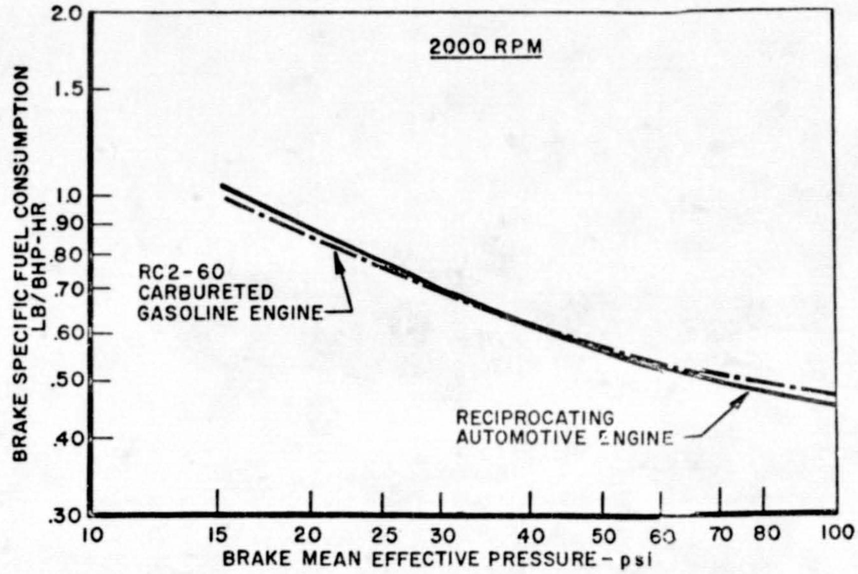
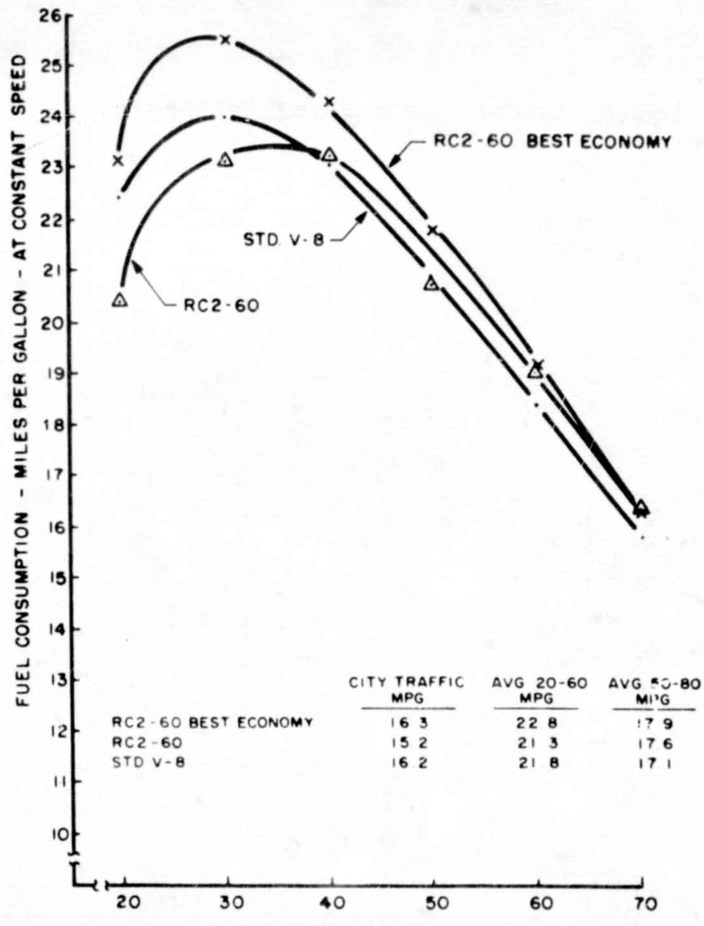


Figure 6. - RC2-60 part load fuel consumption.



	CITY TRAFFIC MPG	AVG 20-60 MPG	AVG 50-80 MPG
RC2-60 BEST ECONOMY	16.3	22.8	17.9
RC2-60	15.2	21.3	17.6
STD V-8	16.2	21.8	17.1

Figure 7. - Automobile fuel economy with RC2-60 and standard V-8 production engine.

Figure 8. - Lockheed Q-Star airplane with RC2-60 engine.

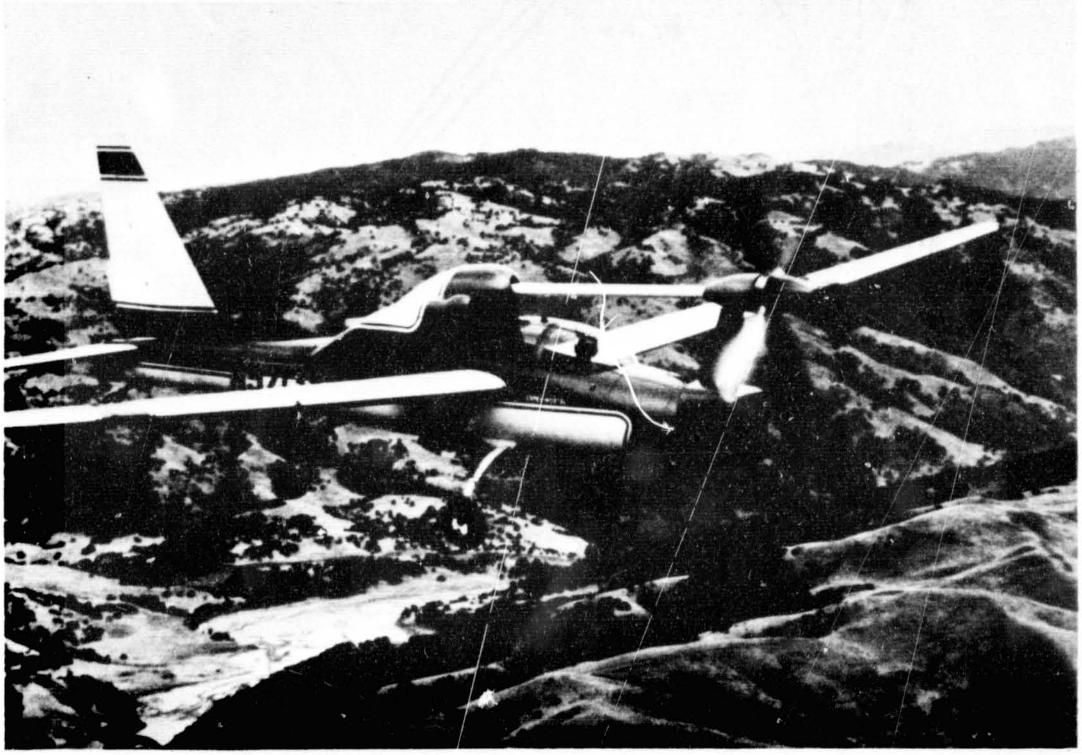


Figure 9. - Cessna Cardinal airplane with RC2-60 engine.

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Figure 10. - Hughes helicopter with RC2-60 engine.

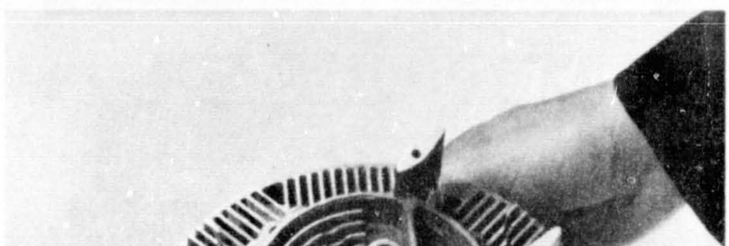

Figure 11. - RC1-4.3 engine.

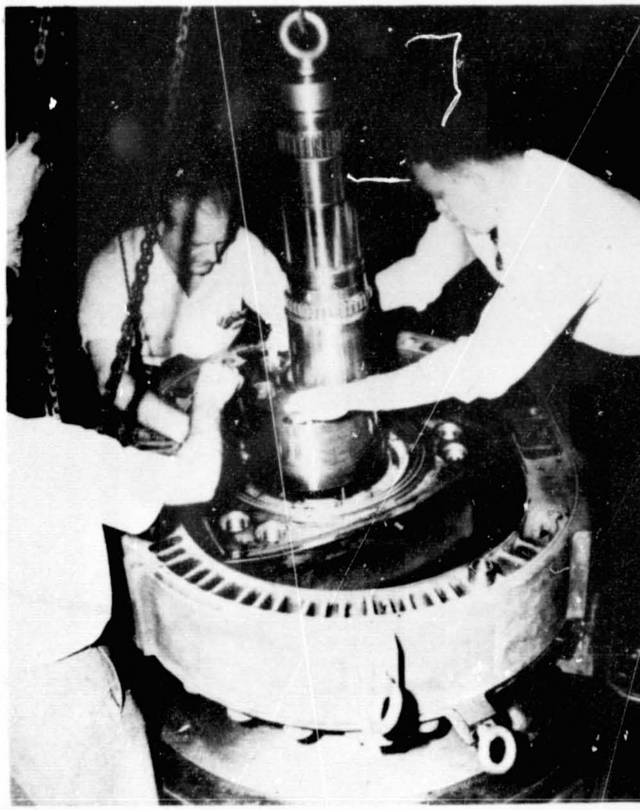

Figure 12. - RC1-1920 engine, assembly of power section.

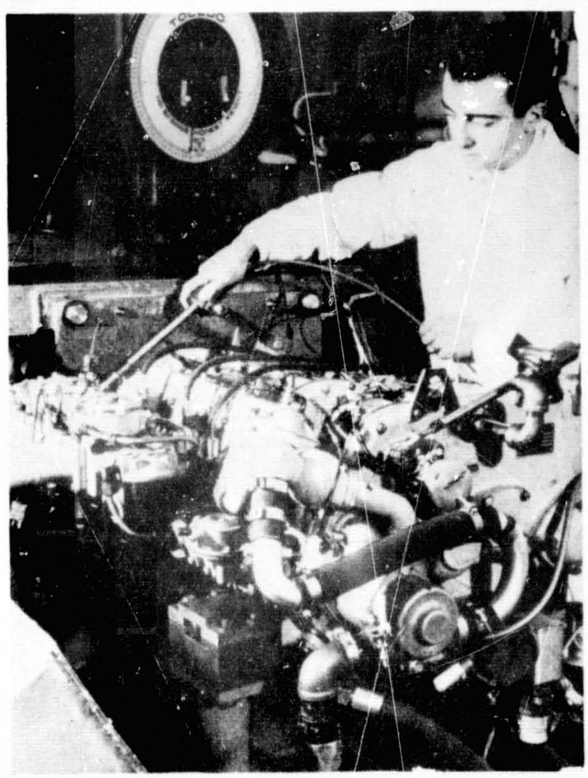

Figure 13. - RC4-60 engine, three-quarter rear view, carburetor side.

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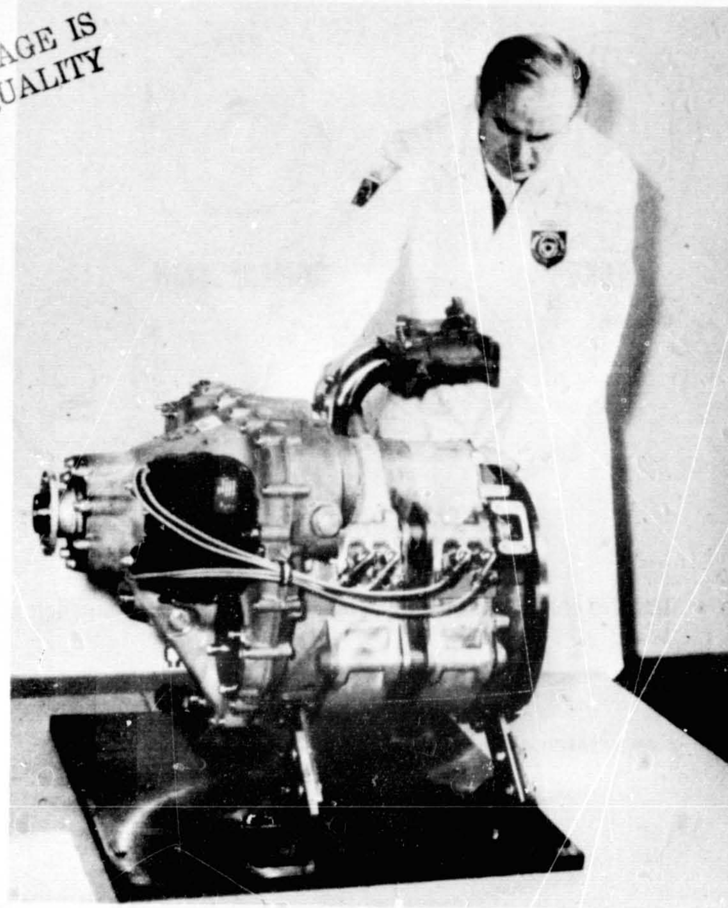

Figure 14. - RC2-75 engine.

