ADVANCED ROTARY ENGINE STUDIES

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INTRODUCTION

The intent of this paper is to review recent Rotary Engine Developments relevant to a Stratified Charge Rotary Aircraft Engine. In addition, present status of the NASA-funded Advanced Aircraft Engine Study, which is currently underway, will be briefly described.

Background Work

Although Curtiss-Wright designed their first Wankel-type Rotary Engine in 1958 and ran this engine in early 1959, developments continued into 1962 before a reliable, durable and efficient baseline engine was demonstrated.

The first Stratified Charge trials were made that same year, directed towards a multi-fuel military engine. During the mid-60's period, two prototype Stratified Charge Rotary Engines were designed, built and developed through the early operational test stand stage (ref. 1). The RC2-60U10 (figure 1) was a liquid-cooled two rotor vehicular engine in the 160 - 200 HP class and the RC2-90 (figure 2) an air cooled 300 HP helicopter drone engine. The trochoid dimensions of these engines was the same as the 1958-designed 60 cubic inch single rotor engine (the RC1-60), but the rotor width was increased 50% for the RC2-90. Both engines proved their multi-fuel capabilities, but neither could match the fuel economy of our carbureted RC2-60U5 automotive prototype engine of the same era, which was comparable to existing automotive engines (ref. 2). Furthermore, the RC2-60U10 performed well at the lower powers and speeds, with shortcomings apparent at the other end of the operating regime, whereas the 90 cubic inch combustion configuration was subsequently developed to meet high power goals, only to show low end deficiencies. In both cases, however, the engines showed sufficient technical promise for their specific designed applications, but as a result of changes in military planning, the intended uses did not materialize and development was shelved.

Although thermal efficiency equal to our homogeneous charge Rotaries was never demonstrated with these engines, the inherent compatibility of the Rotary geometry with unthrottled and direct chamber injected Stratified Charge combustion led some to believe that the potential for superior performance had to be there. Figure 3 illustrates how the Rotary provides the required repetitive scheduled turbulence, without losses, while direct chamber injected reciprocating engines have to generate the required velocity gradients at a cost of both volumetric and mechanical efficiency, further widening the specific power advantage of the Rotary.

Following the fuel crises of 1973, R&D efforts were reinitiated in an attempt to resolve whether or not this higher efficiency potential really existed. This time, our feasibility trials were directed towards automotive applications which meant not only wide power and speed range flexibility with fuel economy, but low or controllable emissions as well. Since hydrocarbon emissions at the very low speeds and powers typical of an automotive operating regime had proved the most difficult area for the homogeneous charge Rotary, new configurations were screened on the basis of road-load brake specific fuel consumption (BSFC) and brake specific hydrocarbons (BSHC). The 1973 attempt to combine the best features of RC2-60U10 and final RC2-90 injection/ignition designs into a single configuration which could run full range was successful and, for the first time, achieved better fuel consumption, on a variety of fuels, than the gasoline carbureted engine. This design improvement led to, in 1974, a more flexible arrangement whereby a separate pilot nozzle, with relatively small fuel flow, is used to trigger combustion. This design, shown in figure 4, uses a multi-hole main nozzle, located close to the trochoid surface to modulate fuel flow in response to power demand.

A number of variations of this basic approach were tested during the 1975 and 1976 periods of increased R&D activity and the results showed that the localized and controlled combustion could produce low "raw" hydrocarbons. The test findings did indicate, however, that increased rotor combustion pocket temperatures were required. In this case, these temperatures were achieved by use of an air-gap insulated surface plate attached to the rotor combustion face. The results, for two successive 8.5:1 compression ratio hot rotor designs (figure 5) show that the best of these was able to match the shaded area which represents modern automotive engine untreated HC levels. These data also illustrate that the results were similar for the different fuels tested. Although BSFC vs. BMEP also showed relatively small differences with these fuels there was no significant reduction of BSFC with the increased rotor temperatures used to reduce BSHC.

This early test work indicated that further HC reductions are possible with moderate intake throttling at the very low power/speed end of the regime and by an increase of compression ratio. Accordingly, the first test on the RC1-60 since interruption of the automotive-directed activity between early 1977 and the present, is now being run with a 10:1 compression ratio rotor. Since this compression ratio increase will also improve SFC, it is germane to look at the comparative trends. The test evaluation, which started in October, has not yet completely covered the nozzle-matching and injection dynamics sorting out process. Preliminary data, presented on an Indicated basis in figure 6, shows some promise; however, gain on a brake basis will be slightly less as a result of some friction increase.

The 1976 specific fuel consumption baseline curves (8.5:1 compression ratio) are shown in figures 7 and 8. Figure 7 compares results, for the same designs that demonstrated low hydrocarbons, to data which are representative for full-sized European automobiles powered by Diesel engines. Figure 8 adds other speeds and compares VW sub-compact "Rabbit" Diesel 4 cylinder engine data developed for DOT (refs. 3-5). The relative sizes and weights of the comparable output Volkswagen Diesel 6 cylinder engine and a Stratified Charge Rotary engine are shown in figure 9.

The "cast iron rotor housing" curve illustrates the type of SFC improvement that was attained with a moderate increase of trochoid surface temperature. While a cast iron rotor housing was used for this test exploration, the temperatures tested do not preclude use of aluminum. Further work is required to define gain at higher levels.

It follows that if one can match the swirl or pre-chamber diesel on an engine-for-engine fuel consumption basis, then the smaller dimensions and reduced bulk has to mean better total vehicle system fuel efficiency. Furthermore, it is significant to note that Texaco has developed data (refs. 6, 7) to show that the United States would be able to obtain more usable Btu's per barrel of crude oil if the refineries were optimized to produce a broad base middle distillate fuel.

Testing of Other Sizes

The combustion efficiency shown for the automotive sized module is of interest for other applications only to the extent that the same technology can be scaled to the sizes required for the particular application. The scaling flexibility of the homogeneous charge engine has been demonstrated adequately over a per rotor displacement range of about 500:1 and 1 to 4 rotors but until 1978, Stratified Charge Rotaries with the current full-range design features had not been run in any other size. The earlier configurations (figure 2) had been run in the wider rotor 90"^{3} chamber and shown the same thermal efficiency (ISFC) as the RC1-60 (ref. 8).

In early 1977 the RC1-60 testing program was deferred for Engineering activity on a larger 350 cubic inch module. The 350 cubic inches per rotor was achieved by enlarging the trochoid by approximately two-thirds and widening rotor proportions by 25 percent.

The same technology and basic configurations developed in the RC1-60 were used for the 350 cubic inch engine, including a "reversed" configuration (ATC pilot) where the pilot and main nozzle relative position (BTC pilot) shown in figure 4 are interchanged. As of the end of 1976, this reversed design had showed promise but had not been evaluated to the point where it had surpassed the BTC pilot. The output targets for the larger engine were all established from the RC1-60 test results.

Although emissions will be measured subsequently in the program, none have been evaluated up to this point which has thus far concentrated on basic configuration and systems evaluations. The fuel economy and power milestones for this program to develop a military engine which, similar to an aircraft engine, emphasizes the higher output spectrum have all been met to date. Nonetheless, a comparison of excerpted basic performance results is of interest for those phases of technology which are directly applicable and because of the illustration of scaling effects that it affords. Although the result comparisons will be from RC1-350 test results, the complete 4 rotor engine, the RC4-350, is shown in figure 10 for related interest in a multi-rotor engine.

The baseline performance work on the 1-350 engine has also been conducted with the same inserted rotor design and an 8.5:1 compression ratio, although higher compression ratio rotors will be evaluated in the near future.

The larger module size has the general advantage of more available space to accommodate nozzle variations within a given rotor housing and, operationally, is less constrained by spray impingement on the rotor and housing surfaces. There are other advantages to the larger combustion chamber size, which include reduced sealing line and leakage area ratio to charge volume, a similar favorable ratio for heat losses, and the same type of reduction in FMEP with scale that is generally observed with reciprocating engines.

To facilitate a direct comparison, the current available data for the two engine sizes, both having the design configuration shown in figure 4 (BTC pilot) are compared on an Indicated basis and equivalent (same apex seal velocity) RPM in figure 11. From figure 11 it can be seen that the RC1-350 and RC1-60 are very close at the lower IMEP's, whereas the 1-60 data shows lower ISFC (or better thermal efficiency) at the higher loads, indicating further probable improvements for the larger engine. The difference is believed to reflect the concentration of effort at this speed for the smaller engine, in view of its automotive significance, whereas the low speed range of the larger engine is of less interest for current applications. For the reasons just stated there is less available RC1-60 data at the higher speeds, but what is available suggests that the thermal efficiencies are reasonably close for both engines.

