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Multi-Fuel Rotary Engine for General Aviation Aircraft

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ABSTRACT

Design studies, conducted for NASA, of Advanced Multi-fuel General Aviation and Commuter Aircraft Rotary Stratified Charge Engines are summarized. Conceptual design studies were performed at two levels of technology, on advanced general aviation engines sized to provide 186/250 shaft kW/hp under cruise conditions at 7620 (25 000 m/ft) altitude. A follow-on study extended the results to larger (2500 hp max.) engine sizes suitable for applications such as commuter transports and helicopters. The study engine designs were derived from relevant engine development background including both prior and recent engine test results using direct injected unthrottled Rotary engine technology. Aircraft studies, using these resultant growth engines, define anticipated system effects of the performance and power density improvements for both single engine and twin engine airplanes. The calculated results indicate superior system performance and 27 to 33 percent fuel economy improvement for the rotary-engine airplanes as compared to equivalent airframe concept designs with current baseline engines. The Research and Technology activities required to attain the projected engine performance levels are also discussed.

E-1718

INTRODUCTION

The NASA-Lewis Research Center has been working on intermittent-combustion (IC) propulsion systems for general aviation aircraft since 1973. The initial NASA, FAA and Contractor efforts were directed toward the measurement and characterization of engine exhaust emissions, in response to the proposed EPA aircraft emissions standards. NASA's program also included consideration of alternative, completely different engine types (such as rotaries) as well as trying to improve the current-production recips.

As part of this effort, the Curtiss-Wright RC2-75 aircraft rotary engine was tested to determine the exhaust emission levels characteristic of this type of engine. The test results showed that the HC emissions exceeded the formerly proposed emissions standard only by 39 percent, while both the CO and NO_x were within the proposed limits. The brake specific fuel consumption

(BSFC) at the cruise condition of 77 percent power was 0.54 lb/bhp-hr (328 g/kW-hr). This BSFC was 15 to 20 percent higher than typical, then-current aircraft gasoline piston engines of comparable power. However, the rotary's specific weight was 1.26 lb/hp (0.766 kg/kW), which was about 20 percent lower than typical, non-turbocharged aircraft piston engines.

A follow-on contract with Curtiss-Wright which incorporated a higher compression ratio and other minor modifications to this engine reduced the cruise BSFC to 0.45 lb/bhp-hr (274 g/kW-hr), while meeting the former aircraft exhaust emission standards.

Encouraged by these favorable results, NASA has established a parallel, in-house rotary engine test program at the Lewis Research Center. Early results include the development of specialized diagnostic instrumentation for rotary combustion processes (1)* and initial tests of a turbocharged rotary engine (2). In the latter tests, the measured minimum BSFC of an automotive-type rotary engine was improved from 0.53 lbs/bhp-hr (in stock form) to 0.45 lb/bhp-hr (after minor modifications to accept turbocharging and a leaner fuel schedule). Thus, the NASA and C-W results tend to confirm one another while showing that the rotary can definitely be competitive, fuel economy wise, with otherwise comparable reciprocating gasoline engines.

Meanwhile, parallel advances in stratified-charge rotary engine technology have been made by Curtiss-Wright in the design and development of a large (350 in^3/rotor) multifuel engine for the United States Navy/Marine Corps. This multifuel combustion system and several other features were used as baseline data for an Advanced Stratified Charge Rotary Aircraft Engine Design Study, which was performed under a NASA contract with Curtiss-Wright. Presently under a new NASA contract, Curtiss-Wright will design and build a single rotor test engine to evaluate the various technologies needed for an advanced rotary engine design for aircraft use.

THE STRATIFIED CHARGE ROTARY ENGINE

Over the last several years all Rotary (Wankel-type) engine technology research at Curtiss-Wright has been directed at stratified charge direct chamber injection. During this period, successive improvements (3,4) have resulted in an efficient multifuel combustion configuration which is incorporated in a large vehicle powerplant being developed for potential military applications.

The same basic technology, which was defined in the smaller RC1-60 displacement (one rotor of 60 in^3 displacement) single rotor research rig, is applicable to a wide range of engine sizes and engine applications. As a result of the aforementioned design study contract for General Aviation and a subsequent Commuter Aircraft applications study sponsored by NASA (5), which were complemented by C-W research testing using both the RC1-60 and RC1-350, growth directions have been confirmed and concept engines defined. The key elements for reduced fuel consumption and higher power density of the advanced aircraft engines are increased BMEP and operation at very lean mixtures by turbocharging to higher engine airflow rates.

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*Numbers in parentheses designate references at end of paper.

Specific engine choices for general aviation. - The NASA Advanced Rotary Combustion Aircraft Engine Design Study objectives included a 75 percent cruise BSFC of 0.38 lb/hp-hr, or better, at 250 hp and 25 000 feet minimum altitude. Two liquid-cooled engines were selected (5) to meet the program objectives. Both were twin rotor machines, representing a compromise between minimum weight, favored by more rotors, and low cost, generally pointing to less rotors. The larger of the two, an RC2-47, represents a less ambitious technology projection, noted as "Advanced," while the smaller machine, the RC2-32, would require a larger development effort to meet the same timing goals and is designated "Highly Advanced". The key difference between the two is that the "Highly Advanced" engines include a further increase in BMEP and speeds, the latter possibly requiring reduced contact force or retracting apex seals, and more emphasis on advanced weight reduction materials and manufacturing techniques. The "Highly Advanced" engine assumes use of a variable area turbine in the turbocharger system but other design approaches are also possible. The specific fuel consumption prediction for the RC2-32 is shown in figure 1.

The RC2-32 BMEP is 211 psi at the 320 hp take-off power and 198 psi at 250 hp cruise. The engine rpm is 9420 which, on an equal RC-60 apex seal sliding velocity basis, is equivalent to 7050 rpm, which has been run in the RC-60 trochoid sized engines (RC-60, 75 and 90). The cruise rpm is 7850 which is equivalent to 5875 for the RC-60 and derivative geometries. Corresponding values for the RC2-47 are 191 psi BMEP at 320 hp take-off, 179 psi at cruise, 7030 T.O. rpm (6000 "equivalent") and 5860 rpm cruise rpm (5000 "equivalent"). The rotor width proportions for both engines (width/eccentricity ratio) are the same as the RC2-75 aircraft engine prototype and the 350 in^3 military engines.

The comparison of cruise SFC and overall dimensions with the selected current reciprocating baseline engine, the TSIO-550 is shown in Table 1.

The RC2-32 installation longitudinal layout is shown in figure 2. To achieve a small frontal area (a 16 in. square), most of the accessories are mounted at the anti-propeller end and the turbocharger spaced even farther aft. For improved packaging and to minimize the number of drives and associated gearings, the coolant and oil pumps (scavenge and pressure) are coaxial mounted on the same shaft. Drives are included for an air-conditioning compressor, vacuum pump and hydraulic pump, but the weights given include only the accessories needed to start and run the engine.

While only one engine size is shown for each of the two levels of technology, a number of other engine possibilities, all representing the same degree of "advancement" were defined and tested via the Cessna Aircraft Company analytical model before the choices shown were made. In either category, improved BSFC can be realized, for the same IMEP level, by either reducing the engine speed, going to a larger displacement single rotor engine, or both. In all cases analyzed, however, the Cessna aircraft analysis programs indicated more sensitivity to weight and size than to the degree of SFC change which had been calculated.

To put the projections in perspective, while the BMEP's assumed are not high relative to turbocharged diesel engines and are on the order of only about a third higher than Curtiss-Wright has run in developed Rotary homogeneous charge engines which have demonstrated in a stratified charge Rotary engine as of this point. Homogeneous charge Rotary engines have been performance tested to these levels but operation at periods longer than a 24-hr race has been limited. The "best compromises" to attain projected goals cannot be evaluated on paper but requires testing to successively increasing BMEP and speed levels, with each new plateau yielding both new inputs and new solutions - this of course, is the normal engine technology advancement process.

ENGINE/AIRFRAME INTEGRATION STUDY PERFORMED BY CESSNA AIRCRAFT

This section deals with the integration of the advanced Rotary Combustion Engines with typical airframes. Performance, cost, and installation factors are compared with those for a conventional aircraft engine. An outline of the design mission and performance constraints is given, followed by a discussion of the method of comparison and the results obtained.

MISSIONS AND PERFORMANCE CONSTRAINTS

The design mission is transportation oriented and consists of a maximum rate climb to 7620 m (25 000 ft) followed by a constant altitude cruise segment at rated cruise power over a prescribed distance. Fuel for 45 min of operation at cruise power is reserved. In addition to basic payload and range requirements, minimum levels of performance must be met in other areas as indicated in the following listing:

	Single-Engine	Twin-Engine
PAYLOAD - occupants and baggage	544 kg (1200 lb)	635 kg (1400 lb)
STAGE LENGTH - with IFR fuel reserves	1296 km (700 nm)	1482 km (800 nm)
CRUISE SPEED - min.	370 km/hr (200 kt)	417 km/hr (225 kt)
CRUISE ALTITUDE	7620 m (25 000 ft)	7620 m (25 000 ft)
TIME TO CLIMB - max.	30 min	30 min
RATE TO CLIMB at 25 000 ft., min.	152 m/min (500 ft/min)	152 m/min (500 ft/min)
SINGLE ENGINE RATE OF CLIMB at 5000 ft., min.	--	76 m/min (250 ft/min)
TAKEOFF DISTANCE AT SEA LEVEL - maximum	762 m (2500 ft)	914 m (3000 ft)
STALL SPEED, max.	113 km/hr (61 kt)	138 km/hr (75 kt)

The missions chosen are demanding ones which cannot be accomplished in total by presently available airplanes; the other performance constraints assure that contemporary standards of utility are attained.

THE SIZING PROCESS

With mission and performance constraints defined, a computerized sizing program is used to determine the "best" airframe for each engine. In the context of this study, "best" is equated with lowest mission fuel, direct operating cost, and acquisition cost.

The sizing program is covered in detail in reference 19. For the purpose of this discussion, it is sufficient to know that the program performs two basic calculations, the first determining the weight required to meet the payload/range requirement, the second giving performance at a given weight. A carpet plot format conveniently displays the computed performance as a function of weight and any two design variables such as wing area and aspect ratio; performance constraints are overlaid on the carpet, defining areas where all requirements are met as shown in figure 3.

If the solution space defined by the constraints is well defined, the normal choice will be the smallest, lightest airframe since that will be the lowest cost case. Sometimes few constraints appear on the carpet, and engineering judgement concerning such things as practical aspect ratios and efficiency at off-design operating points must enter into the choice.

The above process was used to define "baseline" singleand twin-engine airplanes powered by a conventional piston engine, and resized versions taking advantage of the smaller size and weight and lower fuel consumption of the Rotary Combustion Engines.

BASELINE AIRPLANES

In general, the baseline airplanes may be considered to be refined versions of typical 1981 technology products, using conventional light metal structure joined by riveting and bonding. This approach was taken in preference to one calling for advanced composite materials or unconventional aerodynamic layouts, for example, in order to take advantage of well documented design procedures and weight, drag, and cost data bases, and to focus attention on powerplant advances rather than airframe features.

The single engine baseline airplane is a high wing tractor monoplane seating six, with a cabin pressurized to 31 kPa (4.5 psi) differential so as to obtain a cabin altitude of 3048 m (10 000 ft) when flying at 7620 m (25 000 ft). The wing features a long-span single-slotted flap to meet the current FAR requirement that stalling speed be less than 113 km/hr (61 kt); a combination of small "feeler ailerons" and slot-lip spoilers are employed for roll control. Takeoff gross weight (arrived at by the sizing process described earlier) is 2023 kg (4600 lb), while empty weight is 1241 kg (2736 lb).

Similarly, the twin-engine baseline airplane features a conventional low-wing tractor layout and eight-place seating in a pressurized cabin (same 31 kPa (4.5 psi) differential). Empty weight is 2008 kg (4428 lb) and takeoff gross weight is 3107 kg (6850 lb).

The powerplant for both baseline airplanes is the Teledyne Continental Motors TSIO-550, a conventional six-cylinder, horizontally-opposed, aircooled engine developing 254 kW (340 bhp) at 2700 rpm for takeoff. A cruise rating of 186 kW (250 bhp) at 2300 rpm is used for this study; specific fuel consumption at cruise power is 271 g/kW-hr (0.446 lb/hp-hr). Installed powerplant weight is 320 kg (706 lb) for a single engine.

Three view drawings of the baseline airplanes are shown in figures 4 and 5.

ROTARY POWERED AIRPLANES

The single-engine design with the rotary combustion engine is shown in figure 6. For considerations of passenger comfort, the size of the cabin cannot be appreciably altered from that of the baseline. For structural and aerodynamic reasons, the wing cannot be moved very far fore or aft, so the lighter rotary must be located well foward compared to the baseline engine in order to keep the center of gravity in the right position. This has the advantage of allowing a baggage compartment to be located ahead of the cabin, increasing allowable baggage volume and loading flexibility. The wing is significantly smaller than that of the baseline due to the reduction in gross weight brought about by the favorable interaction of lower engine weight and less fuel required to accomplish the specified mission.

The engine installation concept is shown in figure 7 for the RC2-32 version (the RC2-47 would be essentially the same). The small size of the powerplant allows it to fit easily into the engine compartment since the cross-section is set mainly by cabin dimensions. Accessibility should be very good relative to the baseline. The radiator, which is large and thin for minimum cooling drag, fits comfortably alongside the engine. Induction and cooling air are brought in through NACA flush scoops on the sides of the cowling. Installed powerplant weight is 221 kg (487 lb) for the RC2-47 and 178 kg (393 lb) for the RC2-32.

The twin-engine configuration using the rotary engines is shown in figure 8. Radiators are housed in leading edge extensions on the inboard wing panels similar to the scheme used on the British DeHavilland Mosquito of World War II. As indicated also in the installation concept in figure 9, the nacelles are much smaller in cross-section than those of the baseline, thereby reducing both drag and destabilizing pitching moments. As with the single, substantial reductions in wing size and gross weight are achieved.