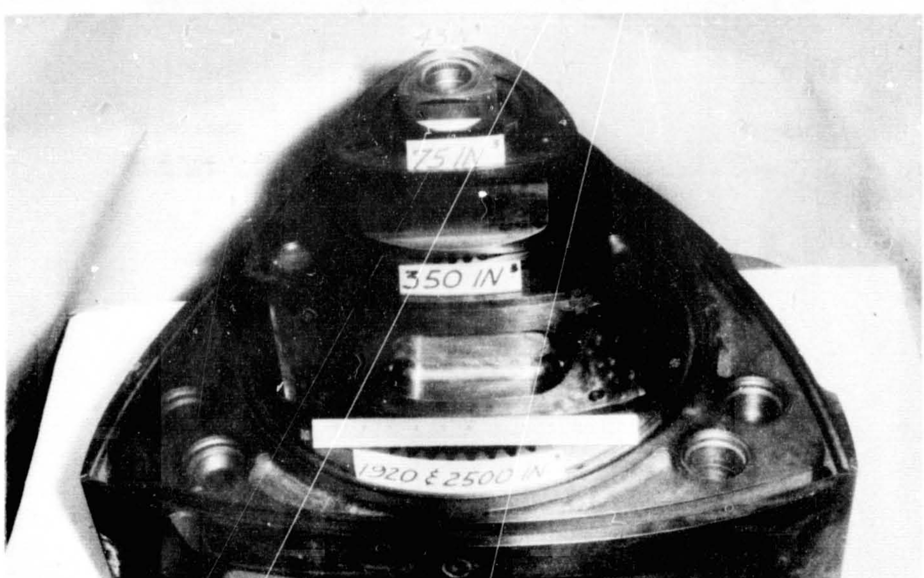

Figure 15. - Rotor comparison, 4.3 to 2500 cubic inch displacement.

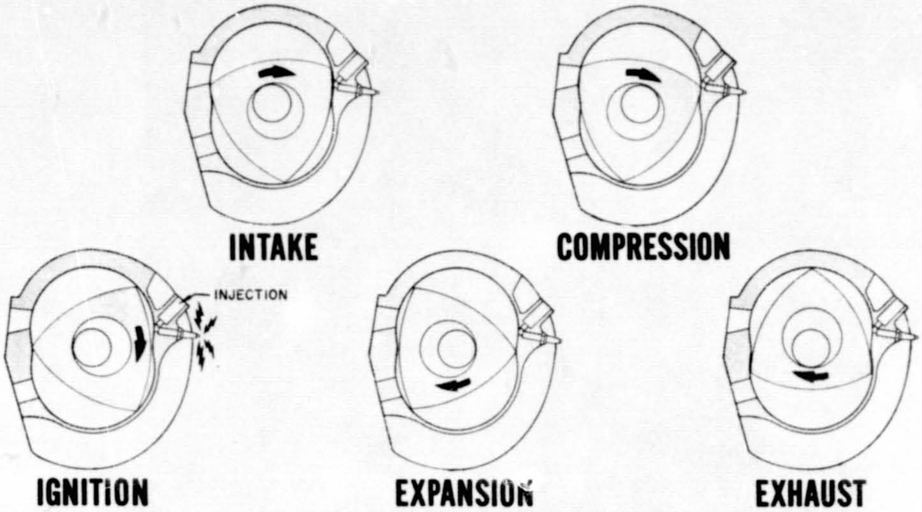

Figure 16. - Stratified charge combustion cycle of rotating combustion engine.

RC-1668

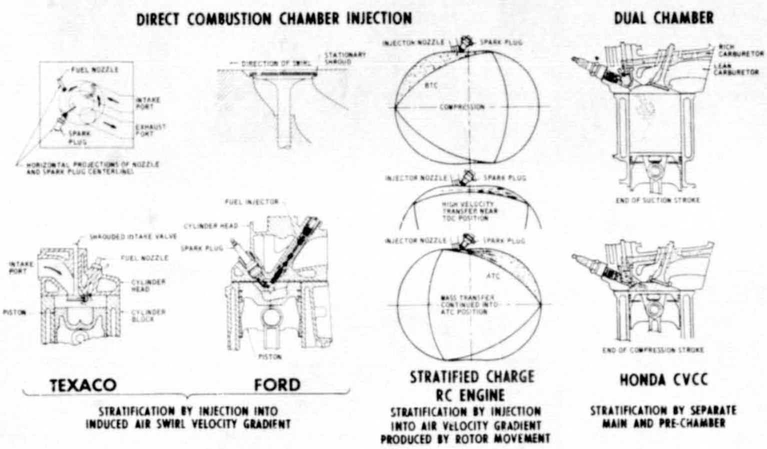

Figure 17. - Stratified charge processes.

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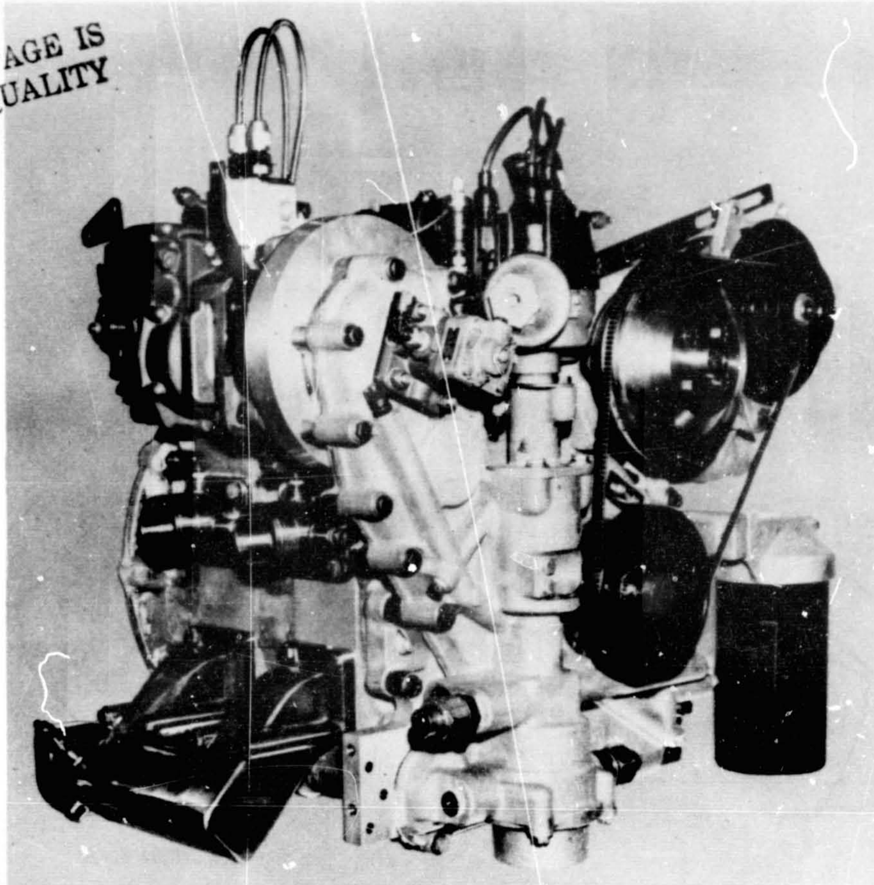

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HEIGHT	24 IN.

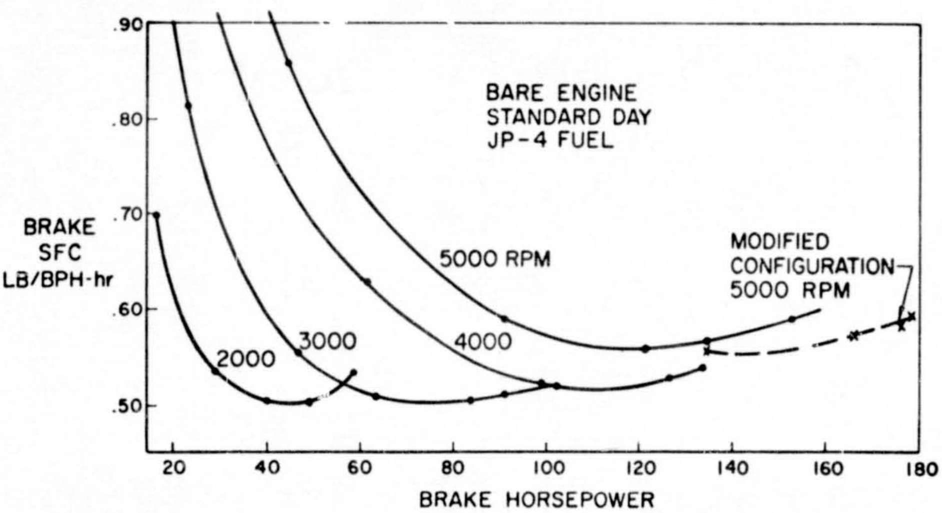

Figure 18. - RC2-60U10 liquid-cooled stratified charge engine (1965).

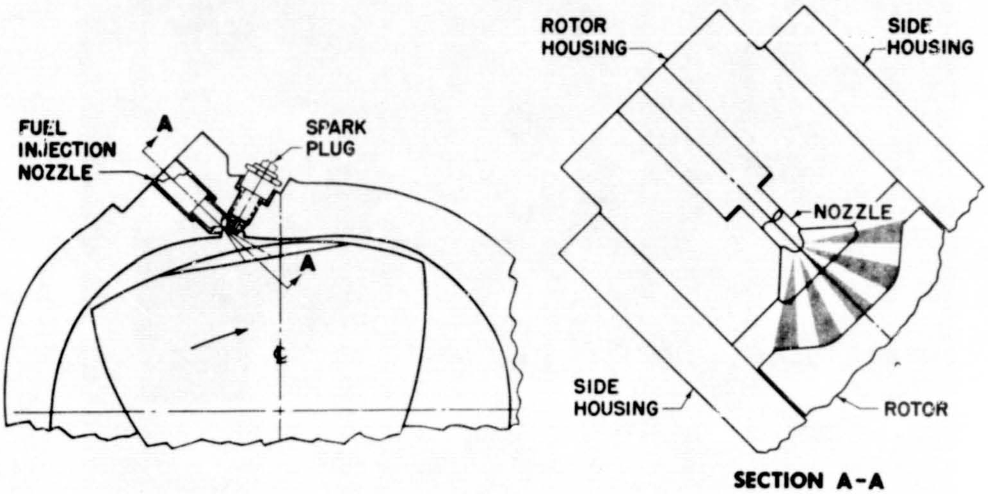

Figure 19. - Stratified charge RC engine, co-planar injection.

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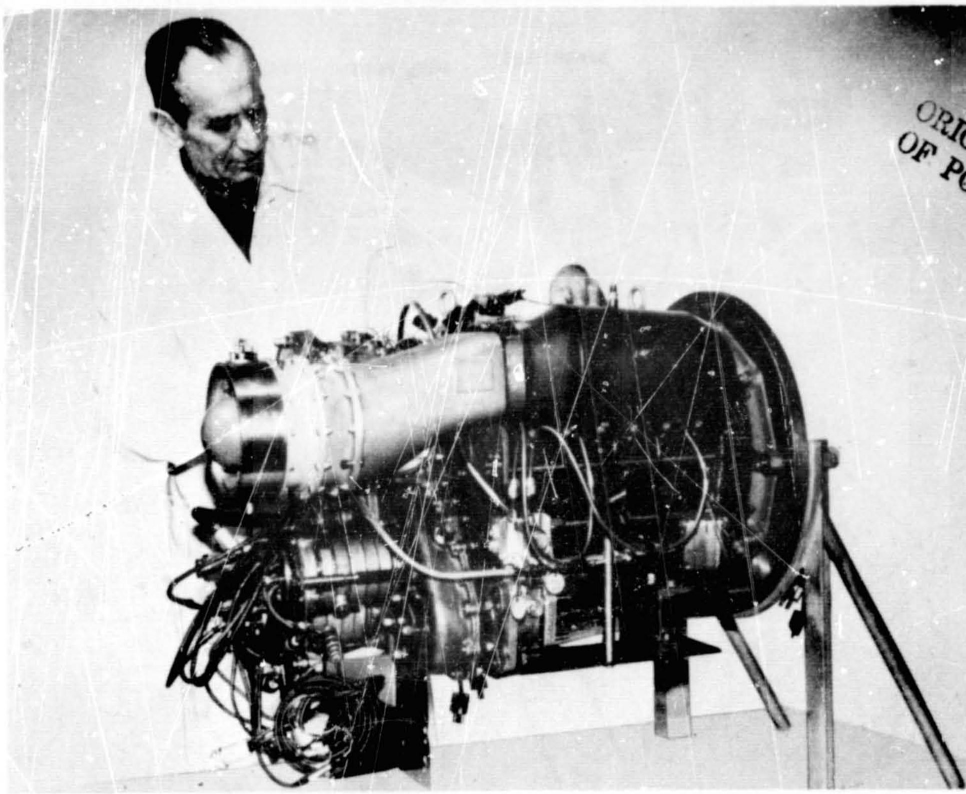


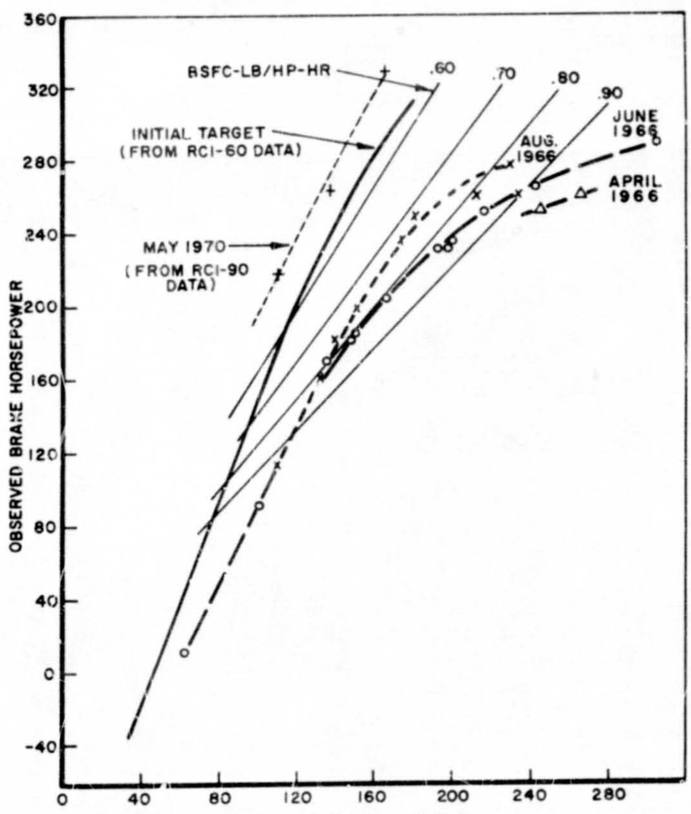


Figure 20. - RC2-90 air-cooled stratified charge RC engine (1966).