Figure 12 compares the RC1-350 data of figure 11 plus available RC1-350 data for the "reversed" configuration (ATC pilot) mentioned earlier, versus F/A ratio. The observed data shows that for a given mixture strength the RC1-60 develops higher IMEP's at equivalent speed, which would imply more effective air utilization. This IMEP trend may be misleading because the engines were not run with similar induction systems. If the IMEP data is "normalized" by correction to an equal volumetric efficiency basis (which has little effect on other plotted variables), the RC1-60 and RC1-350 with BTC pilot are very close and the RC1-350 with ATC pilot is slightly higher at the increased power end. The higher thermal efficiency of the RC1-350 ATC pilot does not say that the differences noted will necessarily hold for the RC1-60 size but it does imply that there is additional potential to be realized.

Figure 13 shows both curves on a BSFC basis, reflecting the differences in friction. Figure 13 shows that, despite the lower thermal efficiency at higher power with the BTC pilot design, the RC1-350 shows a brake basis advantage over the RC1-60 because of the lower specific friction. The ATC pilot configuration curve reflects both friction and combustion advantages. In addition to lower friction, the 350 cubic inch engine enjoys the advantage of better injection and ignition equipment. The influence of this last point will be clearer when the current RC1-60 testing, which also enjoys a similar equipment advantage over the earlier work, has progressed further.

The conclusion of this comparison is that the engine scales well, although demonstrated only in the larger sized direction. The baseline data of the RC1-350 at higher powers and speeds, with the scaling trends noted, will be used to estimate performance for the aircraft engine regime. This input will be important when weighing the system advantages of a lighter, smaller multi-rotor aircraft engine versus a somewhat heavier, but less expensive and slightly more efficient, larger module single rotor engine. The factors influencing this balance process for the current NASA contract are thus in clear focus and Cessna Aircraft Co., under sub-contract to Curtiss-Wright, will study the aircraft system trade-off sensitivity of various engine size choices.

Current NASA Advanced Engine Study

Approach and Status

The objectives of the current NASA Advanced Rotary Combustion Aircraft Engine Design Study contract are to define advanced and highly advanced engines which will satisfy the following goals and criteria:

1. Engine performance and efficiency improved as compared to current engines: BSFC $\leq$ 0.38 lb/hp-hr @ 75% power cruise; specific weight $\leq$ 1.0 lb/hp @ takeoff power; cooling airflow x pressure drop product decreased by a factor of 2.

2. Efficient operation on 100/130 octane aviation fuel and one or more alternative fuels such as jet or diesel fuel, or low octane unleaded automotive fuel.

3. Emissions that meet the EPA 1979 piston aircraft standards. (If and when the revocation of these standards occurs, this goal will be reevaluated).

4. Engine direct manufacturing costs comparable to or less than present day spark-ignition piston aircraft engines.

5. Overall life cycle costs and maintenance lower than for current aircraft engines.

6. Altitude capability equal to present day spark ignition aircraft engines.

The approach that has been taken was to first survey all parallel and related technologies for application to an extension of the Stratified Charge developments summarized earlier. A total of 35 significant sources were identified and solicited for information. In addition many hundreds of abstracts located by source search were read and 220 papers obtained.

From a review of data from the above contacts, papers, and previous technology information developed by Curtiss-Wright, the candidate technologies shown in Table I were selected for more detailed evaluation. The evaluation form (figure 14) was developed as a means of carrying out the procedure for ranking of the candidate technologies. The technology evaluation criteria were utilized in a system patterned after the one described in ref. 9.

A technology base was defined from which new approach selections were made for an "advanced" engine. They were the approaches estimated to be the most advanced technologies sufficiently proven and highly ranked to be available to an engine design initiated in 1985 or 1986. It is estimated commercial introduction would take place in the early 1990's.

In addition a selection of design approaches for a "highly advanced" engine were made. These were higher risk approaches likely to require a more extensive development program and/or a later introduction to the commercial market.

As a result of this ranking process, with the additional balancing overview reflecting concentrated rotary engine experience of those who did not participate in ranking, specific candidate technologies were selected (Table II). These inputs will be used to define a conceptual design for the advanced engine. The "highly advanced" engine will be described but not defined with installation, cross-sectional drawings, performance data, etc. which will be developed for the advanced engine. Comparative system analysis will be performed, however, by Cessna for both engine concepts in compatible general aviation aircraft.

Until the design study has been completed and we can assess the relative trade-offs of these candidate technologies against the contract objectives and goals, we cannot specifically weigh contribution significance. However, the promising choices have been sufficiently defined in the aforementioned screening process to single out selected items which can illustrate, in the following paragraphs, the nature of our choices.

1. Turbocharging

The requirement of a near-future aircraft engine (250 HP cruise class) for increased altitude (25,000 feet plus) capability has focused more attention on the effects of turbocharging. Here, the Rotary Stratified Engine more closely resembles a Diesel than a conventional gasoline fueled engine, because of its ability to run well on extremely lean mixture ratios. Increasing the air charge rate to the engine not only improves the fuel economy by raising the mechanical efficiency (i.e., getting more output for essentially the same friction losses), but it permits operation at A/F ratios which give the best combustion and thermal efficiency. The characteristic curve shape for ISFC vs. mixture strength, shown in figure 12 for low speed, holds for cruise speeds as well although the absolute values change with speed. In essence, the BSFC curve can effectively be driven down to lower levels as shown qualitatively in figure 15 (ref. 10).

The quantitative degree that can be practically realized remains an unknown at this point, but from trends observed on the current naturally aspirated stratified engines, an SFC reduction of 17 percent can be predicted by high power cruise turbocharging to increase the airflow from an approximately 18 to 28 air-fuel ratio. The baseline absolute value of BSFC for the stratified charge naturally aspirated engine is probably not the same as it would be for the corresponding cruise point of a gasoline engine at its approximately 15:1 air-fuel ratio, but the turbocharged stratified charge cruise BSFC would be lower than either type (stratified or homogeneous) naturally aspirated engine.

2. Increased IMEP and Speed/Improved Apex Seal Wear Materials/Retracting Apex Seals

The increase of mean effective pressure is accomplished by the turbocharging described above, trading-off the complexities of boost ratios higher than can be attained from commercial low-cost turbocharger units against engine size. However, wherever this best point resolution obtains as a result of our current analyses, the fact remains that higher effective pressures will be required. These higher operating levels of temperature and pressure have both stress and durability implications, which in turn will be reflected in the selection of specific operating limits and design configurations, some of which will be briefly reviewed in succeeding paragraphs.

The same type of trade-off has to be made with respect to maximum operating speed. Higher speeds obviously increase the engine output and thus improve specific power density. The Rotary engine has significant growth potential in the higher speed direction because it is not limited by valve dynamics and valve breathing restrictions, has complete dynamic balance, does not reverse direction of its sealing elements at top center, and has a relatively modest increase of friction with speed. Nonetheless, friction increases exponentially with speed and unless this high speed capability is reserved only for take-off power, the best specific fuel consumption will dictate rating at the lowest possible speed consistent with acceptable specific weight. Again, the Cessna sensitivity study will provide some insights into how this higher speed capability can be best utilized.

a. Improved Apex Seal/Trochoid Material Combinations

The increase in engine output may require further development of superior apex seal and trochoid wear surfacing materials which have either been identified by our prior research efforts or have emerged as new technologies. The current tungsten carbide trochoid wear surfacing material has thus far shown relatively low apex seal velocity sensitivity and is adequate, with acceptable TBO and reliability standards, for any operating speed under consideration (ref. 11). It will probably also prove acceptable, possibly with lower wear apex seals, for any of the IMEP levels which can be obtained with single stage turbocharging. However, to illustrate potential, figure 16 shows that use of a Titanium carbide trochoid coating, in this case in a steel matrix, and with apex seals of the same material, shows substantially less wear than current materials. The particular material shown in this figure was plasma sprayed, which is a less expensive application technique than the current detonation gun process. At this stage of development, plasma-spraying cannot attain the same bond strengths, but plasma-spray technology is moving very fast and is expected to be a serious contender within a short time.

b. Retracting Apex Seals

For a more ambitious technology step, which we reserve for the "Highly Advanced Design", it is possible to have the high specific output of high speed without facing the more severe apex seal wear environment of higher seal pressures plus higher speed. Since apex seal leakage is a time-weighted factor, at high engine speeds a small leakage area can be tolerated without serious consequence. Seal designs which retract from trochoid contact at high rotational speeds are available, but not tested. One of several alternate approaches, in this case taking advantage of the centrifugal forces to pull the seal back at high speeds, is shown in figure 17.

