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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 of an advanced and highly advanced engine sized to provide 186/250 shaft KW/HP under cruise conditions at 7620/25,000 m/ft. altitude. Relevant engine development background covering both prior and recent engine test results of the direct injected unthrottled Rotary engine technology, including the capability to interchangeably operate on gasoline, diesel fuel, kerosene, or aviation jet fuel, are presented and related to growth predictions. 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 30-35% 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.

This paper is organized into three basic sections. The Introduction presents the NASA perspective and briefly covers how the Lewis Research Center interest in the Rotary first developed and then describes the initial steps which led to advanced aircraft design studies. The second major section discusses the Rotary stratified charge engine background and related developments from the Curtiss-Wright viewpoint and the third describes Cessna's application studies. The closure, presents an overview from the NASA co-author.

INTRODUCTION

The Lewis Research Center of the National Aeronautics and Space Administration began working on intermittent-combustion (IC) propulsion systems for general aviation aircraft in 1973. At that time, the primary concern was with the reduction of exhaust emissions from these engines. The Environmental Protection Agency (EPA) had proposed exhaust emissions standards for hydrocarbon (HC), carbon monoxide (CO) and nitric oxides (NO_x) which were to take effect in 1979. The initial NASA, FAA and Contractor efforts were directed toward the measurement and characterization of these emissions. Based on the results, it soon became apparent that nearly all of the then-current gasoline recips would be in trouble if the standards were to be enforced. The next order of business, therefore, was to find methods to reduce the emissions and meet the proposed standards. This 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 (Figure 1) was tested to determine the exhaust emission levels characteristic of this type of engine. This low-compression, non-turbocharged engine was originally designed to operate on 80/87 octane aviation gasoline. The test results showed that the HC emissions exceeded the 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 cruise conditions of 77 percent power was 0.54 lb/BHP-hr (328g/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 15 percent lower than typical, non-turbocharged aircraft piston engines.

The program emphasis was later redirected from emissions reduction to improved fuel economy, when it was learned that the proposed exhaust emissions standards for light aircraft were to be withdrawn. 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 (274g/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 lbs/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, 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) multi-fuel engine under contracts with the United States Navy/Marine Corps. One-, two-, and four-rotor versions of this multi-fuel engine (Figures 2 and 3) have been successfully tested and have achieved the required design goals. The minimum BSFC in this program to date has been measured as 0.426 lbs/BHP-hr. Its multi-fuel combustion system and several other features were used as baseline data for the Advanced Stratified Charge Rotary Aircraft Engine Design Study, which was performed under a NASA contract with Curtiss-Wright.

( ) = Numbers in parentheses designate references at end of paper.

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 multi-fuel combustion configuration which is incorporated in the military vehicle powerplant being developed for the USMC.

The same basic technology, which was defined in the smaller RC1-60 displacement (one rotor of 60"^{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 supplemented 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 high engine airflow rates.

ROTARY AIRCRAFT ENGINE BACKGROUND

Briefly summarizing Curtiss-Wright's aircraft Rotary engine background, initial interest was directed to propeller driven or helicopter military applications where it was felt that the RC Engine could compete with small gas turbines. In early studies conducted for NASA (6) the RC Engine plus fuel weight usually proved lighter in all but very short missions. In 1966 the RC2-90 was built and tested. This Stratified Charge air-cooled 300HP drone helicopter engine 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 aircraft powerplants and led to a U.S. Navy sponsored test series with a carbureted RC2-60 engine in the Lockheed Q-Star aircraft. This aircraft (the first to be wholly dependent upon a Rotary Combustion Engine for flight) 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. This test series also met the sound level goals established by the U.S. Navy. A flight test in a Hughes model TH-55 helicopter was also completed demonstrating improvement in auto-rotation entry, reduced airframe vibrations, and maintenance accessibility.

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, and there was no speed or descent limitation for thermal stresses from over-cooling.

The RC2-75 Engine (Figure 1) was designed as a carbureted General Aviation prototype, reflecting this experience. The configuration and approaches were reviewed with Piper, Cessna, Beech, the FAA, accessory suppliers, foundries, and machining vendors, and their inputs reflected in the design. Significant factors in the choice of liquid cooling over the lighter weight air-cooling were that air-cooling did not give growth margin to accommodate future power output increases and it results in higher parasitic drag losses.

The RC2-75 is 21.5 x 23.7 x 31.4 inches overall and weighs 280 lbs. dry, 358 lbs. wet ready to fly, with heat exchangers. This model has completed 1500 test hours, including 100 hours WOT and speeds to 7000RPM, 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, our Stratified Charge research efforts were intensified and, in 1973, our 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 RC2-75.

THE DIRECT INJECTED STRATIFIED CHARGE ENGINE

The direct injected Stratified Charge Rotary competes with the advanced diesel and the shaft gas turbine as future General Aviation powerplants. The future of the small gas turbine which suffers a BSFC penalty by scaling to the smaller sizes, will be strongly influenced by breakthroughs in ceramic technology, which will have to include significant structural gains to insure aircraft level reliability. Nonetheless, the shaft gas turbine may provide a viable General Aviation contender in the long-range picture.

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 capability 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; and moderate NOx emissions.

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 lower NOx emissions, better cold-starting, capability for operation on a wide range of fuels, and lower particulate emissions. The naturally-aspirated stratified Rotary state-of-the-art is competitive with the indirect-injected automotive diesel now and the turbocharged advanced version will challenge the advanced direct-injected diesel.

The Rotary Stratified Charge Engine can provide significantly higher power density than either the current Diesel or the 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 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, and a significantly leaner mixture ratio is maintained at all other points in the combustion chamber.

This essential flow/velocity gradient has to be generated in the incoming air charge of a reciprocating engine by some combination of swirl inlets or shrouded intake valves, special cylinder heads and piston shapes, etc., all of which introduce pumping work which limit the possible fuel economy gain and also reduce the volumetric efficiency, which, in turn, increases engine size and weight. In addition these reciprocating engine "modifications" often show significant change with engine speed.

The moving rotor in a Rotary engine, regardless of the type of combustion employed, 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 this develops the necessary flow distribution for stratification without flow friction losses or reduced breathing capacity. Multi-fuel 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 ~~of~~ OR "squish" past the trochoid "waist" can be determined by shape of the rotor combustion pocket - a powerful development tool. The trailing quench of the homogeneous charge engine is handled by designing the pocket and nozzle spray to avoid depositing fuel at the extreme trailing section of the rotor combustion face. In addition, flame propagation and heat release rate respond strongly to these design parameters.

In addition to the general advantages of the Rotary listed earlier, the stratified charge version offers another significant plus with 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.

BACKGROUND

Although Curtiss-Wright designed their first Wankel-type Rotary Engine in 1958 and ran this engine in early 1959, that engine was significantly different from any other experimental versions in existence at that time and developments continued into 1962 before a reliable, durable and efficient baseline conventionally carbureted engine could be 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 operational test stand stage (19). The RC2-60U10 (Figure 5) is a liquid-cooled two rotor vehicular engine in the 160 - 200HP class and the RC2-90 (Figure 4) an air cooled 310HP helicopter drone engine. The trochoid of these engines was the same size as the 1958-designed 60 cubic inch single rotor engine (the RC1-60), but the rotor width was increased 50 percent 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 (8). Furthermore, the RC2-60U10 performed well (including cold-starting on JP-4, without aids, down to -35^{o}F) only within any specific narrow speed band, whereas the 90 cubic inch combustion configuration which was subsequently developed to meet high power goals, showed low load deficiencies. In both cases, however, the engine showed sufficient technical promise for their specific 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 (gasoline) Rotaries was never demonstrated with these engines, the inherent compatibility of the Rotary geometry with unthrottled and direct chamber injected Stratified Charge combustion led Curtiss-Wright to believe that the potential for superior performance had to be there.

Following the fuel crises of 1973, R&D efforts were resumed in an attempt to resolve whether or not this perceived potential was real and, if so, if it could be realized with a practical machine. This time, feasibility trials were directed towards automotive applications which meant not only wide range power and speed flexibility with good fuel economy, but low and/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 raw 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 well throughout the 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 (3) led, in 1974, to a more flexible arrangement whereby a separate pilot nozzle, with relatively small fuel flow, is used to trigger combustion. This two-nozzle design, shown in Figure 6, 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 (8) has served for a number of developments over the past 23 years.

The R&D activity through 1976 included test of a number of geometric variations of the basic dual injection configuration, primarily location of the main nozzles, spray pattern of the main nozzle in relation to rotor combustion pocket form, and basic rotor modifications. The design arrangement shown in Figure 6 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 potential was realizable.

As of the completion of the 1976 Research Program, 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 (9), the prognosis for low particulate emission levels (10) 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 (7), in Figure 7. The "cast iron rotor housing" curve illustrates the SFC improvement attained with a moderate increase of trochoid temperature but the temperatures that were actually tested with a cast iron housing do not preclude the use of aluminum. The size comparison of a complete RC1-60 engine with accessories, against the comparable output six cylinder VW Diesel version is shown in Figure 8.

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% improvement in BSFC that a direct injected diesel could provide. As of this point, noise, power density, wide range and emission factors have favored the pre and swirl chamber for automotive, but future direct injected automotive diesels are a distinct possibility.

ALCOHOL FEASIBILITY

Using a non-optimized (rotor pocket/main spray pattern) configuration that was tested at 10:1 compression ratio (Figure 9) 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 value on a mass basis and roughly twice the heat content of the alcohol on a volume basis. Therefore, the results are presented (Figure 10) in terms of specific heat input.

RC1-350 TESTING

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 basic configuration and system evaluation work 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, which has correlated very well with complete multi-rotor data, is essentially independent of the number of rotors in the final machine and was initially in support of a 4 rotor 1500HP engine (Figure 2). The RC4-350 was subsequently redirected in 1980 to a 2 rotor version (Figure 3), also under Advanced Development contract to the USMC. The two rotor engine can produce 750HP naturally aspirated, with significant growth capability when turbo-charged.

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

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

The larger 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" 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 of the larger stratified charge engine program 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 6 (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 11. 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 12 shows both curves on a BSFC basis, reflecting the differences in friction. This plot shows that the RC1-350 enjoys a brake basis advantage over the RC1-60 because of the lower specific friction. The ATC pilot ("reversed") configuration curve additionally reflects a combustion advantage. The improved thermal efficiency of the ATC pilot design is one of the potential gains over the automotive prototype data previously shown, which would obviously be included in an "updated" engine. In addition to lower friction, the 350 cubic inch engine enjoys the advantage of considerably more development effort, particularly with support injection and ignition systems. Further, brake values for multi-rotor engines are slightly better than the single rotor rigs, even though the rig enjoys the benefit of slave accessories, since the FMEP of the multi-rotor engines are generally somewhat lower. The conclusion of these and several other comparisons, however, 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"^{3} category has been proven elsewhere.

IMPROVED COMBUSTION EFFICIENCY THROUGH TURBOCHARGING

1. <u>Rationale</u> - The stratified charge engine air utilization is closer to a diesel than a conventional carbureted engine because it can run well on the very lean mixtures which give best combustion and thermal efficiency. Predictions based on data obtained from tests of naturally aspirated stratified charge rotary engines indicated that turbocharging was not only a means of obtaining a higher power density, but offered potential for further improvements in fuel economy.

The theory that turbocharging could permit broader operation at optimum combustion efficiency points was predicated on the characteristic ISFC vs. F/A curve shapes shown in Figure 13, which is representative for both the RC1-60 and RC-350 engines. The bulk of the data is for the BTC pilot configuration. The preferred ATC pilot is spotted in for one test at 1200RPM to show the comparison. Since ISFC is inversely proportional to thermal efficiency, it can be seen that the engine not only can run at the extreme lean mixture ratios of the diesel, but does so more efficiently than at higher F/A ratios. Accordingly, based on analyses, the qualitative effects of turbocharging are shown on Figure 14. 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 predicted that higher power BSFC could be reduced approximately 17% by driving the BSFC curve "hook" out beyond the "normal" naturally aspirated range. "Normal" is an arbitrary high limit mixture strength (generally about .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 appear to be substantially lower, which is conceptually attributed to the absence of compression ignition combustion lag. Although both NASA study General Aviation and Commuter Aircraft engines (13) 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. <u>Feasibility Testing Results 60 Cubic Inch Module</u> - 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 (Figure 3) with an available integral pocket (non-inserted) rotor from another engine 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, on the RC1-350 program, to be less efficient than the ATC pilot variation. The tests were run nonetheless because performance trends were expected to be applicable to later configurations. The tests, it should be added, were biased towards the higher speed regimes of interest for military and aircraft applications.

Figure 15 shows that, as additional air is supplied by turbocharging, bringing the F/A ratio at 50HP from .044 to .025, the ISFC ($\propto \frac{1}{\text{Thermal Efficiency}}$) remains at the same minimum value that it had obtained at 20HP. Accordingly, the 4000RPM BSFC curve, instead of "hooking up" in the customary curve shape, continues to decrease, showing an improvement of 19% at an assumed limiting .055 F/A naturally aspirated, both test curves extrapolated to this point. The BSFC improvement related to best BSFC naturally aspirated, at approximately 3/4 N.S. power, is 11% on the same basis.

This improvement is consistent with the growth engine predictions. Although the absolute BSFC values shown on Figure 15 do not represent current capabilities, there was good confidence that the same general trends would hold for more developed configurations as well. Therefore, the basic theoretical contention that the Indicated Specific Fuel Consumption (ISFC) would remain essentially at its optimum value for higher inputs, if the corresponding F/A ratio was maintained, is considered to have been confirmed by the RC1-60 tests. The obvious next steps are to run state-of-the-art combustion configurations and to test at higher powers.

The comparable data for dual side ports indicated that the airflow restriction of the inherently late-opening side ports was more detrimental than excess air through-flow with the higher overlap of the peripheral intake ports. From these specific tests, the peripheral port configurations performed better but one cannot conclude that this trend will hold with higher pressure ratio compressors and/or later side port closing angles.

The testing at 6.0:1 compression ratio, shown compared to the 8.5:1 C.R. results in Figure 16, is particularly instructive because, despite anticipated poorer performance when 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 17 shows these effects more clearly, plotted here for 5000RPM.

The test results clearly indicate that a lower compression ratio is desirable when turbocharging and further work is in order to 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 reduce with the leaner operation. This will further increase the current 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"^{3} Module - The 60"^{3} sized hardware, of circa 1974-5 origins, 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, first noted as a promising trend on the RC1-60 in 1976.

While the test did include these performance gain features, there was insufficient lapsed 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% higher than our 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 18 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 well. 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 19 shows intercooled BSFC vs BMEP at various speeds. The slope of the curves indicates that further BSFC improvements can be anticipated at higher loads.

While further work is clearly in order, the results are supportive of the advanced engine growth predictions.

ADVANCED STRATIFIED CHARGE ROTARY ENGINES

1. Technology - Based on the described current Rotary Stratified Charge technology, considering additional technology judged to be realizable by mid-decade to allow production inclusion early next decade, several scaled engines have been defined and analyzed.

The supporting parallel technology gains assumed for the aircraft engine are covered in more detail in Reference 11, 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 will prove rewarding 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 fuel injection development by a number of major manufacturers in the field. Experimental and limited production (for a military 8000RPM) 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 (12, 13), 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, 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.

As early as 1961 Curtiss-Wright had tested a tungsten carbide/cobalt detonation gun applied trochoid coating compatible with cast iron apex seals that met all of the technical requirements but was prohibitively expencive for automotive use. However, this same system could be used in the aircraft and military engine market place. 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 (14) and in initial pre-production runs of an air-cooled multi-purpose engine by SYVARO (15), both tested at relatively high outputs and speeds. In addition, plasma-sprayed Ferro-Tic, tested experimentally at Curtiss-Wright (16) had shown promise of even lower wear rates, with both materials and application method attractive economically.

Carbide-based coatings, in combination with a promising apex seal material now being tested on the military engine program 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 a satisfactory solution 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 close to 300 horsepower (naturally aspirated) at speeds in the 10,000RPM 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 the required long-term durability at these peak outputs, but the directions provide relevant inputs.

Thermal Insulation for Reduced Coolant and Oil Heat Rejection - The use of cermets as trochoid coatings may provide improved 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, ringless design or hydrodynamic film gas sealing and is thus more dependent on the material choice, such as ceramic 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 the diesel. When turbocharged, calculations and 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 improved thermal efficiency removes more of the input fuel energy as shaft work while the heat rejected to the coolant does not change appreciably since internal (engine casing) pressures and temperatures remain closer to spark ignition ranges than to compression-ignition engine levels.

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 is now being commercially cast for aircraft quality components. In fact, C-W has recently poured AMS 4229 rotor housings for the 350"^{3} engines and the castings look promising. While high speed engines demand light strong rotors, modular 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 turbocharger assumptions used to predict aircraft engine performance were relatively conservative. However, the fuel economy gains were limited by the turbocharger pressure ratios expected to obtain over the next several years. For 25,000 feet 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 limits sea level pressure ratios to around 2:1. If anticipated turbocharging improvements do not materialize, an obvious alternative is to series turbocharge for high altitude performance.

2. Specific Engine Choices for General Aviation - The NASA Advanced Rotary Combustion Aircraft Engine Design Study objectives included a 75% cruise BSFC of .38 lb/HP-hr, or better, at 250HP and 25,000 feet minimum altitude. Two

liquid-cooled engines were selected (11) 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 there is some question of whether this will be necessary to achieve predicted performance levels. The specific fuel consumption prediction for the RC2-32 is shown in Figure 20.

The RC2-32 BMEP is 211psi at the 320HP take-off power and 198psi at 250HP cruise. The engine RPM is 9420 which, on an equal RC-60 apex seal sliding velocity basis, is equivalent to 7050RPM, 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 191psi BMEP at 320HP take-off, 179psi at cruise, 7030 T.O. RPM (6000 "equivalent") and 5860RPM 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 $350''^3$ military engines.

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

The RC2-32 installation longitudinal layout is shown in Figure 21. To achieve a small frontal area (a 16 inch 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 gearing, 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 durability at sustained high output, they have not been demonstrated in a stratified charge Rotary engine as of this point. Turbocharged homogeneous charge Rotary engines have been performance tested to these levels and, separately, at the projected engine speeds, but long-term durability testing at high outputs has been limited. Therefore, it is recognized that the resulting best compromise to attain projected goals may not be exactly those shown even though the direction is believed correct. The "best compromises" 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 STUDIED 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 minutes 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 rm	1482 km/800 nm
CRUISE SPEED - minimum	3700 km/hr/200 kt	417 km/hr/225 kt
CRUISE ALTITUDE	7620 m/25,000 ft	7620 m/25,000 ft
TIME TO CLIMB - maximum	30 min	30 min
RATE OF CLIMB at 25,000 ft., minimum	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, maximum	113 km/hr/61 kt	138 km/hr/75 kt

Ths 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 18. For the purposes 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 22.