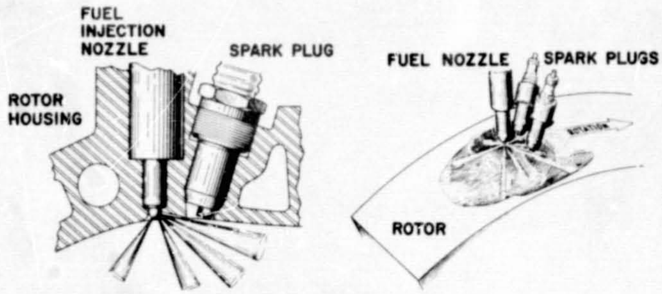
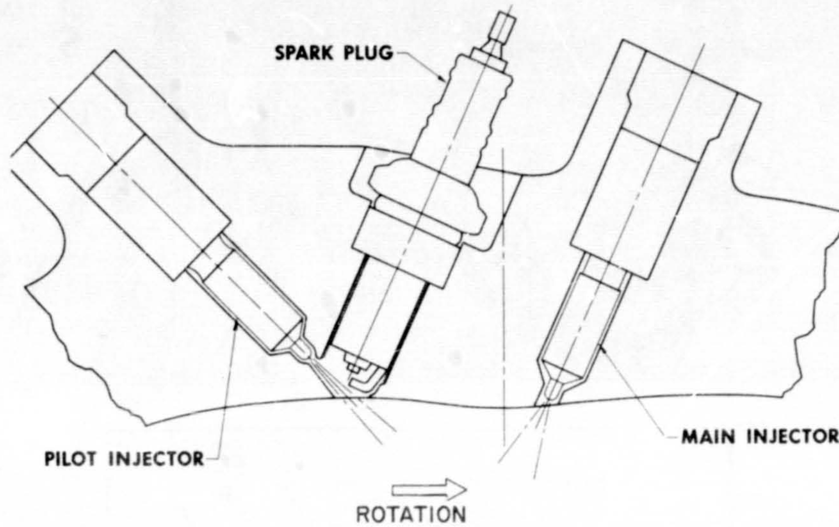


Figure 21. - Stratified charge RC engine showerhead injection.



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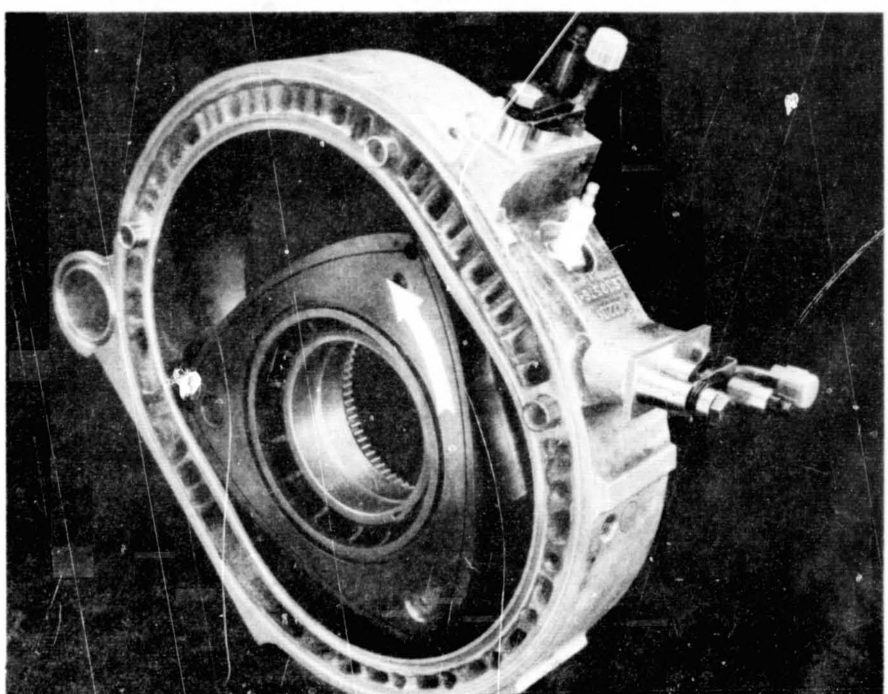

Figure 22. - Stratified charge RC1-60, BTC pilot tandem dual.

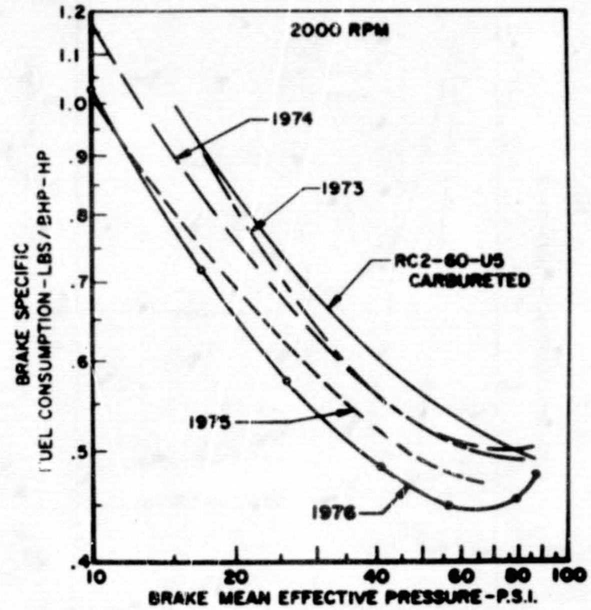

Figure 23. - Current status of fuel consumption for stratified charge rotary engines.

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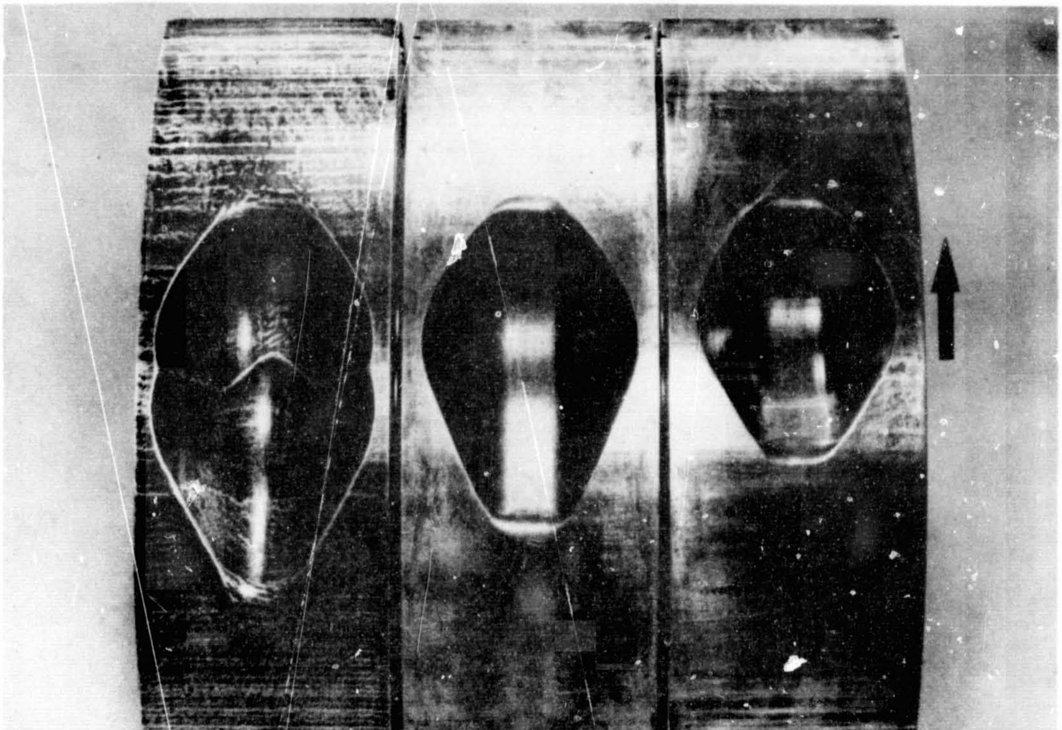

Figure 24. - Rotor pocket variation with compression ratio.

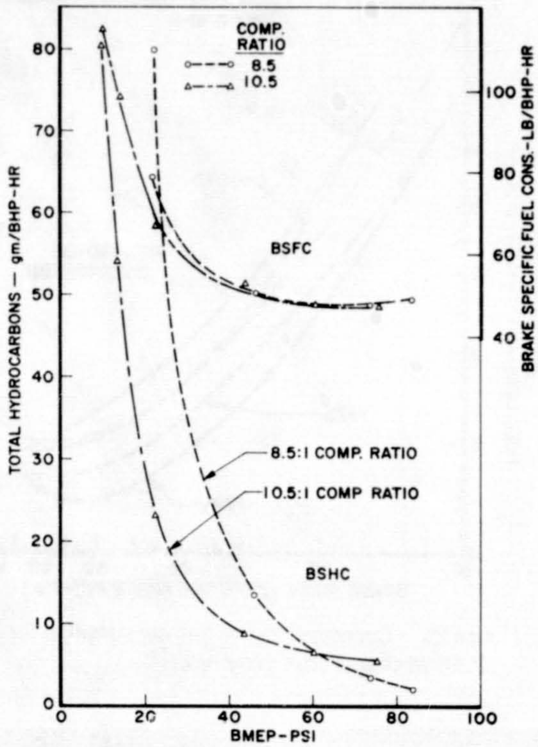

Figure 25. - Effect of compression ratio on fuel consumption and exhaust hydrocarbons.

Without insert

Assembled - after test

Figure 26. - Bolt-on hot insert rotor.

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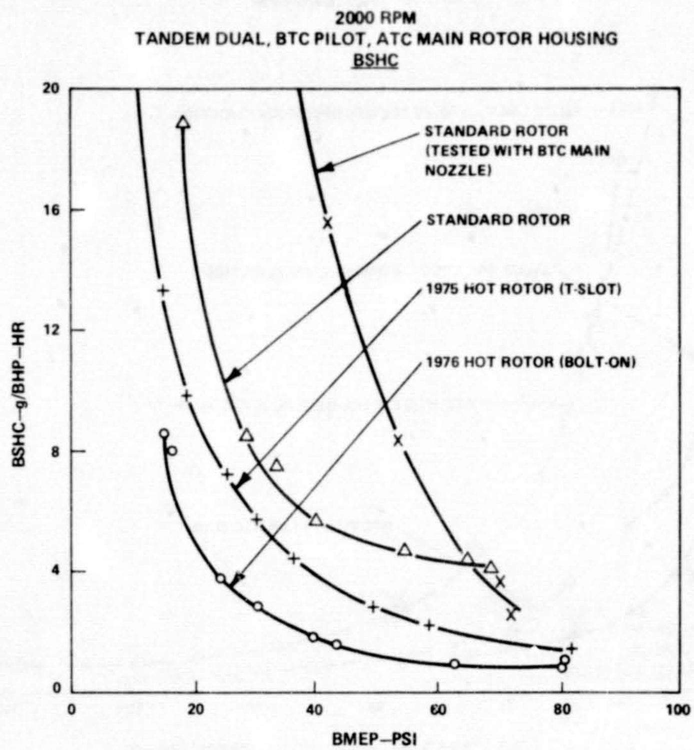

Figure 27. - Specific hydrocarbon emissions with standard and hot-insert rotors.