3. High Strength High Temperature Aluminum Casting Alloy

The increases in IMEP and speed, as stated earlier, will introduce higher operating temperatures. The anticipated degree of temperature increase, to be confirmed as the current study progresses, can be paced by the degree of strength improvement that new materials have introduced. The choice of liquid cooling for general aviation engines (ref. 10) on the basis of improved system efficiency and better metal temperature control is particularly significant at the higher outputs of the advanced engines.

Essentially all of our Rotary engine cast aluminum rotor housings have been AMS 4220, based on our reciprocating aircraft engine experience. It has proven to be a durable high temperature material with good fatigue life under cyclic loading. A new aluminum high temperature casting alloy, AMS 4229, has been on the scene for several years. It has not been tried here because our applications have not required the additional strength and, until recently, very few foundries were willing to cast the new alloy. Today, however, 15 foundries in the U.S. use this alloy, which has markedly higher strength and ductility than AMS 4220.

Figure 18 shows calculated predictions, based on ultimate tensile strength, ductility, and modulus of elasticity, of low cycle thermal fatigue life at 400°F, representative of high power cruise peak temperatures, for AMS 4220 and 4229. The same type of improvements can be demonstrated at higher temperature levels, should they prove desirable as the study progresses.

4. Rotor Combustion Flank Insulation/Adiabatic Engine

The background discussion of Stratified Charge hydrocarbon testing made reference to rotor combustion surfaces which were raised in temperature, by use of insulated plates, to reduce HC formation. HC formation is not expected to be a consideration for an aircraft engine operating regime (ref. 10), but the insulated rotor surface will reduce oil heat rejection and thus reduce system weight and bulk.

Early testing with the RC engine had shown that Zirconium oxide, plasma sprayed on the rotor combustion face, was effective with gasoline homogeneous charge engines, but did not have adequate thermal shock strength in a stratified charge application where direct fuel impingement was possible. However, considerable development of thermal barrier coatings of this type has taken place, largely at NASA-Lewis, since that time, particularly for gas turbine components.

The "Highly Advanced Engine" (Table II) reflects inclusion of a zirconium oxide rotor hot surface coating of .060" thickness. Figure 19 shows that, for an assumed 90"^{3} rotor this coating thickness is calculated to reduce the rotor heat rejection to the engine oil by approximately one third.

The same type of coating would also be applicable for an "Adiabatic" Rotary engine. However, despite the fact that we consider Rotary engines intrinsically more adaptable to the completely unlubricated "Adiabatic" engine approach than a reciprocating engine (largely because either retracting or the uni-directional ceramic apex seals with their advantage of gas hydrodynamic film lubrication, against a ceramic trochoid surface appear closer to realization than their reciprocating counterparts) we did not consider an engine of this type to be within contract objective guidelines of even the "highly advanced design technology" and did not consider it further.

Directions

Our present carbureted prototype aircraft engine, the liquid-cooled RC2-75 (ref. 10) shown in figures 20 and 21 was the obvious starting point. To illustrate what the presently planned trends of higher IMEP and RPM would mean in terms of this engine, mock-ups of both single and twin rotor 75 cubic inch Stratified Charge and turbocharged aircraft engines have been prepared to supplement this presentation. The RC1-75, which measures 34 1/2" x 21 1/2" x 20", without coolers, is predicted to develop 235 HP @ take-off under currently envisioned limits for IMEP and speed for the advanced engine and 300 HP for the "Highly Advanced" technology. The same numbers for the RC2-75 are 40 1/4" x 21 1/2" x 20" and 470 HP and 600 HP for respective technology levels. Taking the same values of IMEP and speed used to make the advanced engine estimates, and applying it to the contract goal engine of 250 HP cruise to 25,000 feet, results in a two rotor engine outline as shown in figure 22. The coolant and oil coolers, which presumably would be remotely located for system optimization, are not included.

This particular arrangement, with accessories held to a minimum overall diameter, would be biased towards a twin engine installation. However, it should be understood that this is a preliminary look since, as stated earlier, the economic advantages, as well as fuel injection technology limits, favor a larger single rotor engine and, secondarily, more precise definition of IMEP and speed, upon which these projections were based, is still being determined.

While the specifics may vary from those defined at the point when all work on this contract has been completed, the effort to date has clarified what we see as the advantages of this type of Rotary Stratified Charge engine. These are listed in Table III.

Closure

The Rotary Engine, in its carbureted form, is uniquely suited to aircraft engine propulsion because of its advantages of size, weight, simplicity, smoothness, scaling flexibility and growth potential. Recent parallel hardware and test developments have shown that this engine type is particularly adaptable to unthrottled direct injected stratified charge, resulting in additional features of wide range fuel capability and superior fuel economy. As a result of the Stratified Charge Rotary Engine's ability to perform efficiently over a broader range of mixture strengths, without regard for fuel octane or cetane rating, turbocharging can extend the demonstrated potential to the complete aircraft engine operating regime. This combination of system efficiency plus fuel choice optimization possibilities is being carefully examined as we continue into an era of critical energy resource allocations.

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TABLE I

CANDIDATE TECHNOLOGIES CONSIDERED

- SOLID-STATE IGNITION TRIGGER VS MECHANICAL TRIGGER
- PLASMA JET IGNITION SYSTEM
- ELIMINATING PILOT INJECTOR
- HIGH TEMPERATURE ALUMINUM CASTINGS
- TURBOCHARGER
- THIN WALL (IRON) ROTOR
- EXHAUST PORT THERMAL LINER (METALLIC)
- IMPROVED LUBRICANTS
- MULTIPLE POWER SOURCE FOR IGNITION
- INDUCTION AIR INTERCOOLER
- VARIABLE DISPLACEMENT PRESSURE OIL PUMP
- PROVISION FOR COUNTER-ROTATING PROPELLERS
- TOTAL DIAGNOSTICS
- ELECTRONIC IGNITION SCHEDULE
- COMPUTER VS MECHANICAL TIMING
- FIBER OPTICS DATA BUS
- LOW PRESSURE DROP HEAT EXCHANGERS
- NASVYTIS TRACTION SPEED REDUCER (PROP)
- ALTERNATE COOLING FLUID
- COMPOSITE ROTOR HOUSING (WEAR RESISTANT LINER)
- WING LEADING EDGE WITH INTEGRAL COOLANT COOLER
- ALTERNATE MATERIALS SEALS
- RETRACTING APEX SEALS
- THERMOSTATICALLY CONTROLLED ROTOR OIL COOLING
- TURBOCHARGER WITH VARIABLE AREA TURBINE
- SPARK IGNITION START/AUTO-IGNITION RUN
- ALUMINUM ROTOR (REINFORCED LANDS)
- INSULATED ROTOR - THERMAL BARRIER COATING
- INDEPENDENT DUAL IGNITION
- VARIABLE COMPRESSION RATIO
- INSULATED ROTOR - INSERTS ON METALLIC PAD INSULATOR
- ADIABATIC ENGINE CERAMIC END WALLS
- COMPOSITE ROTOR (REINFORCED APEX SEAL LAND)
- ELECTRONIC INJECTION (FUEL)
- ADIABATIC ENGINE CERAMIC ROTOR INSERTS
- TURBOCOMPOUND
- ADIABATIC ENGINE - CERAMIC ROTOR HOUSING LINER
- PILOT NOZZLE TRIGGER FOR IGNITION SYSTEM
- HIGH SPEED PROPELLER (NO REDUCTION GEAR)
- NASVYTIS TRACTION SPEED REDUCER (TURBOCOMPOUND DRIVE - IF USED)
- ADIABATIC ENGINE - CERAMIC ROLLING ELEMENT BEARINGS

