NASA Contractor Report 165399

(NASA-CR-165399) STUDY OF ADVANCED ROTARY COMBUSTION ENGINES FOR COMMUTER AIRCRAFT Final Report (Curtiss-Wright Corp.) 58 p
HC A04/MF A01 CSCL 21E
N83-17545
Unclas
G3/07 02805

STUDY OF ADVANCED ROTARY COMBUSTION ENGINES FOR COMMUTER AIRCRAFT

M. Berkowitz, C. Jones, and D. Myers

Curtiss-Wright Corporation
Wood-Ridge, New Jersey 07075

February 1983

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract NAS 3-22140

TABLE OF CONTENTS

Page No.

INTRODUCTION

Goals and Approach

The stratified-charge rotary engine is an attractive alternative engine candidate for future commuter aircraft since it can burn a broad range of diesel, kerosene and gasoline-type fuels very efficiently. Its well-known advantages of broad fuel tolerance and good fuel economy, coupled with the weight and package-volume reductions achievable via advanced design and technology, suggest that a stratified-charge rotary engine could be a competitive powerplant for commuter type aircraft.

The goal of this effort was to provide performance, weight, size, and maintenance data for advanced rotary aircraft engines suitable for computerized comparative aircraft system evaluation studies of alternate engine candidates. At the moment, there are no aircraft rotary engines made that are suitable for commuter aircraft. Therefore, hypothetical engines were defined (an RC4-74 at 895 Kw and an RC6-87 at 1490 Kw) based on the same new technologies and design approaches used in the "Highly Advanced" engine of the Reference 3 engine study. The data provided covers the size range of shaft power from 597 Kw (800 HP) to 1865 Kw (2500 HP) and is in the form of drawings, tables, curves and written text. These include data on internal geometry and configuration, installation information, design features and new technologies, engine cooling, fuels, scaling for weight-size-BSFC and heat rejection for varying horsepower, engine operating and peformance data, and TBO and maintenance requirements.

The market introduction goal for these engines was assumed to be the early 1990's.

Characteristics of the Direct Injected Stratified Charge Engine

Stratified charge engines burn leaner (More air in relation to the quantity of fuel) fuel-air mixtures than conventional spark ignited internal combustion engines. The direct injected unthrottled rotary engine is the only stratified charge engine variation which can operate as lean as a diesel, and achieve automotive diesel fuel efficiency levels. To do this throughout the complete operating range a varying air velocity field must be induced to allow the injected fuel to be effectively stratified so that an ignitable mixture of fuel and air is consistently developed at the spark plug where the "triggering" combustion is initiated, with a significantly leaner mixture ratio at all other points in the combustion chamber.

The Rotary Stratified Charge Engine offers high power density because of its compact geometry and related kinematics which are uniquely compatible to direct injected stratified charge combustion. 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 fuel injection nozzles, as an inherent function of its geometry (Figure 1.0.0). This develops the necessary flow distribution for stratification without the added price of friction and pumping losses exacted from a reciprocating engine in which this flow pattern must be generated.