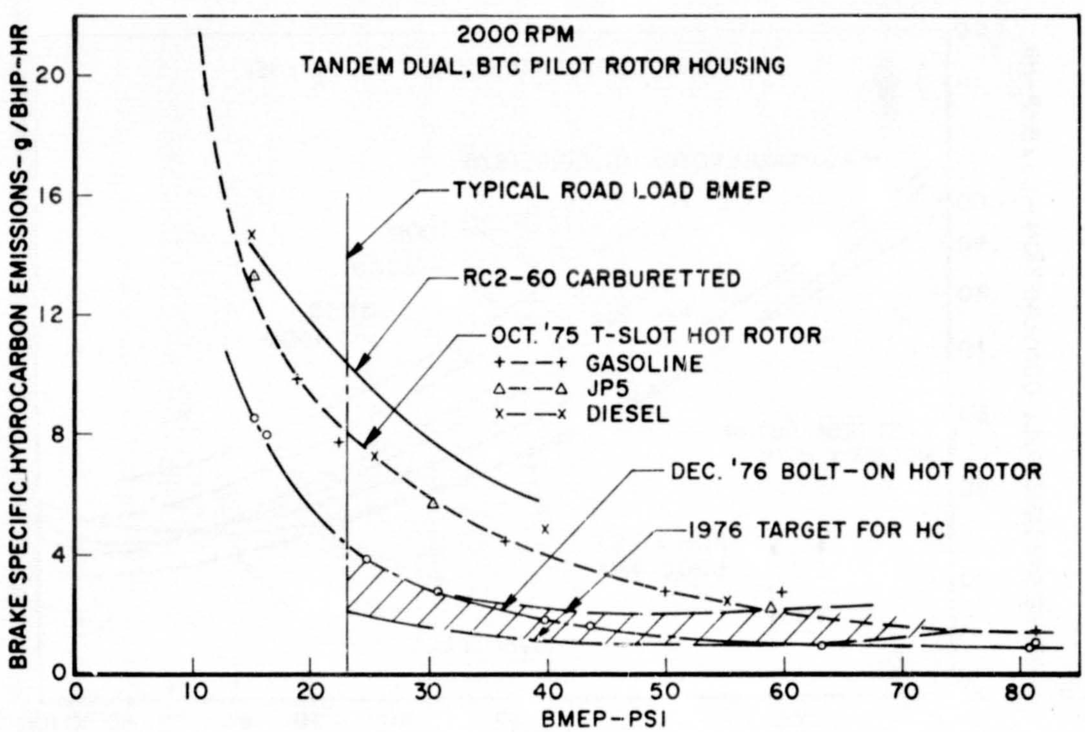

Figure 28. - Specific hydrocarbon emissions.

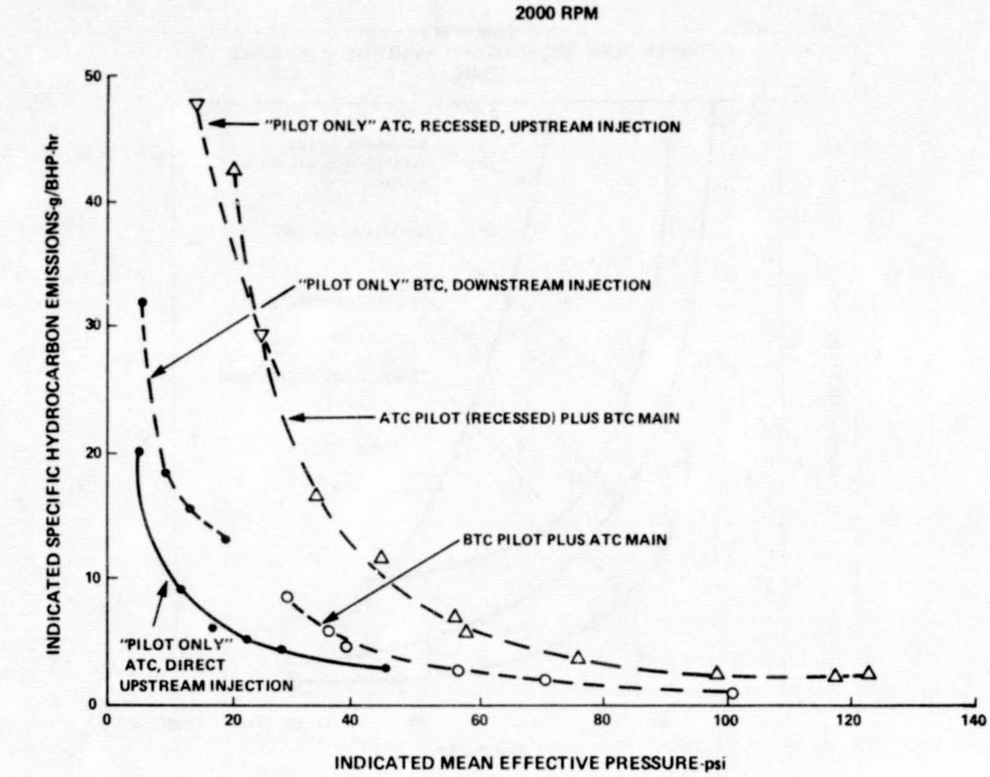

Figure 29. - Indicated specific hydrocarbon emissions comparison of different pilot locations.

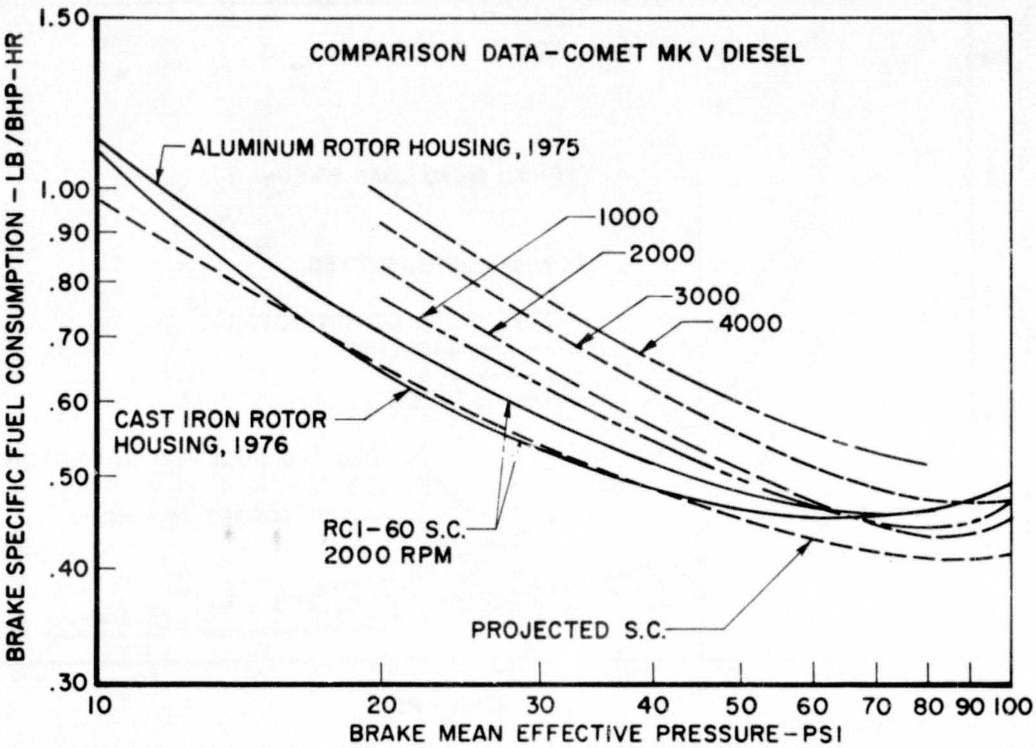

Figure 30. - Part load fuel consumption.

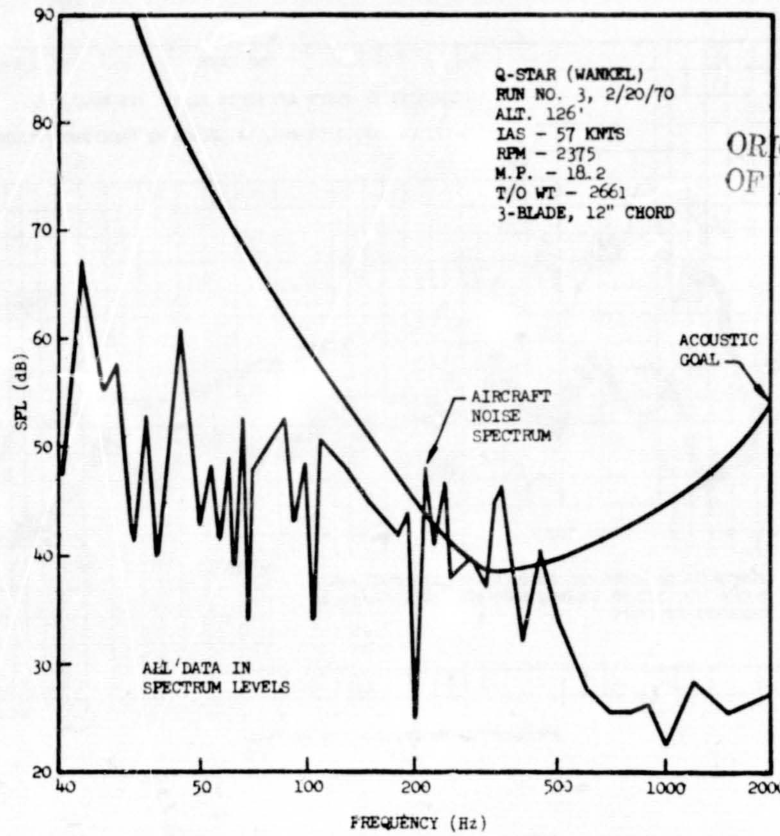

Figure 31. - Q-Star noise spectrum.

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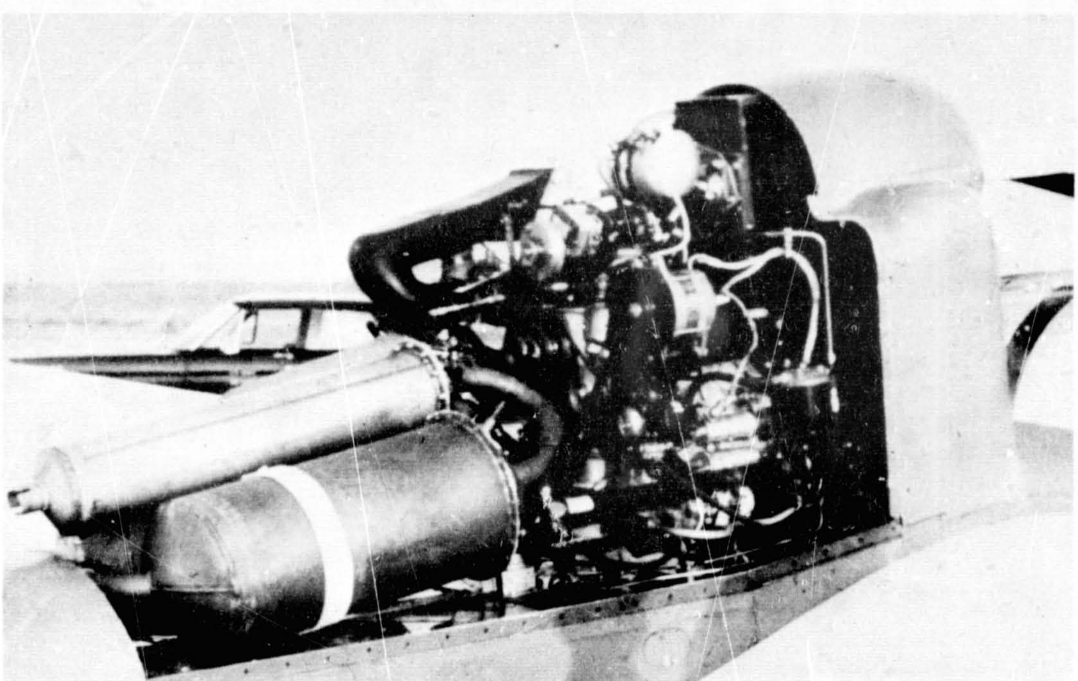

Figure 32. - RC2-60-Y8, Q-Star installation details.

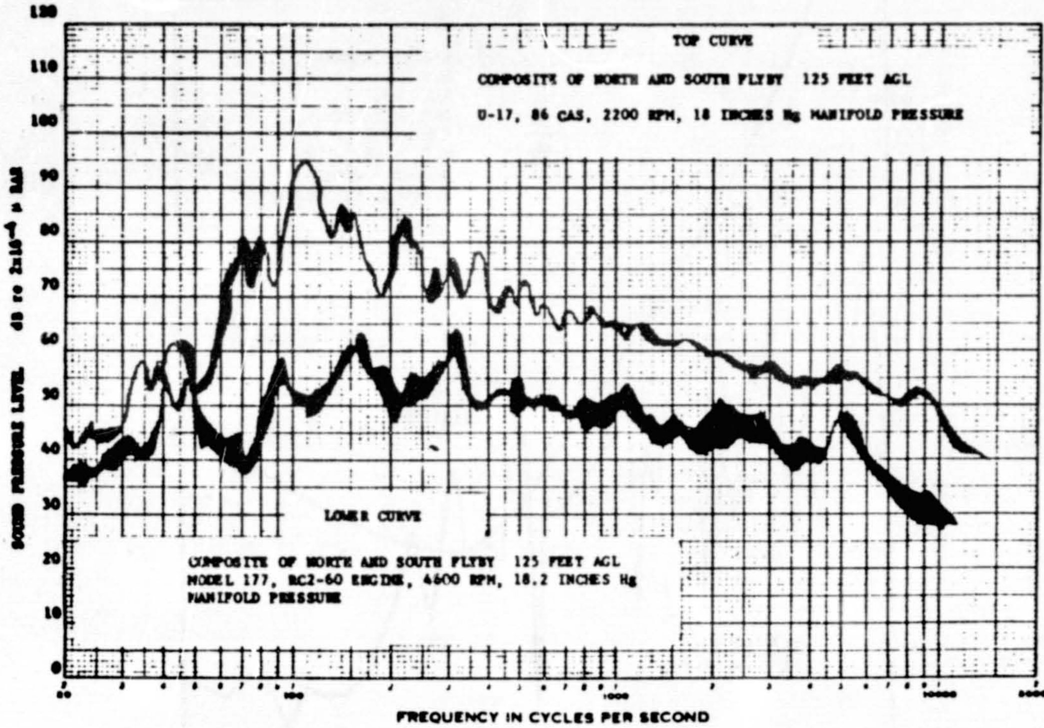

Figure 33. - Cessna 177 RC2-60 installation noise spectrum

Figure 34. - Cessna 177, standard propeller speed installation.