TABLE II

NEW TECHNOLOGY SURVEY: CANDIDATE TECHNOLOGIES SELECTED FOR DESIGN STUDY

ADVANCED DESIGN

TURBOCHARGING

HIGH STRENGTH HIGH TEMPERATURE ALUMINUM CASTING ALLOY

LIGHTWEIGHT ROTOR

EXHAUST PORT THERMAL LINER

INDUCTION AIR INTERCOOLER

COUNTER-ROTATING PROPELLERS

ON-BOARD DIAGNOSTICS

IMPROVED APEX SEAL/TROCHOID MATERIAL COMBINATIONS

INCREASED IMEP AND SPEED

HIGHLY ADVANCED DESIGN

VARIABLE AREA TURBINE TURBOCHARGER

RETRACTING APEX SEALS

ROTOR COMBUSTION FLANK INSULATION

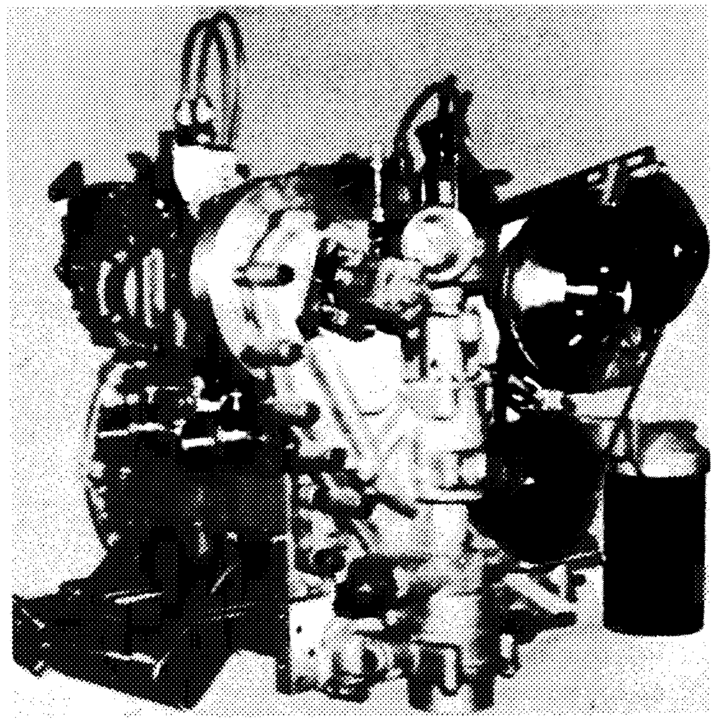
ADDITIONAL INCREASED IMEP AND RPM

TABLE III

ADVANTAGES OF THE ROTARY STRATIFIED CHARGE AIRCRAFT ENGINE

- MULTI-FUEL CAPABILITY
- SMALL FRONTAL AREA
- LOW ENGINE WEIGHT
- REDUCED ENGINE COOLING AIR DRAG
- IMPROVED RELIABILITY DUE TO FEWER PARTS
- LOWER EXHAUST GAS TEMPERATURES
- NO VALVES OR CAMS
- SAFER CABIN HEAT
- COOLANT COOLERS CAN BE WING DE-ICING
- MORE RAPID FLIGHT DESCENTS PERMISSIBLE
- LOW COST TURBOCHARGER FROM OTHER PRODUCTION RETAINED
- SMALL EXHAUST AND INTAKE MANIFOLD VOLUMES BENEFIT TURBOCHARGING
- LOW EXHAUST EMISSIONS
- LOW FUEL CONSUMPTION
- SMOOTH - BALANCED OPERATION
- GOOD LOW TEMPERATURE STARTING CAPABILITY
- LOW NOISE LEVEL
- PROVEN PRODUCIBILITY OF ROTARY ENGINE

RC2-60U10 LIQUID-COOLED STRATIFIED ENGINE (1965)



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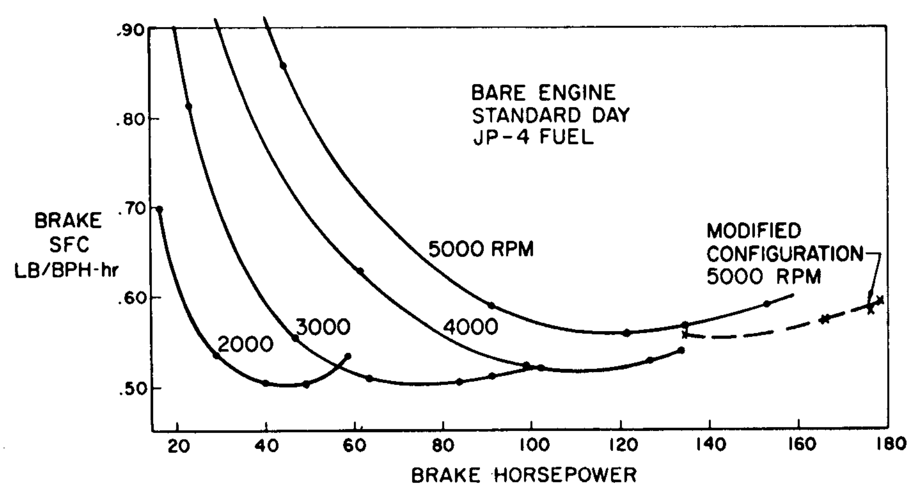
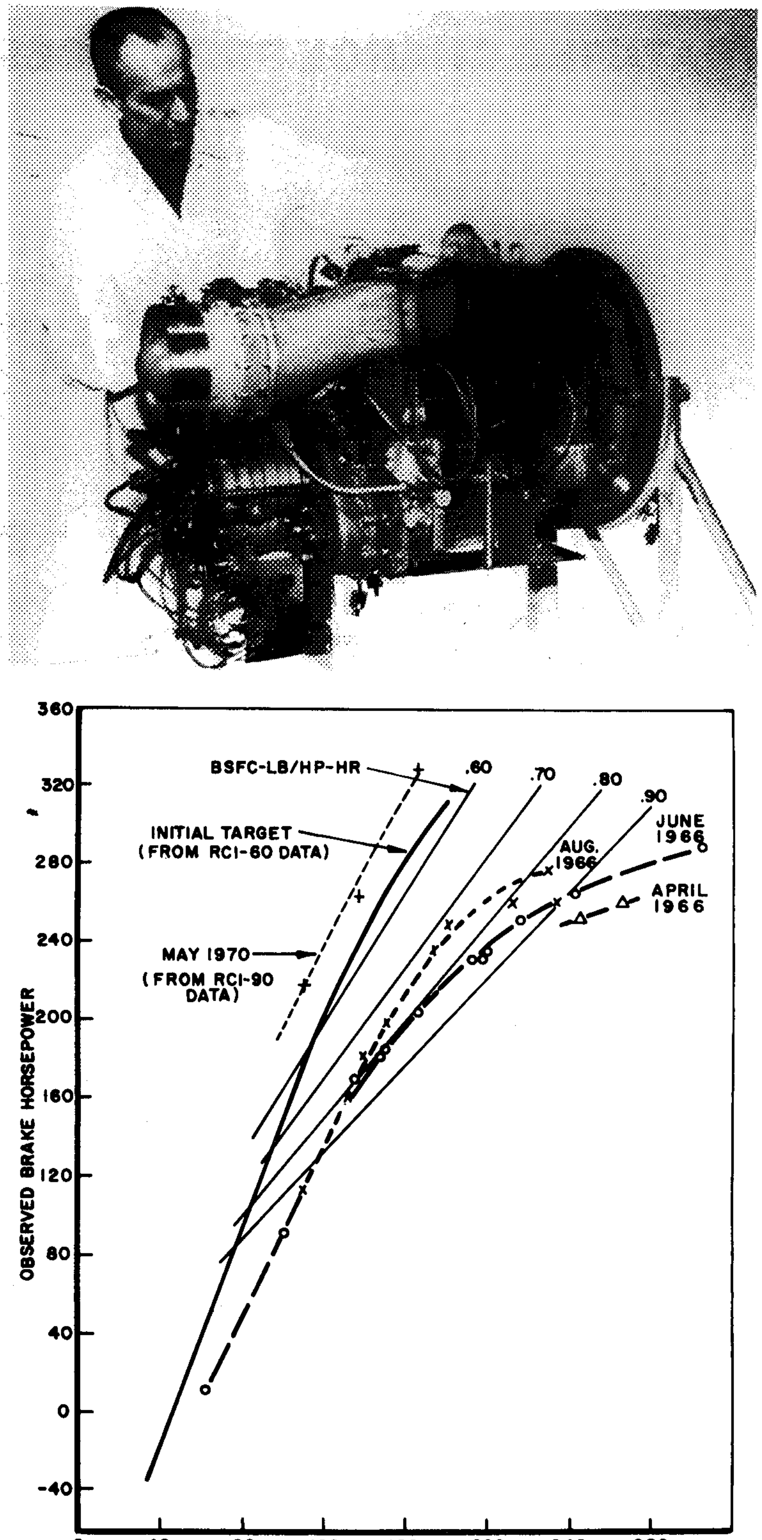