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 choise.

The above process was used to define "baseline" single- and 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 powerplane 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/4.5psi 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/4.5psi differential). Empty weight is 2008 kg/4428 lb. and takeoff gross weight is 3107 lg/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/340BHP at 2700RPM for takeoff. A cruise rating of 186 kw/250BHP at 2300RPM 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 23 and 24.

ROTARY-POWERED AIRPLANES

The single-engine design with the rotary-combustion engine is shown in Figure 25. 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 forward 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 26 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 27. 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 28, 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 2 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% reduction in required mission fuel
- 12% to 17% reduction in direct operating costs*

* Calculations based upon methods and data of Reference 18.

- 9% to 16% reduction in acquisition costs*
- Substantial gains in cruising speed, climb performance and takeoff distance

Parametric studies reported in Reference 18 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.

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

- Multi-fuel 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 2700RPM)

CONCLUDING REMARKS

In this study, single-and 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

*Calculations based upon methods and data of Reference 18.

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 2500HP. 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 with 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 2500HP 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 29. 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 RC1-350 turbocharging 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 feet, 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 800HP RC4-41 installation longitudinal view is shown in Figure 30 and the 2500HP RC6-122 in Figure 31.

The displacement vs T.O. power is shown in Figure 32 and the engine dimensions, less gearbox, in Figure 33 with corresponding weights plotted in Figure 34. Estimated advanced gearbox weights and length are shown on Figure 35.

CLOSURE

The two engine General Aviation designs of different technology levels show very promising potential as advanced aircraft engines. NASA is in the process of negotiating a contract with Curtiss-Wright Corporation to produce and demonstrate the key technologies required for advanced rotary engines which could be commercially introduced in the 1990's time frame. The contract will result in the design and fabrication of a single rotor technology enablement test engine which will be used to determine the basic engine performance and to evaluate the various technologies needed for the advanced engine design. After initial testing of the first engine, a second engine will be built for additional testing in-house at NASA Lewis Research Center. The research and technology program will take approximately three and one-half years and hopefully will result in technology for a highly advanced stratified-charge engine which will operate efficiently on all available aviation fuels and will be smaller, lighter and/or more economical than currently-available choices.

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RC2-75 AIRCRAFT ENGINE PROTOTYPE

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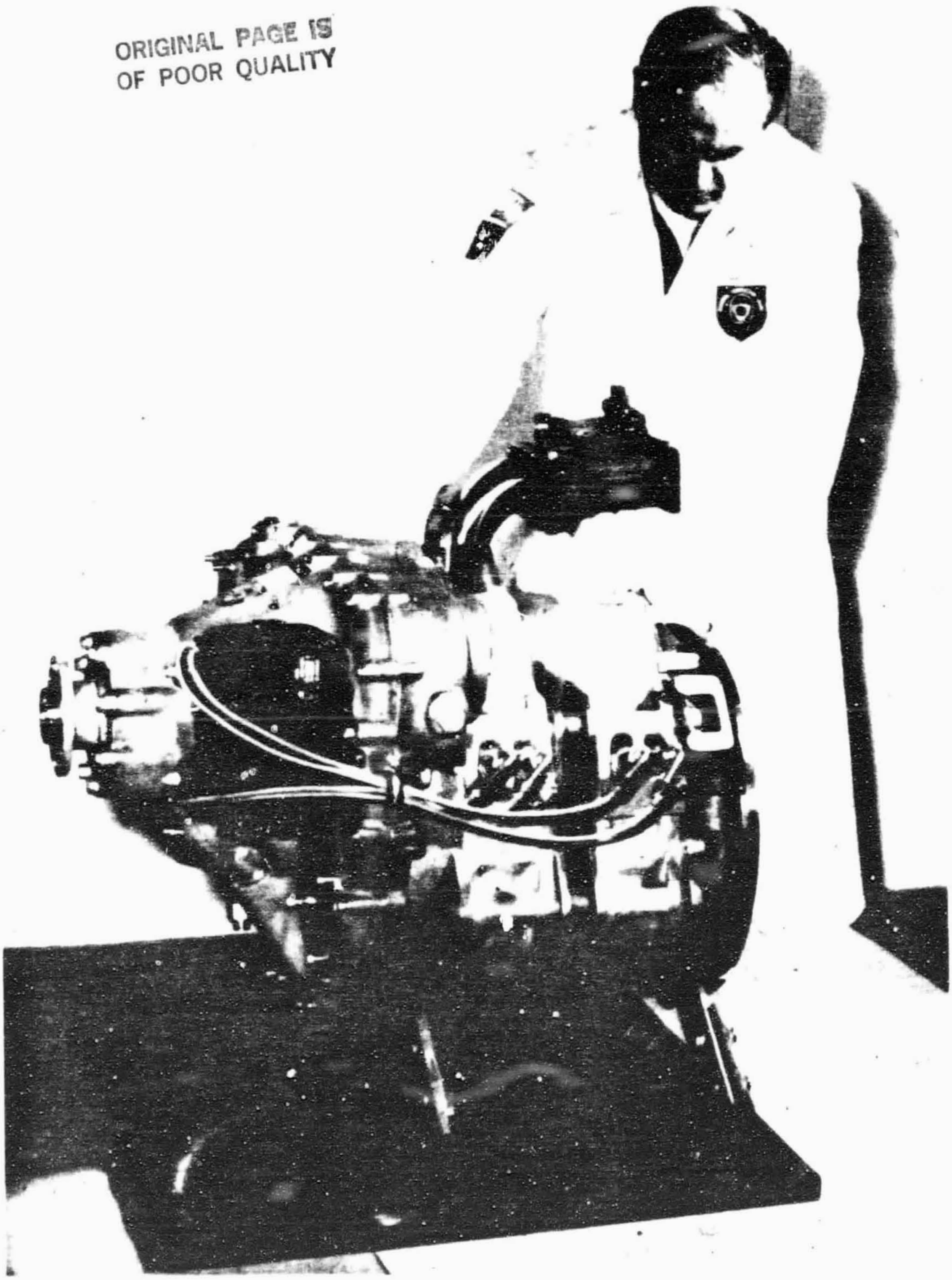

Figure 1

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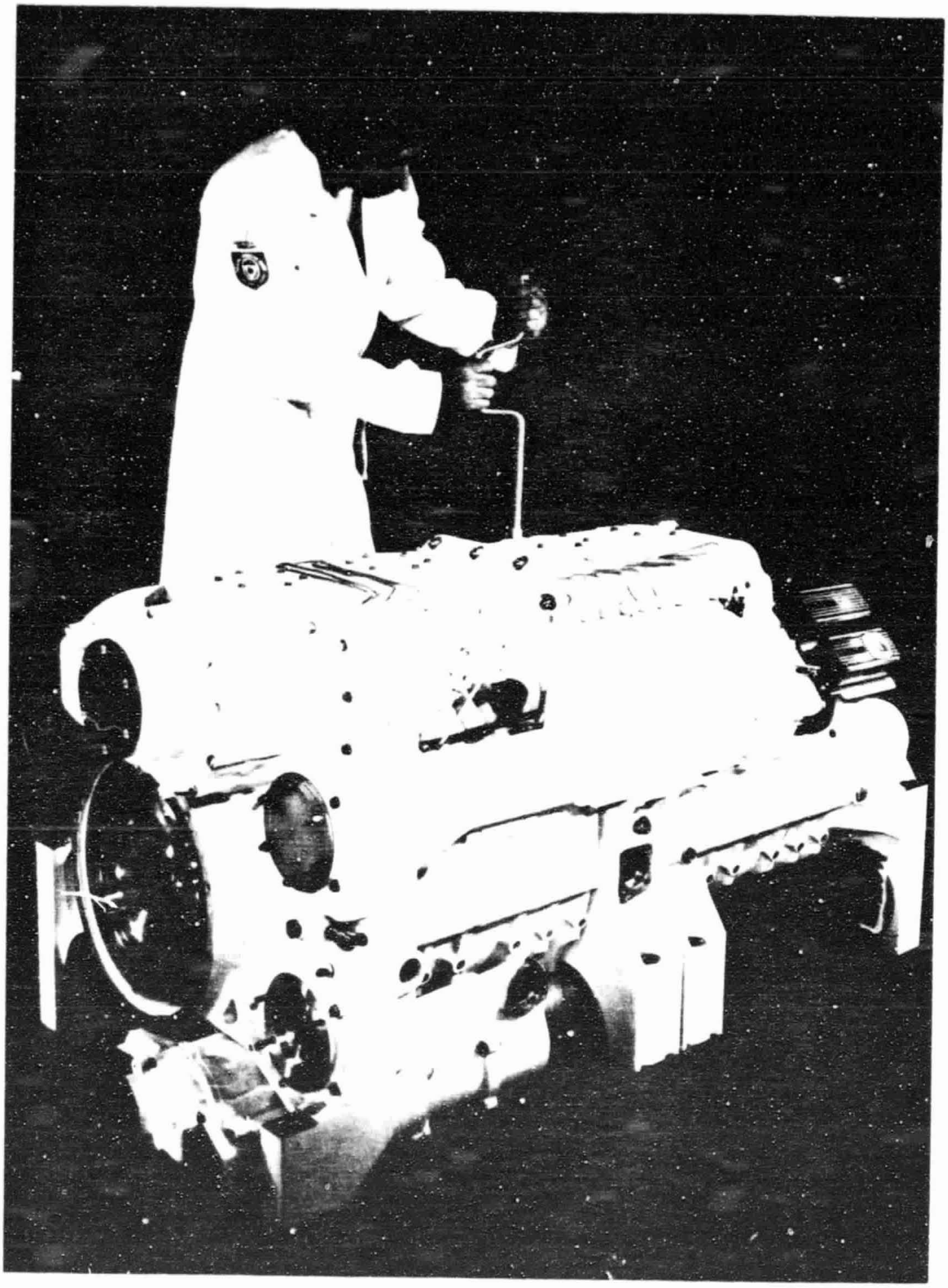

RC4-350 Engine

Figure 2

CURTISS-WRIGHT ROTARY COMBUSTION ENGINE
Stratified Charge Model RC2-350

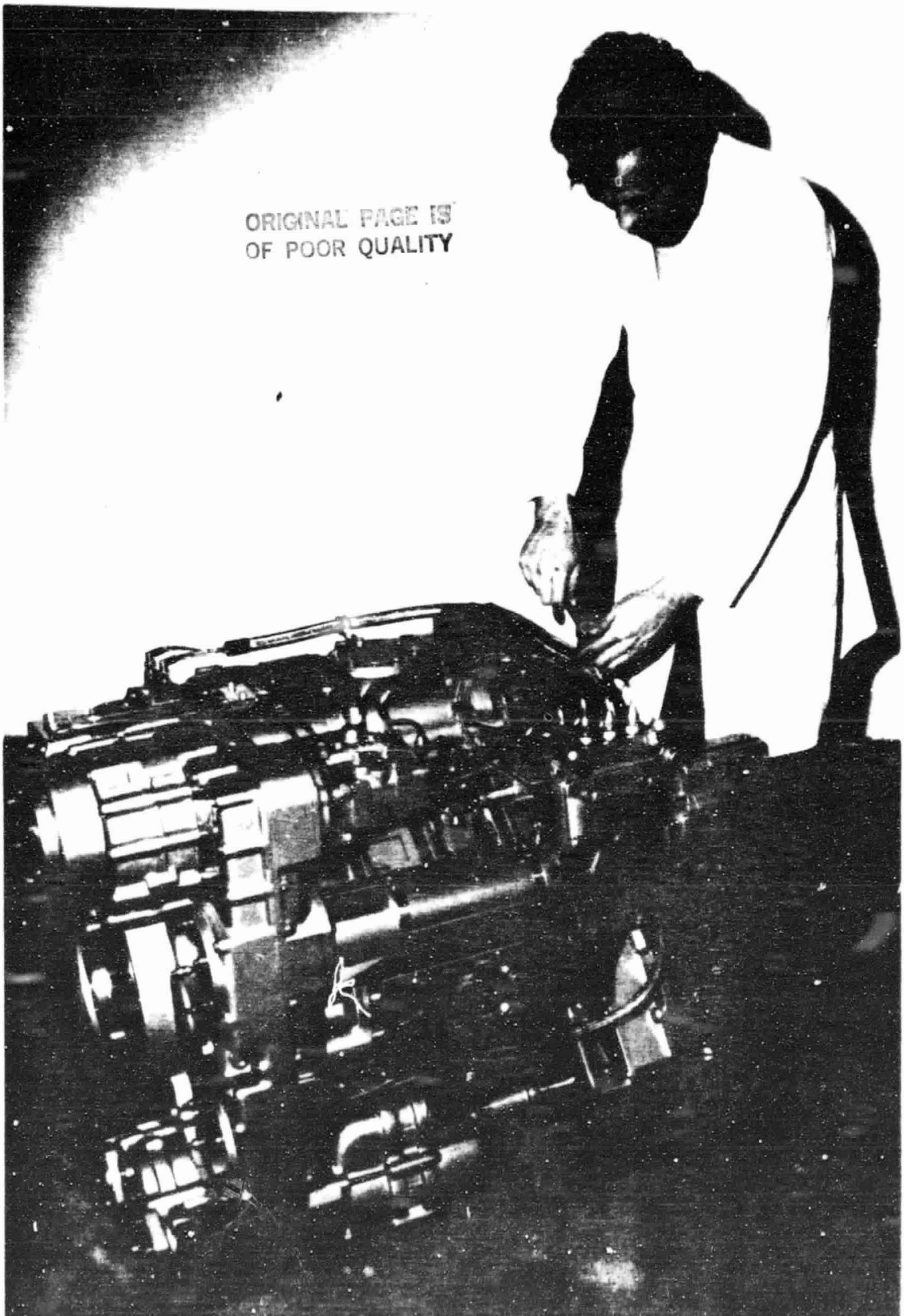
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Figure 3

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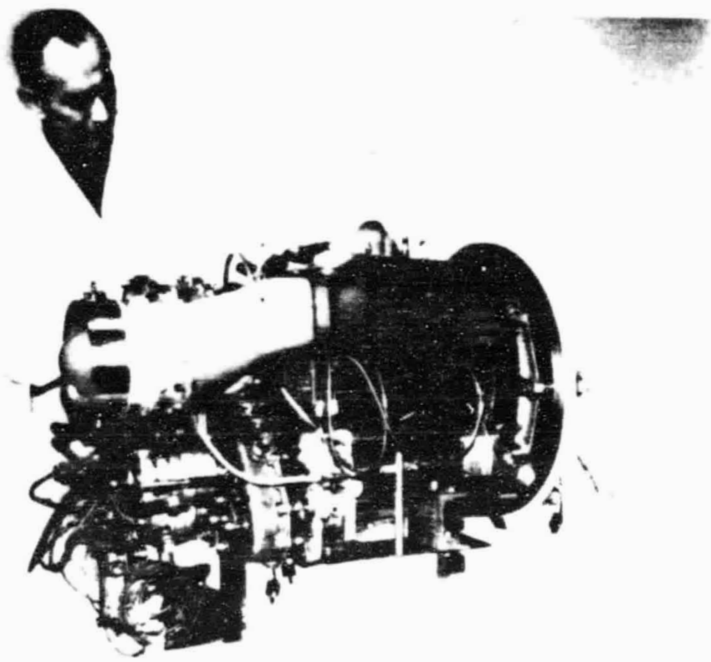

WEIGHT	285 LB.*
WIDTH	25 IN.
LENGTH	34 IN.
HEIGHT . . .	19-1/2 IN.