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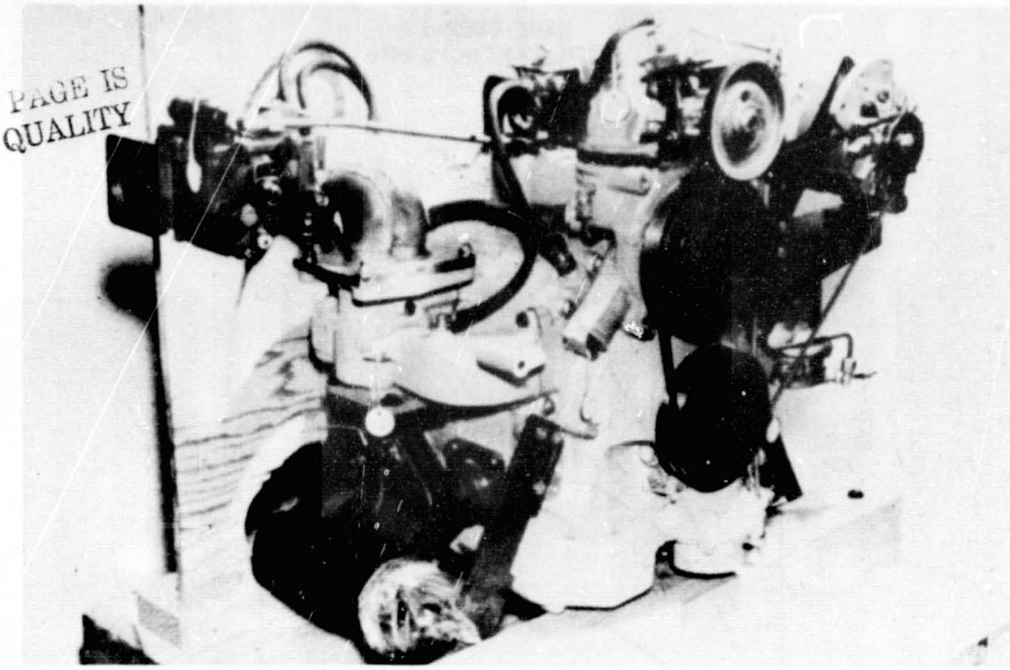

Figure 35. - RC2-60-Y8 engine, aircraft carburetor, modified ignition, and manifolding.

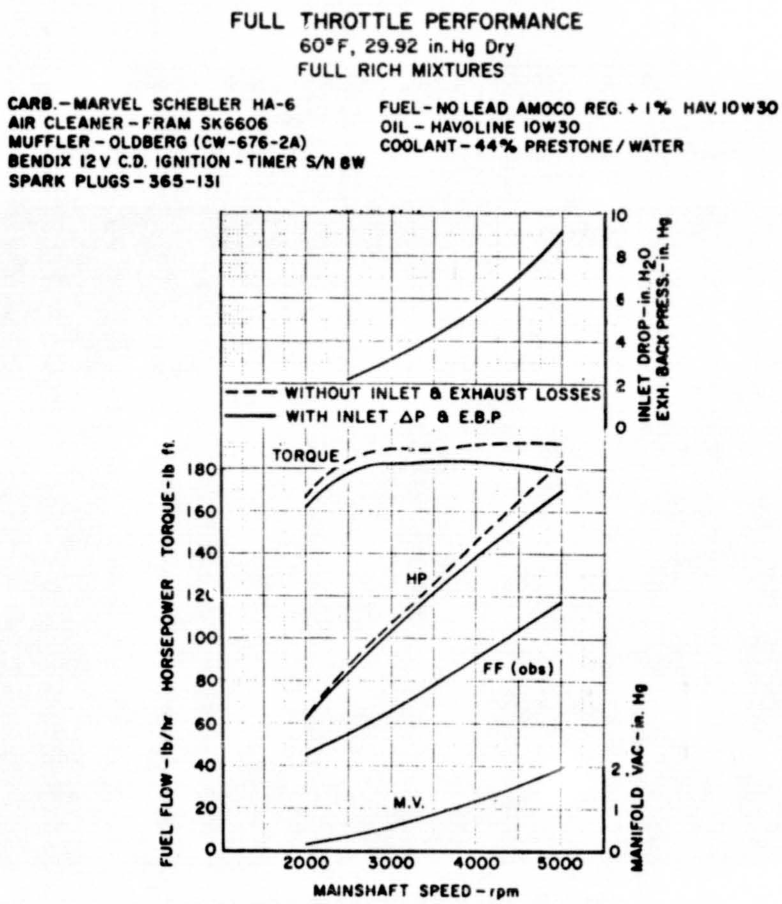

Figure 36. - RC2-60-Y8 test stand performance.

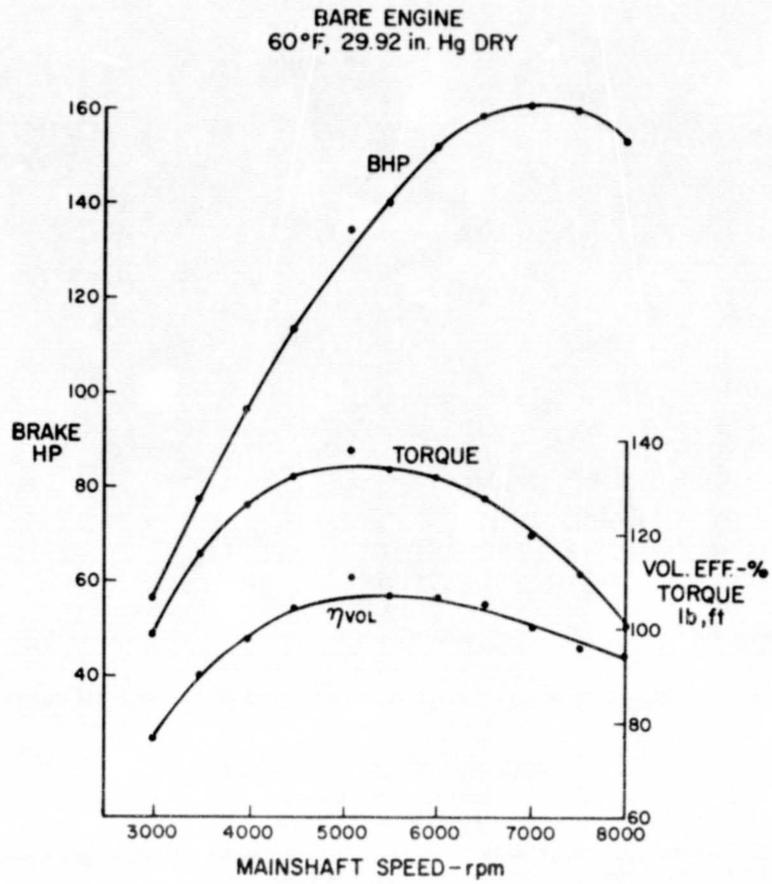

Figure 37. - RC1-60, peripheral port engine, performance at higher speeds.

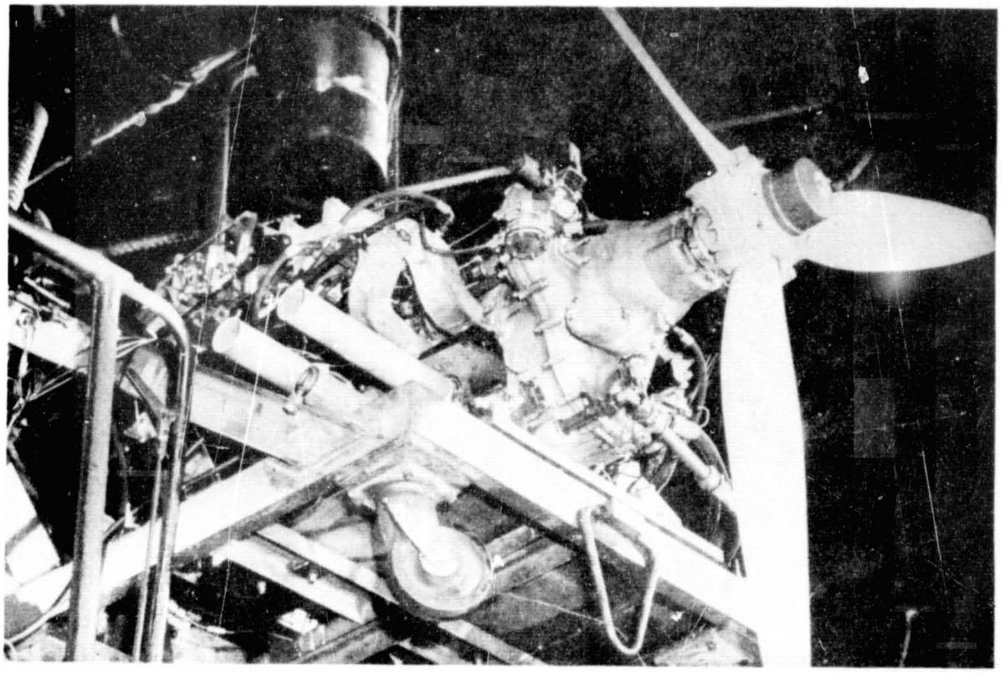

Figure 38. - RC2-75 engine on propeller test stand.

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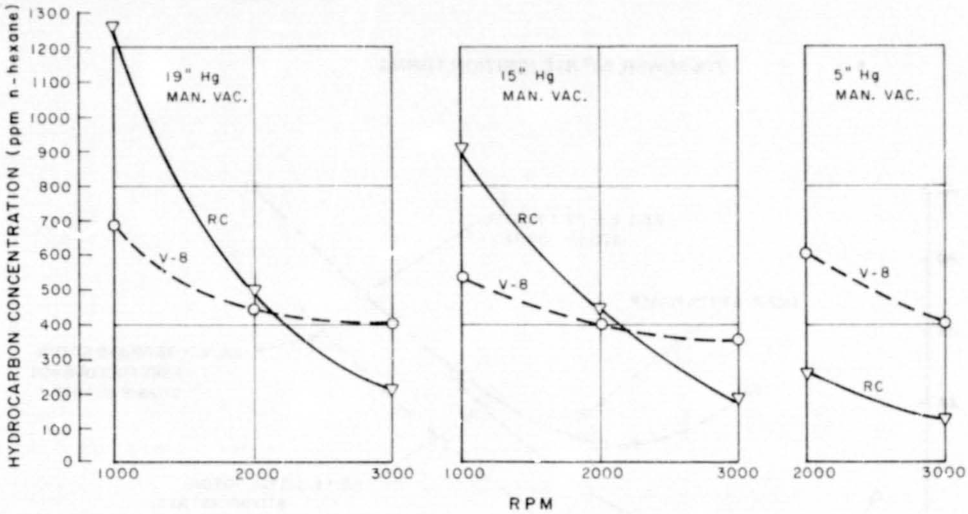

Figure 39. - RC2-60U5 and automotive V-8 engine raw emissions as function of engine speed.