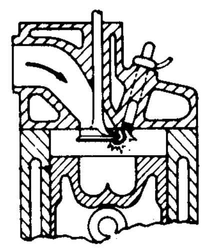
Figure 1



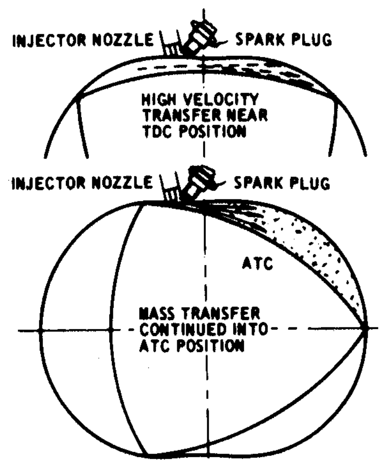
RC2-90 AIR-COOLED STRATIFIED CHARGE RC ENGINE (1966)

Figure 2

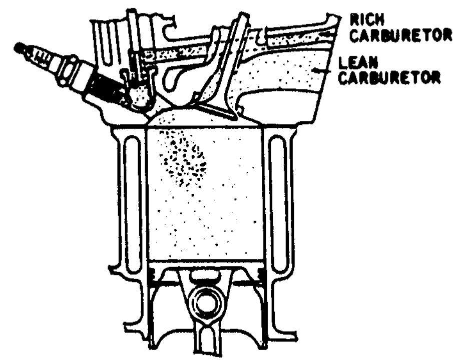
STRATIFIED CHARGE PROCESSES



TEXACO TCCS
FORD PROCO



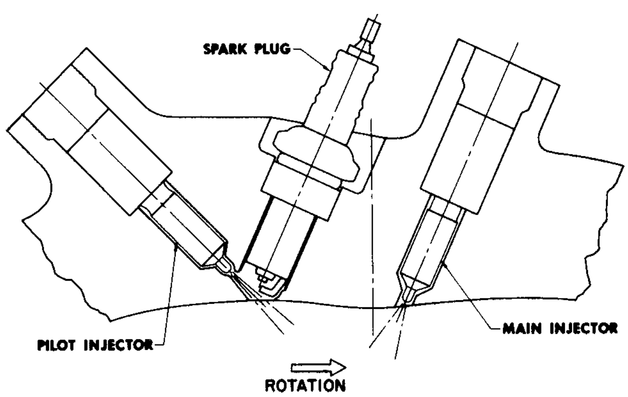
ROTARY



HONDA

Figure 3

BTC PILOT TANDEM DUAL



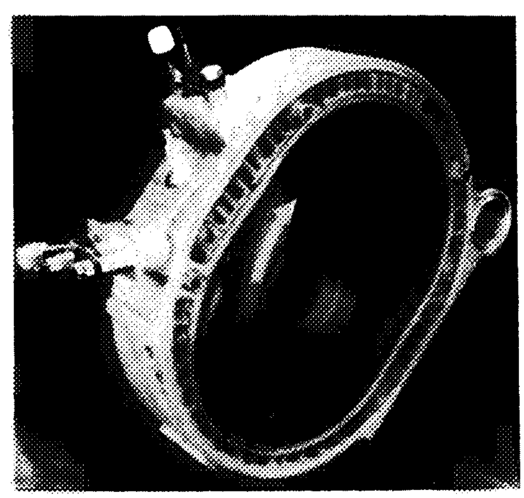


Figure 4

SPECIFIC HYDROCARBON EMISSIONS

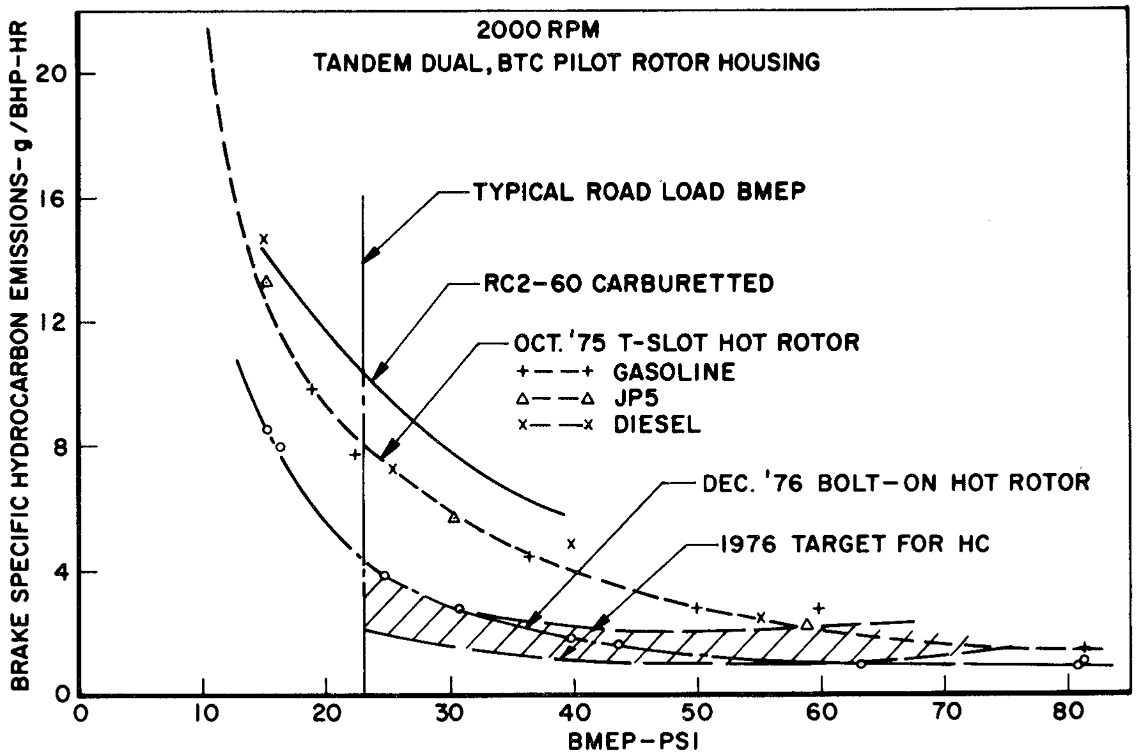


Figure 5

ISFC vs MEP, RC1-60 BTC PILOT

Preliminary Data for 10:1 Compression Ratio vs 8.5:1

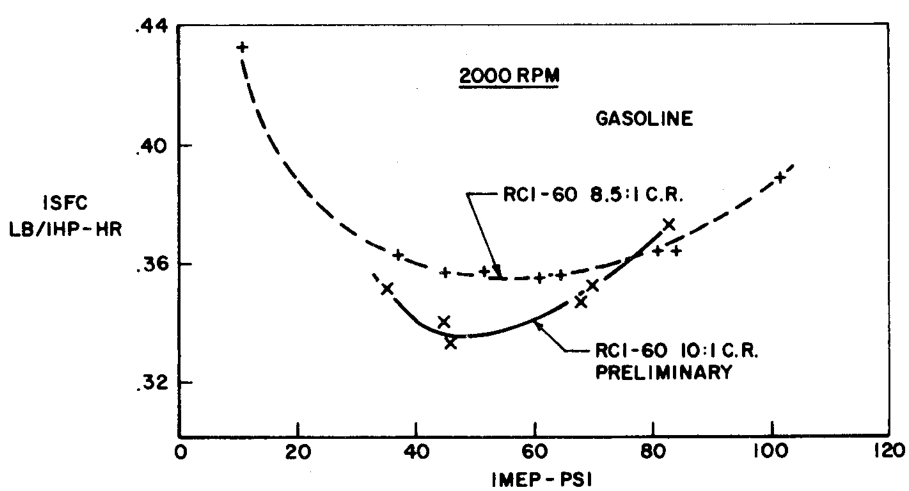


Figure 6