COMPARATIVE RESULTS

A detailed comparison of the baseline and rotary-powered airplanes is possible by reference to Table II which lists weights, dimensions, and performance parameters. The rotary-engined machines are clearly superior to the baseline airplanes in every respect, with the following items being especially noteworthy:

- 27 to 33 percent reduction in required mission fuel
- 12 to 17 percent reduction in direct operating costs*
- 9 to 16 percent reduction in acquisition costs*
- Substantial gains in crusing speed, climb performance and takeoff distance

Parametric studies reported in reference 19 show that the above findings are relatively insensitive to mission definition. In addition, the assumption of zero cooling drag for the rotary-powered airplanes has little influence on any of the results except cruise speed, which would decrease about 10 kt if the drag were increased to the level of the air-cooled baseline.

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*Calculations based upon methods and data of reference 19.

Other areas in which the rotary-engined airplanes would be expected to show advantages over the baseline are:

- Multifuel capability
- Inherently low vibration levels
- Better control of engine temperature, particularly for low power descents
- Effective, carbon-monoxide free cabin heating
- Possible use of engine coolant for heating of inlets
- Lower flyover noise due to lower propeller speed at maximum power (2400 vs. 2700 rpm)

In summary, singleand twin-engine airplanes were designed to suit the features of two aircraft rotary combustion engines - the "advanced technology" RC2-47 and the "highly advanced technology" RC2-32 - and the results were compared with similar baseline airplanes using a conventional horizontally opposed air cooled engine, the TCM TSIO-550.

The baseline airplanes are very capable machines in their own right, meeting or exceeding all mission requirements, and offering transportation capability not presently available in production piston-engine aircraft. However, the rotary-engined airplanes are clearly superior in every performance and cost category due to lower weight and fuel consumption. Other factors, including multi-fuel capability, noise, vibration and installation factors also favor the rotary combustion powerplant.

From an airframe manufacturer's standpoint, the rotary engines offer an attractive alternative to presently available powerplants.

COMMUTER AIRCRAFT ENGINE

Under a separate subsequent NASA contract (NAS3-22140), Curtiss-Wright was requested to apply the Rotary Engine "Highly Advanced" technology approach to the Commuter Aircraft requirements at 800 to 2500 hp. The engine needs for future commuter aircraft are expected to emphasize reduced operating costs that can accrue to engines of small size, light weight and better fuel consumption. While aircraft system studies were not part of this contract effort, NASA has data for turboprop and diesel powerplants to complete trade-off and comparative studies.

In view of the larger power class, turbo-compounding was considered, without benefit of supporting studies to evaluate cost-effectiveness, and more emphasis was placed on multi-rotor engines for greater weight saving.

The 800 and 2500 hp examples, again each was one of a number of possibilities, are described geometrically in Table III and the operating range data summarized in Tables IV and V.

As can be seen from Tables IV and V, the power gain for turbo-compounding is relatively small, shown as a function of power and speed in figure 10. The turbo-compounding fuel consumption (calculated to unrealistic precision to show comparisons) gain, however, is more significant and can be assessed, with some indirect manipulations against the weight penalty, by use of weight charts which follow. This is because the turbocharging (particularly with the excess air used for improved thermal efficiency) has used most of the available exhaust energy. The recent RCI-350 turbcharging tests, which showed very high exhaust energy, may challenge these assumptions.

Similar to earlier mention relative to the General Aviation engines, these engines would also gain in BSFC for a lower F/A ratio as a function of improved turbochargers. In the case of the Commuter Aircraft, where the cruise altitude is 15 000 instead of 25 000 ft, the justification for not assuming more boost was only by reason of direct comparison with General Aviation engines rather than the limiting assumption of 1990 turbocharger status technology.

The 800 hp RC4-41 installation longitudinal view is shown in figure 11 and the 2500 hp RC6-122 in figure 12.

The displacemet versus T.O. power is shown in figure 13 and the engine dimensions, less gearbox, in figure 14 with corresponding weights plotted in figure 15. Estimated advanced gearbox weights and length are shown on figure 16.

TECHNOLOGY NEEDS FOR ADVANCED STRATIFIED CHARGE ROTARY ENGINES

What is required for the practical realization of the very attractive engines and performance benefits that have been described Based on the current status of stratified charge rotary engine technology as described in the Appendix, and considering additional technology judged to be realizable by mid-decade to allow production inclusion early next decade, several study engines have been defined and analyzed.

The supporting technology gains assumed for such engines, are covered in more detail in reference 5, but the most important of these are high speed electronic diesel level fuel injection, seal/coating materials, and improved strength aluminum alloys. Further gains in turbocharging technology are also required for aircraft altitude performance.

High speed injection. - The developing field of small high speed diesel automotive engines has provided the required impetus for active electronic high pressure fuel injection development. Experimental and limited production (for military 8000 rpm application) high speed units are already operational and there are many indications to believe that additional developments to reduce cost and improve reliability will be forthcoming.

Seal durability. - Developments of durable apex seal materials and compatible coatings for higher outputs also show a favorable prognosis, but verifications and final choices can only be established on the basis of engine testing. The early (pre-1974) problems of Rotary production automotive engines, resolved by the successful experience of Toyo Kogyo (13,14), were driven by a different set of requirements: The need to have an apex seal of material strong enough to incorporate an "adjustable" triangular corner for city driving cycle fuel economy and, with a compatible coating, still provide engine life comparable to piston automotive engines at an acceptable production cost. This was a difficult task, taken in total, even with consideration that the automotive service regime is relatively light duty. Notwithstanding popular-press inferences to the contrary, the problem with the earlier Mazdas was never one of apex seal durability but one of poor low speed performance with a one-piece reinforced graphite seal which had high end leakage.

As early as 1961 Curtiss-Wright had tested a tungsten carbide/cobalt detonation gun applied trochoid coating compatible with ferrous apex seals that met all of the technical requirements but was prohibitively expensive for automotive use. Versions of the same coating, applied by the lower cost plasma spray process, have since been successfully used in small air-cooled snowmobile engines produced by OMC (15) and in initial pre-production runs of an air-cooled multi-purpose engine by SYVARO (16), both tested at relatively high outputs and speeds. In addition, plasma-sprayed Ferro-Tic, tested experimentally at Curtiss-Wright (17) had shown promise of even lower wear rates, while offering processing and material economic advantages as well.

Carbide-based coatings, in combination with low-wear compatible apex seal materials, may prove satisfactory at the higher BMEP levels anticipated for growth military/aircraft engines. If this does not prove to be the case there are a number of other combinations which have shown screening rig indications of lower wear rates, not needed at current power levels, which can be tested as well as a number of newly developed promising candidates which await screening. Therefore, the probability of arriving at a selection that satisfies both technical and economic goals is judged to be high.

Finally, the material compatibility search for apex seals and trochoid wear surfaces that have growth capacity and good economics may receive help from another direction: automobile racing Toyo Kogyo, having developed an eminently successful seal/coating configuration for the engine of their production RX-7, also support a racing version which develops 300 plus horsepower (naturally aspirated) at speeds in the 9 000 to 10 000 rpm range.

At these high speeds a one piece seal is acceptable, as demonstrated by the excellent high speed fuel consumption of this engine, which uses a relatively strong reinforced graphite single piece seal compatible with the chromium plated trochoid bore. Other licensees have run at BMEPs considerably in excess of our growth engine ratings, admittedly without demonstrating long-term durability at these peak outputs, but the directions may provide relevant inputs.

Thermal insulation for reduced coolant and oil heat rejection. - The use of thicker cermet trochoid coatings could provide wear resistance plus thermal insulation. The latter could prove particularly significant for ultra-high speed engines where the apex seals can be supported by a hydrodynamic gas film or else be retracted slightly from the trochoid surface (17). Thus, without a need to provide oil lubrication, the allowable surface temperature limits could be increased to whatever limits the material could withstand. The reciprocating piston engine, with a reversal of a piston direction at TDC and BDC positions, is less amenable to a non-lubricated design or hydrodynamic film gas sealing and is thus more dependent on the material choice, such as ceramic piston rings on ceramic bores, for "adiabatic" or extreme low heat rejection engines.

The total (water plus oil) heat rejection of the direct injected stratified charge engine when naturally aspirated is roughly the same as a gasoline engine, which makes it less than a diesel. When turbocharged, calculations and the limited test data indicate that the specific heat rejection will drop significantly even without use of techniques to insulate coolant walls and/or run at higher temperatures. This is rational since the lean mixtures lower gas-side temperatures and improved thermal efficiency removes more of the input fuel energy as shaft work.

Higher strength alloys. - The improved aluminum alloys that would be preferred choices for aircraft engine housing use, such as AMS-4229 (17), are progressing along the commercial development path and are now being cast for aircraft quality components. In fact, C-W has poured AMS-4229 rotor housings for the 350 in^3 engines and the 50 percent higher power engine previously discussed was of this alloy. While high speed engines demand light strong rotors, nodular iron rotors are acceptable for speeds proposed and there are a number of promising alternatives (such as advances in materials, powder metal and sintering technology, welded constructions) for ultra-high speed engines.

Turbochargers. - The predicted fuel economy gains are limited by the turbocharger pressure ratios expected to be available over the next several years. For 25 000 ft cruise performance, the maximum practical (i.e., good efficiency and wide range surge-free operation) pressure ratio was assumed to be between five and six, which reduces at sea level to about a 2:1 pressure ratio. If, however, turbocharger improvements can be realized to provide higher pressure ratios than assumed, further gains in fuel economy are possible. An obvious, but probably heavier, alternative is to series turbocharge for high altitude performance.

CLOSURE

The Rotary Stratified Charge Aircraft Engine shows considerable potential for a small lightweight engine which can operate economically on all available aviation fuels. Exploration of this potential, as well as identification of the most promising avenues for maximum exploitation, is expected to be realized with the NASA-sponsored General Aviation engine research rig now being designed by Curtiss-Wright for test initiation next year.

APPENDIX. - ROTARY AIRCRAFT ENGINE BACKGROUND

Briefly summarizing Curtiss-Wright's aircraft Rotary engine background, initial interest was directed to propeller driven aircraft or helicopter military applications where it was felt that the Rotary could compete with small gas turbines. In early studies conducted for NASA (7) the RC Engine plus fuel weight usually proved lighter in all but very short missions. In 1966 the RC2-90 (fig. 17) was built and tested. This showed technical promise for its designed application but was not developed beyond test stand operational status as a result of changes in military planning.

Acoustic measurements made on the test stand during the RC2-90 testing indicated a potential for extremely low noise level and led to a U.S. Navy sponsored test series with a carbureted RC2-60 automotive engine prototype in the Lockheed Q-Star aircraft. This aircraft demonstrated hitherto unattained levels of quiet flight, in part due to the absence of valve and valve train noise. A second quiet-airplane research contract followed in which the RC2-60 engine was installed in a Cessna Cardinal (Model 177) airplane. The same engine model was also flown in a Hughes model TH-55 helicopter (21).

The RC2-60 used in the flights mentioned had been designed as an automotive-carbureted Rotary Engine with low overlap side inlet ports to achieve good fuel economy at low power road loads. Peripheral ports are preferred for high output applications such as aircraft engines, and the performance data achieved in the flight tests reflected the high end breathing limitations of the automotive side ports. In addition, the belted propeller speed reductions were heavy and inefficient. The test, nevertheless, demonstrated Rotary Engine reliability, smoothness, low noise levels, and flexible, efficient liquid cooling. Rich fuel/air ratios were not required for cooling in any flight mode, and there were no speed or descent limitations for thermal stresses from over-cooling.

The RC2-75 Engine (fig. 18) was designed as a carbureted General Aviation prototype, reflecting this experience. Significant factors in the choice of liquid cooling were that air-cooling results in higher parasitic drag losses and did not provide adequate growth margin.

The RC2-75 is 21.5 x 23.7 x 31.4 in. overall and weighs 280 lb dry, 358 lb wet ready to fly, with heat exchangers. This model has completed 1500 test hr, including 100 hr WOT and speeds to 7000 rpm, with all indications that the basic configuration is sound.

The engine was initially designed for a 7.5:1 compression ratio with 80/87 octane fuel. Subsequent limited testing with an 8.5:1 ratio (4), with extrapolation to higher BMEP's and still higher compression ratio for 100/130 fuel, shows essentially the same fuel consumption as current General Aviation engines, although there is an advantage in that liquid cooling does not require richer than optimum mixture strengths in critical cooling regimes as high power climb.

In the early 70's, at the point where it was clear to Curtiss-Wright that this engine enjoyed several advantages over existing General Aviation engines, the first tremors of the energy crunch were beginning to be felt. As a result, and as a response, C-W's Stratified Charge research efforts were intensified and, in 1973, the first breakthrough resulted in specific fuel consumption, on a range of fuels with diverse octane ratings, better than the gasoline engine. Faced with this combination of events, it was decided to defer full development and FAA Certification of the gasoline-fueled RC2-75.

STRATIFIED CHARGE ROTARY RATIONALE

The gasoline homogeneous charge Rotary engine advantages include: reduced size and weight; low vibration with as few as one or two rotors; higher speed cabability by virtue of complete balance, high volumetric efficiency through porting without the limitations of valve dynamics; non-reversibility of seal paths; sizing flexibility; mechanical simplicity.

The direct injected Stratified Charge Rotary compared to the diesel reciprocating engine has the same advantages of the gasoline Rotary and, in addition, the advantages of better cold-starting, capability for operation on a wide range of fuels, and lower NO_x and particulate emissions. The fuel economy of the naturally-aspirated stratified Rotary is now competitive with the indirect-injected diesel and the turbocharged version has shown it can challenge the direct-injected diesel.

The Rotary Stratified Charge Engine can provide significantly higher power density than either current Diesels or a Stratified Charge Reciprocating Engine. Advantage over the latter results from a unique suitability of the Wankel engine geometry to direct injected stratified charge. Briefly stated, stratified charge engines burn leaner (overall) fuel-air mixes, and can achieve automotive diesel level fuel efficiencies as a function of the degree to which this lean-burning is realized. The direct injected unthrottled configuration is the only stratified charge engine variation which can operate as lean as a diesel. To do this throughout the complete range a varying air velocity field must be induced to allow the injected fuel to be effectively "layered" (or, stratified) so that a combustible mixture of fuel and air is consistently developed at the spark plug, where the "triggering" combustion is initiated. At the same time a significantly leaner overall, or average, mixture ratio is maintained.