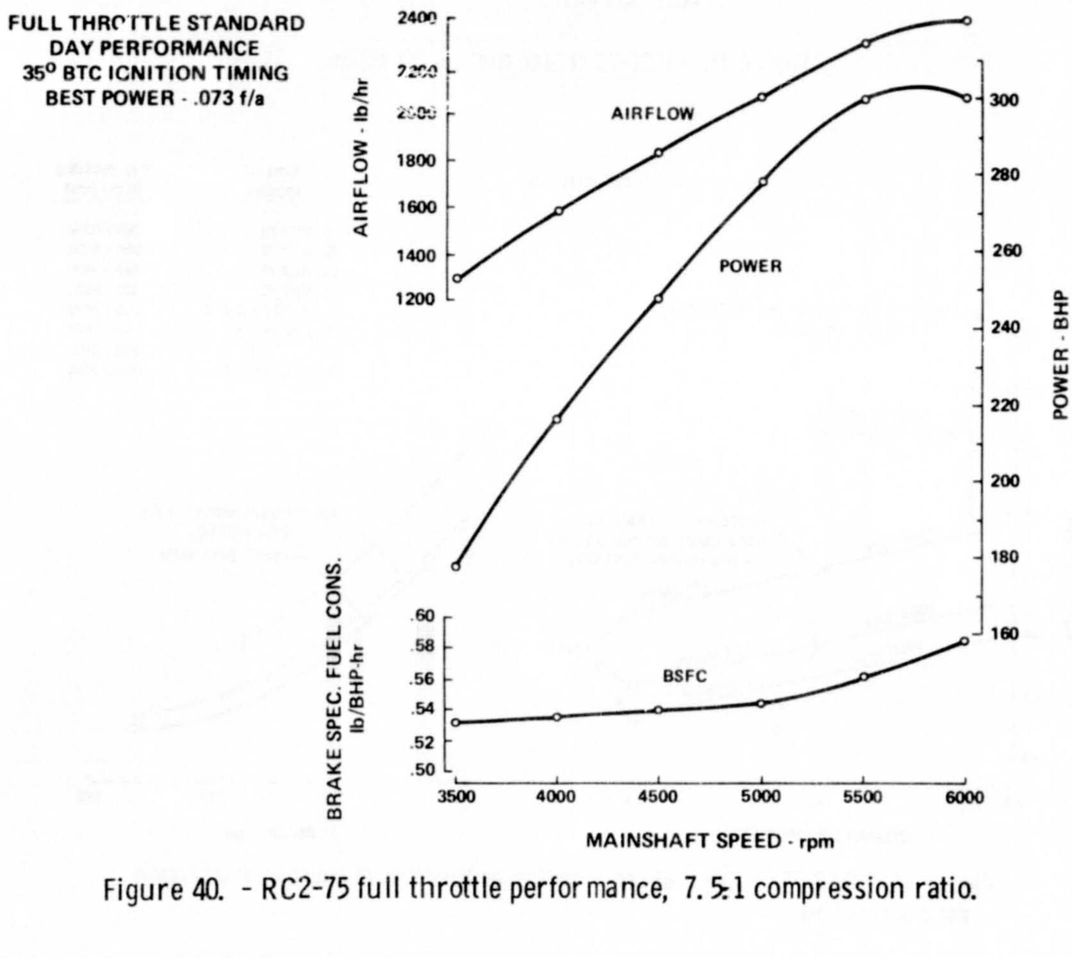

Figure 40. - RC2-75 full throttle performance, 7.5:1 compression ratio.

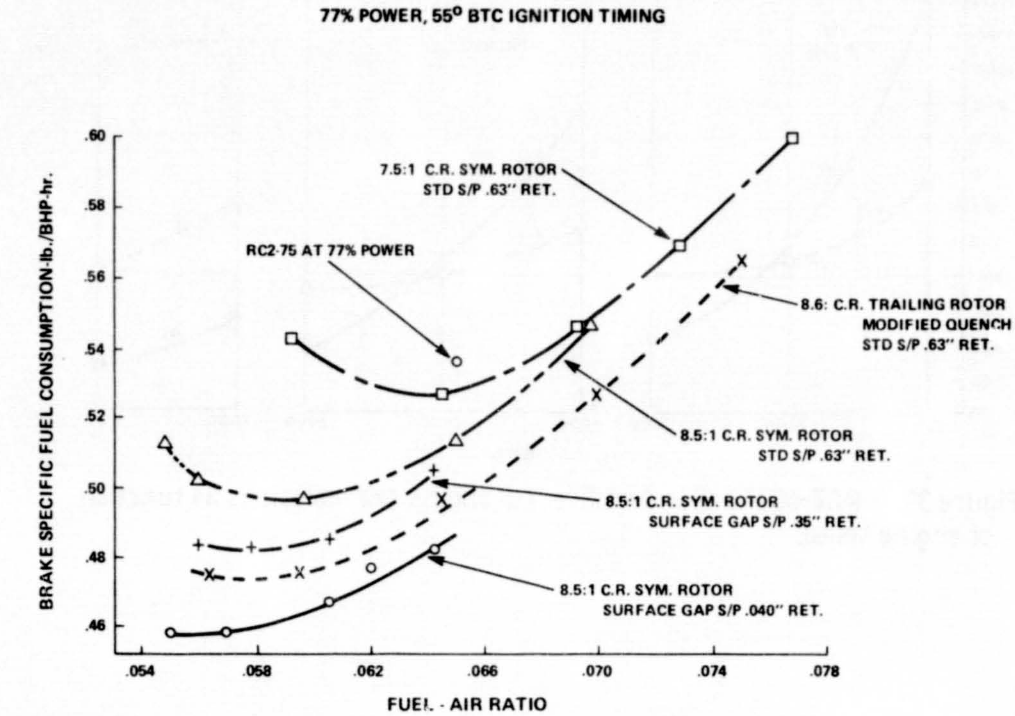

Figure 41. - RC1-75 cruise fuel consumption.

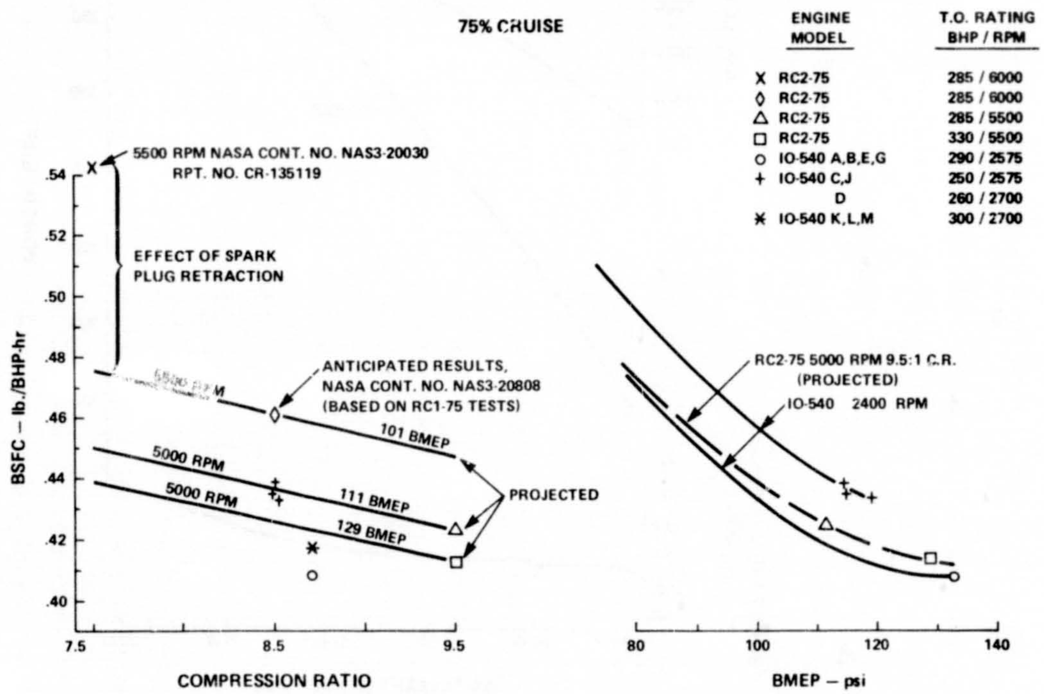

Figure 42. - RC2-75 cruise fuel consumption as function of engine compression ratio and rating.

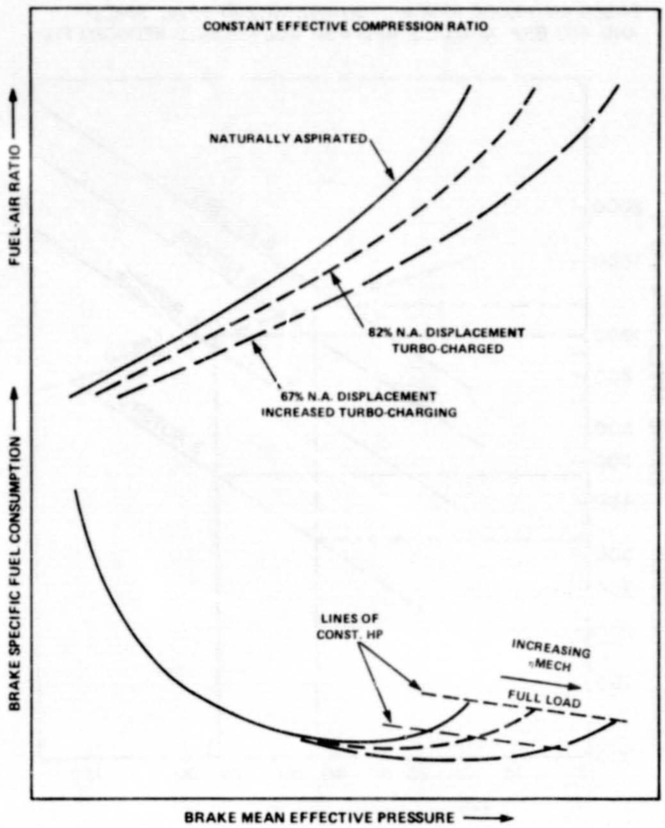

Figure 43. - Effects of decreasing stratified charge rotary engine displacement with corresponding increase in degree of turbocharging.

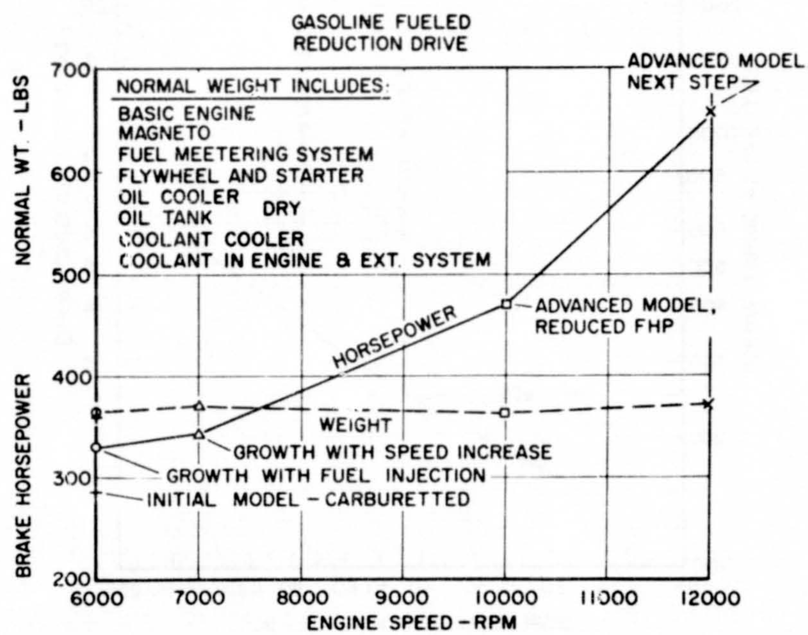

Figure 44. - RC2-75 output growth estimates, carbureted.

BASED ON 10,000 RPM RC1-60 EQUIVALENT SEAL SPEED
AND 470 BHP @ 10,000 RPM FOR RC2-75 WITH REDUCED FHP

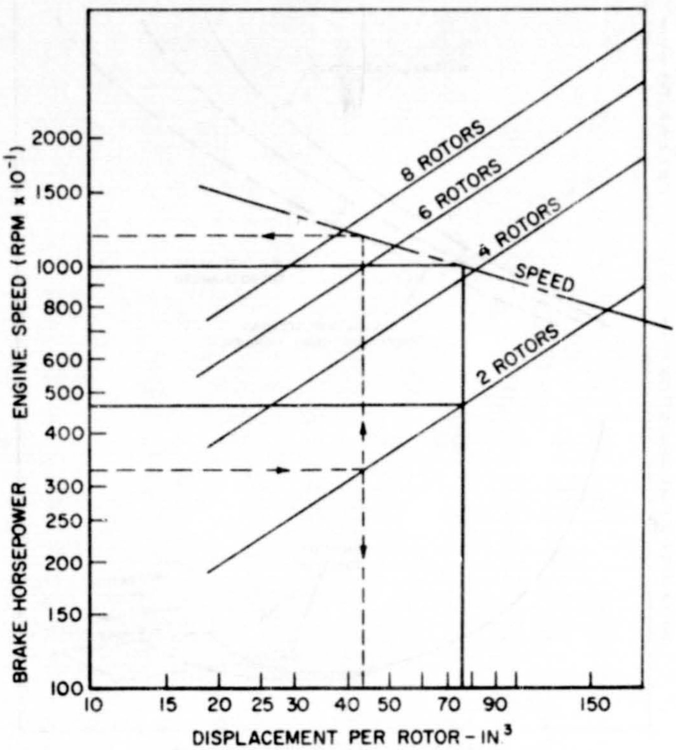

Figure 45. - Estimated RC engine power and speed.

BASED ON 10,000 RPM RC1-60 EQUIVALENT SEAL SPEED
AND 470 BHP C 10,000 RPM FOR RC2-75 WITH REDUCED FHP

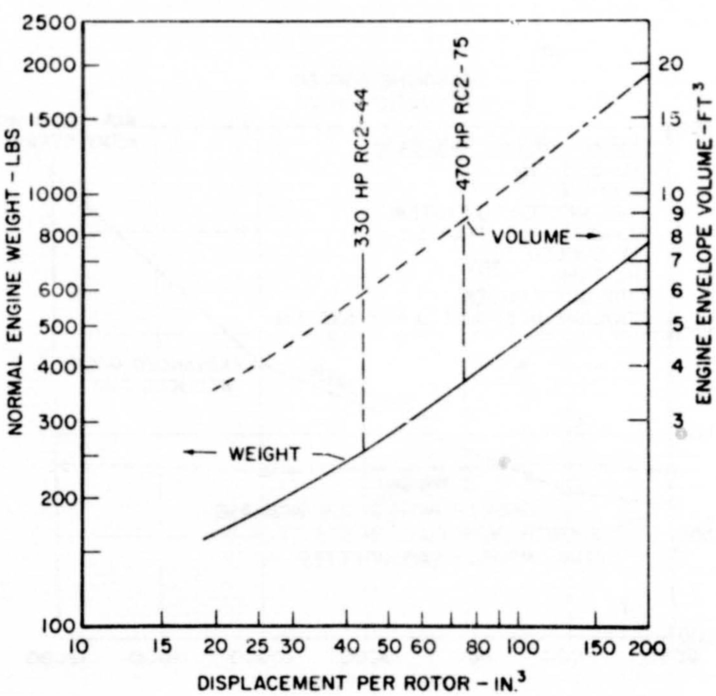

Figure 46. - Estimated high speed RC2-X RC engine weight and size.