PART LOAD FUEL CONSUMPTION COMPARISON

SCRE VS AUTOMOTIVE PRE-CHAMBER DIESEL

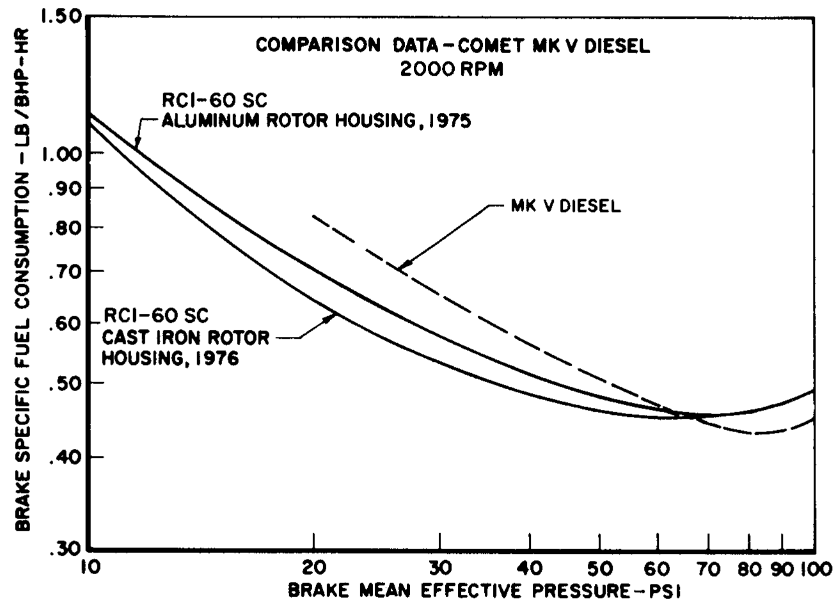


Figure 7

COMPARISON DATA - BSFC vs BMEP

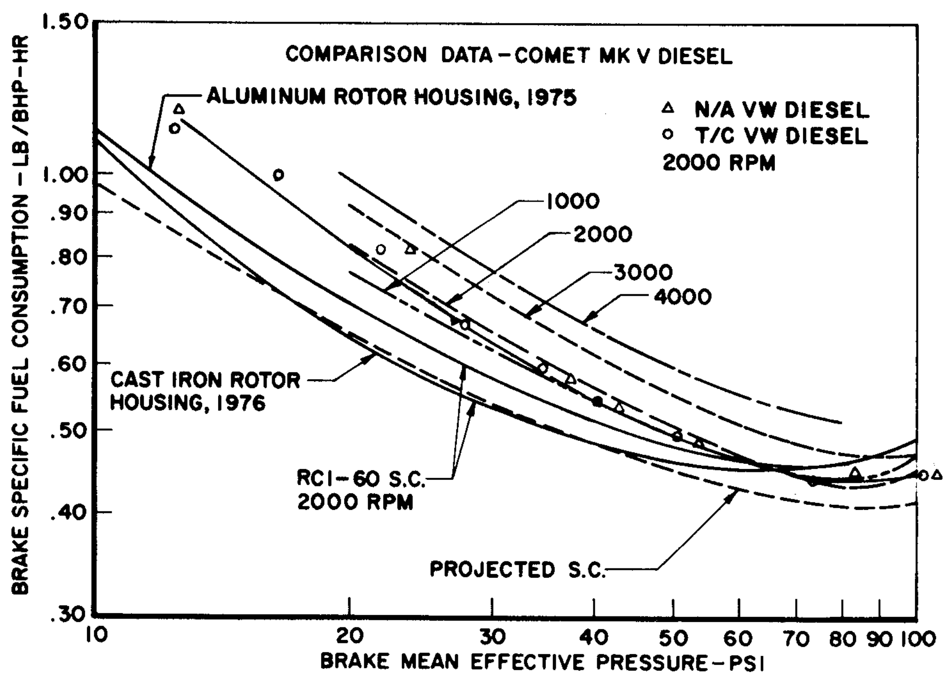
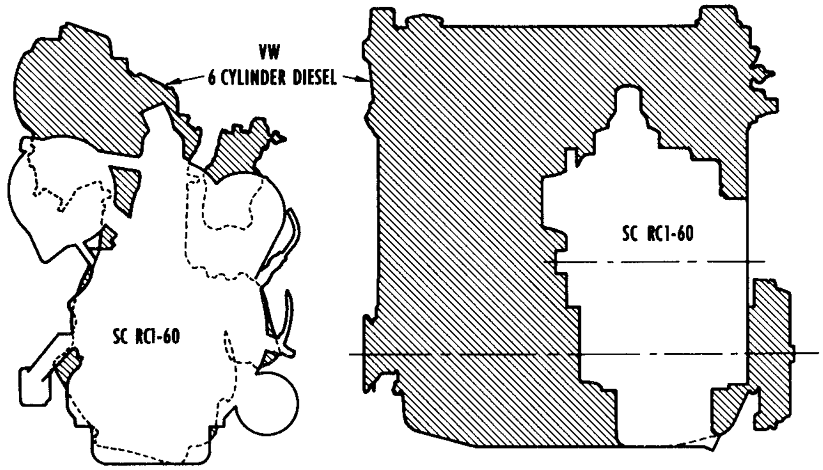


Figure 8

COMPARISON OF SC RC1-60 WITH VOLKSWAGON 6 CYLINDER DIESEL



	SC RC1-60	VW 6 CYL DIESEL
kW (BHP)/RPM	60 (80)/5000	56 (75)/4500
kg (LB)	109 (240)	184 (405)
L×W×H mm	368×559×635	780×490×780
L×W×H INCHES	14.5×22×25	30.7×19.3×30.7

Figure 9

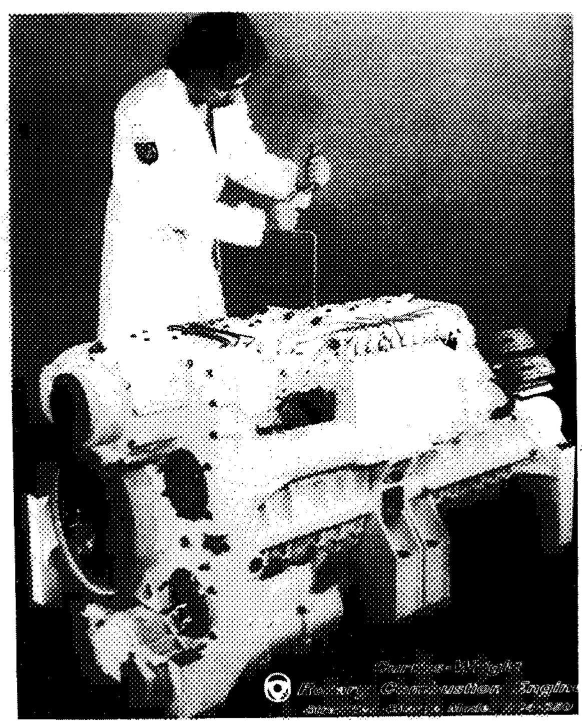


Figure 10

INDICATED SPECIFIC FUEL CONSUMPTION (ISFC) VS INDICATED MEAN EFFECTIVE PRESSURE (IMEP)