STRATIFIED CHARGE ROTARY ENGINE

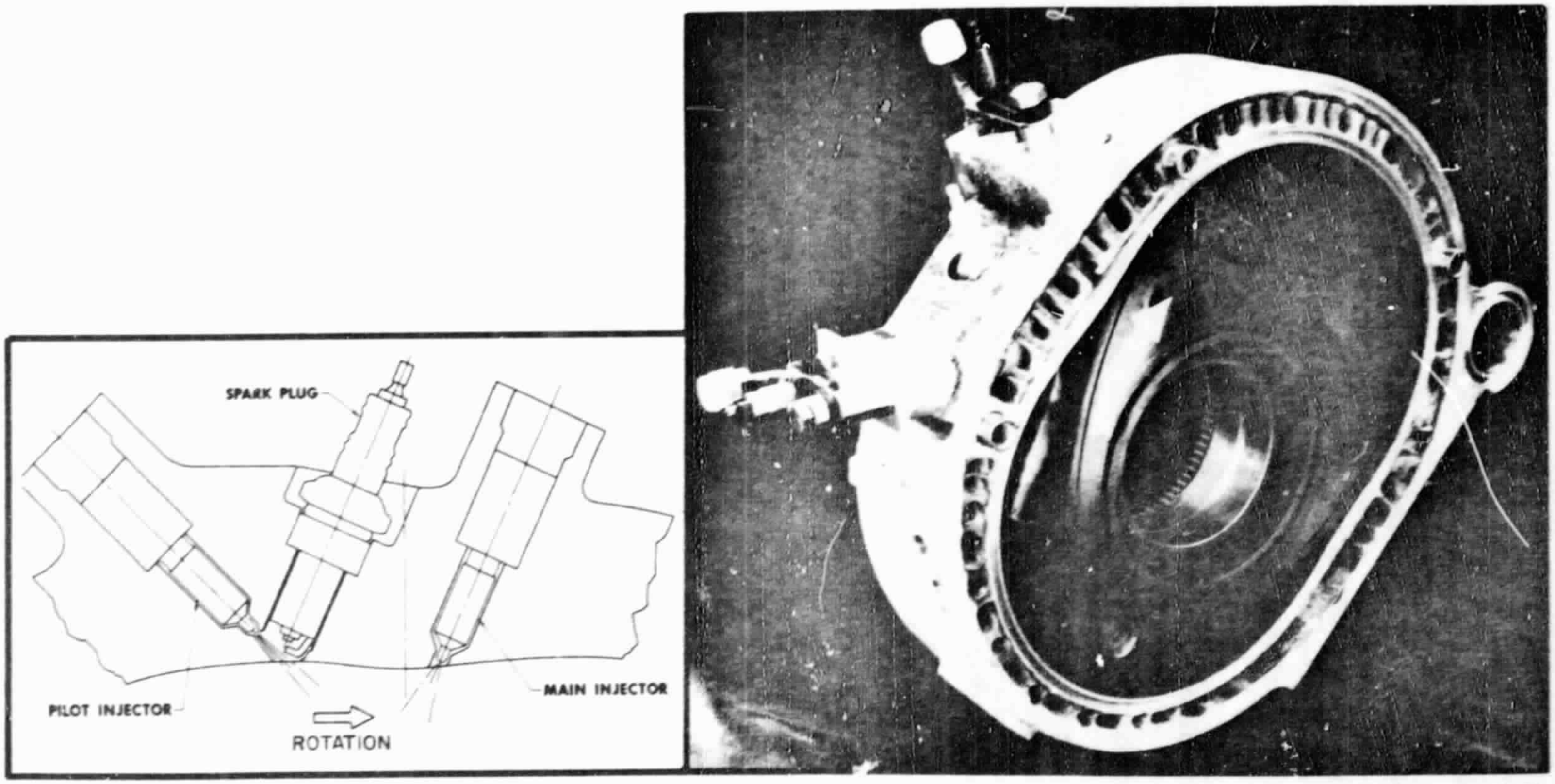


Figure 1.0.0

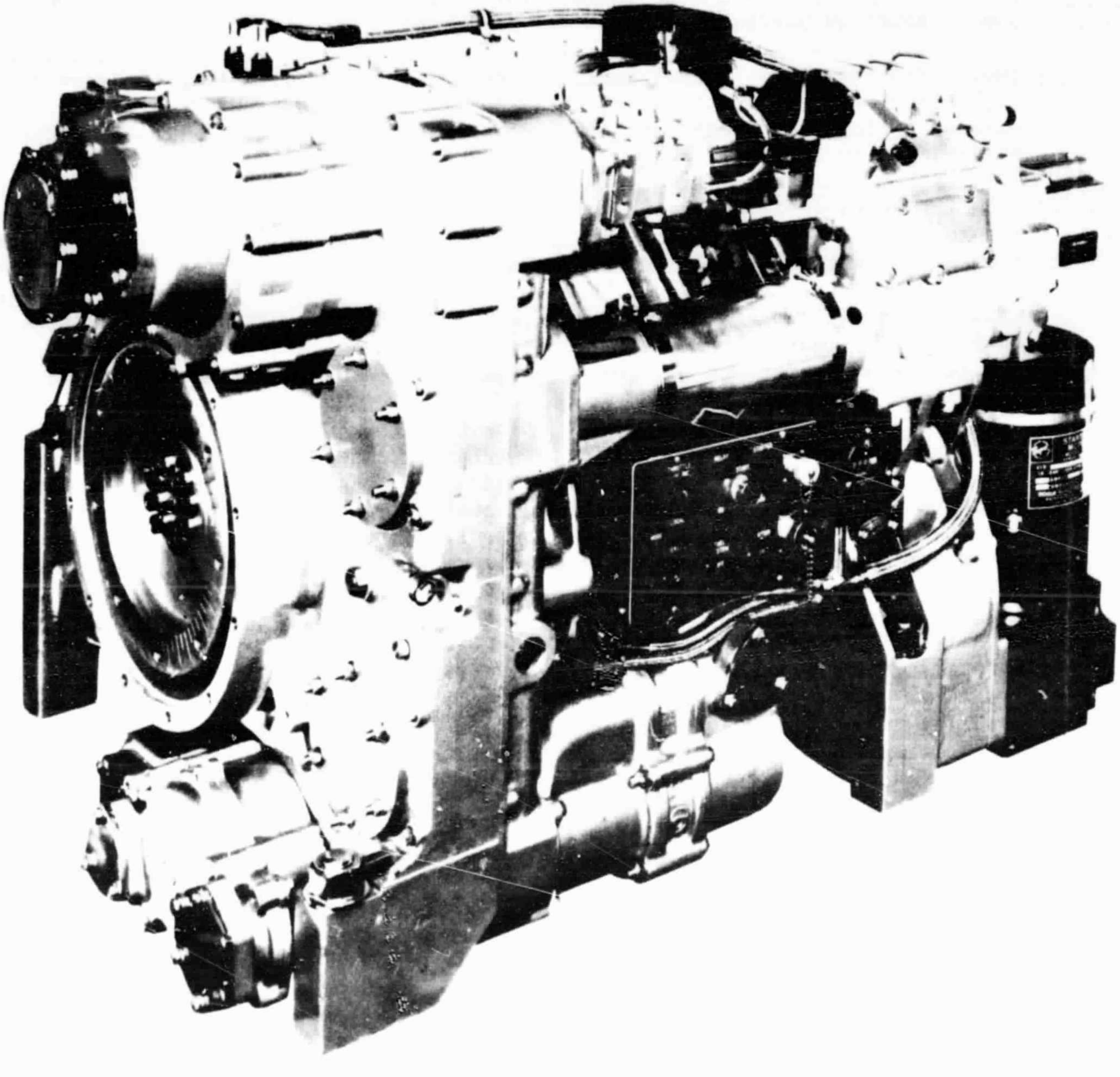
Multi-fuel capability is obtained by direct fuel injection at the approximate combustion rate, again facilitated by the manner in which the combustion chamber form varies with shaft rotation, and spark ignition. Direct injection stratified charge combustion offers broad fuel tolerance over the full speed and load range. This engine has shown essentially the same combustion performance (from all important points of view, including fuel consumption on a BTU basis, power and emissions) on gasoline, jet engine fuel (JP-4 and JP-5), diesel fuel, and methyl alcohol, without a hardware 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 for the fuels mentioned.

Completed development programs have demonstrated that an automotive sized rotary engine 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 (Reference 4), the prognosis for low particulate emission levels (Reference 5) was favorable.

During the last several years all rotary (Wankel-type) engine technology research in the United States has been directed at stratified charge direct chamber injection. During this period, successive improvements (Reference 2) resulted in an efficient multi-fuel combustion configuration which has been incorporated in a relatively large displacement military vehicle powerplant being developed for the United States Marine Corps. This engine, the RC2-350 (Figure 1.0.1) with two rotors of 350 cubic inches each, can produce over 750 HP naturally aspirated. It represents the baseline for the projected highly advanced engines in this study.

The same basic technology, which was defined in a smaller single rotor research rig (an RC1-60, which has one rotor of $60''^3$ displacement) is applicable to a wide range of engine sizes and engine applications. As a result of design studies performed under NASA Contract NAS 3-21285 (Reference 3), growth directions have been defined for highly advanced turbocharged engines. On this basis the growth potential for the RC2-350T is shown in Tables 1.0.2 and 1.0.3.