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ENGINE REQUIREMENTS FOR FUTURE GENERAL AVIATION AIRCRAFT

Joseph W. Stickle
NASA Langley Research Center

The emphasis of papers in this symposium has been on rotary engine test experience with projections of technology improvements that make the rotary concept very attractive for aircraft applications. The market and competition for the rotary engine, however, is not today's aircraft fleet nor the current technology piston or turbine engine. Each of these factors will be changing to adapt to economic and environmental constraints of the future. The intent of this paper is to examine the market place for general aviation aircraft into 1980's and indicate the visible constraints that engine manufacturers regardless of the type of cycle will have to face.

Since 1972 the general aviation industry has enjoyed a steady and healthy expansion, approaching 15 percent per year. Projections by Government and industry indicate a continued growth through the 1980's with guarded optimism over fuel costs and availability and noise constraints. Figure 1 illustrates the growth in sales value over the past several years and indicates the growing importance of general aviation to the U.S. aerospace economy. Last year for instance, general aviation sales exceeded $1.5 billion which is about one-half of the value of transport aircraft sales. General aviation also contributed about $0.5 billion in favorable balance of trade with 25 percent of the over 15,000 aircraft manufactured in 1977 being exported.

The world-wde fleet of general aviation airplanes now exceeds 250,000 airplanes with the U.S. fleet being the single largest at 161,000. Figure 2 shows the projected growth of the U.S. general aviation fleet to reach about 245,000 by 1985 or almost equal to today's world fleet.

In order to maintain perspective, however, one might recall that in 1975 there were 6.8 million U.S. automobiles manufactured and that by 1985 the manufacturing rate is projected to increase to 9.2 million per year. The point is that while the aircraft fleet has a healthy growth projection, the total aircraft engine market is very small compared to the automotive market. This added to the fact that airplane engines have historically been better maintained and tuned than automotive engines indicates a formidable challenge for the introduction of any alternate engine cycle into the aircraft market.

A factor in the projected fleet which could favor the rotary engine is the trend in utilization of general aviation. General aviation is involved in the eight classes or categories of flying including: personal transportation, business, air taxi, and rentals for the commuter aircraft, special purpose aircraft (such as pipeline survey and agricultural aircraft), instructional, sport, and proficiency flying. About 65 percent of general aviation flying is spent in what is called point-to-point travel. That is, the person who wants to get in his airplane and go from point A to point B and get there safely, reliably and these days more economically. Operating economy or efficiency will be a key factor in the future of the general aviation. Business flying appears to be the largest single growth area.

With the airlines dropping service to the lower density communities, general aviation business flying will pick up. The businessman is more schedule dependent than the pleasure flyer and therefore is more likely to be equipped for flying in adverse weather.

FAA projections shown in figure 3 indicate a two-fold increase in instrument operations between 1975 and 1987. In 1975, general aviation accounted for about 45 percent of the instrument operations in the United States and the air carriers about 45 percent. But by 1986 general aviation is projected to grow to about 65 percent. The trend is clearly toward the use of general aviation for business and transportation where schedule reliability and service dependability are of prime importance. Following this trend will be an increase in the number of pressurized aircraft and air condition systems for improved safety and comfort which add to the auxiliary power requirement. This means taking needed horsepower off the propulsive engine. Turbines and perhaps high power rotary engines would appear to have an advantage over the piston engine for power extraction due to their lighter weights. Trends in engine weight as a function of the horsepower are shown on figure 4 for piston and turbine engines. Piston engine weights fall between 1.5 and 2 pounds per horsepower while the turboprop engines are slightly less than 1 pound per horsepower. One of the rotary engine goals mentioned in an earlier paper at the symposium was 1 horsepower per pound. This achievement in a reliable, cost competitive version would provide a real challenge for the aircraft engine market.

Turning now to constraining factors for aircraft of the future, environmental impact appears to be a major concern. Recent federal actions have removed the emissions standards for general aviation piston engine aircraft, but the noise constraint continues to increase. The current FAA flyover noise rule for propeller-driven aircraft (FAR 36-F) is shown in figure 5. Noise measurements of the current general aviation fleet fall within a band of about ± 5 db from the noise rule as indicated by the shaded area. There have been several programs from early 1940's up to very recently involving experimental vehicles in which the engines have been highly muffled and the propellers have been slowly rotated to reduce levels to 70 db or below. The performance and cost penalties for this level of suppression would be prohibitive to the utility of the general aviation aircraft and to its sales in today's market. As a matter of reference the lower shaded area shows the level of non-propulsive or aerodynamic noise associated with this class of airplane and indicates that the noise which is of concern to the airport and surrounding communities is related to the propulsion system. NASA, in its noise reduction research, is now concentrating on technology that will provide up to 5 db reduction with a minimum of penalty that can be applied to aircraft over the next decade. Examples of this research include development of more efficient propellers, evaluating free versus shrouded propulsion systems and techniques to quieten the engine noise.

Interior noise is also seen as a major constraint as general cabins are recognized as a high noise environment for both crew and passengers in a comparison of public transportation modes. The same technologies that reduce exterior propulsion noise should also improve interior noise levels although additional treatment to the airframe and cabin environment is needed and is being researched.

Efficiency is a second major constraint seen for general aviation. From a historical view, the improvement in aerodynamics for general aviation aircraft have not been overly impressive. Figure 6 shows the trend in lift-to-drag (L/D) ratio, which is a measure of the efficiency that has evolved since the very early 1920's. These aircraft have maximum L/D's in the order of 8 to just over 14. As a point of comparison the L/D_{max} for some of the transport aircraft of today are in the range of 16 to 18 so there is room for improvement and a potential for advanced future general aviation aircraft that operate at L/D's of 18 to 20.

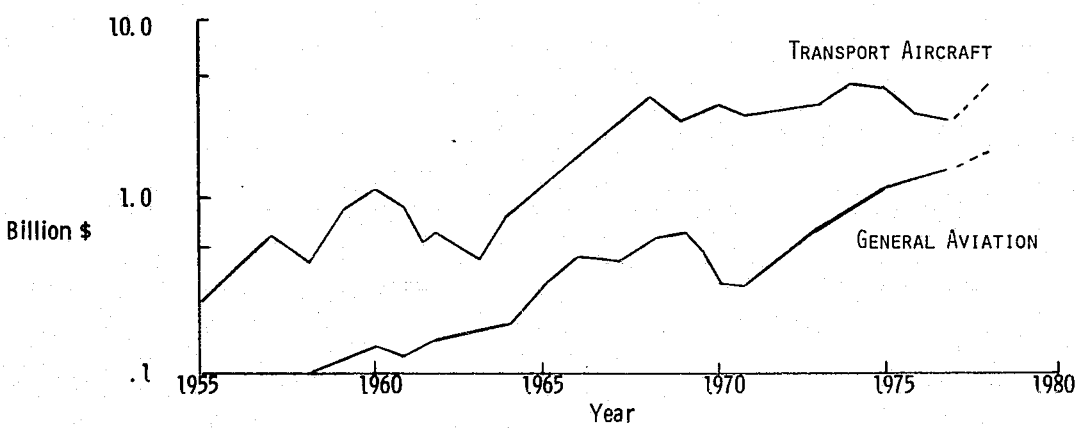
Some recent examples of aircraft good aerodynamic design and innovation include the Bellanca skyrocket and the Vari-Eze. Both of these are all composite airplanes. The skyrocket, figure 7, holds the world speed record for a piston engine airplane of 327 miles an hour. Its cruise drag coefficient is comparable to today's modern jet transports. Figure 8 is a photograph of the Rutan Aircraft Company's Vari-Eze airplane. It has a very high aspect ratio, a lifting canard in front of the wing which eliminates the download carried by a conventional tail, and it incorporates other advanced aerodynamics, such as winglets and a new airfoil section. The Vari-Eze cruises at 138 miles per hour on a 75 horsepower motor and is reportedly achieving over 70 miles per gallon.

A third consideration of efficiency is one I call payload carrying efficiency. Figure 9 is a plot showing the fuel mileage versus payload at maximum fuel load for various aircraft. The typical piston-powered single-engine airplanes are providing from 10 up to 18 or 19 miles per gallon which is pretty economical in terms of personal transportation but with payloads generally less than 1,000 pounds. Adding a second engine to the airplane does not necessarily result in greater payload, but it does cut the fuel efficiency at least in half. For turboprop powered aircraft, the fuel efficiency drops to a level of between 5 and 2 miles per gallon. There are airplanes flying today that are so weight limited that if loaded to full fuel there is no payload at all. In this case the crew establishes the payload and then must determine the range that it will be carrying. An interesting thought for the future involves the tradeoff between reliability and operating cost of a twin-engine piston-driven aircraft compared to a single-engine turboprop. The turboprop engines have a much higher time between overhaul and are noted for very high reliability. Single-engine turboprops are being used in the agricultural industry with surprisingly good success. There are about 7,000 aircraft in the U.S. agricultural aircraft fleet and about 1,400 of them are produced each year. These airplanes,when they are working, operate 16 to 18 hours a day. Their average flight time is 10 to 15 minutes, and some are as low as 3 minutes. Almost 80 percent of the flying time in agricultural spraying is spent in nonproductive flying, that is, turning around in the field and flying back and forth from the field to the home base. Only 20 percent of the time is actually spent spraying. So engine economy and reliability are key factors in this business.

Typical engines range from 300 to 900 horsepower with the higher power engines being world war vintage radial engines. These are no producers of new radial engines in the United States today. The need for an engine in this horsepower class (between 400 and 900 horsepower) is illustrated by the Ag industry.

Many operators are converting to turbine engines despite the higher initial cost. Experience is showing that the turboprop actually becomes profitable in about 2 1/2 years. The incremental cost may be $75,000 to $100,000 for the conversion. The turboprop is proving to provide added power and payload across the field, and a quicker turn time. Those little 10 to 30 second increments that are saved because of the added power and added response of a variable pitch propeller tend to pay off in productivity of the aircraft.

In conclusion, the numbers of aircraft and the growth rate of the industry over the next decade look very favorable. Constraints to the industry include noise and fuel efficiency which are both subject to technology improvements. The trend in general aviation flying appears to be more toward instrument operations with the aircraft role becoming transportation oriented. Safe, reliable high horsepower engines are needed to allow higher power extraction for pressurization, air conditioning and other auxiliary systems as well as for special purpose aircraft such as used in the agricultural mission.



Civil aircraft sales.

Figure 1. - Growth record of civil aircraft sales.

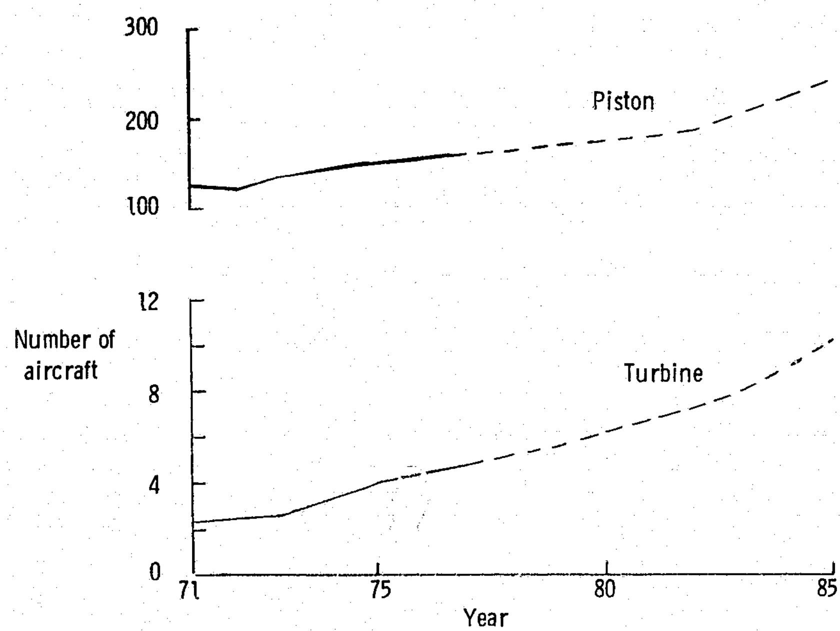


Figure 2. - U.S. general aviation fleet (in thousands).