* LESS STARTER, SEPARATE OIL COOLER/SUMP

Air-Cooled Stratified Charge RC2-90 Engine (1966)

Figure 4

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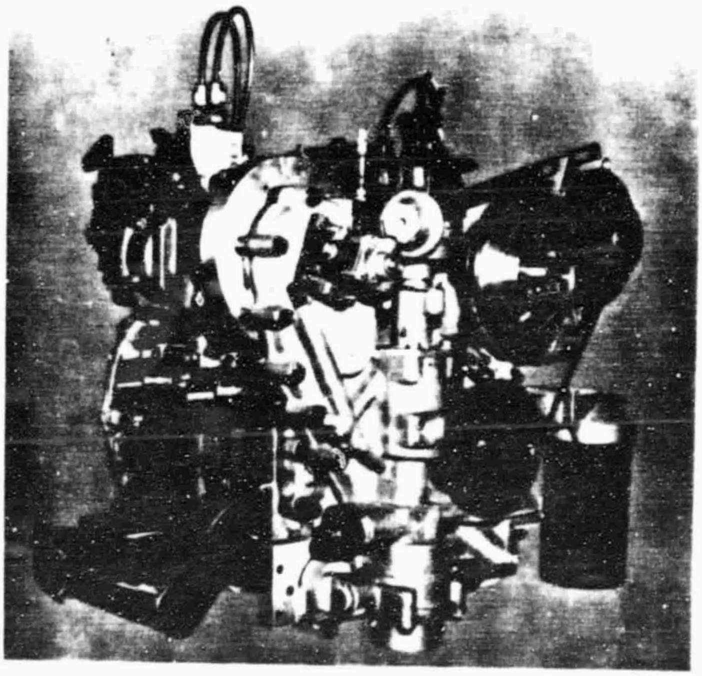
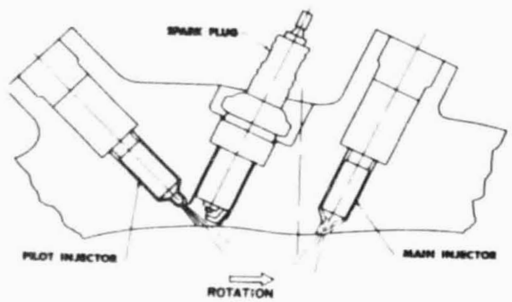
RC2-60U10 LIQUID-COOLED STRATIFIED ENGINE (1965)



WEIGHT	294 LB.
WIDTH	24 IN.
LENGTH	24 IN.
HEIGHT	24 IN.
160-200 HP	

Figure 5

DUAL INJECTOR ROTOR HOUSING CONFIGURATION



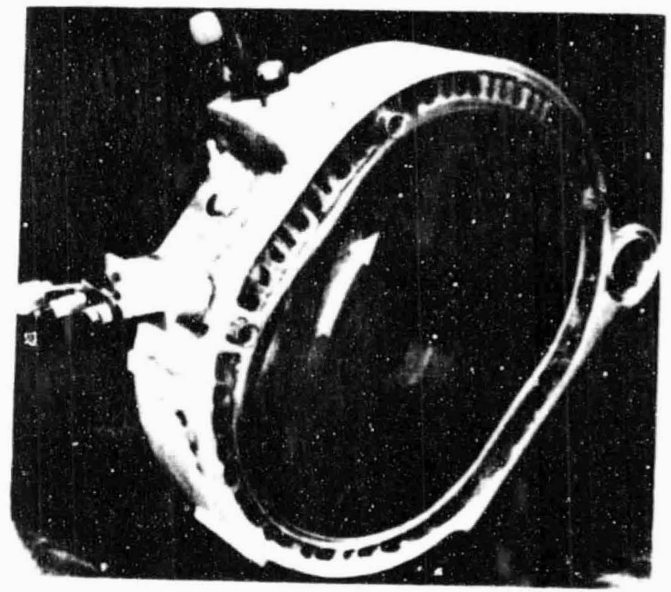


Figure 6

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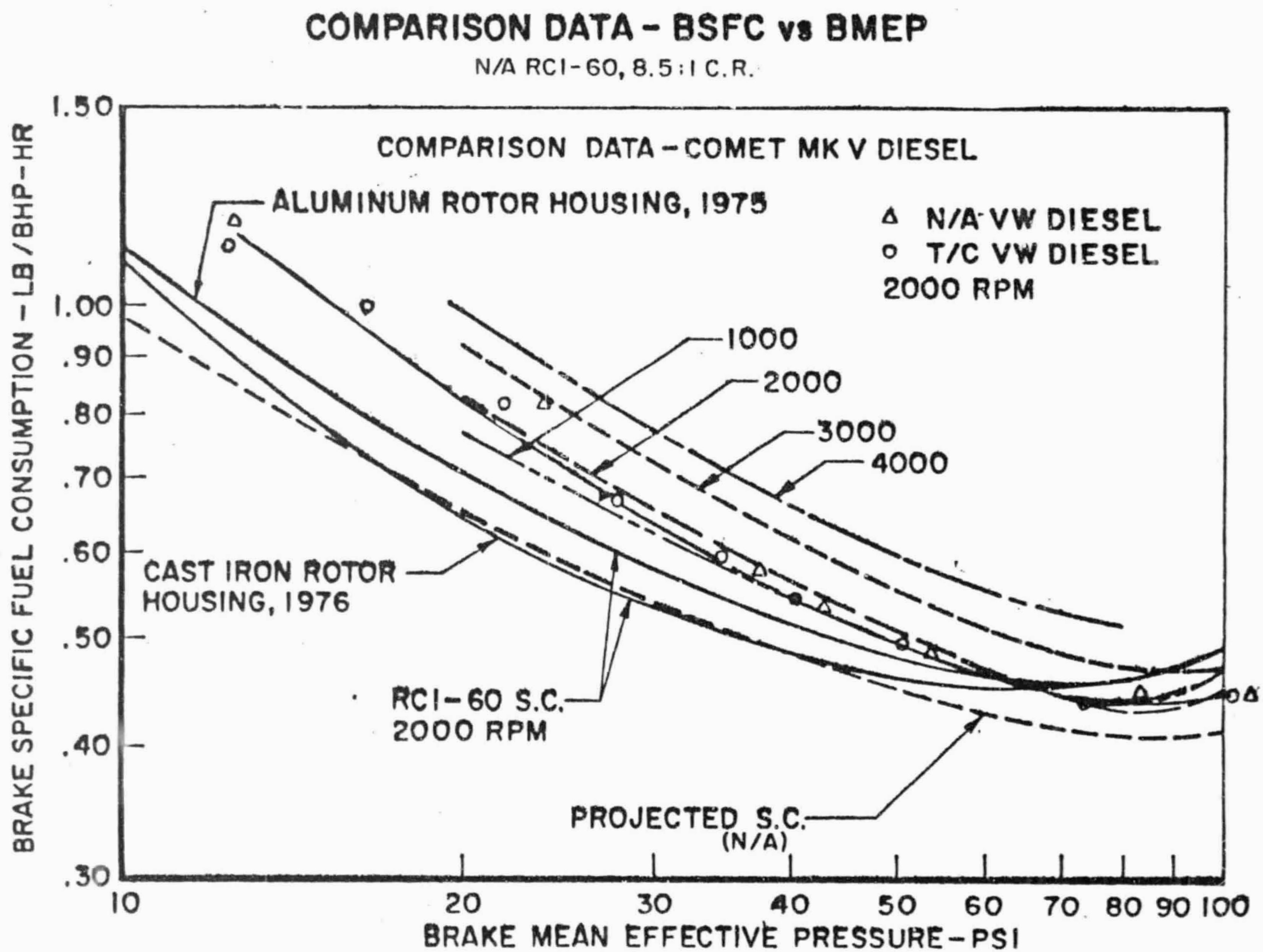

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Figure 7

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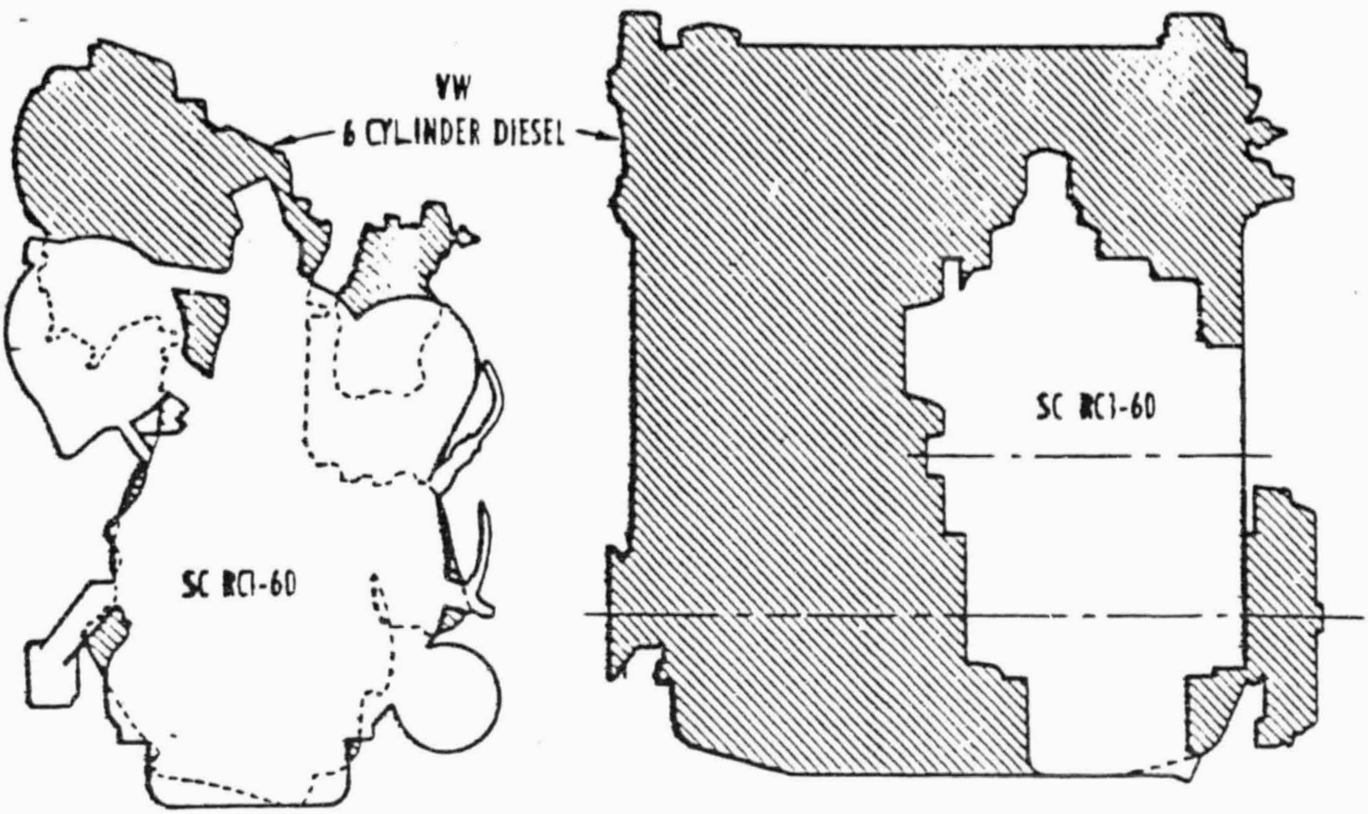

	SC RC1-60	VW 6 CYL DIESEL
kW (BHP) RPM	60 (80) 5000	56 (75) 4500
kg (LB)	109 (240)	184 (405)
L x W x H mm	368 x 559 x 635	780 x 490 x 780
L x W x H INCHES	14.5 x 22 x 25	30.7 x 19.3 x 30.7

Comparison of SCRC1-60 with Volkswagen 6 Cylinder Diesel

Figure 8

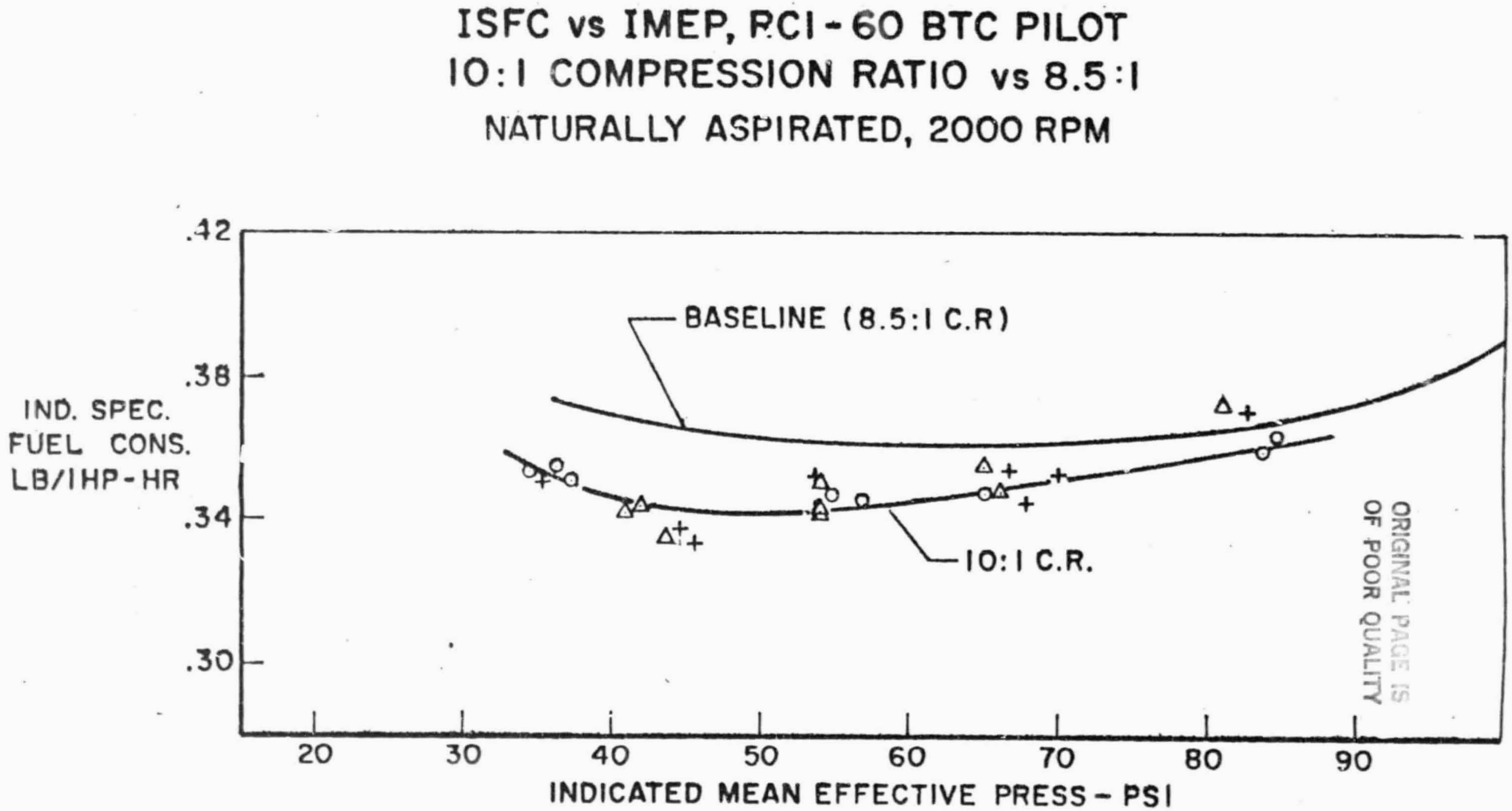
ISFC vs IMEP, RCI - 60 BTC PILOT
10:1 COMPRESSION RATIO vs 8.5:1
NATURALLY ASPIRATED, 2000 RPM
BASELINE (8.5:1 C.R)
10:1 C.R.
IND. SPEC. FUEL CONS. LB/IHP-HR
.42
.38
.34
.30
20
30
40
50
60
70
80
90
INDICATED MEAN EFFECTIVE PRESS - PSI
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Figure 9

RCI-60, 2000 RPM PERFORMANCE, BTC PILOT
10:1 COMPRESSION RATIO NATURALLY ASPIRATED

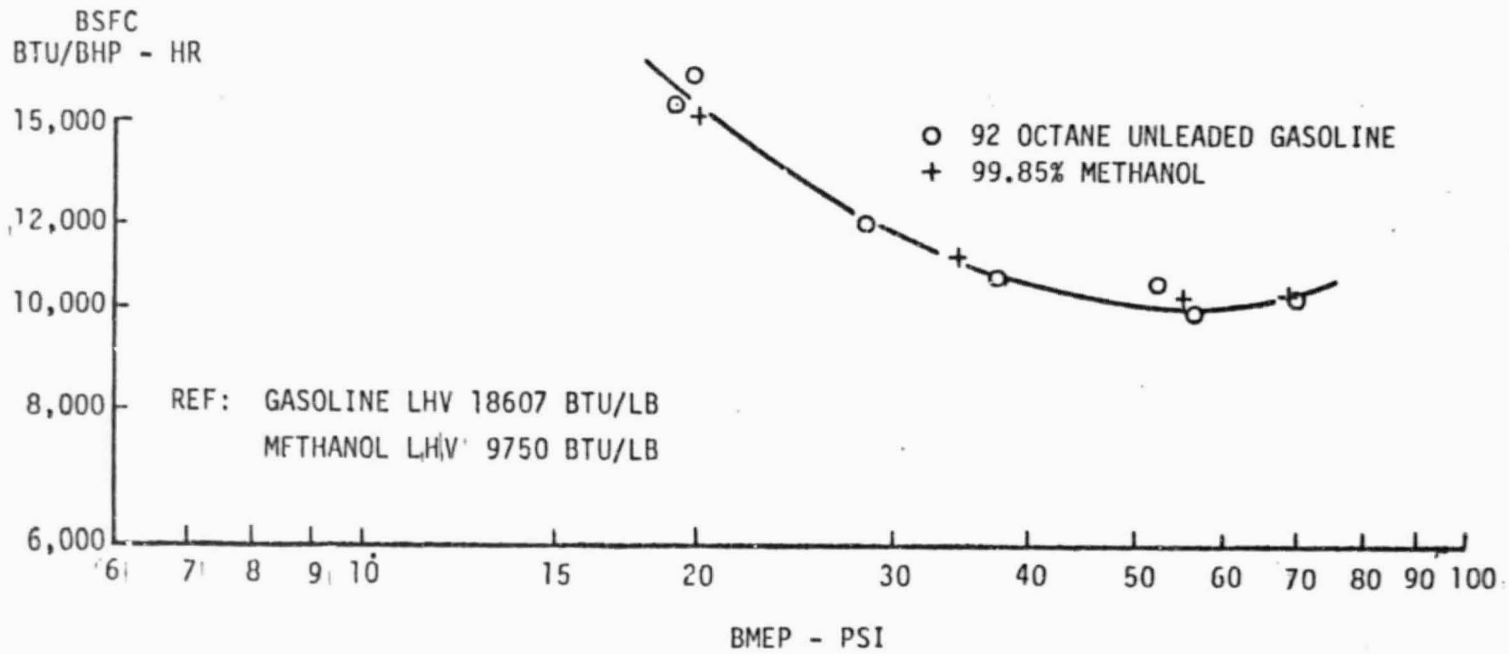

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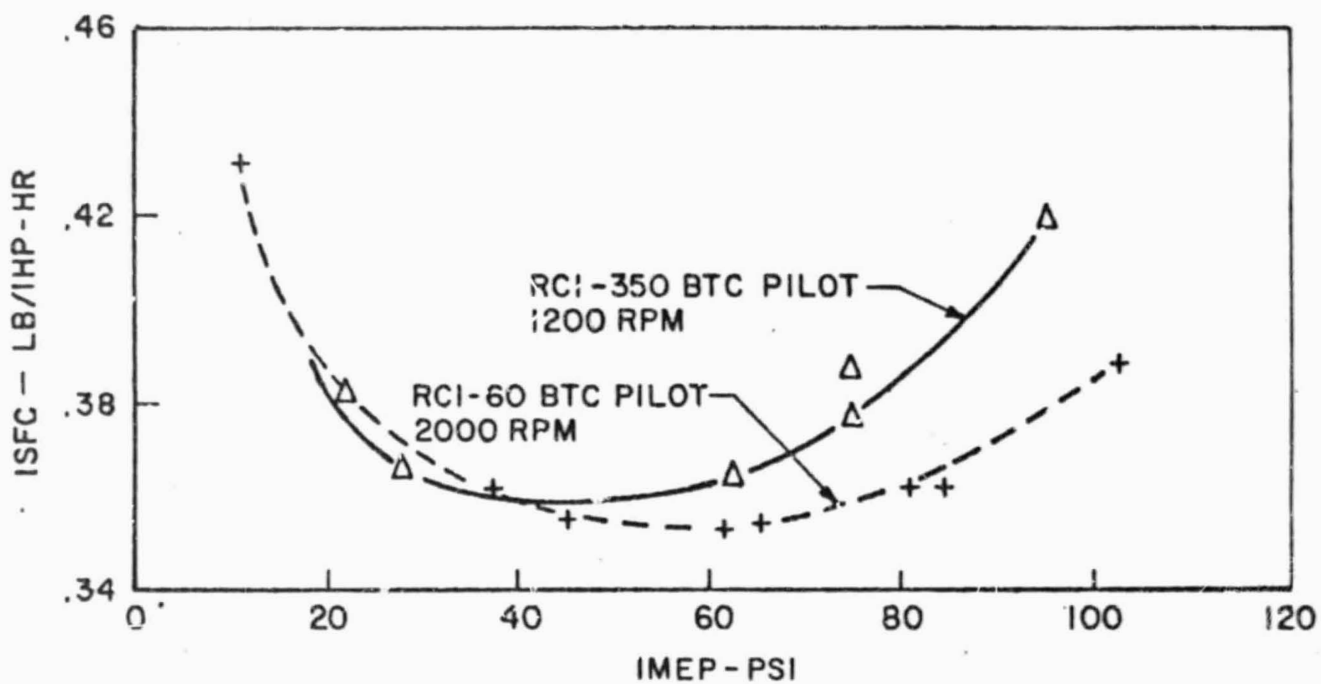
Figure