ORIGINAL PAGE IS
OF POOR QUALITY



Curtiss-Wright Rotary Combustion Engine
Stratified Charge Model RC2-350

Figure 1.0.1

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 1.0.2*

RC2-350T GROWTH POTENTIAL - TURBOCHARGED/MULTI-FUEL

PERFORMANCE

CONFIGURATION	STANDARD	ADVANCED	HIGHLY ADVANCED	HIGHLY ADVANCED (BSFC FAVORED)	HIGHLY ADVANCED EXTREME HIGH SPEED, RETRACTING SEALS
BHP	750	1440	1780	1300	2200
RPM (MAX.)	3600	4300	4800	3600	7200
BMEP (MAX.)	117	187	208	202	172
BSFC @ MAX. HP	.40	.40	.375	.35	.42
BSFC @ 50% POWER	.39	.37	.35	.34	.38
IDLE (NO LOAD) FUEL FLOW, GAL./HR.	1	1	1	1	1

* The values shown are for fuels with a lower heat of combustion of 18,400 BTU/LB. With negligible variation this includes gasoline, jet engine fuel (JP-4 and JP-5) and diesel fuel.

The growth potential values shown in Tables 1.0.2 and 1.0.3 were arrived at by assuming (1) that acceptable cost and durability could be achieved for the increased RPM and BMEP levels shown in the table, and (2) improvements in mechanical and thermal efficiencies could be realized. These higher operating values will increase bearing loads, apex seal/trochoid durability problems, and thermal and mechanical loads. The basis for accommodating these values were data from Curtiss-Wright's rotary engine development testing experience, the improvements from new technologies described in design studies performed under NASA Contract NAS 3-21285 (Reference 3), and the assumption that a new technology enablement program would be carried out.

TABLE 1.0.3

RC2-350T GROWTH POTENTIAL - TURBOCHARGED/MULTI-FUEL

ENVELOPE AND WEIGHT

CONFIGURATION	STANDARD	ADVANCED	HIGHLY ADVANCED	HIGHLY ADVANCED (BSFC FAVORED)	HIGHLY ADVANCED EXTREME HIGH SPEED, RETRACTING SEALS
BHP	750	1440	1780	1300	2200
LENGTH - IN.	44	44	44	44	44
WIDTH - IN.	40	41	42	41	43
HEIGHT - IN.	29.5	29.5	29.5	29.5	29.5
WEIGHT (DRY) - LBS.	1206	1285	1150	1011	1200
SPECIFIC WEIGHT - LBS./HP	1.61*	0.89	0.65	0.78	.55
VOLUME - FT.^{3}	30.0	30.8	31.5	30.8	32.3
HP/FT.^{3}	25*	47	56	42	68

* NATURALLY ASPIRATED "STANDARD" VERSION SPECIFIC WEIGHT IS 1.47 LBS./HP, AND HP/FT^3 = 33.3. VALUES SHOWN IN TABLE FOR TURBOCHARGED "STANDARD" VERSION REFLECT USE OF TURBOCHARGER TO PROVIDE LEANER FUEL/AIR RATIOS TO IMPROVE BSFC, WITHOUT INCREASING POWER.

ENGINE DESIGN DESCRIPTION

Configuration

The projected commuter aircraft engines are turbocharged turbocompounded stratified charge rotary aircraft engines.

The preparation of a longitudinal section drawing of an engine was not included in this contract effort. The sectional drawing of the "Highly Advanced" RC2-32 Rotary Combustion aircraft engine (320 BHP) from Reference 3 is included as Figure 2.0.0 since most of its approaches and arrangement also apply to the larger rotary commuter aircraft engines. The relationship of the integral propeller gear reduction, power section, and accessories has been tailored toward a "cigar" shape with minimum frontal area to minimize drag in externally mounted installations.

Figures 2.0.1 and 2.0.2 are the installation drawings for the RC4-41 (800 HP) and RC6-122 (2500 HP) engines.

The contract Statement of Work has specified parametric designs of 1200 and 2000 shaft horsepower engines, and generalized scaling data for ± 25% of the rated horsepowers. It was decided to depict the range extremes of 800 and 2500 horsepower engines for the simplified installation drawings, since arrangement aspects having to do with the number and size of rotors, and the power section size relative to the accessory package could cause step variations instead of smoothly continuous curves.