For a reciprocating engine, this essential flow/velocity gradient has to be generated in the incoming air charge by some combination of swirl inlets or shrouded intake valves, special cylinder heads and piston shapes, etc. These modifications introduce pumping work which limit the fuel economy gain and also reduce the volumetric efficiency, which, in turn, increases engine size and weight. In addition it has proven difficult to maintain these developed velocity gradients over the full engine speed range.

The moving rotor in a rotary engine always moves the charge (air in stratified charge engines) past the stationary location of the spark plug and nozzles, as an inherent function of its geometry, and thus develops the necessary flow distribution for stratification. Multifuel capability is retained by spark ignition and injection at the approximate combustion rate, again facilitated by the manner which the combustion chamber form varies with shaft rotation. The transfer velocity or "squish" past the trochoid minor axis can be determined by shape of the rotor combustion pocket - a powerful development tool. The trailing quench of the homogeneous charge Rotary engine is avoided by designing the pocket and nozzle spray to deposit fuel within the rotor combustion pocket.

In addition to the general advantages of the Rotary listed earlier, the stratified charge version offers another significant plus: its broad fuel tolerance over the full speed and load range. This engine has shown essentially the same combustion performance on gasoline, jet engine fuel (JP4 and JP5), diesel fuel, and methyl alcohol without a configuration change. Furthermore, while optimized settings may differ for the various fuels, the changes are minor and the engine runs well without change of timings.

The current stratified charge design configuration (3) employs a separate pilot nozzle, with relatively small fuel flow, to trigger combustion. This two-nozzle design, shown in figure 19, uses a multi-hole main nozzle, located close to the trochoid surface to modulate fuel flow in response to power demand.

RC1-60 TESTING

All of the basic stratified charge technology developments were carried out with a single rotor rig engine of 60 cubic inches displacement. Since one "swept volume" moves through the engine with every shaft revolution, the engine size is comparable in output to an approximately two liter (2 x 60 in.^{3}) four stroke reciprocating engine. This RC1-60 test engine (10) has served for a number of developments over the past 24 years.

The R and D activity from 1973 through 1976 included test of a number of geometric variations of the basic dual injection configuration, primarily location of the pilot and main nozzles, spray pattern of the main nozzle in relation to rotor combustion pocket form, and basic rotor recess modifications. The design arrangement shown in figure 19 proved best on an overall basis, but the reversed sense (effectively changing the sense of the rotor direction arrow) of this arrangement (ATC Pilot) showed promise because it could result in less direct spray impingement of the pilot jet on the rotor; however, the required rotor pocket/nozzle combinations compatible with this change were not sufficiently explored at that time to determine if the apparent potential was realizable.

As of the completion of the 1976 Research Program (3), it had been demonstrated, using an RC1-60 rig engine, that an automotive sized module could provide: (1) specific fuel consumption equal to or better than an automotive Diesel, (2) promising HC, CO and NO_x emission levels, (3) capability to burn a wide range of fuels with equal effectiveness, and (4) package size and weight competitive with the regenerated shaft turbine. In addition, based on work done with a similar combustion process on the Texaco stratified charge engine (11), the prognosis for low particulate emission levels (12) was favorable.

The fuel consumption of this engine in the part-load automotive engine operating regime is compared to current diesel automotive (pre-chamber) engines, including points for the normally aspirated and turbocharged Volkswagen Rabbit engine (9), in figure 20. The size comparison of a complete RC1-60 engine with accessories, against the comparable output six cylinder VW Diesel version is shown in figure 21.

To compare advanced versus advanced, it has to be stated that these comparisons against automotive indirect injection diesels do not show the additional 10-15 percent improvement in BSFC that a direct injected diesel could provide. Up to this point, noise, power density, wide speed range and emission factors have favored the pre- or swirl chamber for automotive.

ALCOHOL FEASIBILITY

Using a nonoptimized (rotor pocket/main spray pattern) configuration that was tested at 10:1 compression ratio (fig. 22) on conventional fuels in 1979, the same engine build was briefly run on methanol.

The test was run at power levels tested on gasoline and diesel fuel. No attempt was made to change the configuration for alcohol and, accordingly, the injection durations were significantly longer to run the same power points using nozzles sized for gasoline, diesel, and jet engine fuel. Nonetheless, the engine fired consistently and ran very smoothly.

The petroleum-derived fuels have close to the same heating valve on a mass basis and roughly twice the heat content of the alcohol on a volume basis. Therefore, the results are presented (fig. 23) in the terms of specific heat input.

RC1-350 TESTING

In early 1977 the RC1-60 research program was deferred for Engineering activity on a larger 350 in^3 module. The 350 in^3 per rotor was achieved by enlarging the trochoid by approximately two-thirds and widening rotor proportions by 25 percent. The basic configuration and system evaluation work was conducted on the RC1-350 rig engine, which like the RC1-60 rig engine has test stand driven oil and coolant pumps. The rig test program, initially in support of a 4 rotor 1500 hp engine (fig. 24) has correlated very well with complete multirotor data and is essentially independent of the number of rotors in the final machine. The RC4-350 program, however, was subsequently redirected in 1980 to a two rotor version (fig. 25), also under Advanced Development contract to the USMC. The two rotor engine can produce 750 hp naturally aspirated, with substantial growth capability when turbocharged.

The same technology and basic configuration developed in the RC1-60 were used for the 350 in^3 engine. The output targets for the larger engine were established from the RC1-60 test results.

A comparision of excerpted basic performance results is of interest because of the directly applicable technology and the illustration of scaling effects that it affords.

The larger military engine module size has the advantages of more available space to accommodate nozzle and spark plug variations within a given rotor housing; reduced ratios of sealing line, leakage area, and heat transfer surface to charge volume; and a reduction of FMEP with size. While carbureted "similar" Curtiss-Wright Rotary engines over a displacement range of 500:1 have shown that both thermodynamic and mechanical performance can be predicted, this was the first significant stratified charge scaling exercise.

Therefore, the key technical question at the outset was whether or not stratified charge would scale thermodynamically. To facilitate a direct comparison, the current available data for the two engine sizes, both having the design configuration shown in figure 19 (BTC Pilot) and the same 8.5:1 compression ratio, are compared on an indicated basis and equivalent (same seal sliding speed) rpm in figure 26. It can be seen that the RC1-350 and RC1-60 are very close at the lower IMEPs, whereas the 1-60 data shows lower ISFC (or better thermal efficiency) at the higher loads, indicating further probable improvements for the larger engine.

Figure 27 shows both curves on a BSFC basis, reflecting the differences in friction. This plot shows that the RC1-350 enjoys an advantage over the RC1-60 because of the lower specific friction. The ATC Pilot ("reversed") configuration curve also reflects a combustion advantage. The improved thermal efficiency of the ATC Pilot design is one of the potential gains over the earlier automotive prototype data, which would obviously be included in any "updated" engines. In addition to lower friction, which on an absolute basis

(FMEP) is relatively low for all well-designed Rotary Engines, the 350 cubic inch engine enjoys the advantage of considerably more development effort, particularly with support injection and ignition systems. The conclusion of these and several other comparisons is that performance of the engine scales well, although demonstrated to date only in the larger direction. It should be added, however, that while scaling to smaller sizes has not been demonstrated by test of the same exact full-range configuration, feasibility of applying a direct injected stratified charge basic approach to engines in the 30-45 in^3 category has been proven elsewhere. A more complete answer will be forthcoming since the basic C-W combustion configuration is now being scaled down to a General Aviation sized power section model as part of the NASA contract to design and build a research rig engine.

IMPROVED COMBUSTION EFFICIENCY THROUGH TURBOCHARGING

1. Rationale - Predictions based on data obtained from tests of naturally aspirated stratified charge rotary engines indicated that turbocharging was not only a means of obtaining higher power, but also offered potential for improved fuel economy. The theory that turbocharging could improve combustion efficiency was predicated on the characteristic ISFC vs. F/A curve shapes shown in figure 28, which is representative for both the RC1-60 and RC-350 engines. The bulk of the data is for the BTC pilot configuration. The ATC pilot is spotted in for one test at 1200 rpm to show the comparison. Since ISFC is inversely proportional to thermal efficiency, it can be seen that the engine can not only run at the extreme lean mixture ratios of the diesel, but is markedly more efficient in this regime. Accordingly, the qualitative effects of turbocharging were predicted as shown on figure 29. As output is increased (higher BMEP), the mechanical efficiency also improves and this gain is additive to the improvements in thermal efficiency through leaner mixture strengths.

Based on this trend it was estimated that higher power BSFC could be reduced approximately 17 percent by driving the BSFC curve "hook" out beyond the "normal" naturally aspirated range. "Normal" is an arbitrary high limit mixture strength (generally about 0.055 F/A) where increased fueling provides little additional power increase. Like the diesel the rotary stratified charge engine can also "make smoke" for extreme over-fueling, but the smoke levels throughout the operating range have been shown to be low, which is conceptually attributed to the absence of the combustion lag with compression ignition. Although both the NASA General Aviation Engine Design Study (5) and Commuter Aircraft engines (6) were based on this approach, there was no test data on stratified charge Rotary engines to support the predictions at the time they were made. The succeeding sections describe how, since that point, the bases for these predictions have been confirmed.

2. Feasibility Testing Results 60 Cubic Inch Module - Turbocharging tests on the RC1-60 were conducted during late 1980 with peripheral and side air intakes, both with the standard 8.5:1 compression ratio rotors. In addition, a reduced compression ratio rotor was run to explore wider range operation without exceeding the naturally aspirated engine peak combustion pressure and rotor housing temperature levels.

A basic turbocharger (Schwitzer S6) was selected together with extra turbine casings (3LM) of different area ratios, and an additional compressor (3LM). All engine builds utilized the BTC pilot configuration rotor housing (fig. 19) with an available rotor which, while suitable for a generalized trend evaluation, did not represent an "optimized" system match of rotor combustion pocket, main nozzle spray pattern and rotor housing. In addition, the BTC pilot design has since been shown to be less efficient than the ATC pilot. Despite these limitations, the tests were run because performance trends were expected to hold for more recent configurations. These tests were biased towards the higher speed regimes of interest for military and aircraft applications.

Figure 30 shows that, as additional air is supplied by turbocharging, bringing the F/A ratio at 50 hp from 0.044 to .025, the ISFC (∝ 1/Thermal Efficiency) remains at the same minimum value that it had obtained at 20 hp. Accordingly, the 4000 rpm BSFC curve, instead of "hooking up" as normal, continues to decrease, showing an improvement of 19 percent at a defined natually aspirated F/A limit of 0.055, with both test curves extrapolated to this point. The BSFC improvement related to best BSFC naturally aspirated, at approximately 3/4 naturally aspirated power, is 11 percent on the same basis.

This improvement ratio is consistent with the earlier NASA growth engine predictions, although the absolute BSFC values shown on figure 30 do not represent current capabilities for reasons already stated. Therefore, the basic theoretical contention that the Indicated Specific Fuel Consumption (ISFC) can remain essentially at its optimum value for higher outputs, if the corresponding F/A ratio was maintained, is considered to have been confirmed by the RC1-60 tests. What remained was a test of state-of-the-art combustion configurations at higher powers.

The testing at 6.0:1 compression ratio, shown compared to the 8.5:1 C.R. results in figure 31, is particularly instructive because, despite anticipated poorer performance when run naturally aspirated, the data shows:

1. The improvement by turbocharging is relatively large, bringing the BSFC close to turbocharged results for the higher compression ratios.

2. The reduction in peak pressures and thermal loading is significant as can be inferred by the higher HP reached for the same monitored pressure levels. Figure 32 shows these effects more clearly, plotted here for 5000 rpm.

The test results point to lower compression ratios when turbocharging; further work will establish reduction degree as a function of engine power rating and operating regime.

As would be expected for the mixture strengths tested, the large quantity of excess airflow keeps turbine entry temperatures in the same general moderate range as turbocharged diesels. While all of the structural and thermal loading inputs to evaluate durability of basic engine components have not yet been thoroughly mapped, one positive indication noted thus far is that the specific engine heat rejection appears to drop with leaner operation. This will further increase the total heat rejection advantage over diesel engines. The implication of smaller heat exchanger volume is particularly important for military applications, where total system low specific volume is a key advantage.

3. Second Phase, Turbocharging Feasibility Testing, 350 in^3 Module - The 60 in^3 sized hardware, of circa 1974-5 orgins, did not reflect the performance refinements made during the early (1978-9) phases of the 350 cubic inch program. Therefore, since the RC1-350 engine rig hardware incorporates more advanced state-of-the-art combustion technology than the RC1-60, a brief exploration with the RC1-350 hardware was run in late 1981.

RC-350 test hardware reflects initial program emphasis on demonstrating the interim power and fuel consumption performance targets. Improvements were generally the result of a number of cumulative evolutionary gains in better optimization of rotor pocket form and matching spray pattern, injection system and technique, configuration detail, ignition, structure, etc. The one more "radical" change was the interchange of pilot and main nozzle locations to the ATC pilot design.

While the test did include these performance gain features, there was not sufficient time to procure a lower compression ratio rotor, as suggested by the earlier RC1-60 test series, and the tests were run with the standard 8.5:1 compression ratio. Accordingly, the first survey was run to a peak combustion pressure limit approximately 25 percent higher than the maximum for naturally aspirated operation. This resulted in reduced output, for the same pressure limits, than would have been the case with reduced compression ratio.

Figure 33 shows that the improvement of BSFC with output, as the lean mixture strength is maintained by turbocharging, applies in the same manner to this engine as it did in the RC1-60. However, this initial turbocharger match (modified Schwitzer 5LM) provided more induction air than desired, primarily because of higher than expected exhaust energy, including pulse recovery. The large gain in BSFC when run without intercooling is partially due to a more optimum mixture strength, in this case slightly richer, as well as improved combustion efficiency as a function of the higher temperatures.