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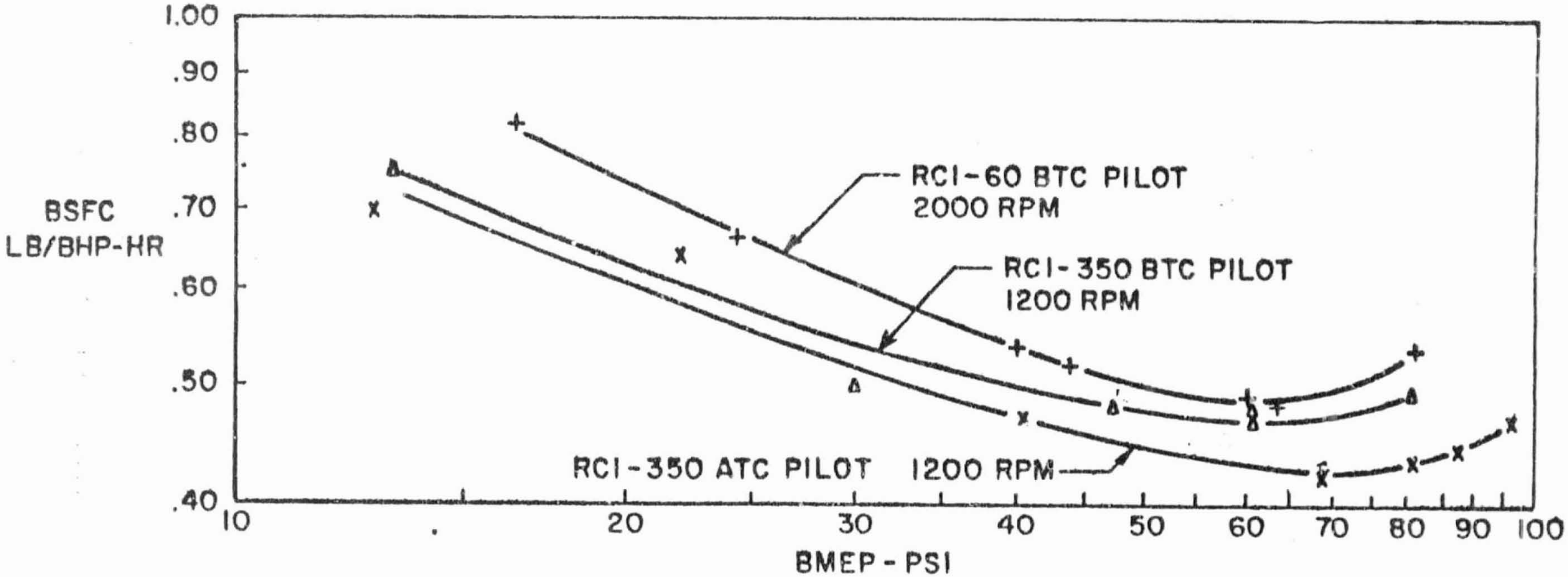
Indicated Specific Fuel Consumption (ISFC) vs Indicated Mean Effective Pressure (IMEP) Comparison of RC1-60 and RC1-350 Data, BTC Pilot, 8.5:1 Compression Ratio

Figure 11



BSFC vs BMEP, RC1-60 and RC1-350, 8.5:1 Compression Ratio

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Figure 12

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ISFC vs F/A RATIO

FOR 5 SEPARATE RC1-350 ENGINE BUILDS,

SAME CONFIGURATION, 8.5:1 COMPRESSION RATIO

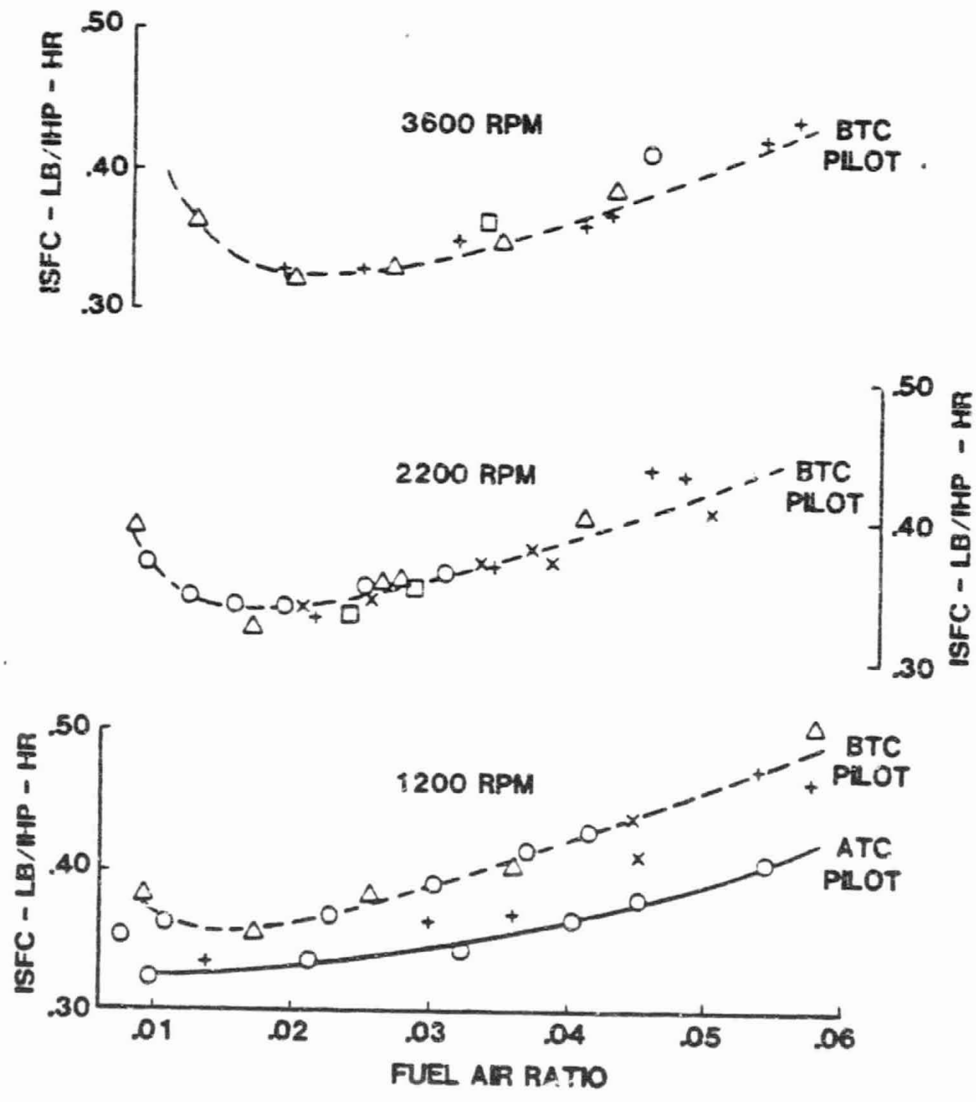

Figure 13

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THEORETICAL TURBOCHARGING EFFECTS
ON BSFC

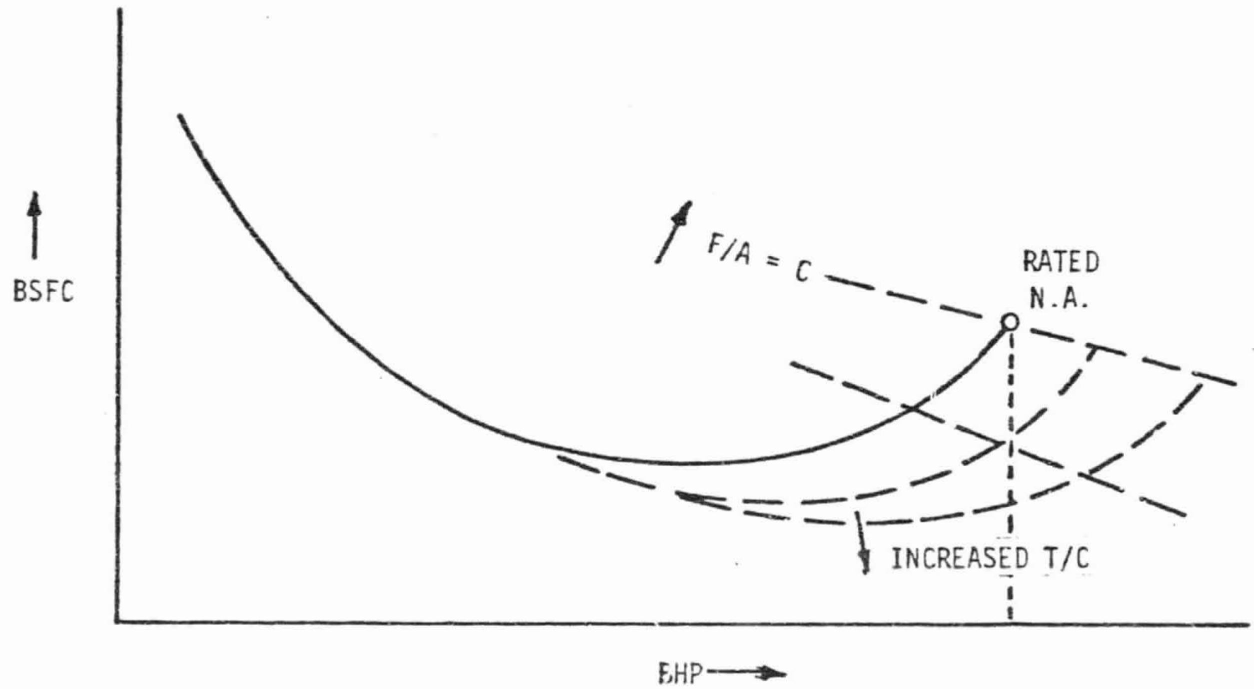

Figure 14

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RC1-60 STRATIFIED CHARGE

4000 RPM PERIPHERAL INTAKE PORTS

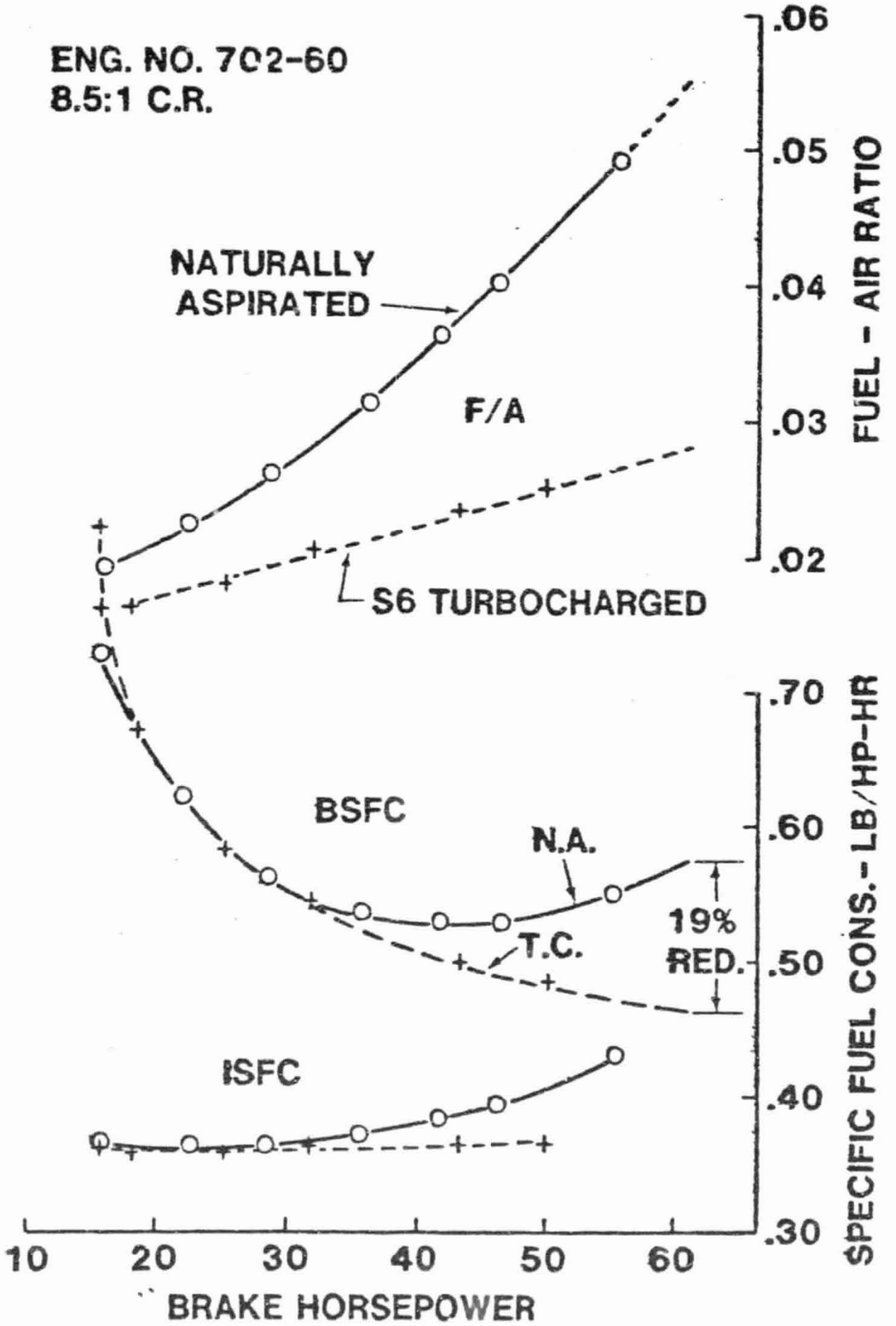

Figure 15

RC1-60
STRATIFIED CHARGE
4000 RPM
PERIPHERAL INTAKES

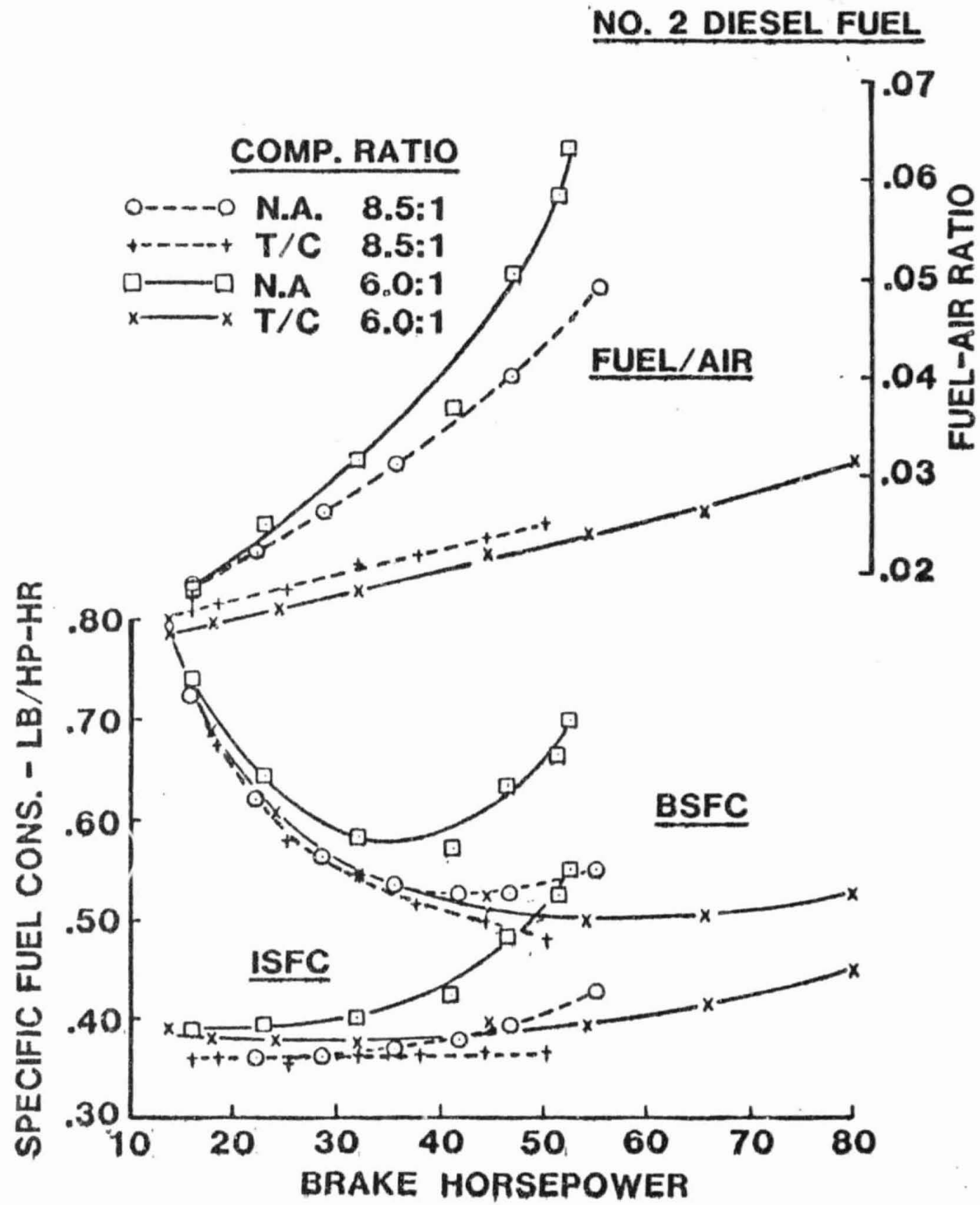

Figure 16

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MEASURED REDUCTION IN THERMAL AND PRESSURE LOADS FROM LOWER COMPRESSION RATIO AND HIGHER AIR/FUEL RATIO