Comparison of RCI-60 and RCI-350 Data, BTC Pilot

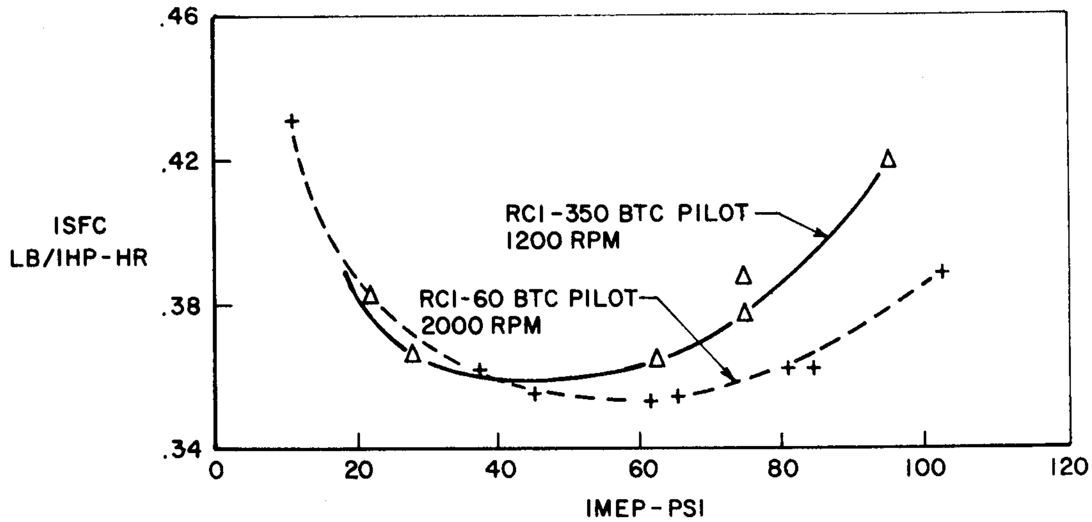


Figure 11

IMEP AND ISFC VS FUEL-AIR RATIO

RCI-60 and RCI-350

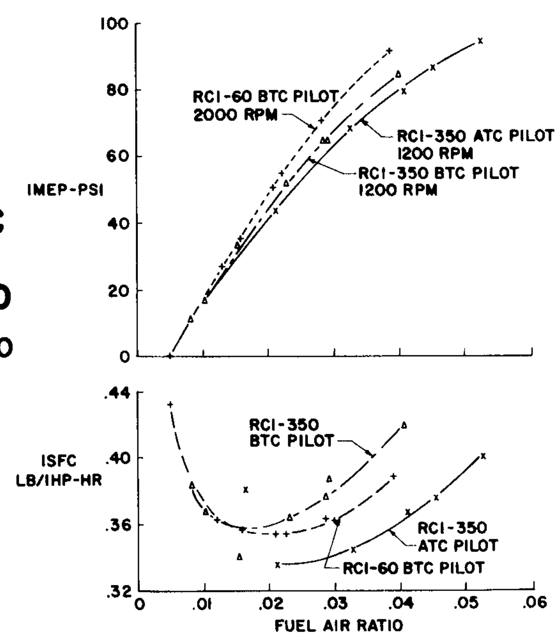


Figure 12

BSFC vs BMEP, RCI-60 AND RCI-350

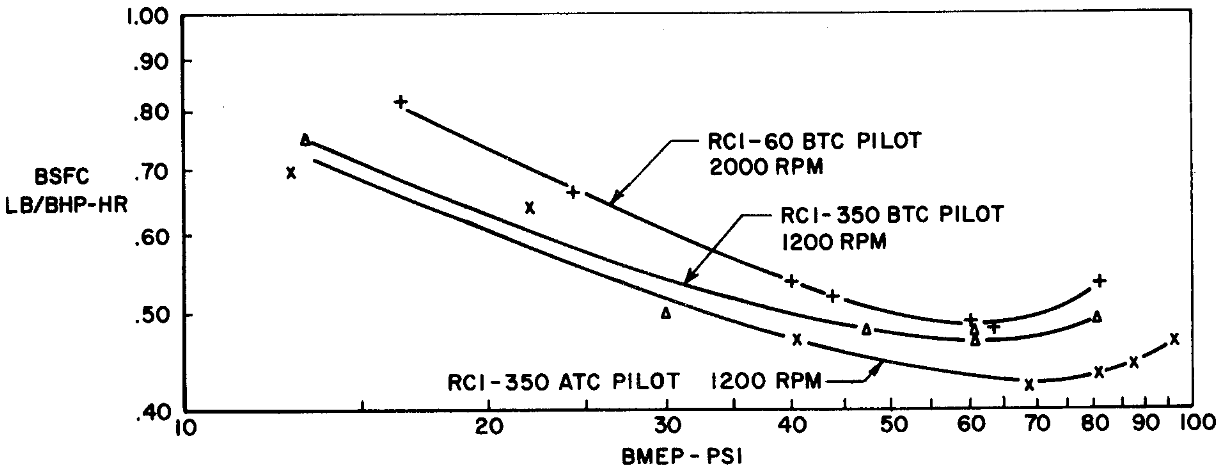


Figure 13

ADVANCE ROTARY COMBUSTION AIRCRAFT ENGINE

TECHNOLOGY/APPROACH EVALUATION

DESCRIPTION; ITEM NO._______

CRITERION	WEIGHTING	RATING (+3 to -3)		PRODUCT (WxR)	
Safety	8				
Reliability	8				
Fuel Consumption	7				
Weight	7				
Cooling	7				
Initial Cost	7				
Multi-Fuel Capability	7				
Performance	7				
Technological Uncertainty	6				
Life Cycle Cost	6				
Size & Shape	6				
Operational Characteristics	6				
Durability	5				
Maintainability	5				
Materials	3				
Noise	3				
Emissions	2				
		A	B	A	B
TOTAL FIGURE OF MERIT					