Non-intercooled data was not run for the full load and speed range. figure 34 shows intercooled BSFC vs. BMEP at various speeds. The slope of the curves indicates that further BSFC improvements can be anticipated at higher loads and that the results are supportive of the advanced engine growth predictions.

A further brief exploratory test, this time with emphasis on increased power rather than fuel consumption was run on the turbocharged RC1-350 in 1982. The engine was fitted with a 7:1 compression ratio rotor and with turbochargers modified to reflect the 1981 experiences. The engine was run to 11 percent overspeed and to approximately 50 percent higher BMEP than for the nominal (naturally aspirated) rating of 375 hp per rotor. The maximum horsepower tested at the time, which is still not the limit, was 559 hp at 4000 rpm. As shown in figure 35, the BSFC and BMEP at maximum power tested was, respectively, 0.463 lb/hp-hr and 157 psi. At the rated rpm of 3600, the corresponding maximum values of power, fuel consumption and BMEP are 510 hp, 0.433 lb/hp-hr and 159 psi.

The main nozzles have not yet been optimized for the low compression rotor pocket and testing at lower speeds, which will give better BSFC, has not yet been explored. It is intended to further evaluate these factors, as well as other turbocharger aviations, before proceeding to higher powers. However, the indications of significantly increased power potential, which was the test purpose, is believed to have been confirmed.

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TABLE I. - BASIC ENGINE DATA

[250 CRUISE hp AT 25 000 ft.]

	TSIO-550	Advanced RC2-47	Highly advanced RC2-32
Length, in.	59.25	52	48.6
Width	33.4	16.5	16
Height	19.25	16.5	16
Weight-flyable, lb	585	348	255
Specific fuel consumption at cruise (lb/hp-hr)	.446	.371	.355

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TABLE II. - AIRPLANE COMPARISONS

		SINGLE ENGINE			TWIN ENGINE		
		TSIO-550	RC2-47	RC2-32	TSIO-550	RC2-47	RC2-32
Takeoff	kW	254	239	239	254	239	239
power	bhp	340	320	320	340	320	320
Cruise	kW	186	186	186	186	186	186
power	bhp	250	250	250	250	250	250
Empty weight	kg	1241	1042	965	2008	1644	1509
	lb	2736	2297	2127	4428	3625	3327
Gross weight	kg	2023	1760	1674	3107	2625	2474
	lb	4460	3881	3691	6850	5788	5454
Wing area	m^2	15.8	13.7	13.0	16.7	13.7	13.5
	ft^2	170	147	140	180	148	145
Wing span	m	12.3	10.6	10.0	13.6	11.6	10.7
	ft	40.2	34.9	32.8	44.5	38.1	35.0
Aspect ratio		9.5	8.3	7.7	11.0	9.8	8.5
ROC	m/min	198	236	249	312	384	408
at 25 000	fpm	650	775	816	1025	1260	1340
Climb time	min	28.4	23.3	22.1	18.7	14.9	14.0
SEROC	m/min				105	122	130
at 5000 ft	fpm				343	400	425
Takeoff	m	683	616	585	713	637	573
distance	ft	2240	2020	1920	2338	2090	1880
Stall	km/hr	113	113	113	135	137	135
speed	KT	61	61	61	73	74	73
Cruise	km/hr	382	420	424	424	465	467
speed	KT	206	227	229	229	251	252
Payload	kg	544	544	544	635	635	635
	lb	1200	1200	1200	1400	1400	1400
Range	km	1296	1296	1296	1481	1481	1481
	NM	700	700	700	800	800	800
Mission fuel	kg	200	142	134	387	283	269
	lb	440	314	296	855	625	592
Cruise	km/L	4.7	7.3	7.7	2.7	4.2	4.5
mileage	NMPG	9.6	14.9	15.8	5.6	8.6	9.1
Price	$1000	202	184	175	381.5	334	320.5
DOC	$/hr	122	107	103	230	196	190

TABLE III. - GEOMETRIC DATA

[In Inches.]

Horsepower	800	2500
Size	RC4-41	RC6-122
Speed rpm	8,600	5,980
Eccentricity, E	0.61	0.88
Rotor width, W	3.05	4.39
Trochoid major axis, in.	9.64	13.85
Trochoid minor axis, in.	7.2	10.35
Number of rotors	4	6
Displacement per rotor, $in.^3$	41	122

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TABLE IV. - 1200 bhp RC4-81 (81.15) OPERATING DATA SUMMARY

	Take-off sea level	70 percent cruise 15 000 ft altitude
Without turbocompounding		
BHP	1200	840
rpm (crankshaft)	6904	5305
IMEP, psi	244.11	217.82
IHP	1381.43	947.10
FMEP, psi	32.06	24.63
FHP	181.43	107.10
BMEP, psi	212.05	193.19
Fuel/air ratio	0.04	0.04
BSFC, lb/bhp-hr	0.3586	0.3529
Airflow, lb/hr	10 757	7410
Compressor press. ratio[a]	2.17	4.15
Eng. inlet temperature, °F	149.8	170.2
Eng. inlet pressure, psi	31.2	33.72
With turbocompounding		
bhp (RC4-75)	1200	840
bhp (RC4-81)	1275.6	900.5
bsfc, lb/bhp-hr	0.3373	0.3292

[a]Before 2 percent intercooler pressure drop. Assumes intercooler effectiveness of 50 percent and compressor efficiency of 70 percent.

TABLE V. - 2000 bhp RC6-95 (94.87) OPERATING DATA SUMMARY

[Standard Day - No Ram.]

	Take-off sea level	70 percent cruise 15 000 ft altitude
Without turbocompounding		
BHP	2000	1400
rpm (crankshaft)	6553	5035
IMEP, psi	244.11	217.88
IHP	2299.93	1577.05
FMEP, psi	31.84	24.46
FHP	299.93	177.05
BMEP, psi	212.26	193.42
Fuel/air ratio	0.04	0.04
BSFC, lb/bhp-hr	0.3582	0.3526
Airflow, lb/hr	11 938	8224
Compressor press. ratio[a]	2.17	4.15
Eng. inlet temperature, °F	149.8	170.2
Eng. inlet pressure, psi	31.2	33.72
With turbocompounding		
bhp (RC6-87)	2000	1400
bhp (RC6-95)	2126	1500.8
bsfc	0.3361	0.3289

[a]Before 2 percent intercooler pressure drop. Assumes intercooler effectiveness of 50 percent and compressor efficiency of 70 percent.

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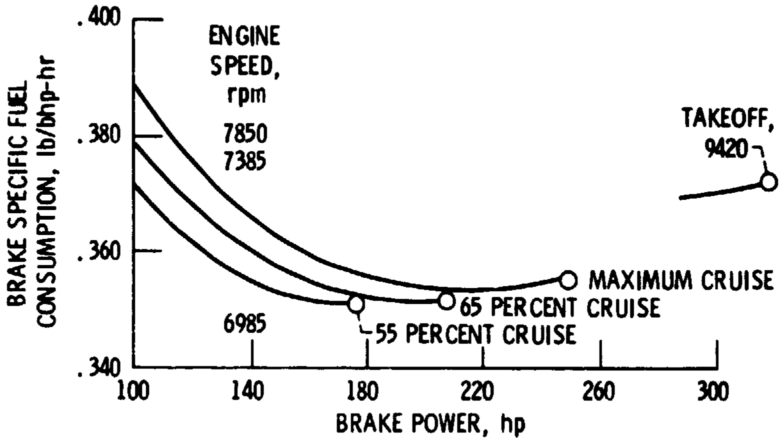

Figure 1. - RC2-32 highly advanced turbocharged, stratified-charge rotary combustion engine - estimated performance.

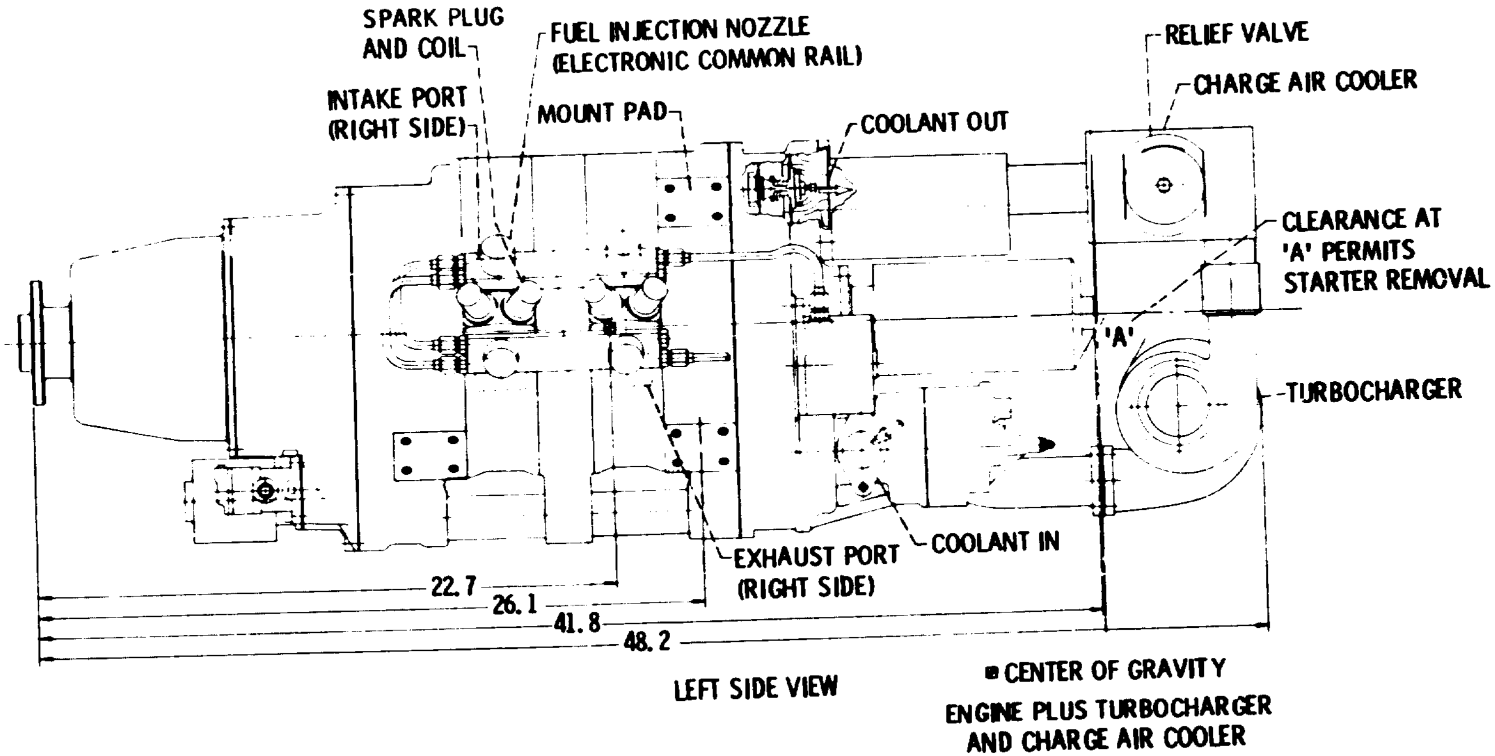

Figure 2. - RC-2-32 engine.

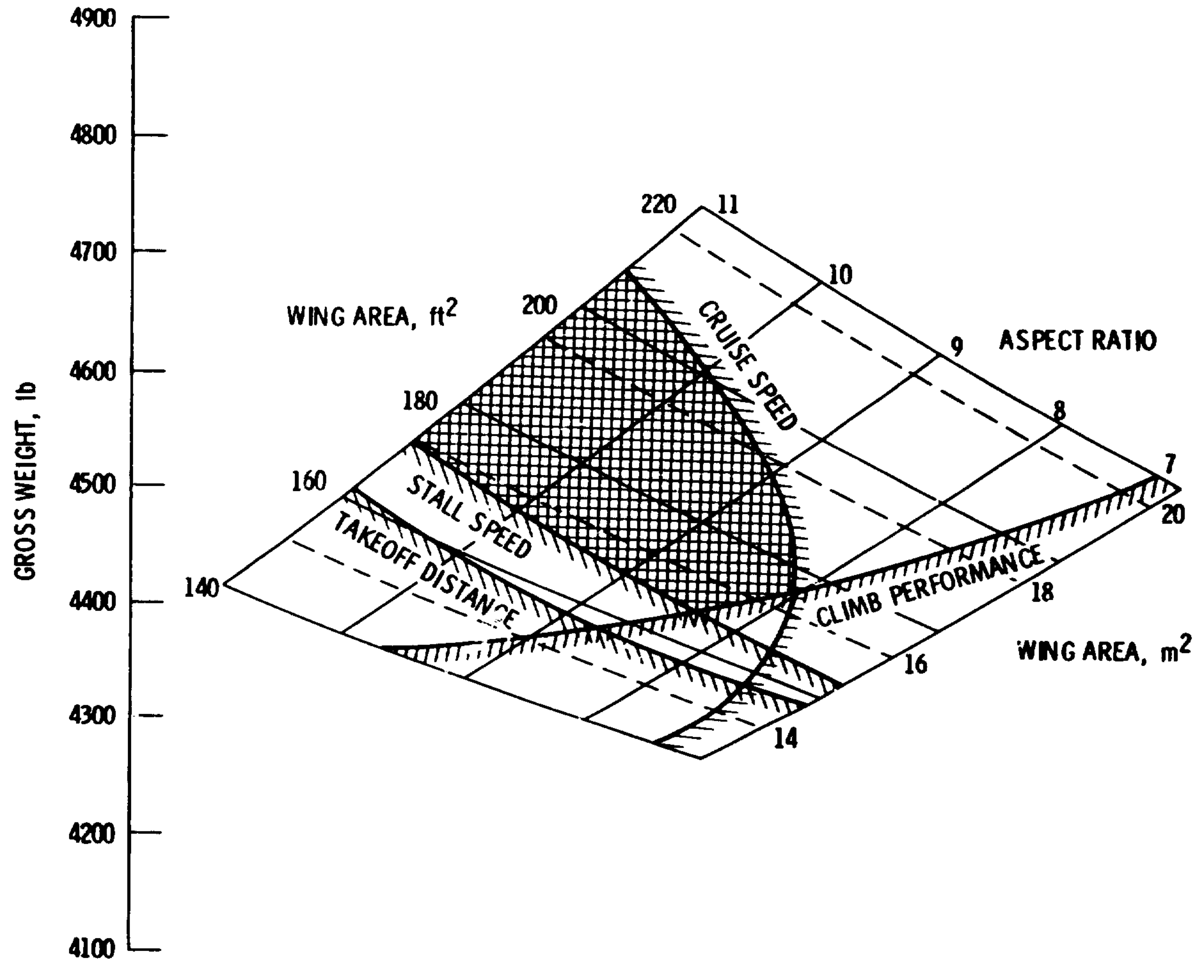

Figure 3. - Performance constraints on carpet plot of constant payload range.