SCRI - 60T ENGINE
5000 RPM

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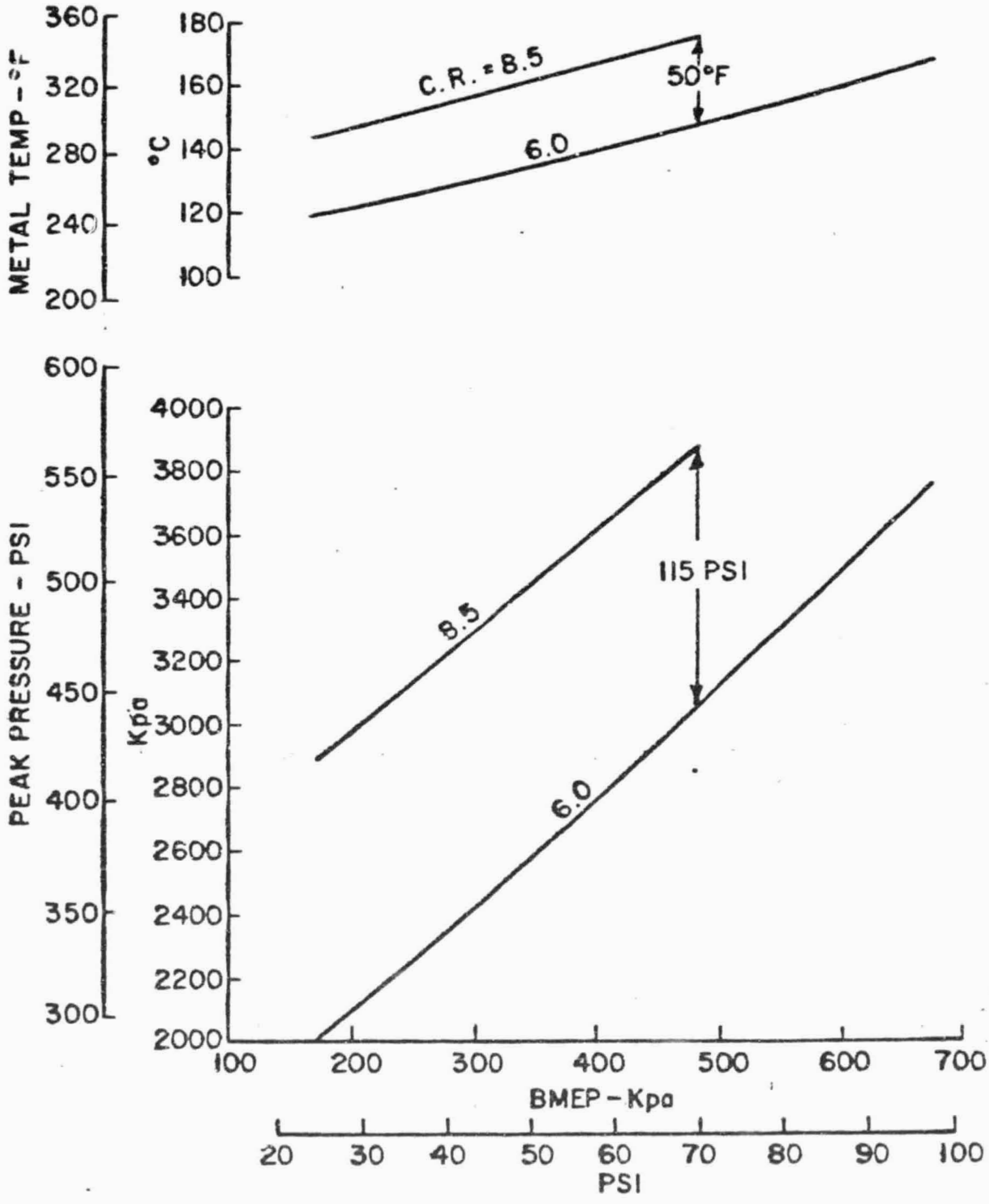

Figure 17

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CURTISS-WRIGHT
RC1-350 TURBOCHARGED STRATIFIED CHARGE ROTARY COMBUSTION ENGINE

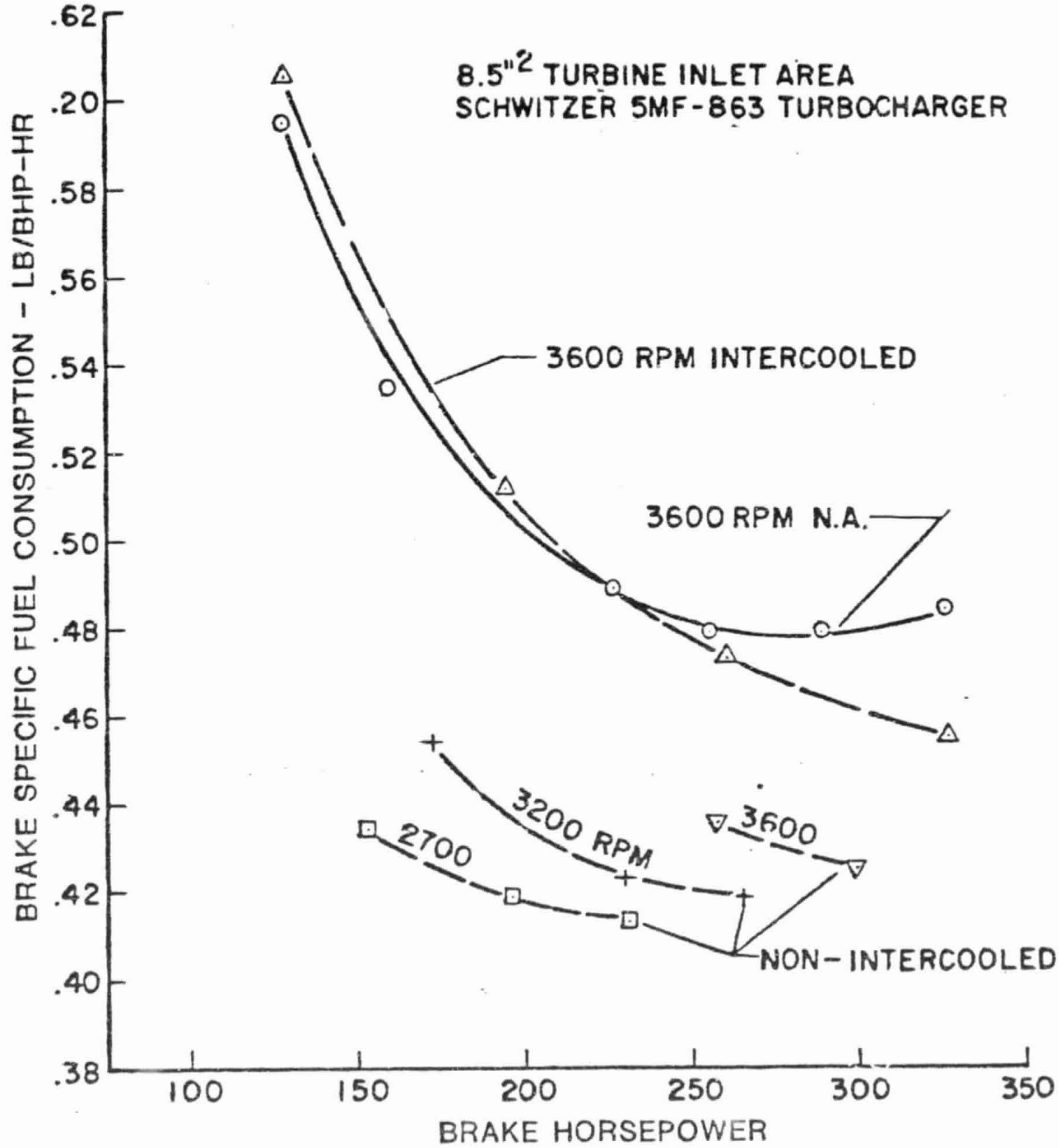

Figure 18

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CURTISS-WRIGHT
RC1-350 TURBOCHARGED STRATIFIED CHARGE ROTARY COMBUSTION ENGINE
INTERCOOLED

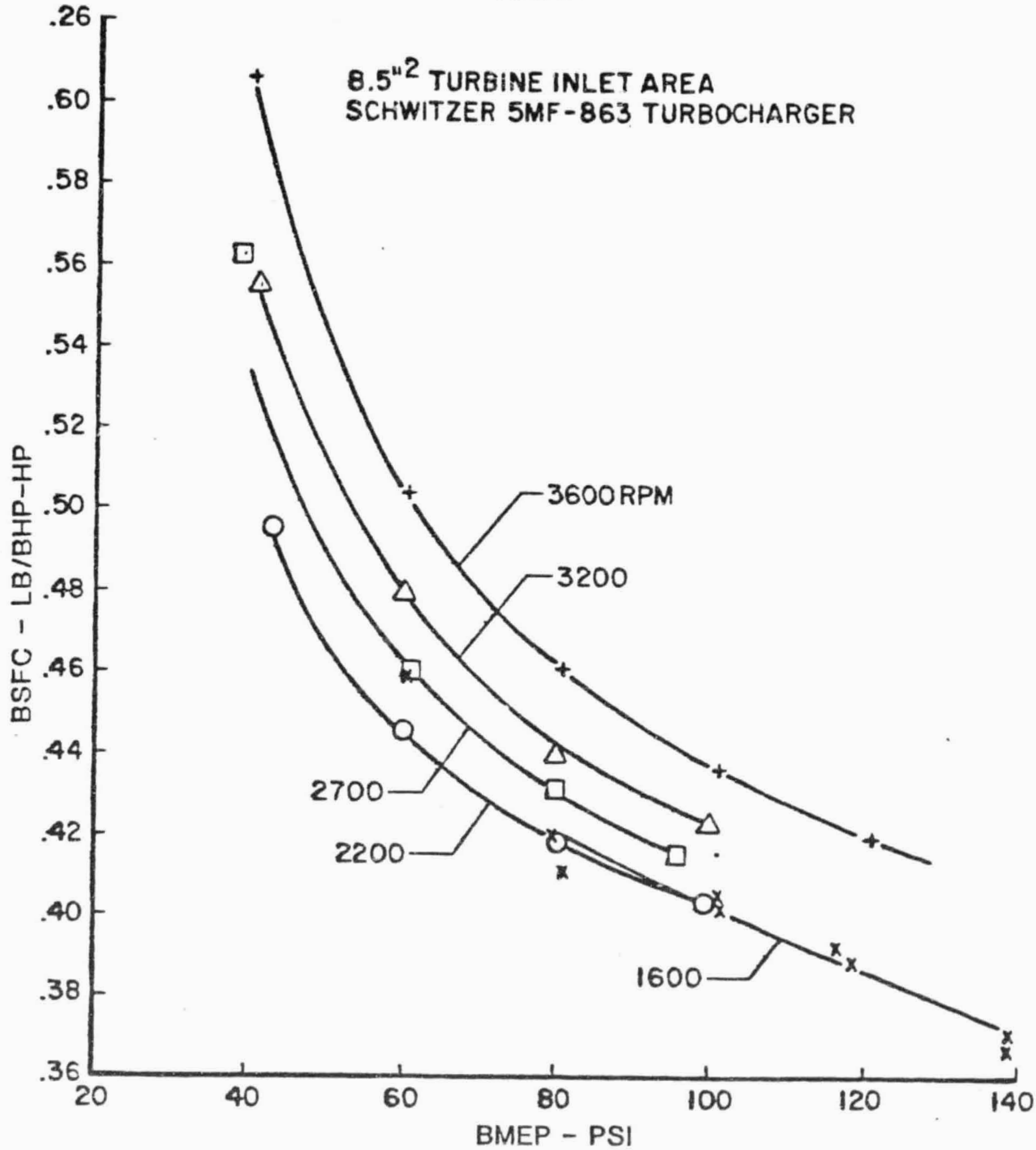

Figure 19

RC2-32 HIGHLY ADVANCED ROTARY AIRCRAFT ENGINE
ESTIMATED PERFORMANCE
TURBOCHARGED STRATIFIED CHARGE

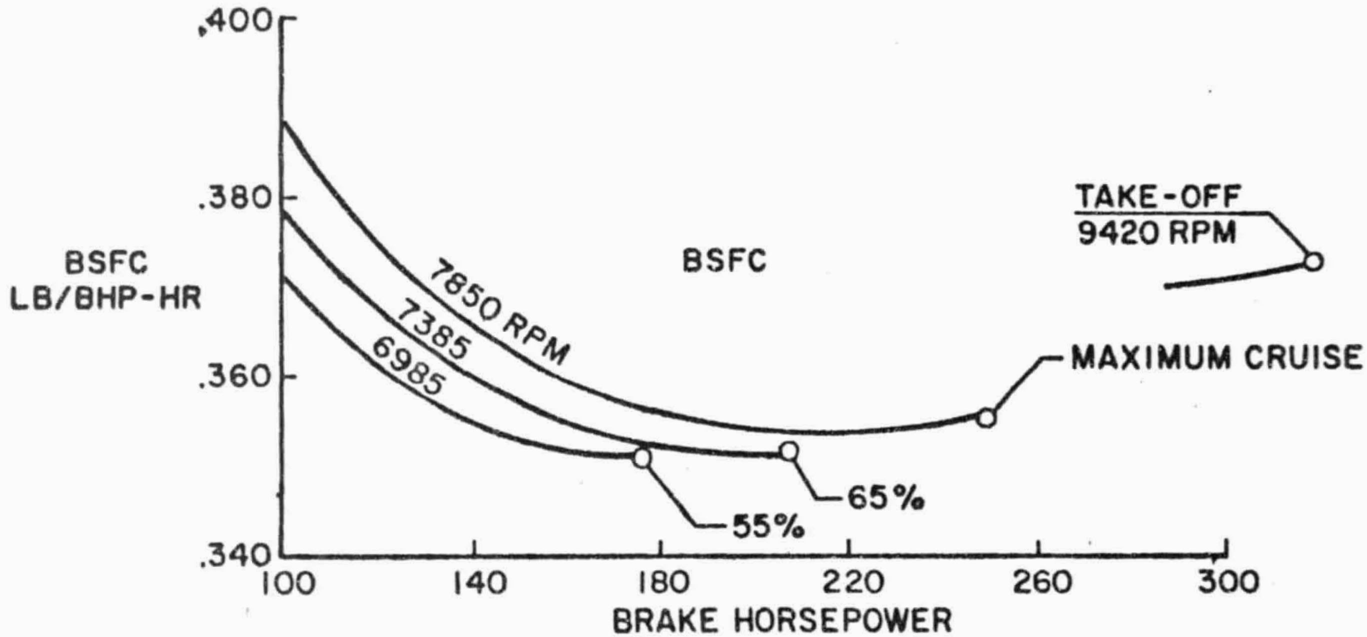

Figure 20

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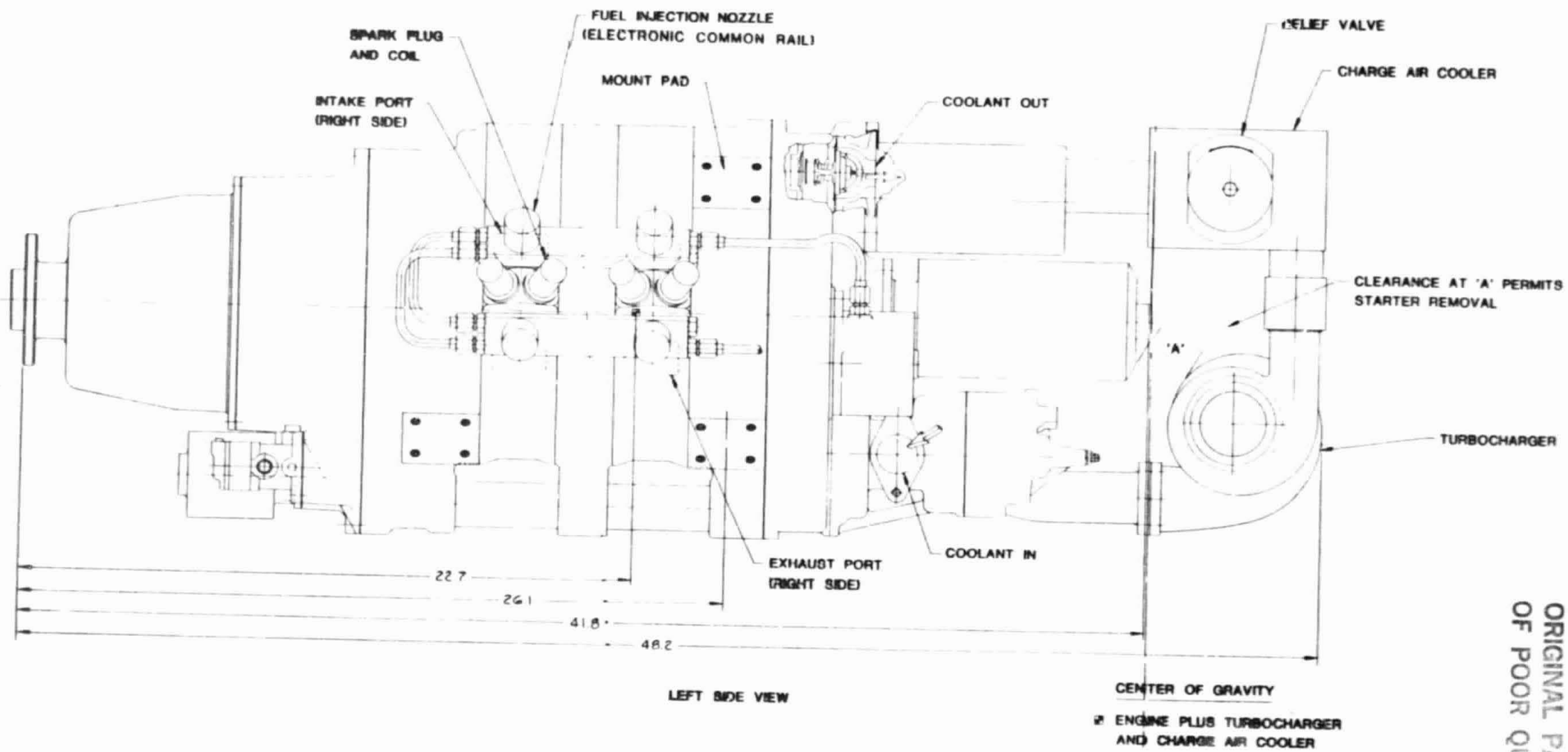