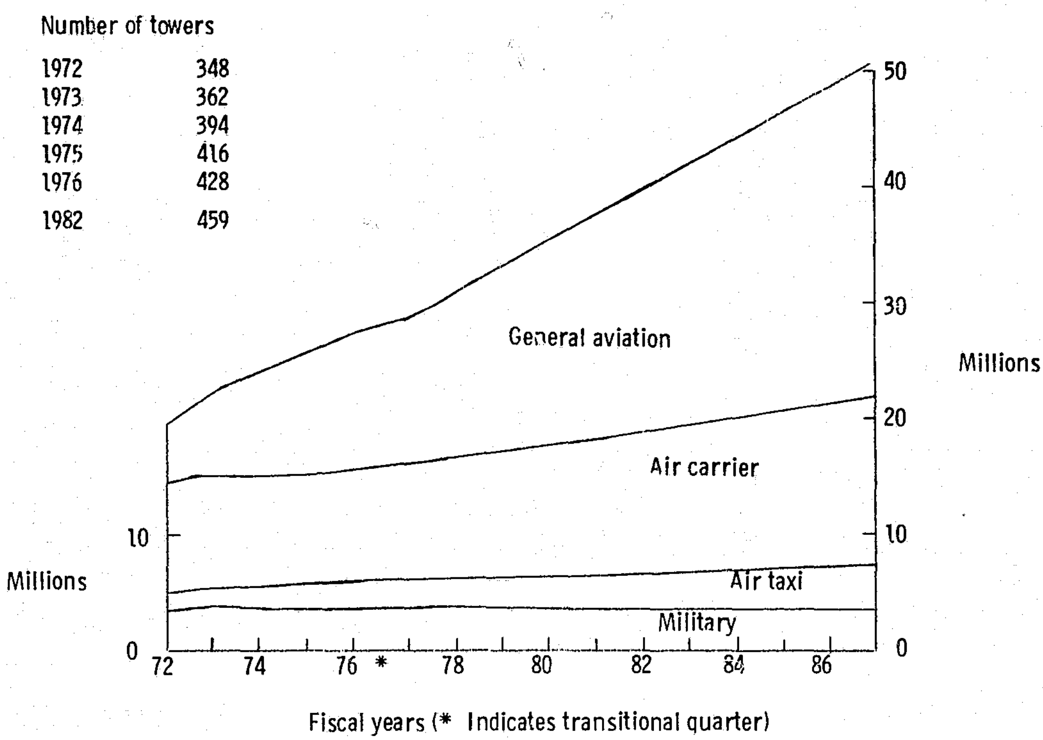


Figure 3. - Instrument operations at airports with FAA traffic control service.

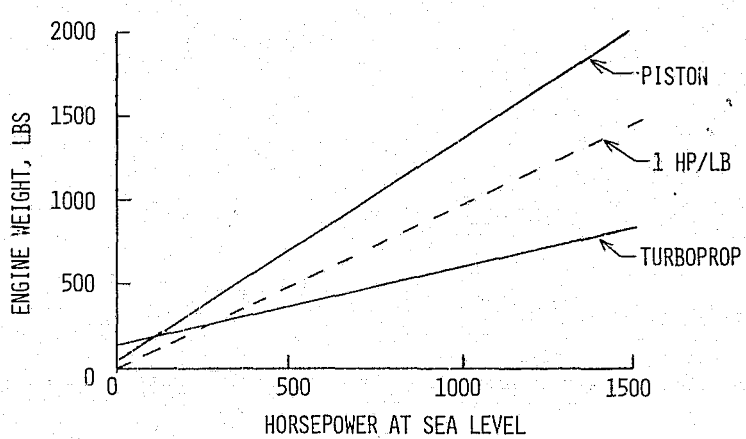


Figure 4. - Trends of engine weight with horsepower.

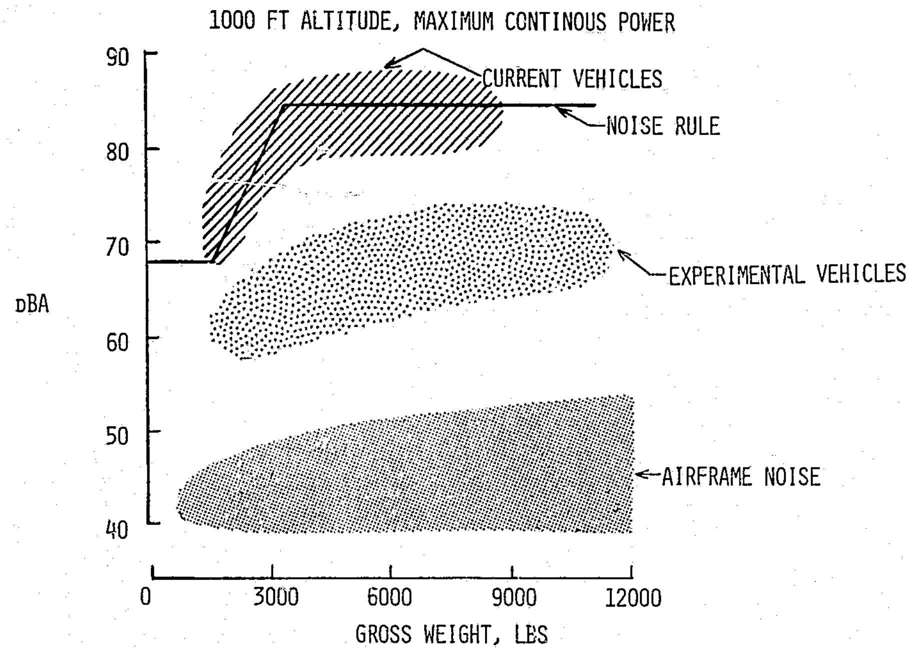


Figure 5. - Noise levels of small propeller driven vehicles.

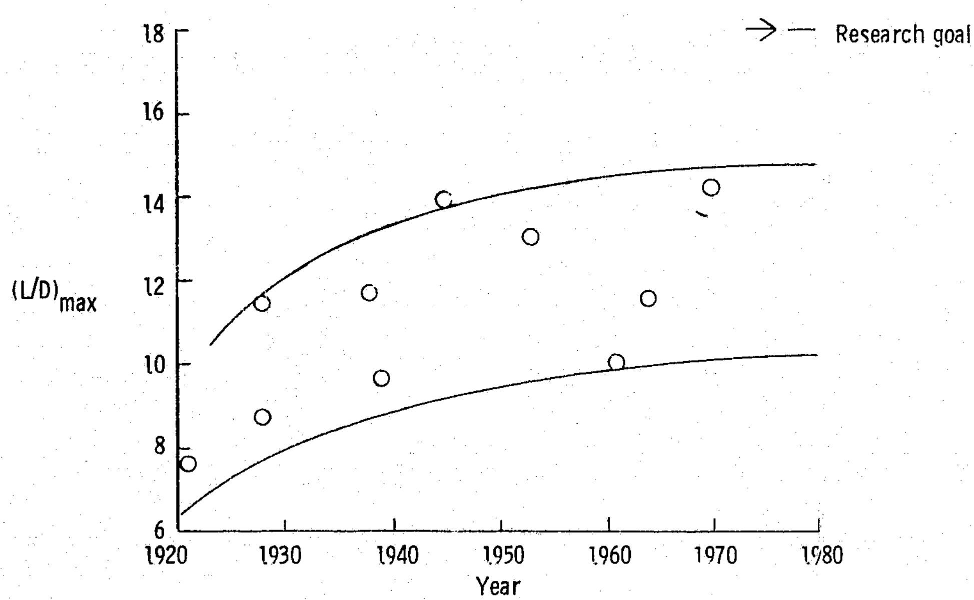


Figure 6. - Trends in maximum lift-drag ratio of propeller driven aircraft.

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Figure 7. - Photograph of Bellanca Skyrocket.

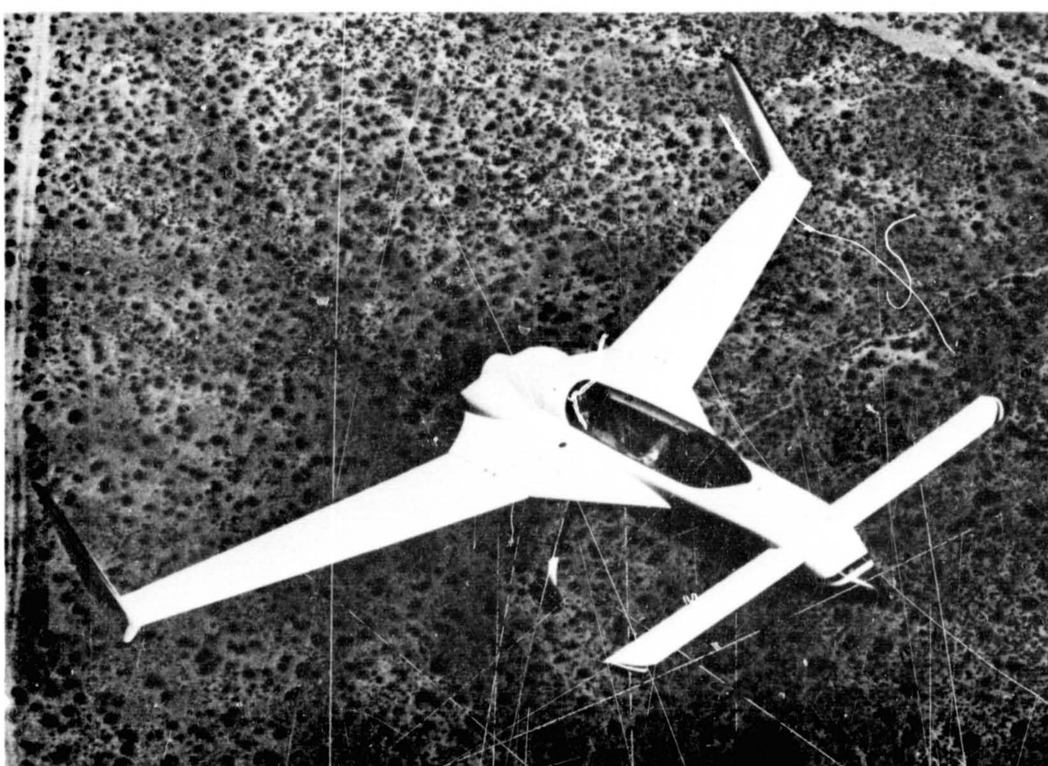

Figure 8. - Photograph of Rutan Aircraft Company Vari-Eze.

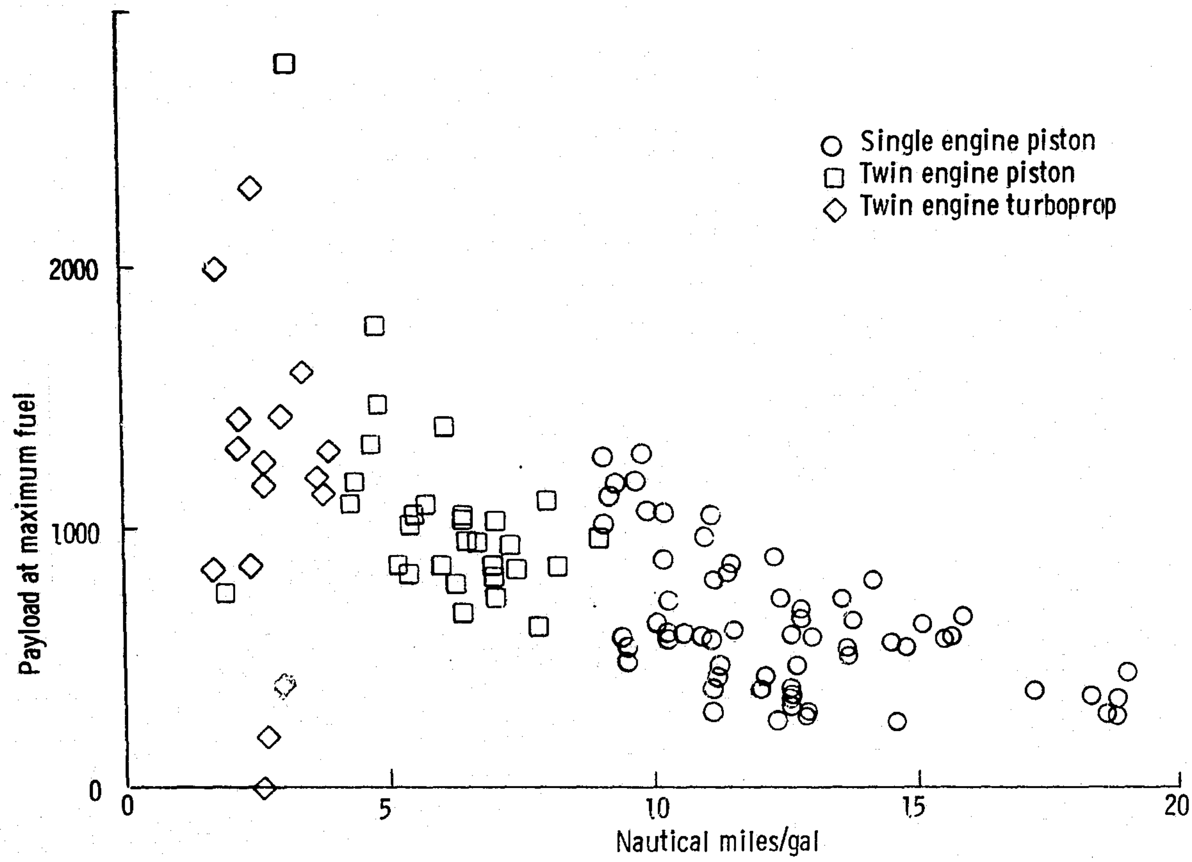

Figure 9. - Payload carrying efficiency for typical general aviation aircraft.