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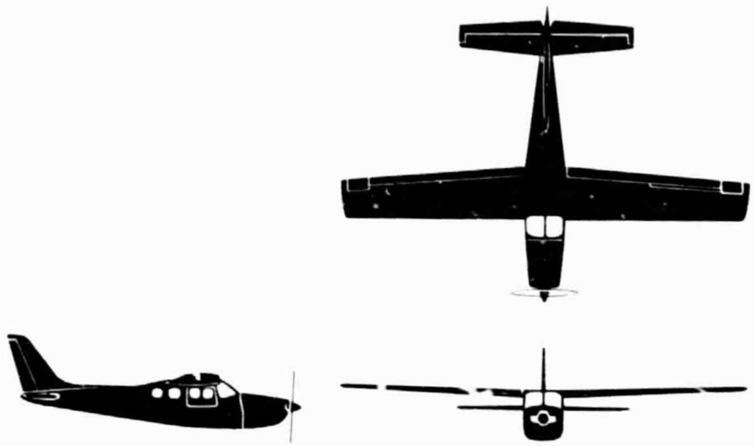

Figure 4. - Baseline single - fixed engine size, variable airframe, and fixed payload range. Gross weight, 4460 lb; span, 40.2 ft; aspect ratio, 9.5.

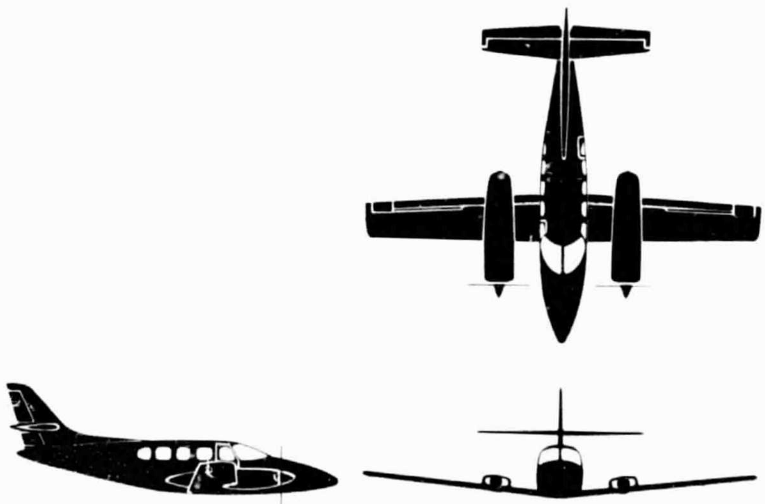

Figure 5. - Baseline twin - fixed engine size, variable airframe, and fixed payload range. Gross weight, 6850 lb; span, 44.5 ft; aspect ratio, 11.0.

WEIGHT	RC2-47	RC2-32
GROSS, lb	3881	3691
SPAN, ft	34.9	32.8
ASPECT RATIO	8.3	7.73

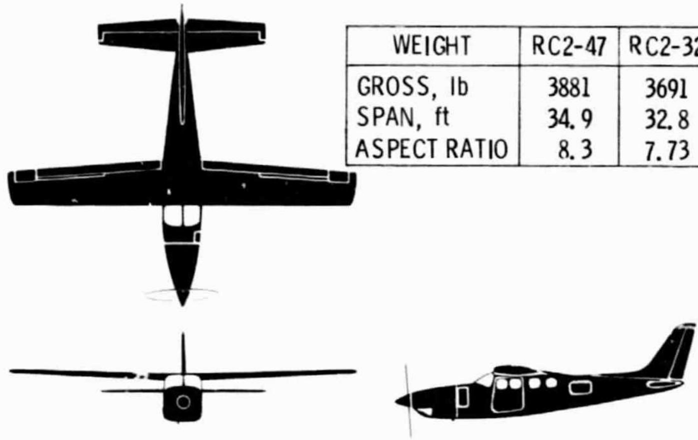

Figure 6. - Rotary single - fixed engine size, variable airframe, and fixed payload range.

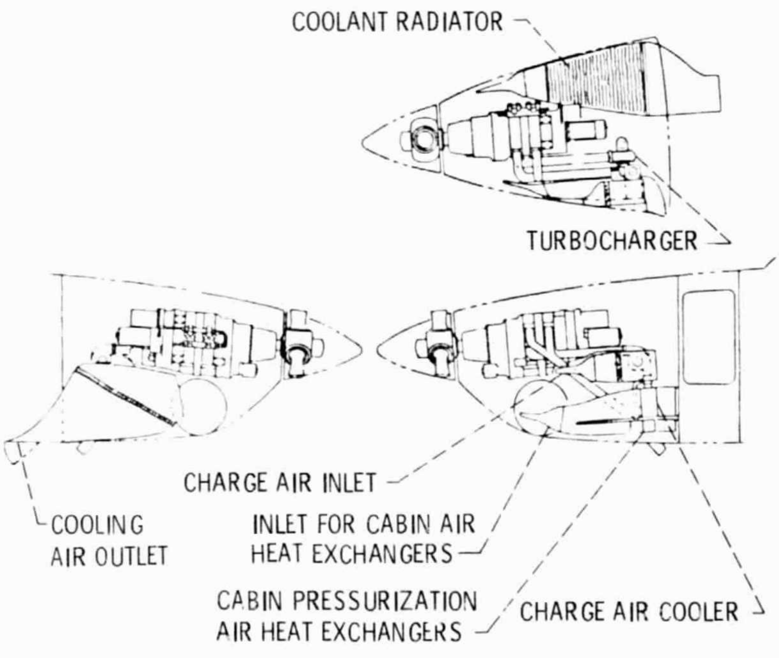

Figure 7. - RC2-32 highly advanced rotary engine - single-engine installation concept.

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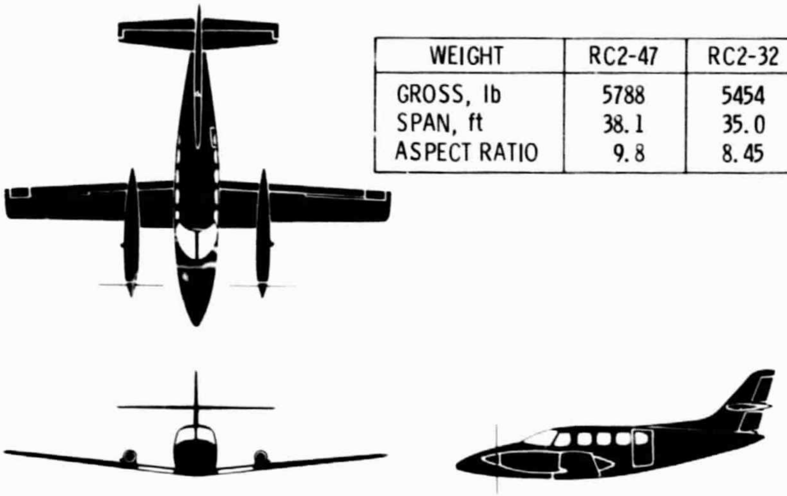

WEIGHT	RC2-47	RC2-32
GROSS, lb	5788	5454
SPAN, ft	38.1	35.0
ASPECT RATIO	9.8	8.45

Figure 8. - Rotary twin - fixed engine size, variable airframe, and fixed payload range.

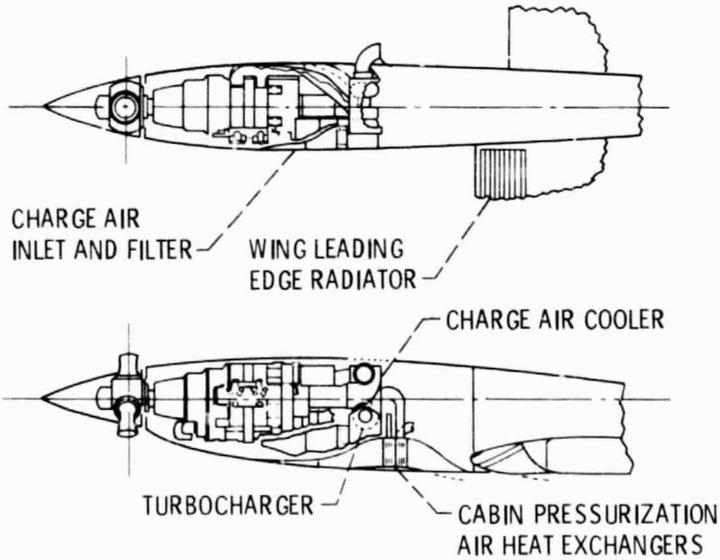

Figure 9. - RC2-32 highly advanced rotary engine - twin-engine installation concept.

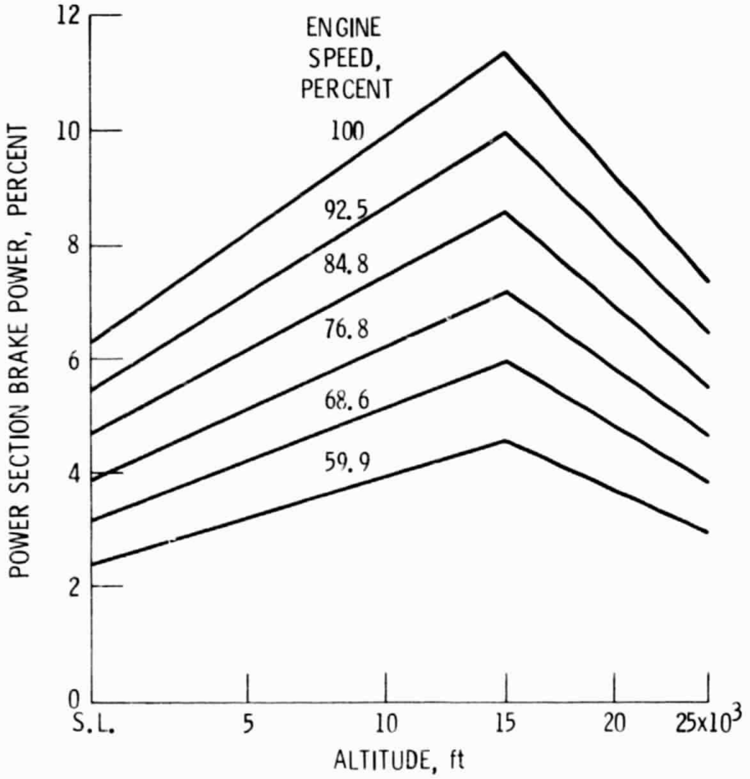

Figure 10. - Estimated power recovery turbine performance. (Estimates are based on standard atmospheric conditions and no ram. Estimates are applied to altitude power curves at respective speeds to the brake power shown.)

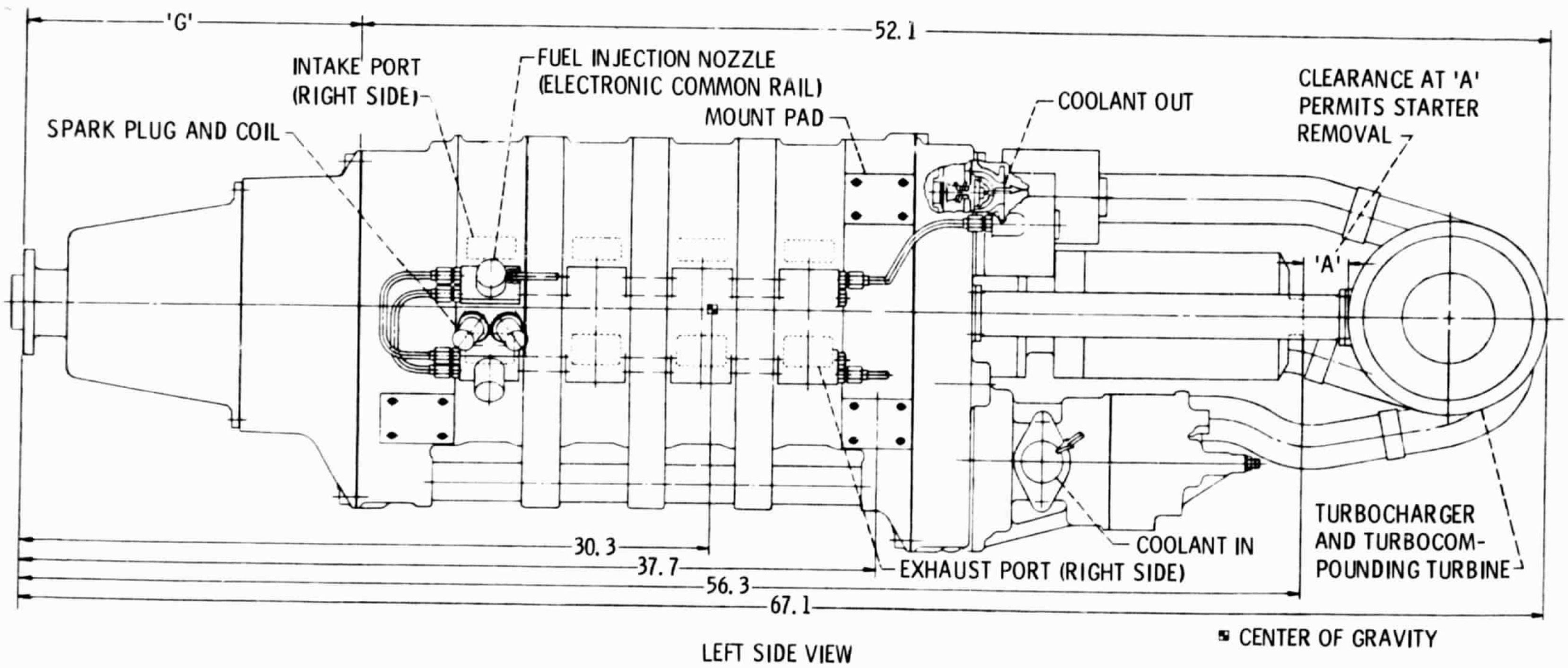

Figure 11. - Installation drawing of highly advanced rotary combustion aircraft engine - 800 hp. (End view is a circle of 19 in. diameter. For dimension 'G' see gear reduction curve configuration shown for 1500 propeller rpm.)