Figure 21

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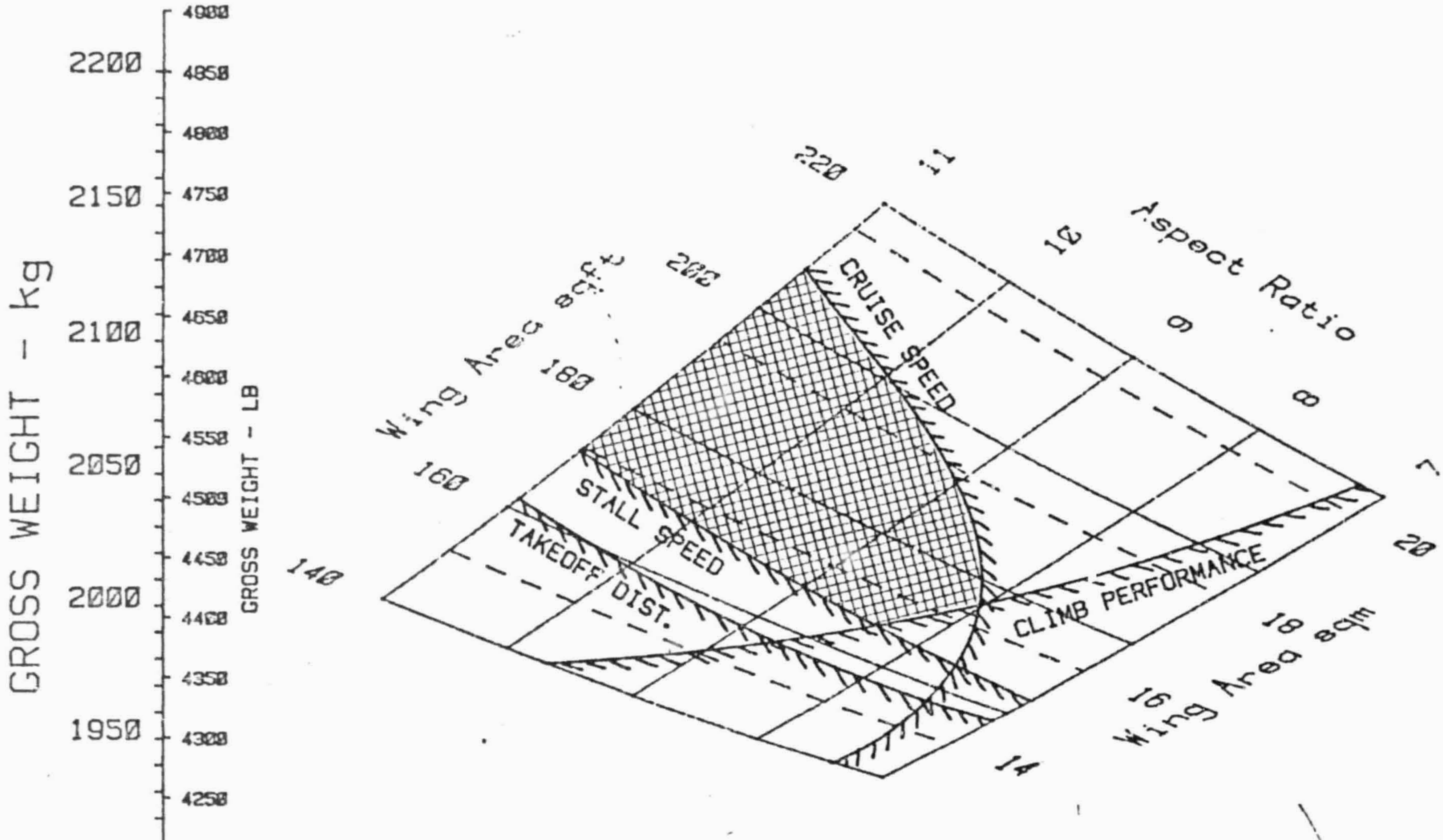

PERFORMANCE CONSTRAINTS ON
CARPET PLOT OF CONSTANT PAYLOAD RANGE

Figure 22

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BASELINE SINGLE

II FIXED ENGINE SIZE, VARIABLE AIRFRAME, FIXED PAYLOAD-RANGE

GROSS WT, LB	4460
SPAN, FT	40.2
ASPECT RATIO	9.5

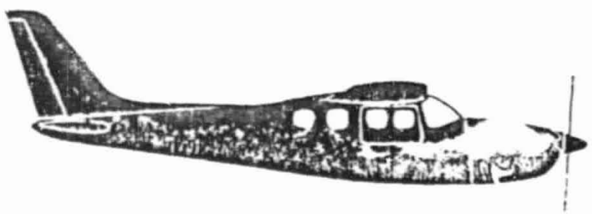

Figure 23

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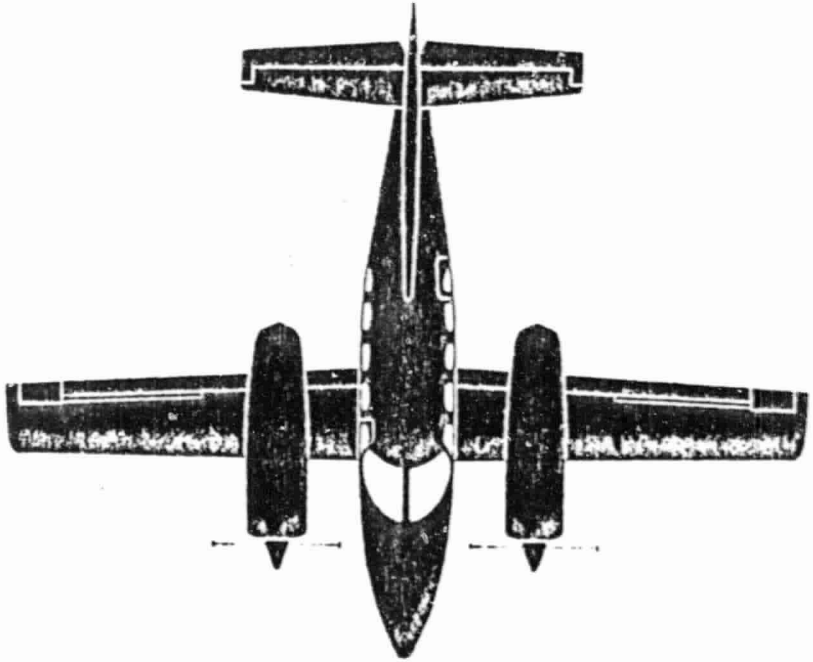
BASELINE TWIN

II FIXED ENGINE SIZE, VARIABLE AIRFRAME, FIXED PAYLOAD-RANGE

GROSS WT, LB	6850
SPAN, FT	44.5
ASPECT RATIO	11.0



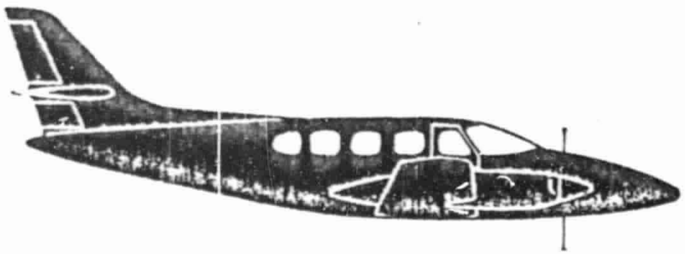


Figure 24

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ROTARY SINGLE

II FIXED ENGINE SIZE, VARIABLE AIRFRAME, FIXED PAYLOAD-RANGE

	RC2-47	RC2-32
GROSS WT, LB	3881	3691
SPAN, FT	34.9	32.8
ASPECT RATIO	8.3	7.73

Figure 25

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RC 2-32 HIGHLY-ADVANCED ROTARY ENGINE
SINGLE-ENGINE INSTALLATION CONCEPT

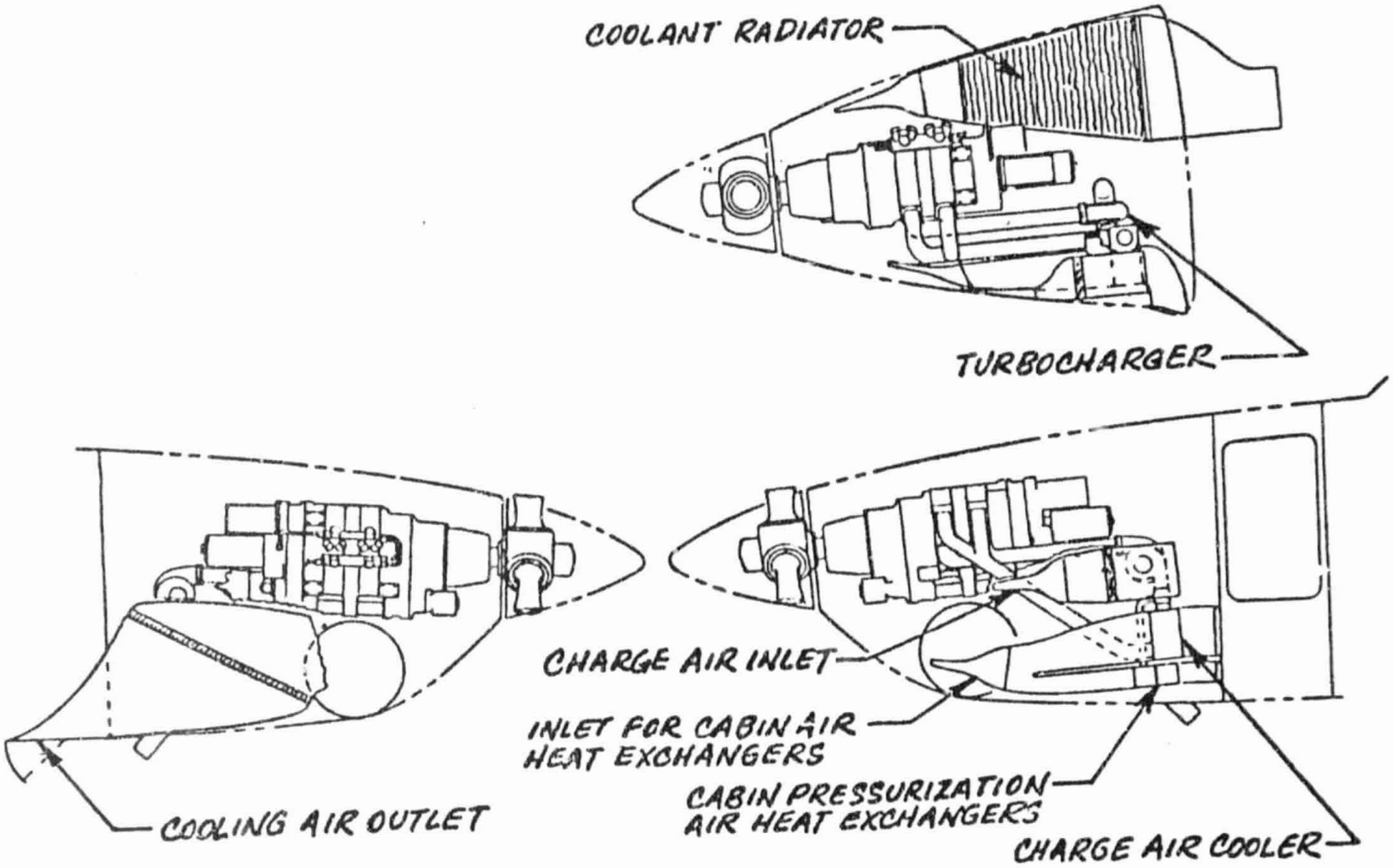

Figure 26

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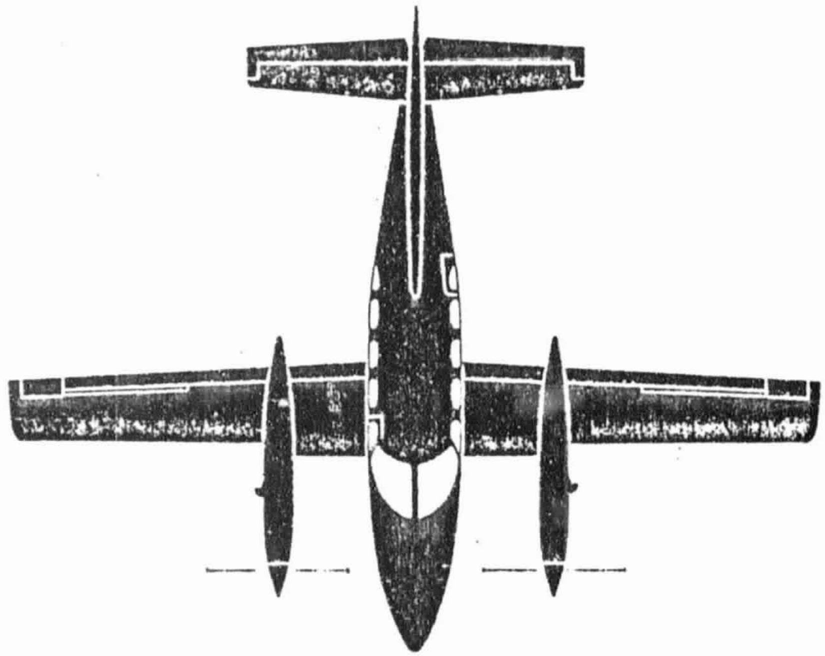
ROTARY TWIN

II FIXED ENGINE SIZE, VARIABLE AIRFRAME, FIXED PAYLOAD-RANGE



	RC2-47	RC2-32
GROSS WT, LB	5788	5454
SPAN, FT	38.1	35.0
ASPECT RATIO	9.8	8.45

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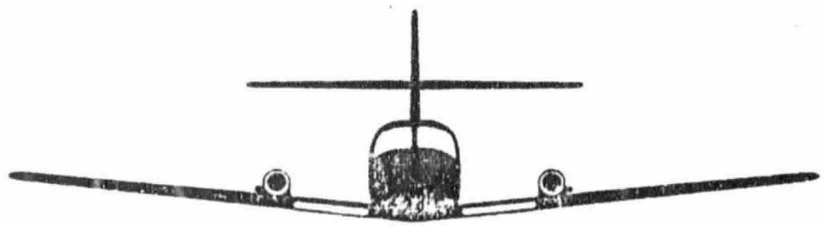

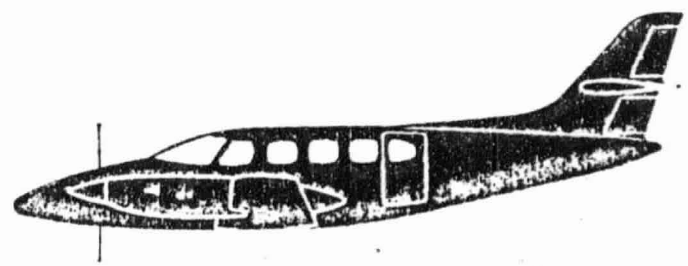

Figure 27

RC 2-32 HIGHLY-ADVANCED ROTARY ENGINE
TWIN-ENGINE INSTALLATION CONCEPT

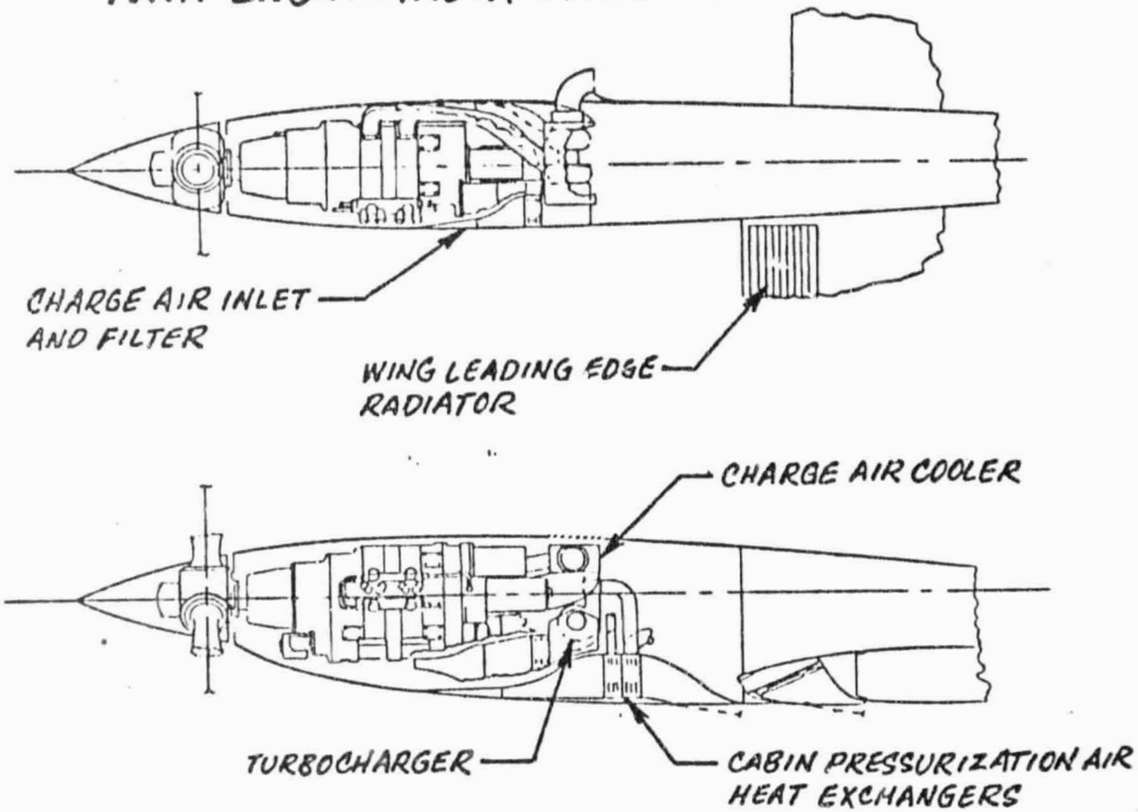

Figure 28

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WRIGHT AIRCRAFT ENGINE PERFORMANCE