NOTES:
A - ADVANCED
B - HIGHLY ADVANCED

Figure 14

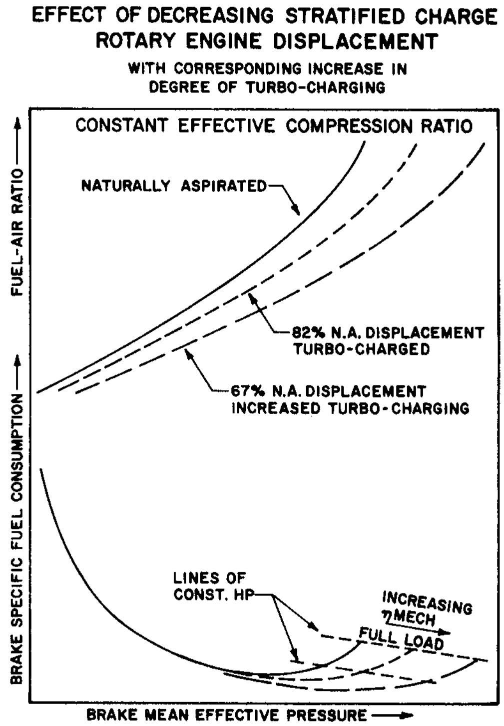


Figure 15

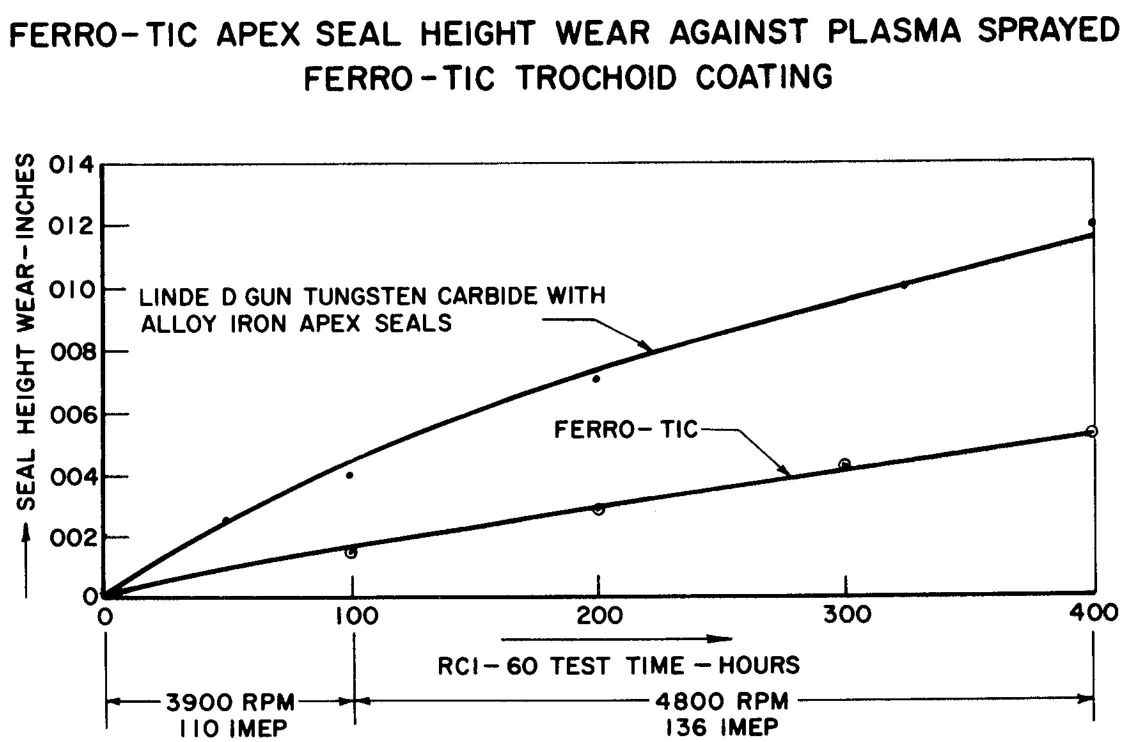


Figure 16

COUNTERWEIGHT RETRACTED SEAL

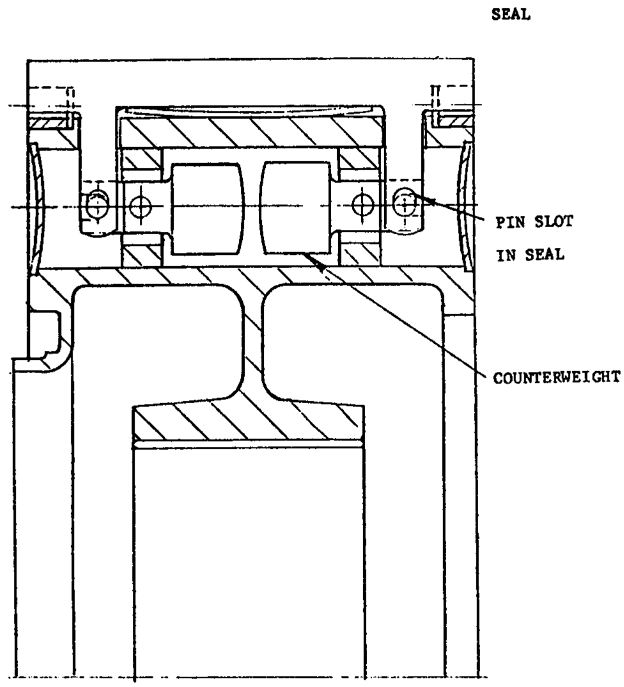


Figure 17

LOW CYCLE THERMAL FATIGUE COMPARISON

STRESS LEVEL VS LIFE CYCLES
AMS 4229 AND AMS 4220

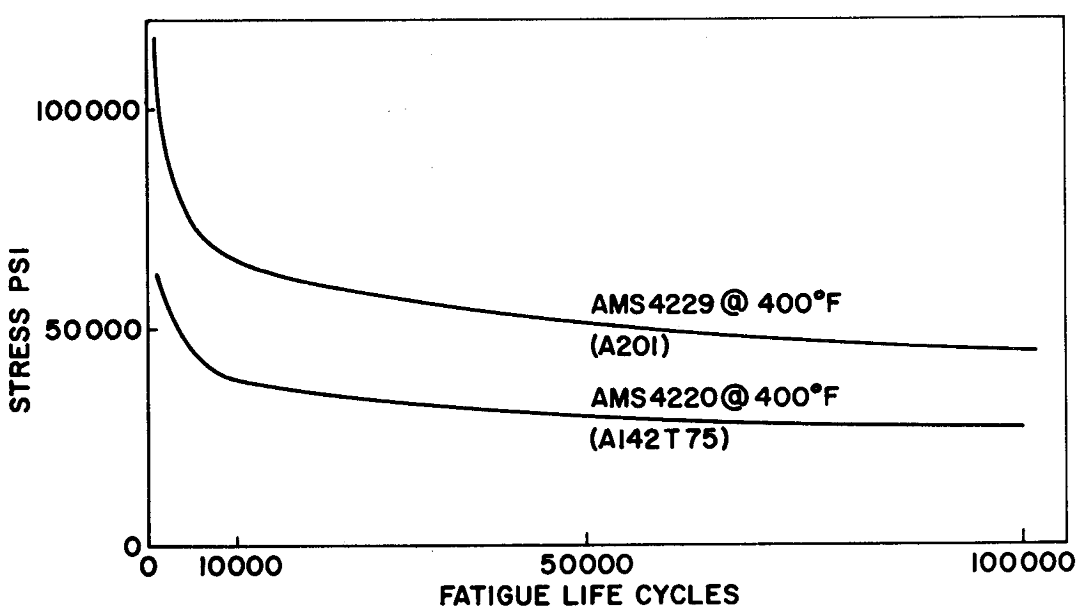


Figure 18

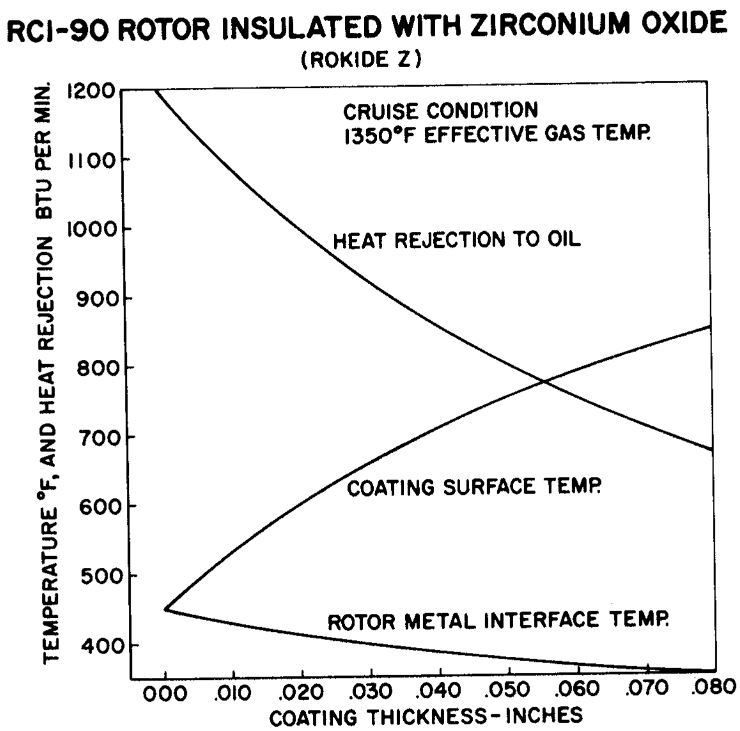


Figure 19

RC2-75 AIRCRAFT ENGINE PROTOTYPE

Figure 20

RC2-75 ON PROPELLER TEST STAND

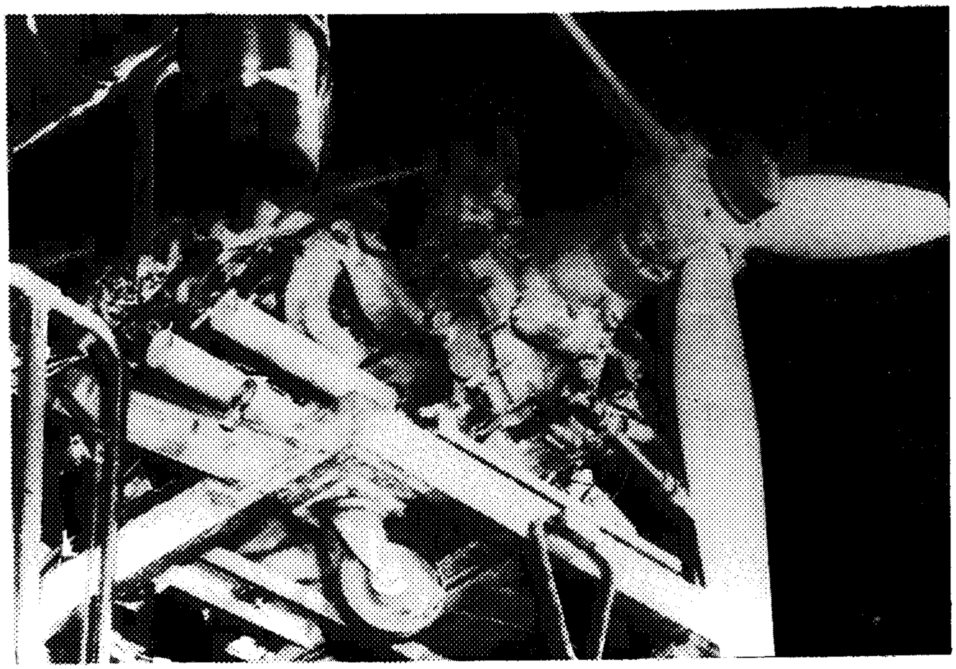


Figure 21

ADVANCED ROTARY COMBUSTION AIRCRAFT ENGINE
PRELIMINARY INSTALLATION STUDY
(250 BHP MAXIMUM CRUISE TO 25000 FEET)

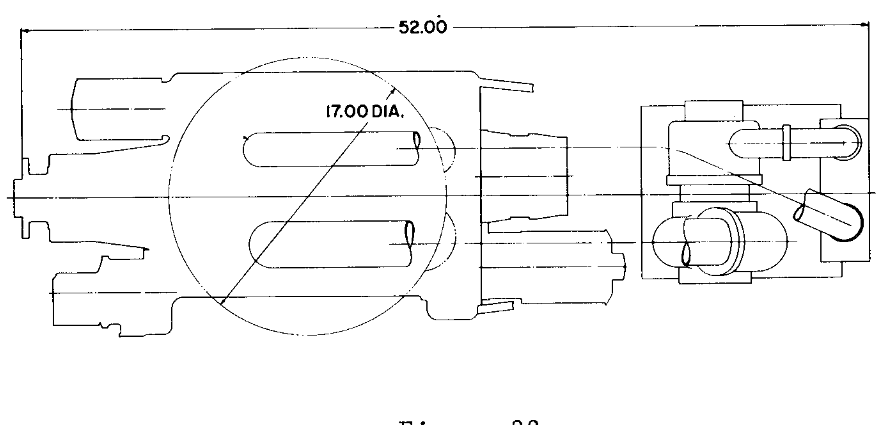


Figure 22