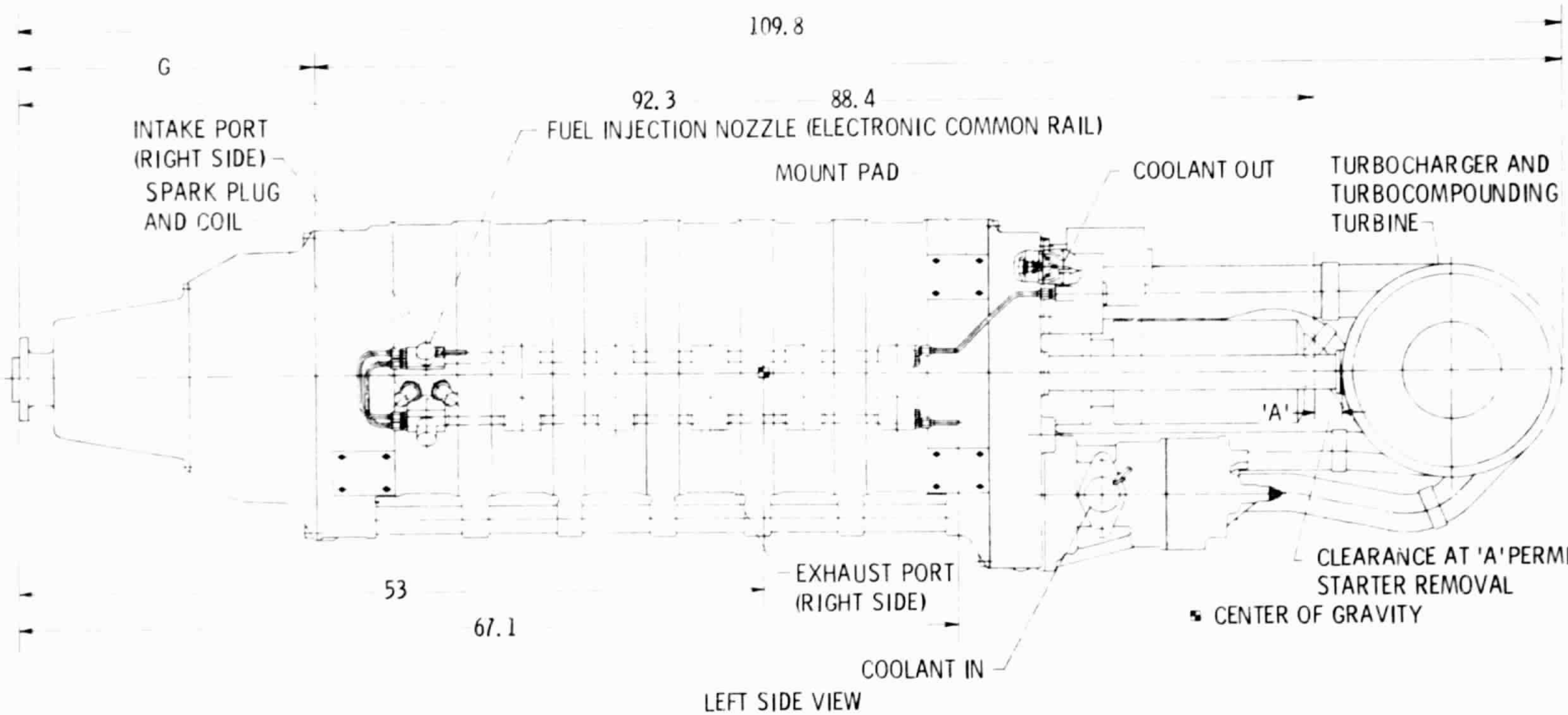

Figure 12. - Installation drawing of highly advanced rotary combustion aircraft engine - 2500 hp. (End view is a circle of 26 in. diameter. For dimension G see gear reduction curve configuration shown for 1500 propeller rpm.)

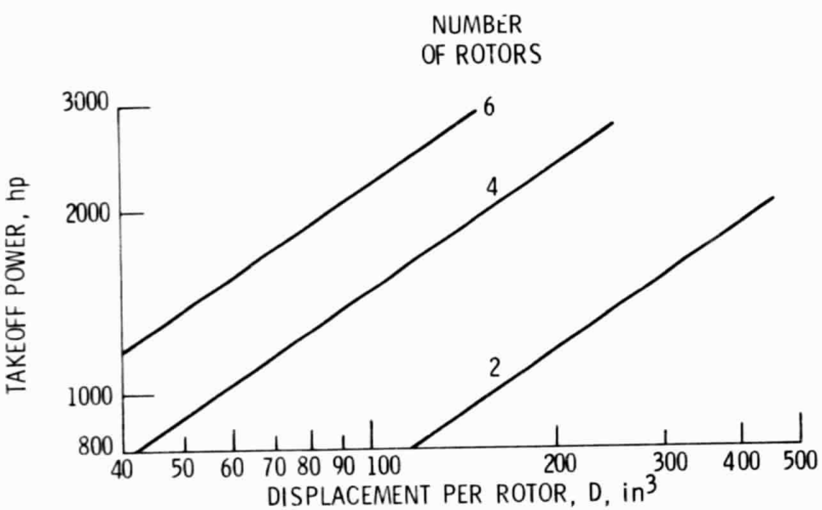

Figure 13. - Takeoff power as a function of displacement per rotor (turbocharge, turbocompounding, and charge air cooler). Engine speed = (29675) $(1/D)^{1/3}$.

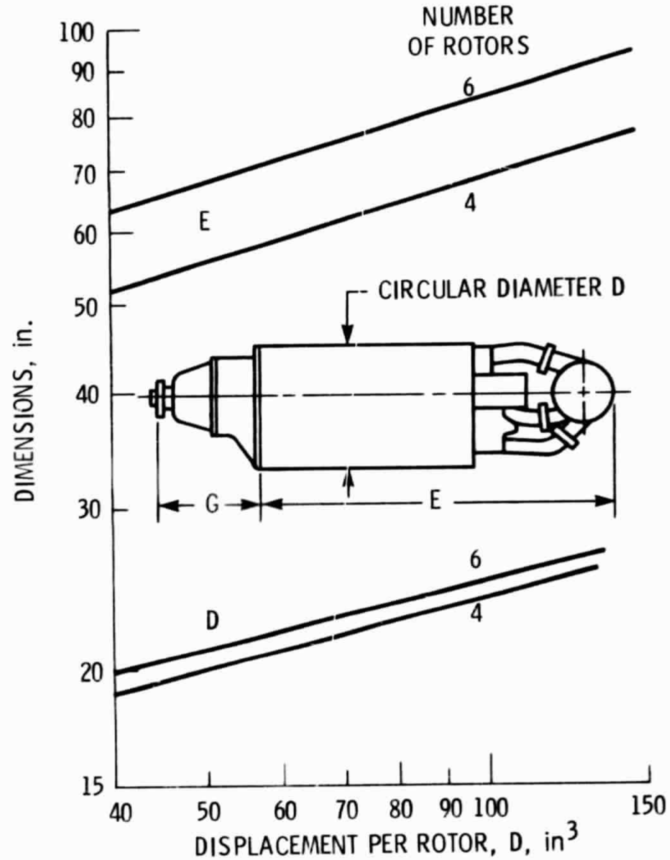

Figure 14. - Engine dimensions as a function of displacement per rotor. (Oil and coolant coolers are not included. For dimension G see propeller reduction gear length curve.)

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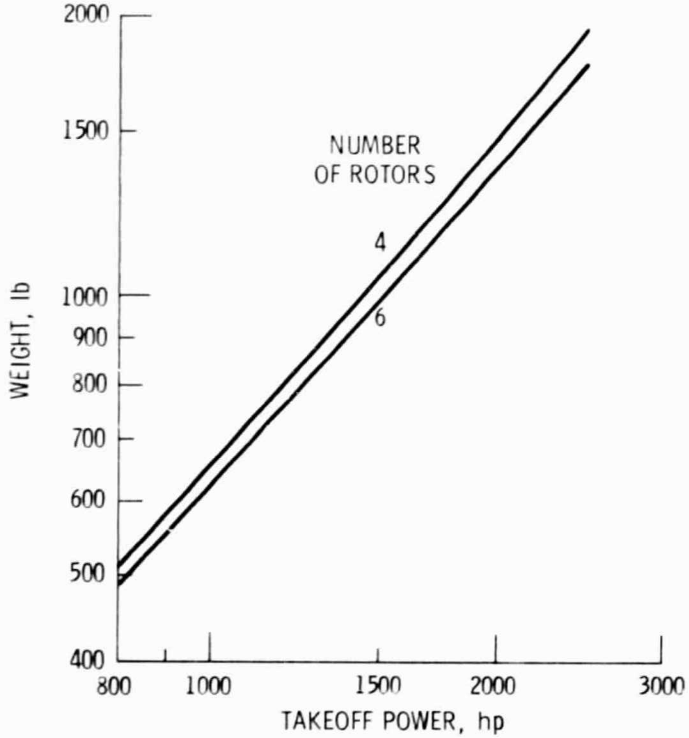


Figure 15. - Rotary engine weight as a function of takeoff power. (Gearbox weight not included. Wet, ready to fly.)

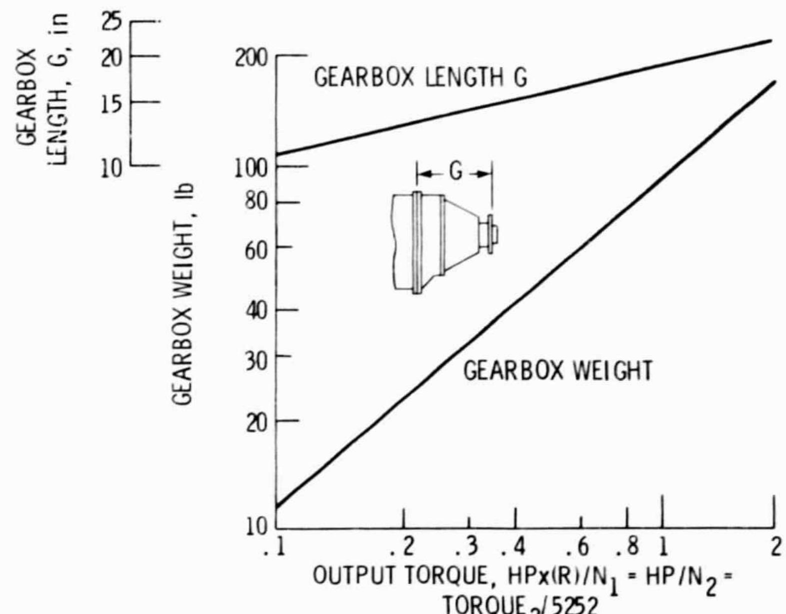
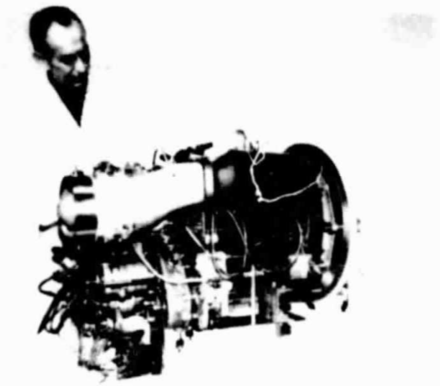


Figure 16. - Integral propeller reduction gearbox length and weight as functions of output torque, where HP is shaft horsepower; N_1 is engine speed, rpm; N_2 is propeller shaft speed, rpm; $torque_2$ is output shaft torque, lb-ft; and R is speed ratio = N_1/N_2.



WEIGHT	285 LB.*
WIDTH	25 IN.
LENGTH	34 IN.
HEIGHT . . .	19-1/2 IN.

* LESS STARTER, SEPARATE OIL COOLER/SUMP

Figure 17. - Air-cooled stratified charge RC2-90 engine (1966).

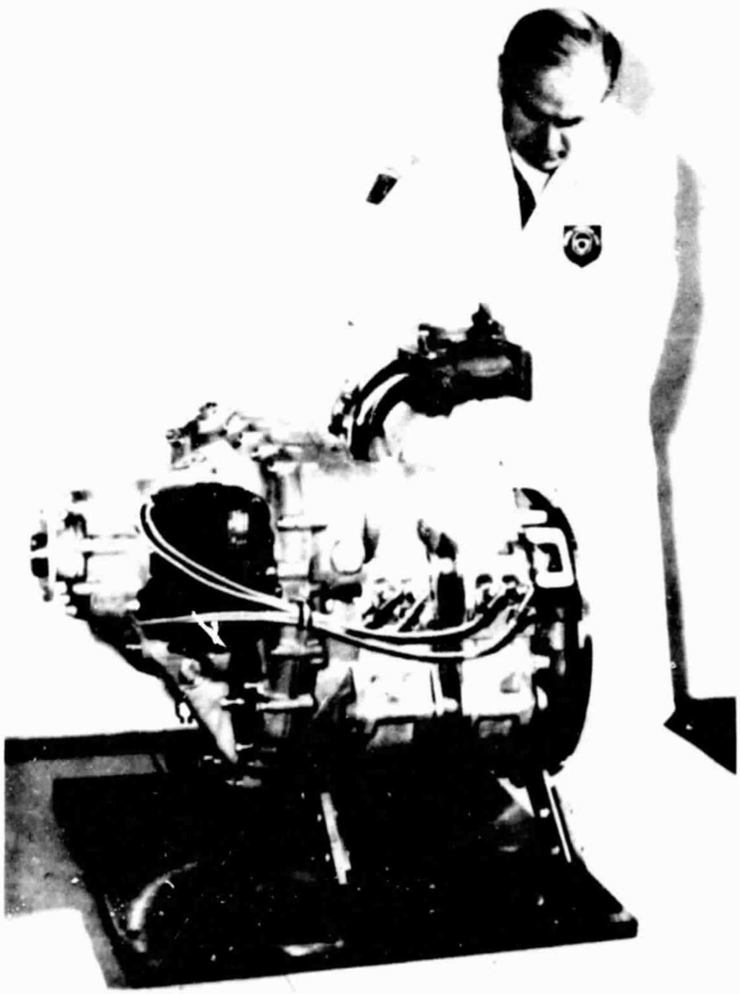


Figure 18. - RC2-75 aircraft engine prototype.