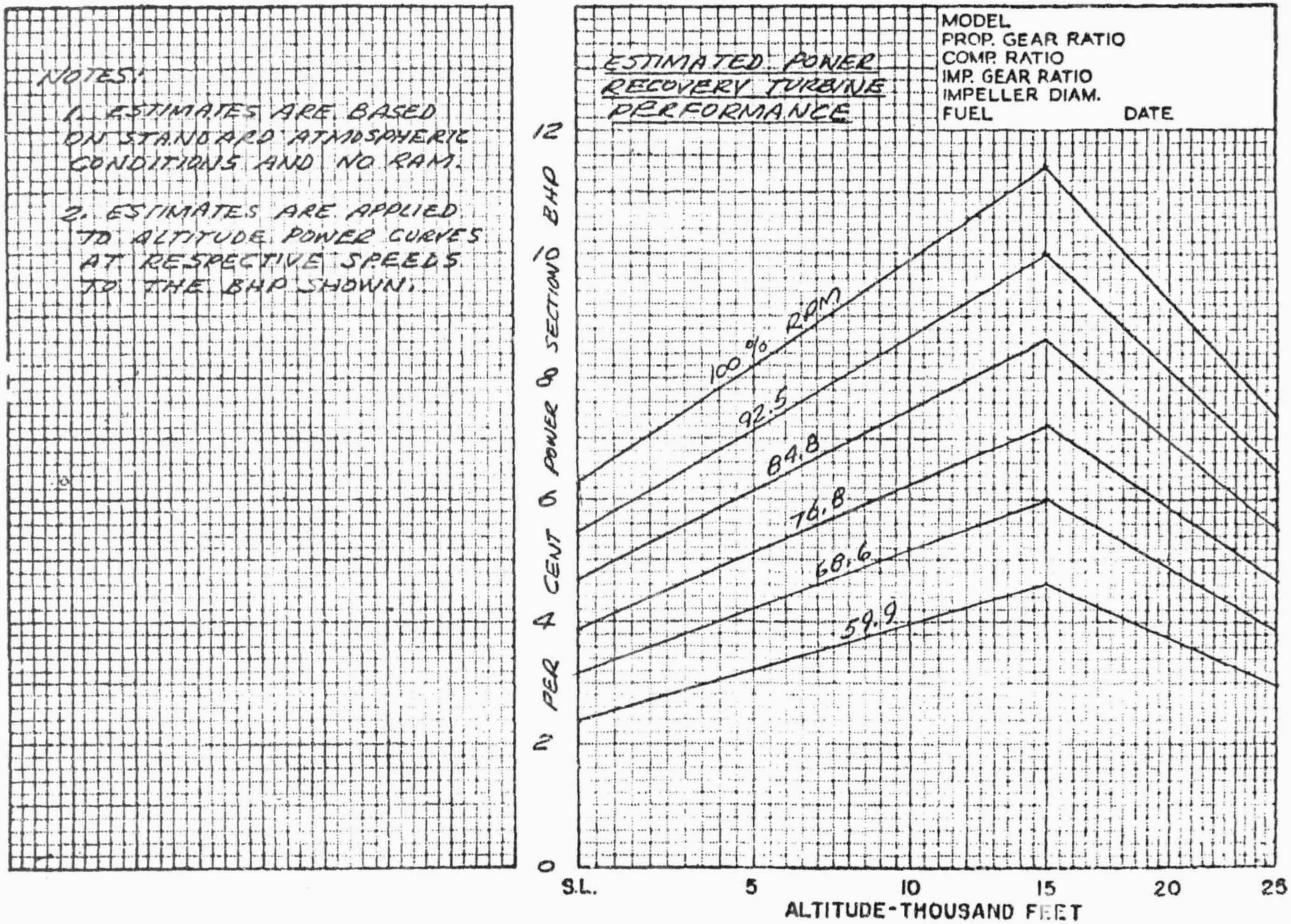

Figure 29

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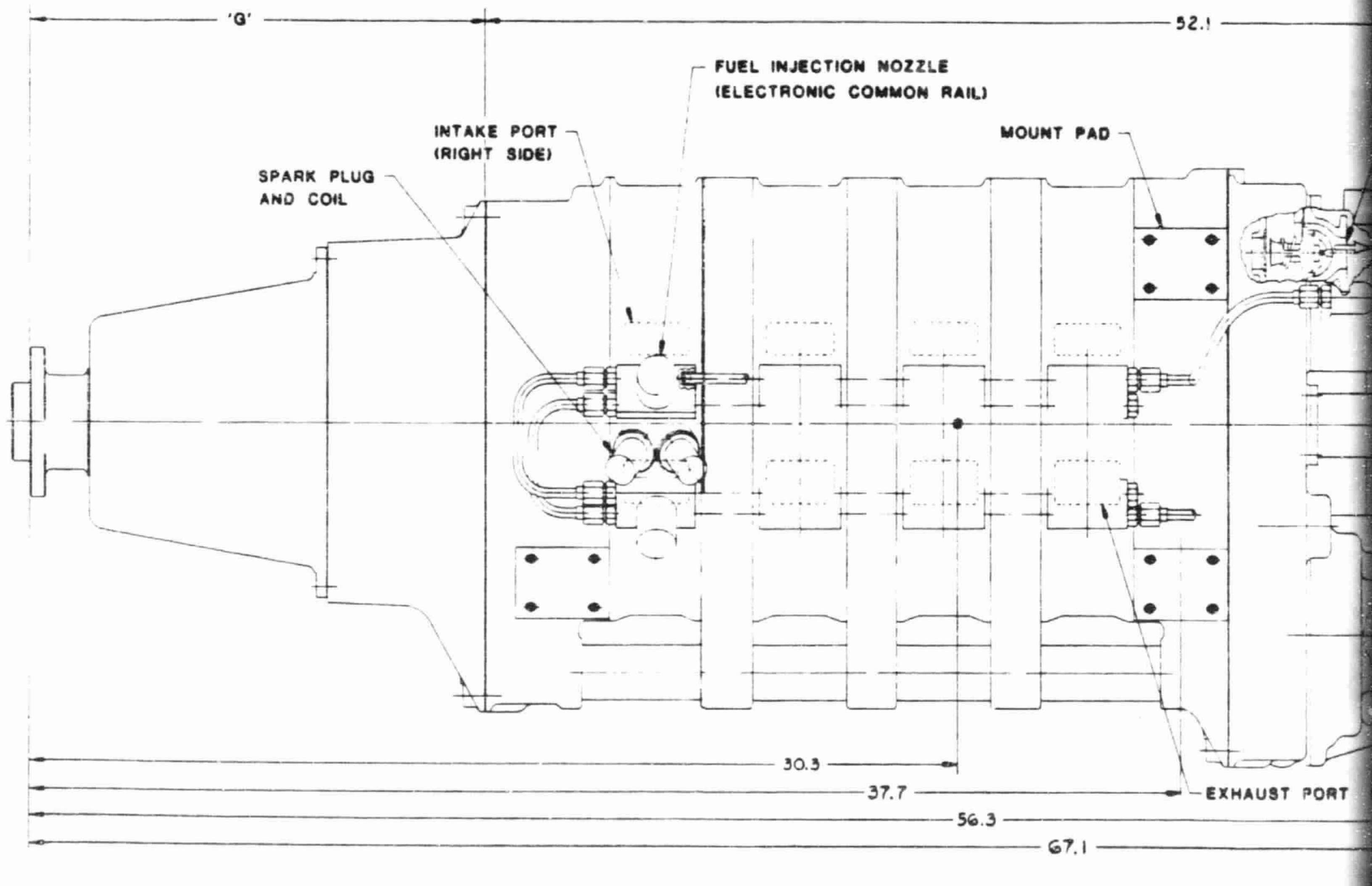

LEFT SIDE VIEW

FOLDOUT FRAME

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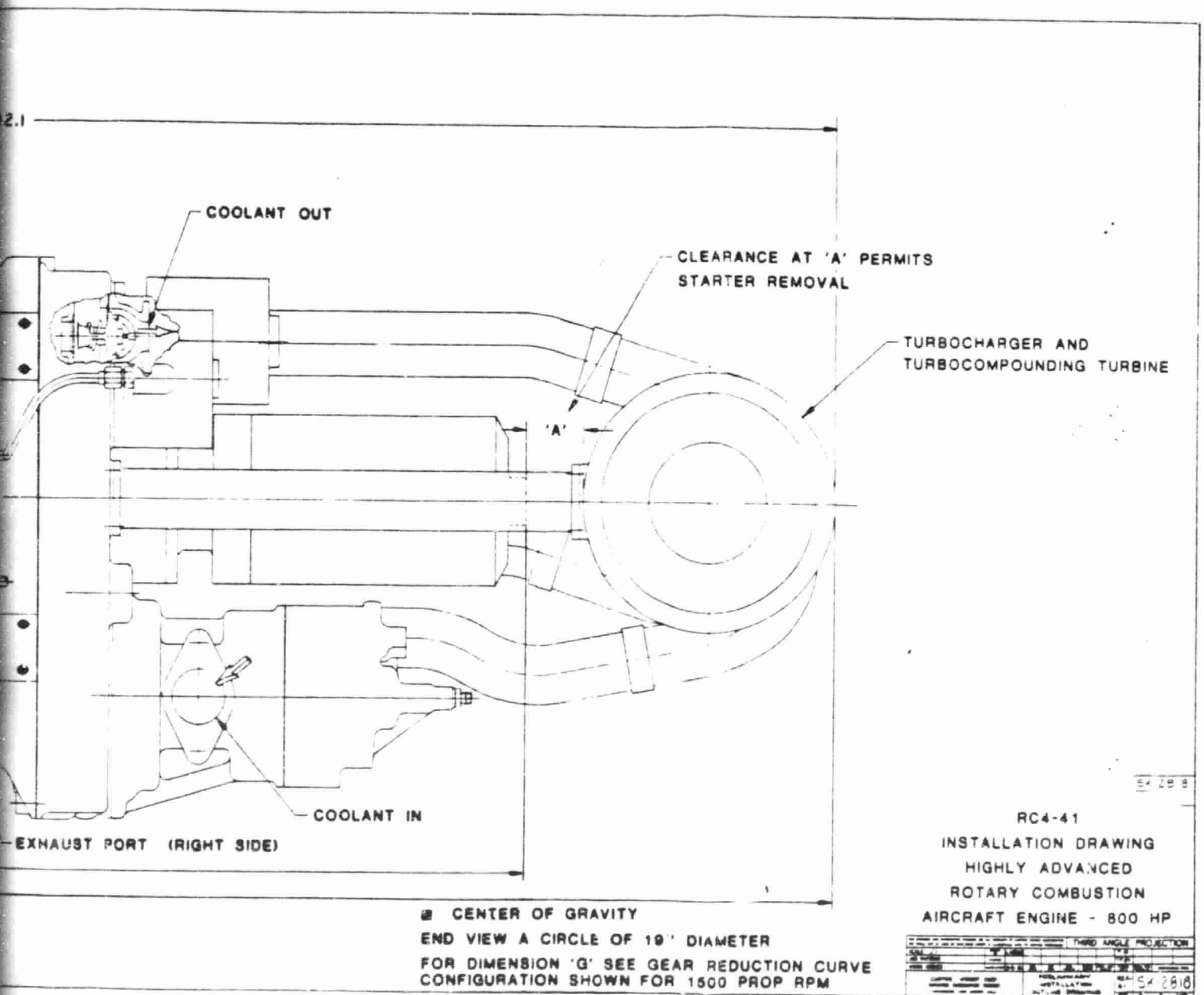

Figure 30

2 FOLDOUT FRAME

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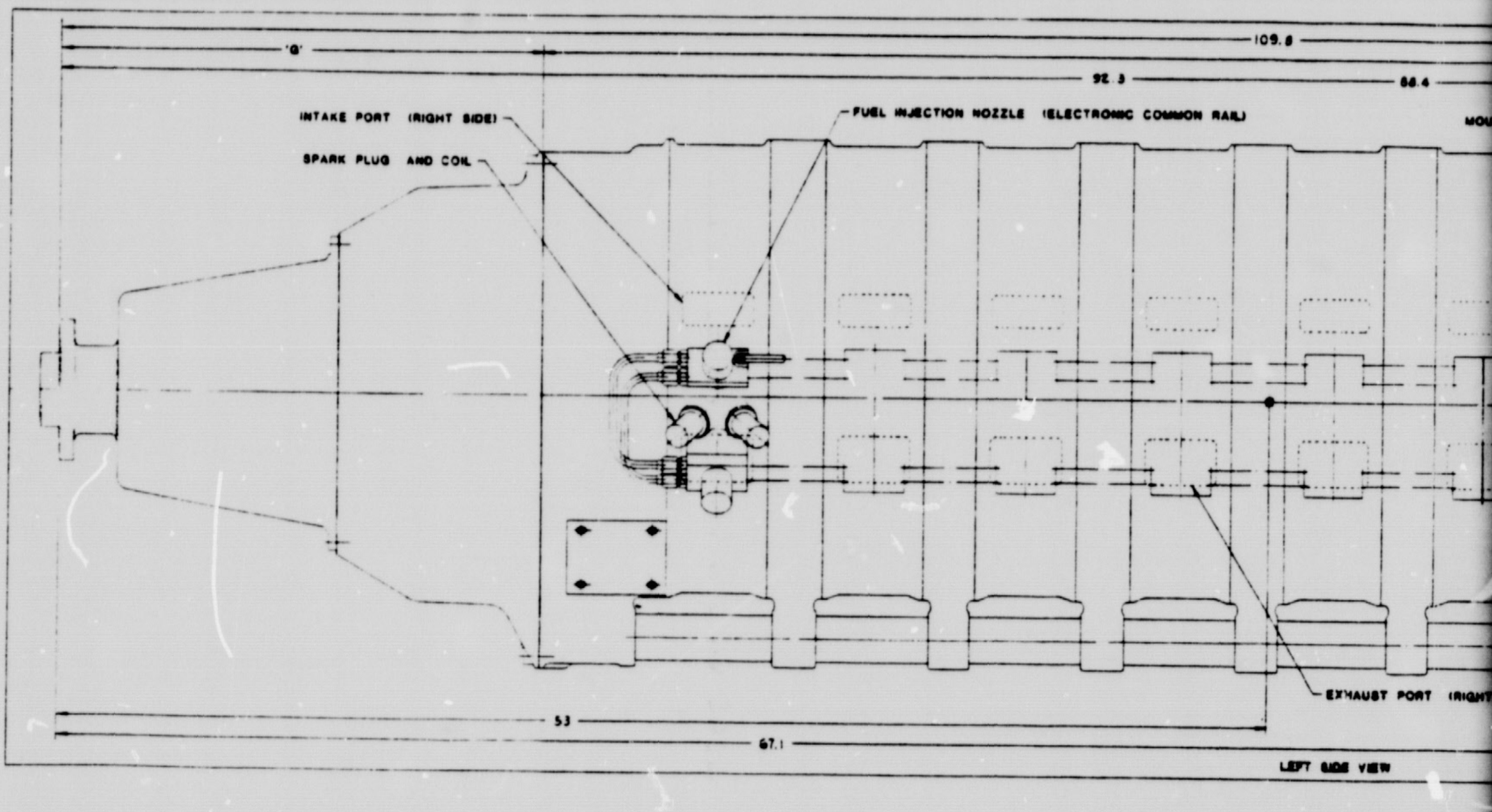

FOLDOUT FRAME

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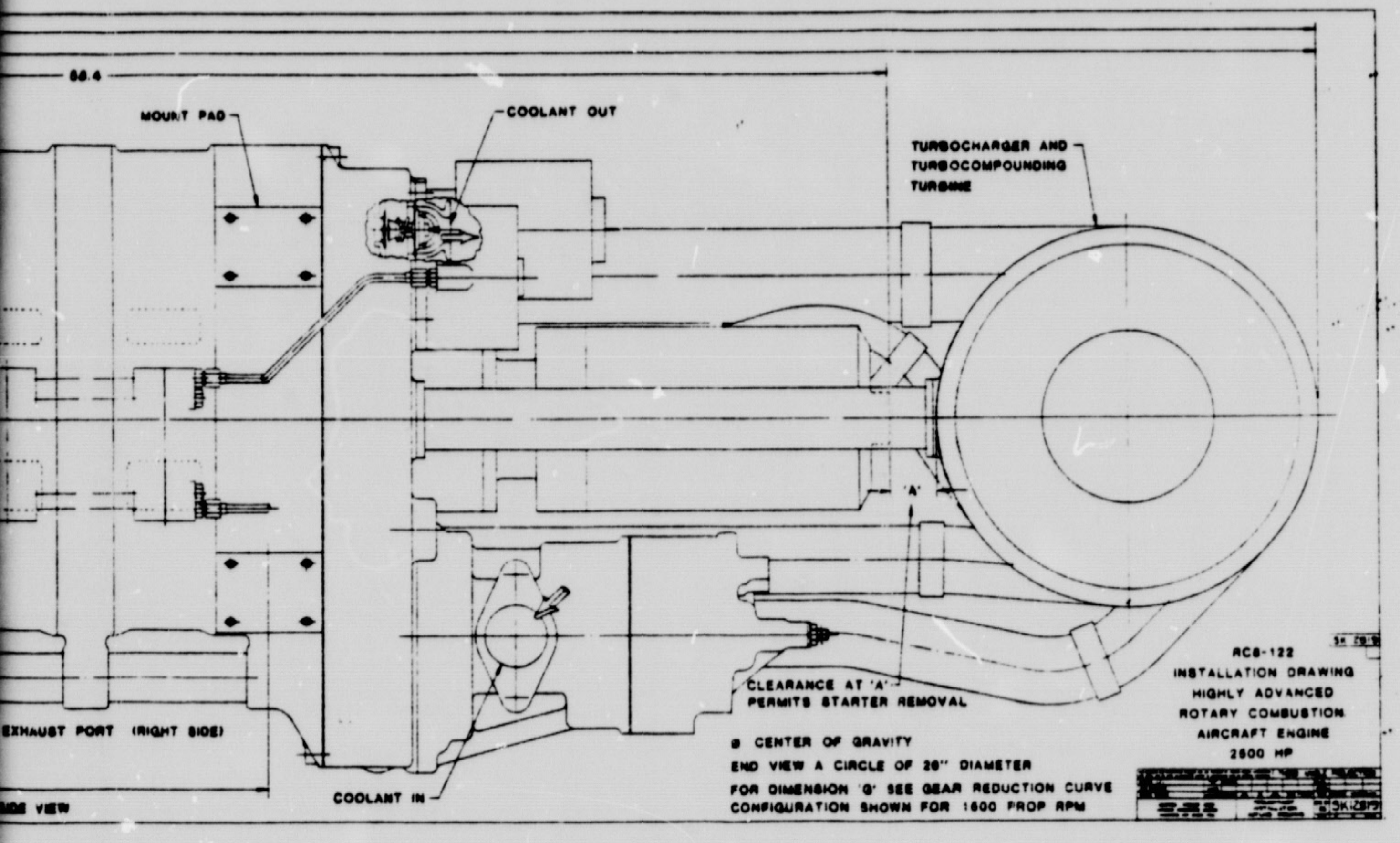