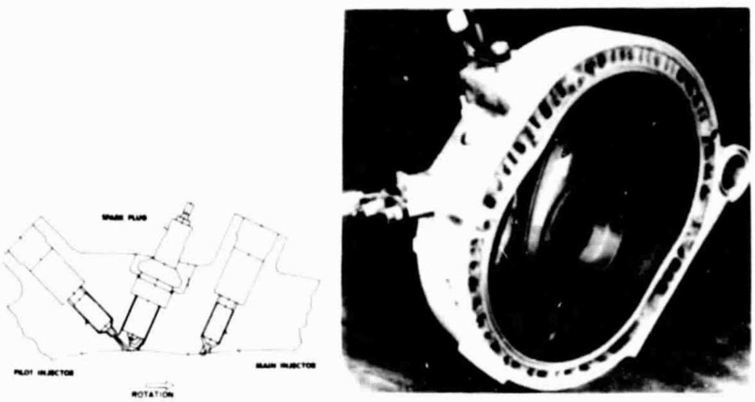
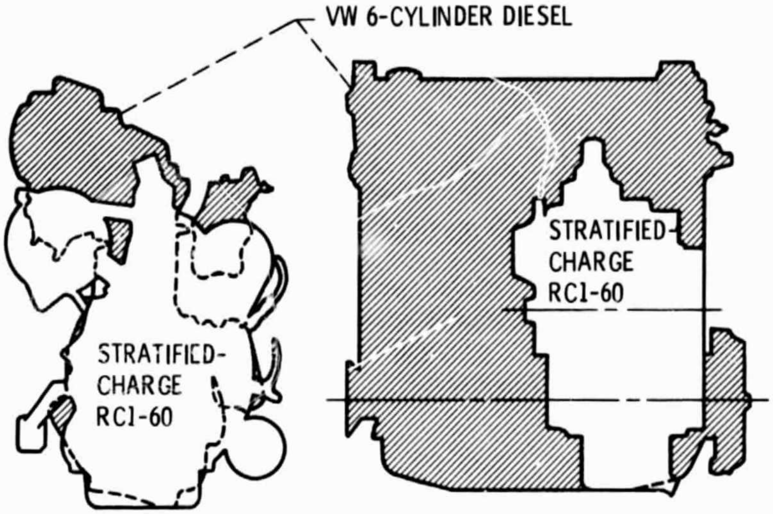


Figure 19. - Dual injection rotor housing configuration.



	STRATIFIED-CHARGE RC1-60	VW SIX-CYLINDER DIESEL
BRAKE POWER, hp	80	75
ENGINE SPEED, rpm	5000	4500
ENGINE WEIGHT, lb	240	405
ENGINE DIMENSIONS (LENGTHxWIDTHx HEIGHT), in.	14.5x22x25	30.7x19.3x30.7

Figure 21. - Comparison of stratified-charge RC1-60 rotary combustion engine with six-cylinder Volkswagen diesel engine.

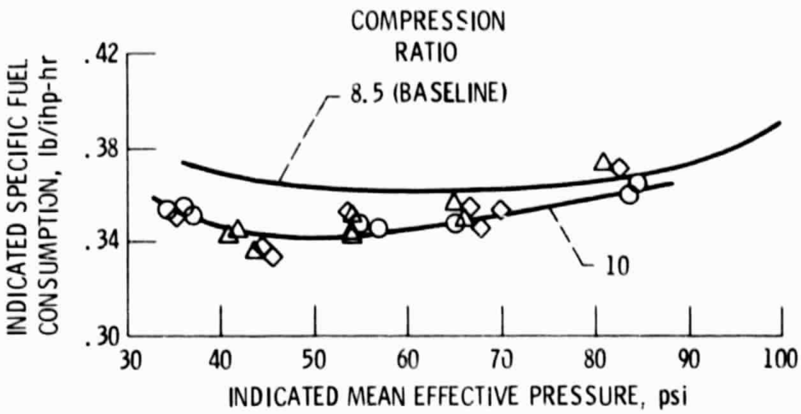


Figure 22. - Indicated specific fuel consumption as a function of indicated mean effective pressure for naturally aspirated RC1-60, BTC pilot with compression ratios of 8.5 and 10 at speed of 2000 rpm.

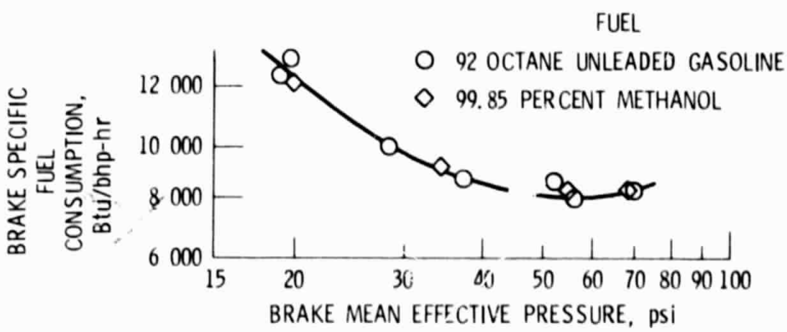


Figure 23. - Brake specific fuel consumption as a function of brake mean effective pressure for naturally aspirated RC1-60, BTC pilot, rotary combustion engine with compression ratio of 10 and speed of 2000 rpm. (Gasoline lower heating value, 18 607 Btu/lb; methanol lower heating value, 9 750 Btu/lb.)

Figure 24. - RC4-350 engine.

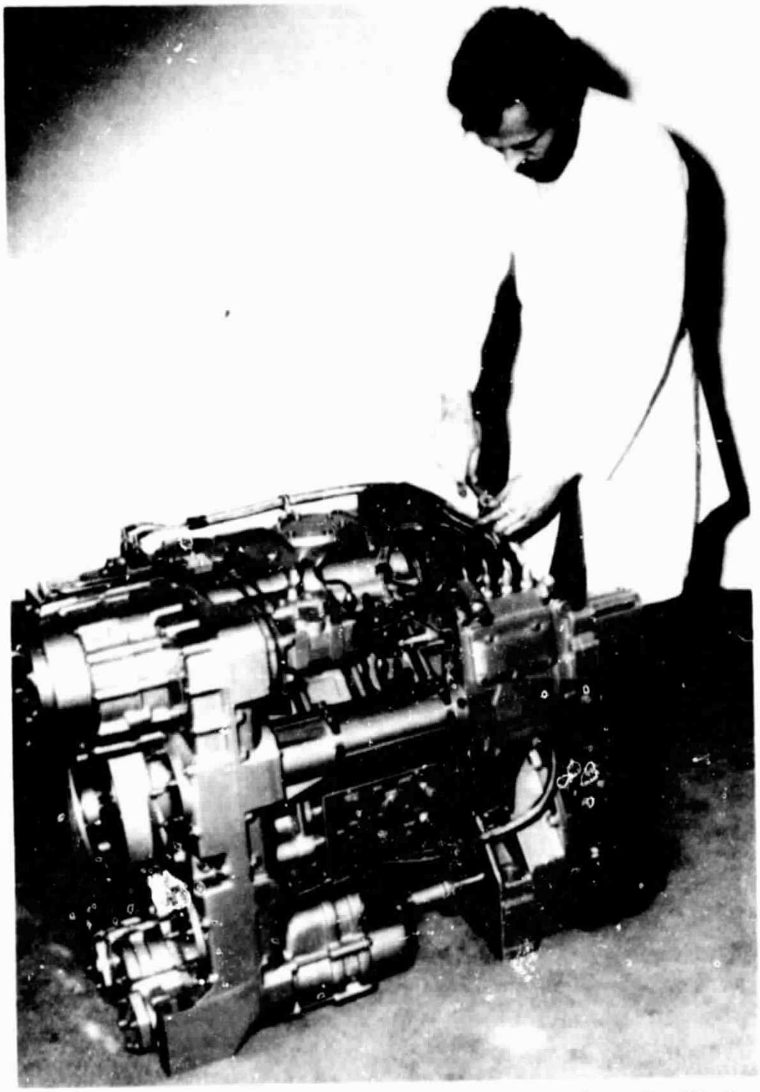


Figure 25. - Curtiss-Wright rotary combustion engine. Stratified charge model RC2-350.

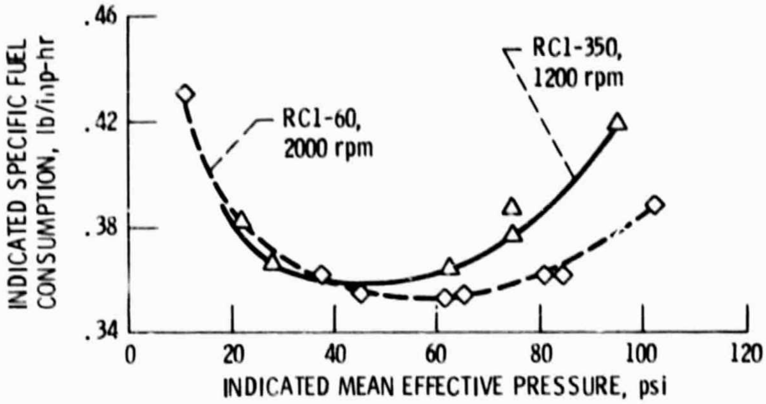


Figure 26. - Indicated specific fuel consumption as a function of indicated mean effective pressure for RC1-60 and RC1-350, BTC pilot, rotary combustion engines with compression ratios of 8.5.

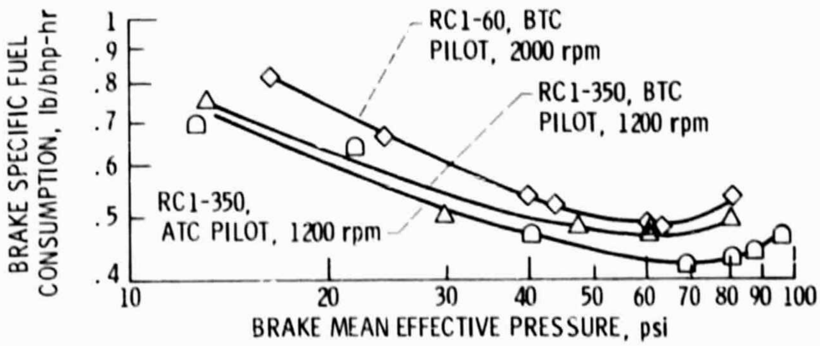


Figure 27. - Brake specific fuel consumption as a function of brake mean effective pressure for RC1-60 and RC1-350 rotary combustion engines with compression ratio of 8.5.

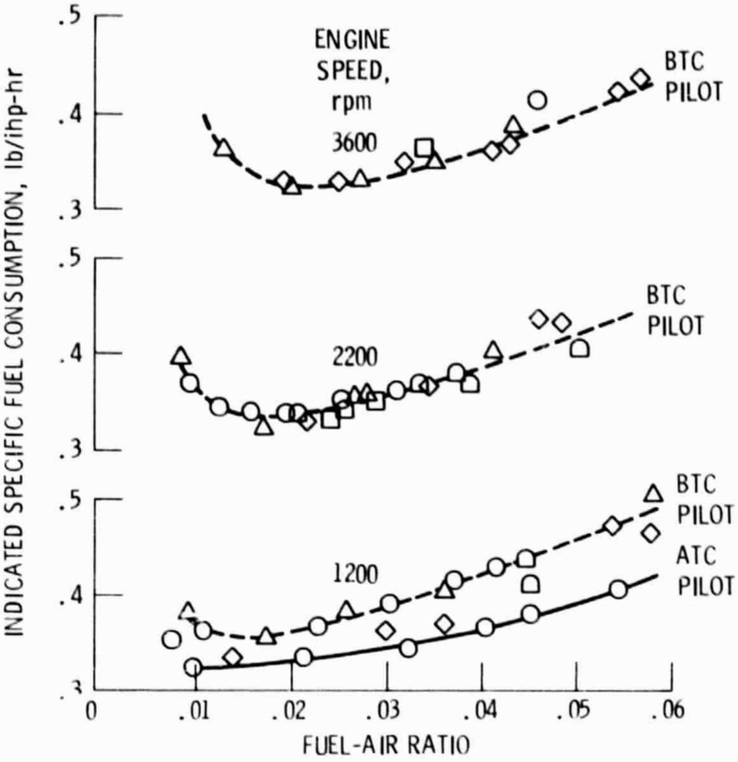


Figure 28. - Indicated specific fuel consumption as function of fuel-air ratio for six RC1-350 rotary combustion engine builds with compression ratio of 8.5.

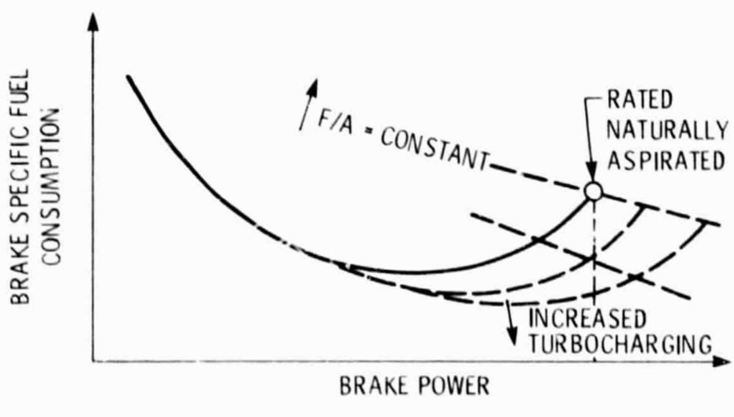


Figure 29. - Theorectical turbocharging effects on brake specific fuel consumption.

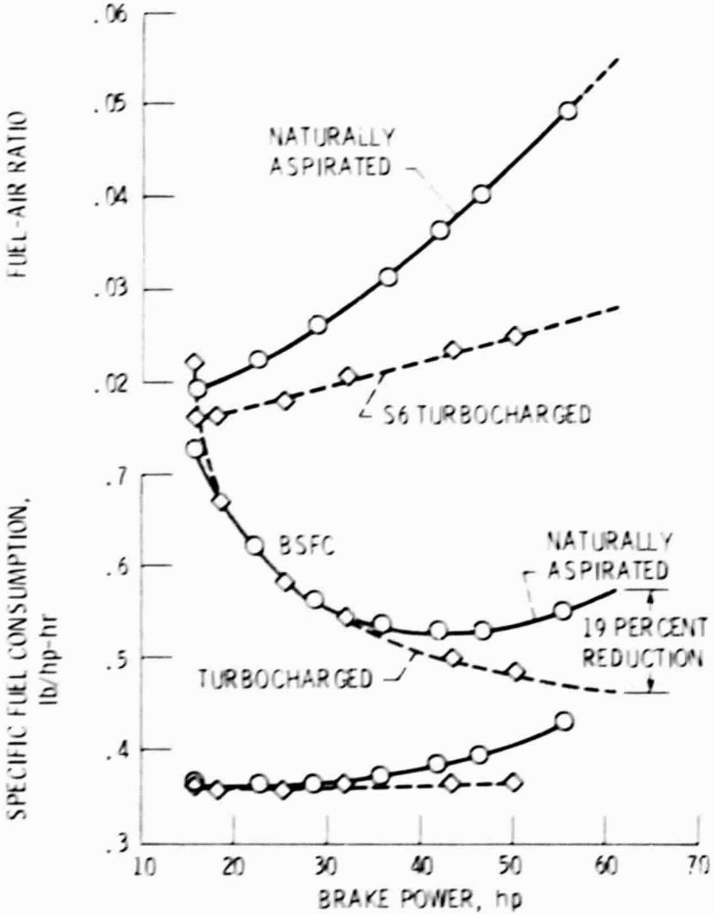


Figure 30. - Fuel-air ratio and indicated and brake specific fuel consumption as function of brake horsepower for stratified-charge RC1-60 rotary combustion engine with compression ratio of 8.5 and peripheral intake ports at 4000 rpm.

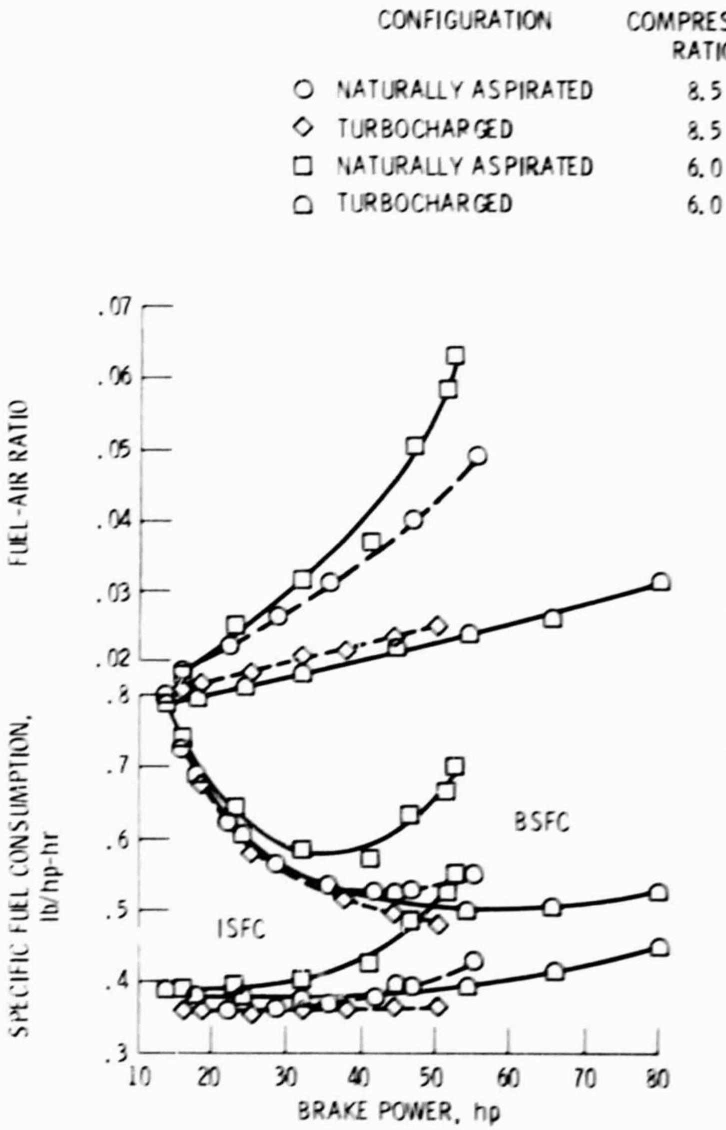


Figure 31. - Fuel-air ratio and indicated and brake specific fuel consumption as functions of brake horsepower for stratified-charge RC1-60 rotary combustion engine with peripheral intake ports at 4000 rpm.

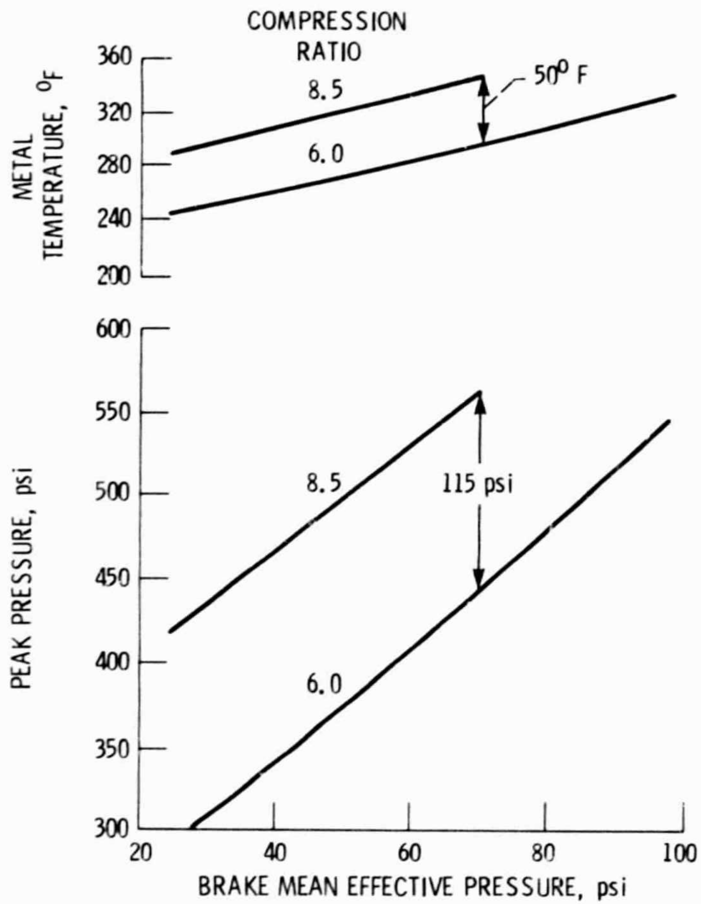


Figure 32. - Measured reduction in thermal and pressure loads from lower compression ratio and lower fuel-air ratio for turbocharged, stratified-charge RC1-60 rotary combustion engine at speed of 5000 rpm.

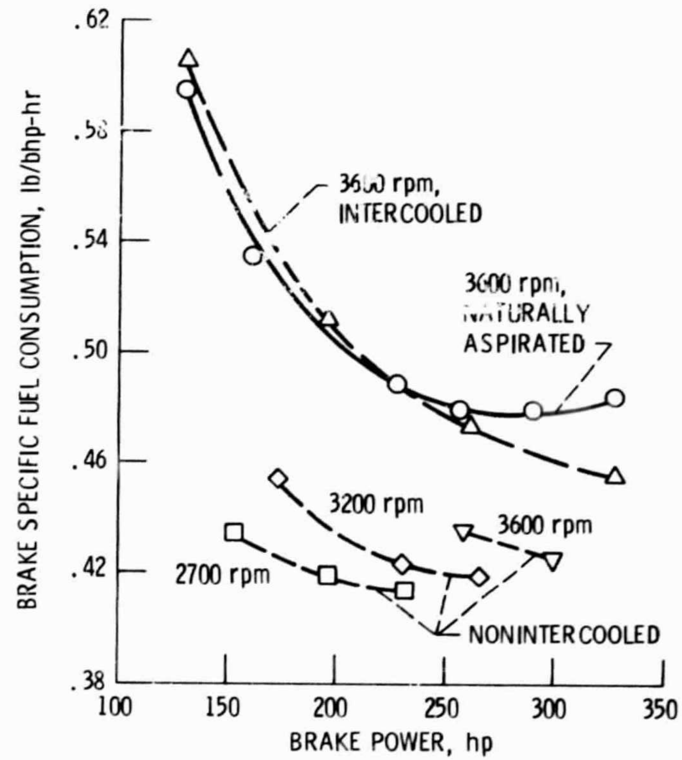


Figure 33. - Brake specific fuel consumption as a function of brake horsepower for turbocharged, stratified-charge RC1-350 rotary combustion engine. Turbine inlet area, 8.5 in^2; Schwitzer 5MF-863 turbocharger.

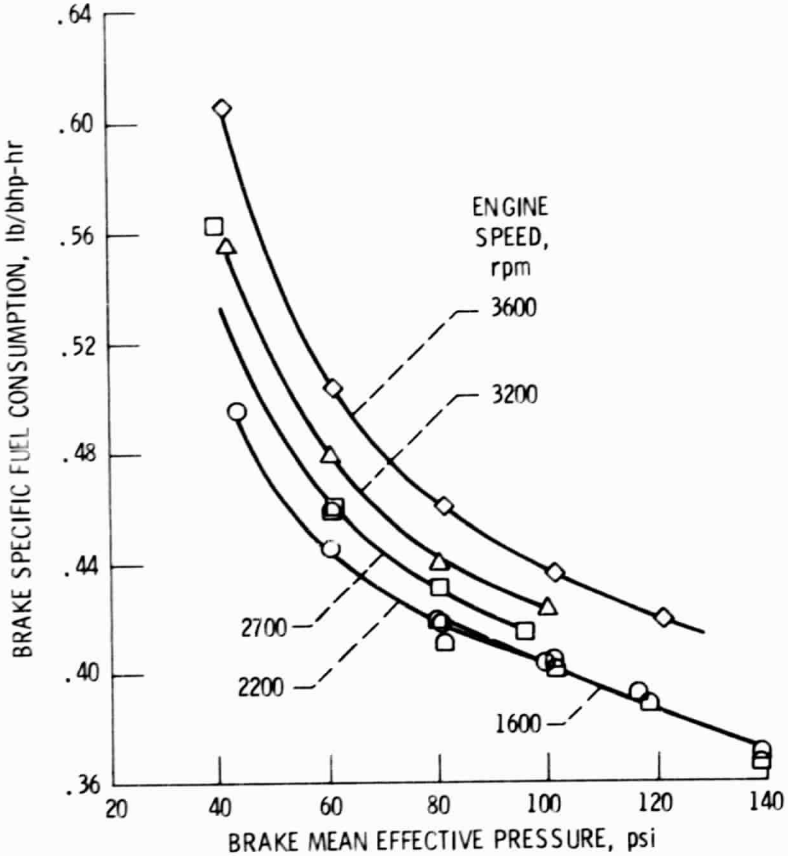


Figure 34. - Brake specific fuel consumption as a function of brake mean effective pressure for turbocharged, stratified-charge, intercooled RC1-350 rotary combustion engine, turbine inlet area, 8.5 in^2; Scwitzer 5MF-863 turbocharger.

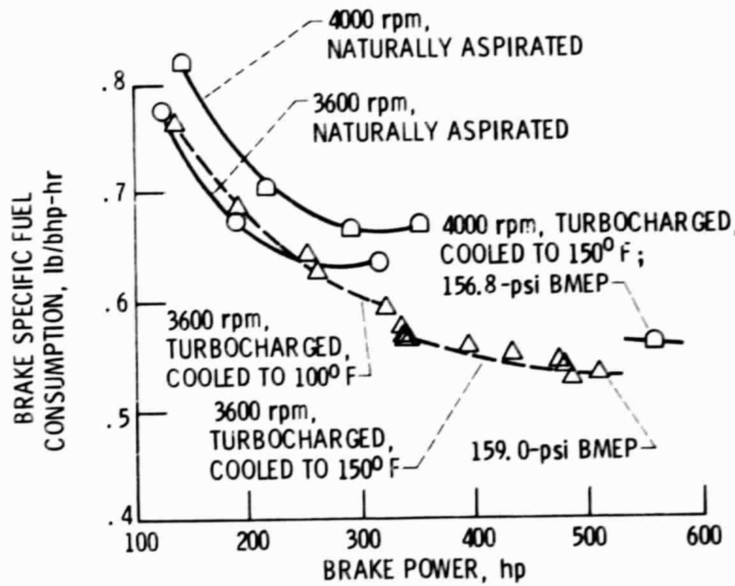


Figure 35. - Brake specific fuel consumption as a function of brake horsepower for stratified-charge RC1-350 rotary combustion engine with compression ratio of 7.0.