Figure 31

2 FOLDOUT FRAME

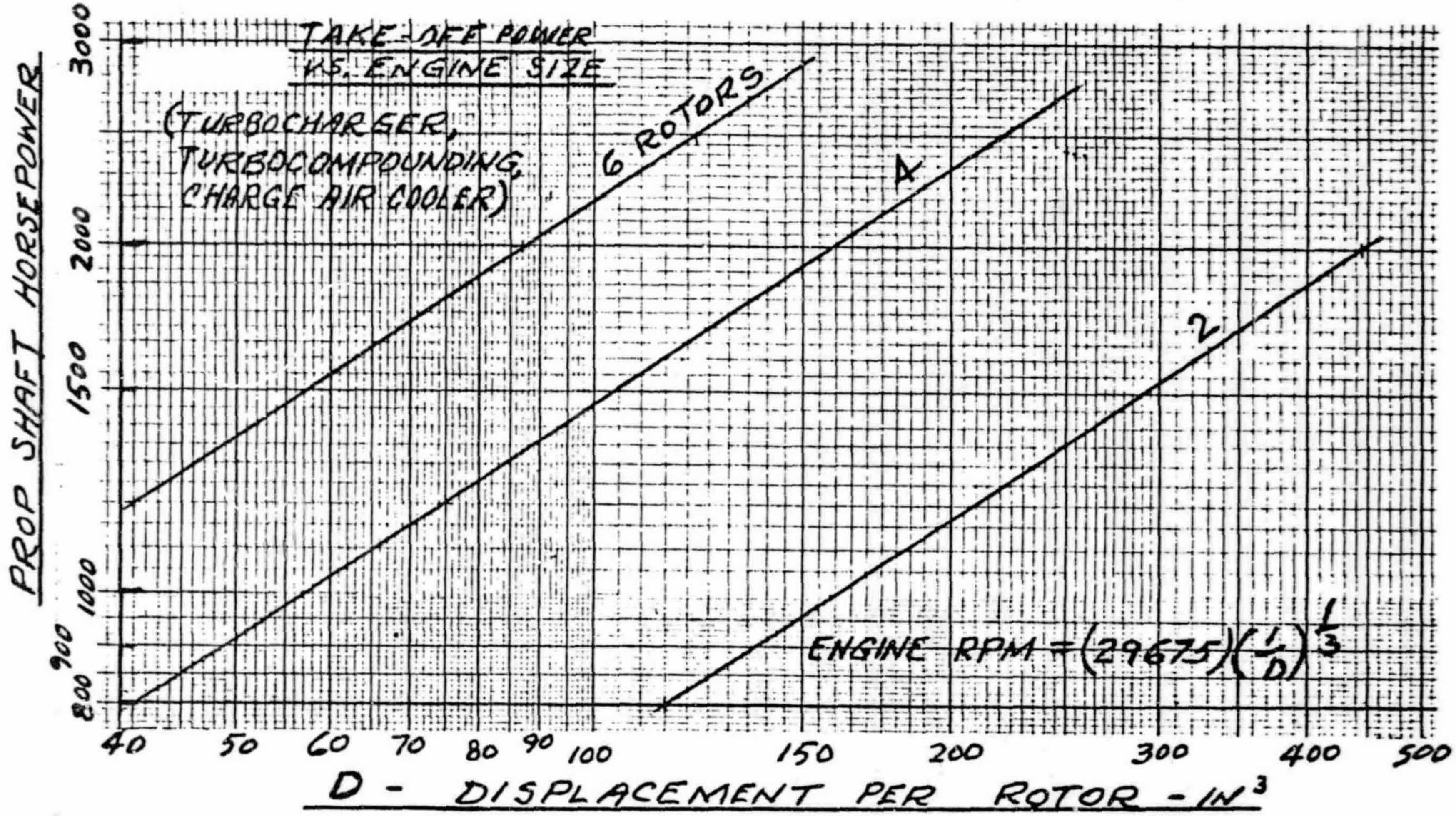

Figure 32

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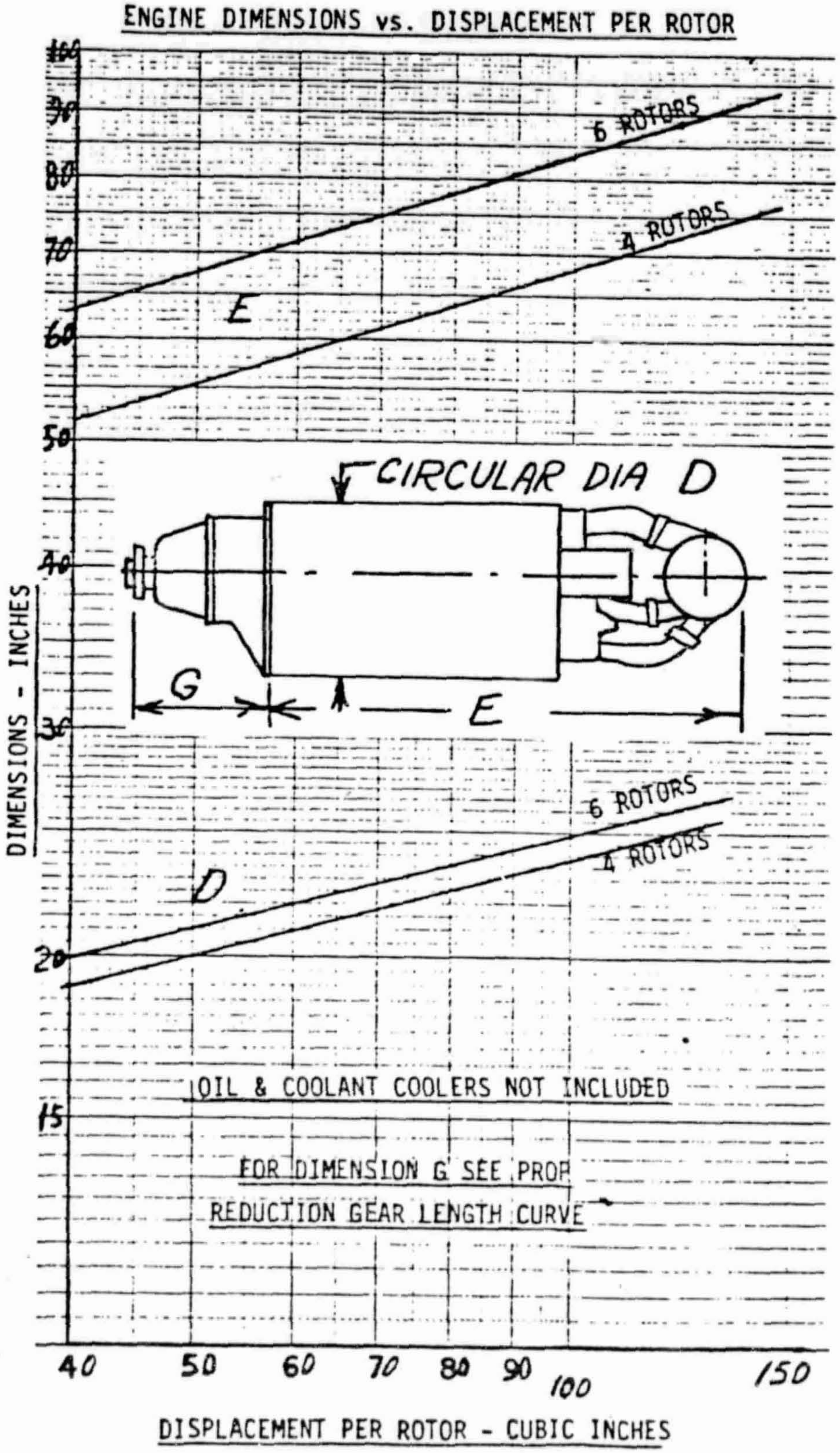

Figure 33

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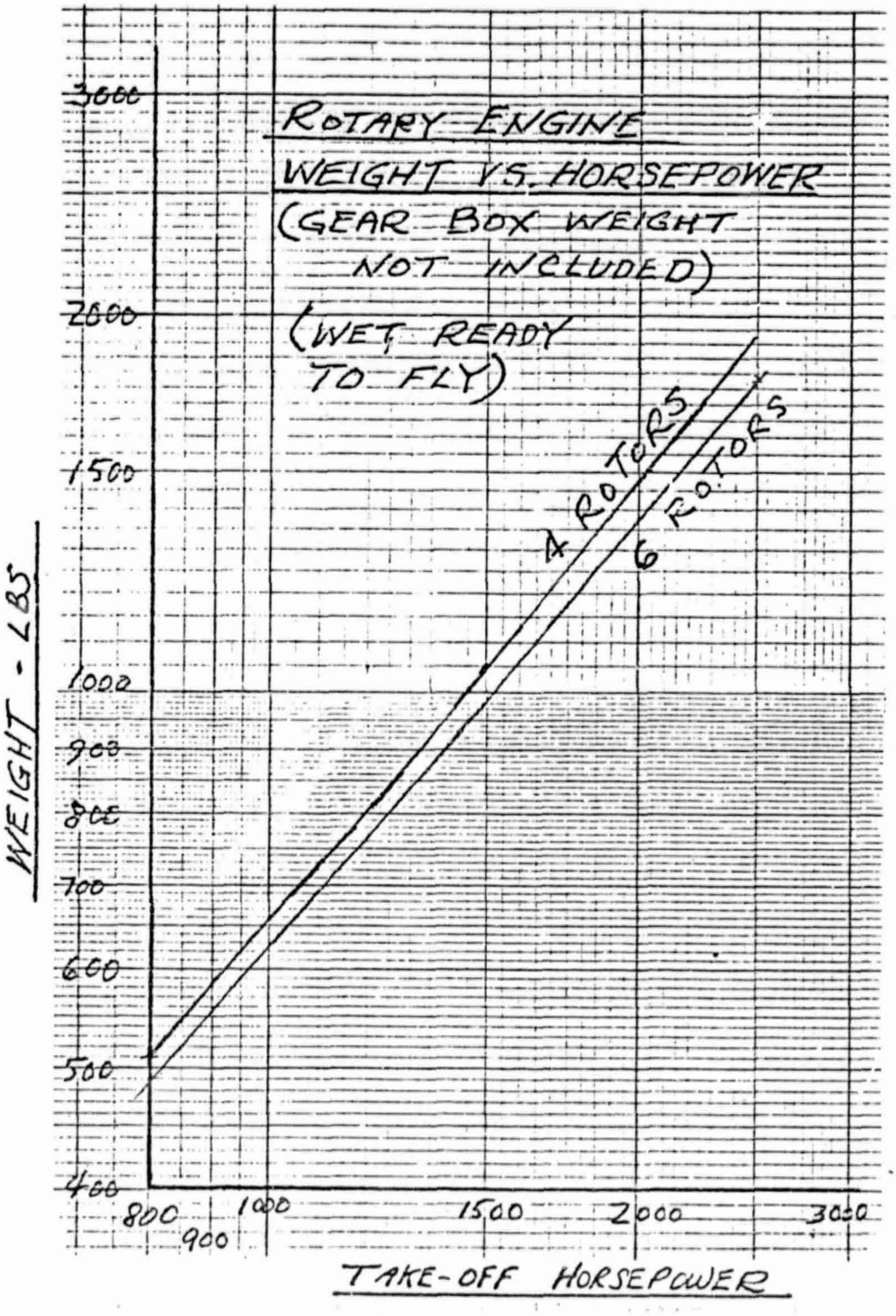

Figure 34

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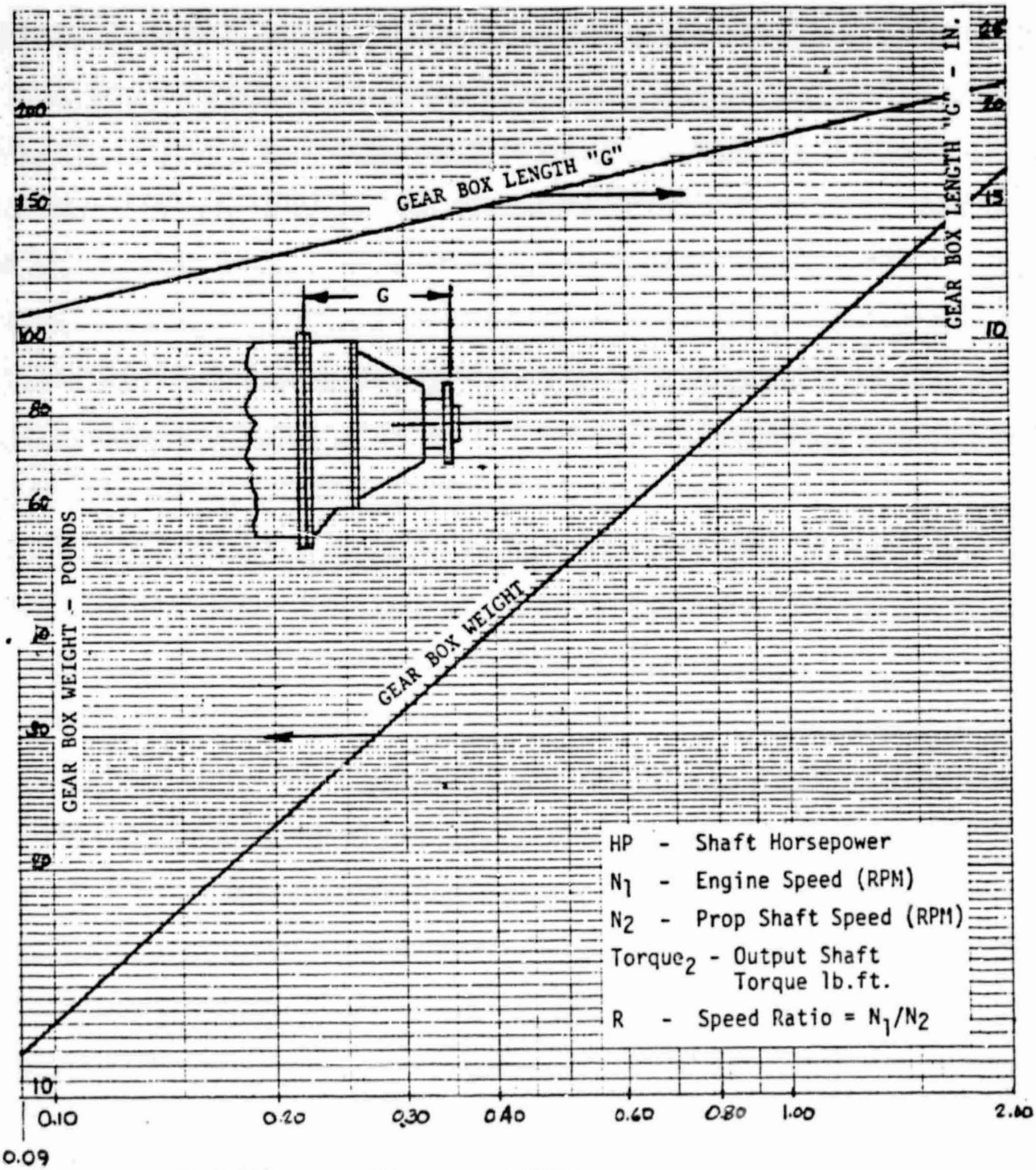
INTEGRAL PROP REDUCTION GEAR BOX

LENGTH & WEIGHT vs. OUTPUT TORQUE



$$\frac{HP \times (R)}{N_1} = \frac{HP}{N_2} = \frac{TORQUE_2}{5252}$$

Figure 35

BASIC ENGINE DATA

250 CRUISE HP AT 25,000 FT.

	TSIO-550	Advanced RC2-47	Highly Advanced RC2-32
Length (")	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

Table I

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AIRPLANE COMPARISONS

		SINGLE ENGINE			TWIN ENGINE		
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	dW	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	3381	3691	6850	5788	5454
WING AREA	sqm	15.8	13.7	13.0	16.7	13.7	13.5
	sqft	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	193	236	249	312	384	408
AT 25000′	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	KTS	61	61	61	73	74	73
CRUISE	km/hr	382	420	424	424	465	467
SPEED	KTS	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	337	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 II

GEOMETRIC DATA

(In Inches)

HORSEPOWER	800	2,500
SIZE	RC4-41	RC6-122
SPEED, RPM	8,600	5,980
ECCENTRICITY E	.61	.88
ROTOR WIDTH W	3.05	4.39
TROCHOID MAJOR AXIS	9.64	13.85
TROCHOID MINOR AXIS	7.2	10.35
NUMBER OF ROTORS	4	6
DISPLACEMENT PER ROTOR	41	122

Table III

1200 BHP

RC4-81 (81.15)

OPERATING DATA SUMMARY

	Take Off Sea Level	70% Cruise 15,000 Ft. Altitude
WITHOUT TURBOCOMPOUNDING		
BHP	1,200	840
RPM (Crankshaft)	6,904	5,305
IMEP, PSI	244.11	217.82
IHP	1,381.43	947.10
FMEP, PSI	32.06	24.63
FHP	181.43	107.10
BMEP, PSI	212.05	193.19
Fuel/Air Ratio	.04	.04
BSFC, Lb/BHP-Hr.	.3586	.3529
Airflow, Lb/Hr.	10,757	7,410
Compressor Press. Ratio*	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)	1,200	840
BHP (RC4-81)	1,275.6	900.5
BSFC, Lb/BHP-Hr.	.3373	.3292

* Before 2% intercooler pressure drop. Assumes intercooler effectiveness of 50% and compressor efficiency of 70%.

Table IV

2000 BHP

RC6-95 (94.87)

OPERATING DATA SUMMARY

Standard Day - No Ram

	Take-Off Sea Level	70% Cruise 15,000 Ft. Altitude
WITHOUT TURBOCOMPOUNDING		
BHP	2,000	1,400
RPM (Crankshaft)	6,553	5,035
IMEP, PSI	244.11	217.88
IHP	2,299.93	1,577.05
FMEP, PSI	31.84	24.46
FHP	299.93	177.05
BMEP, PSI	212.26	193.42
Fuel Air Ratio	.04	.04
BSFC, Lb/BHP-Hr.	.3582	.3526
Airflow, Lb/Hr.	11,938	8,224
Compressor Press. Ratio*	2.17	4.15
Eng. Inlet Temperature, ^{o}F	149.8	170.2
Eng. Inlet Pressure, PSI	31.2	33.72
WITH TURBOCOMPOUNDING		
BHP (RC6-87)	2,000	1,400
BHP (RC6-95)	2,126	1,500.8
BSFC	.3361	.3289

* Before 2% intercooler pressure drop. Assumes intercooler effectiveness of 50% and compressor efficiency of 70%.

Table V