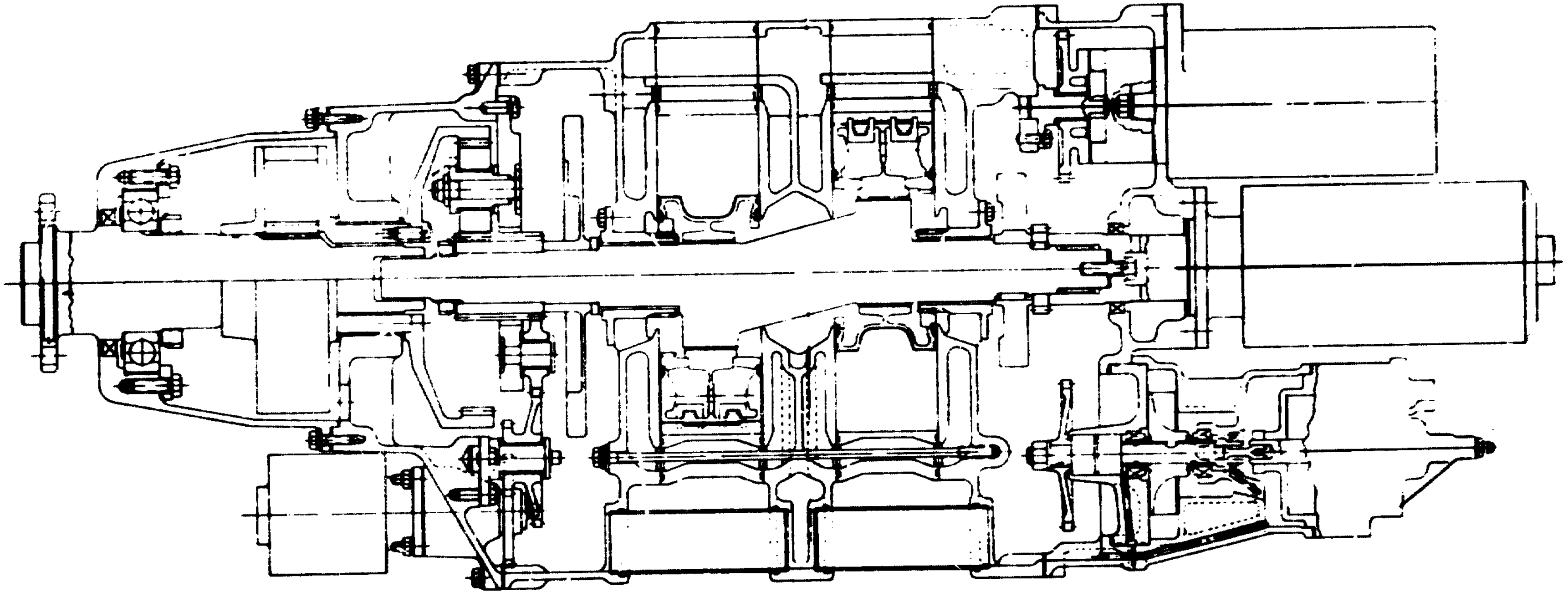
The geometric data for the two engines in Figures 2.0.1 and 2.0.2 are listed in Table 2.0.0.

TABLE 2.0.0

GEOMETRIC DATA
(In Inches)

Horsepower	800	2500
Size	RC4-41	RC6-122
Speed, RPM	8600	5980
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

The geometric proportions (shown in Figure 2.0.0) particularly rotor width to eccentricity ratio (w/e), were selected to permit high speed operation without detrimental shaft deflection or stresses above the elastic limit; in addition, a relatively light rotor furthers these goals. The unbalanced moment resulting from the rotors and eccentric mass is removed by counterweights at each end of the engine, with the propeller end counterweight integral with a small flywheel. The engine is fully balanced, statically and dynamically. The rotor shown in Figure 2.0.0 is a thin-walled nodular iron casting, with thermally insulated combustion chamber faces to reduce heat loss to the oil.



RC2-32
LONGITUDINAL SECTION
HIGHLY ADVANCED
ROTARY COMBUSTION AIRCRAFT ENGINE

Figure 2.0.0

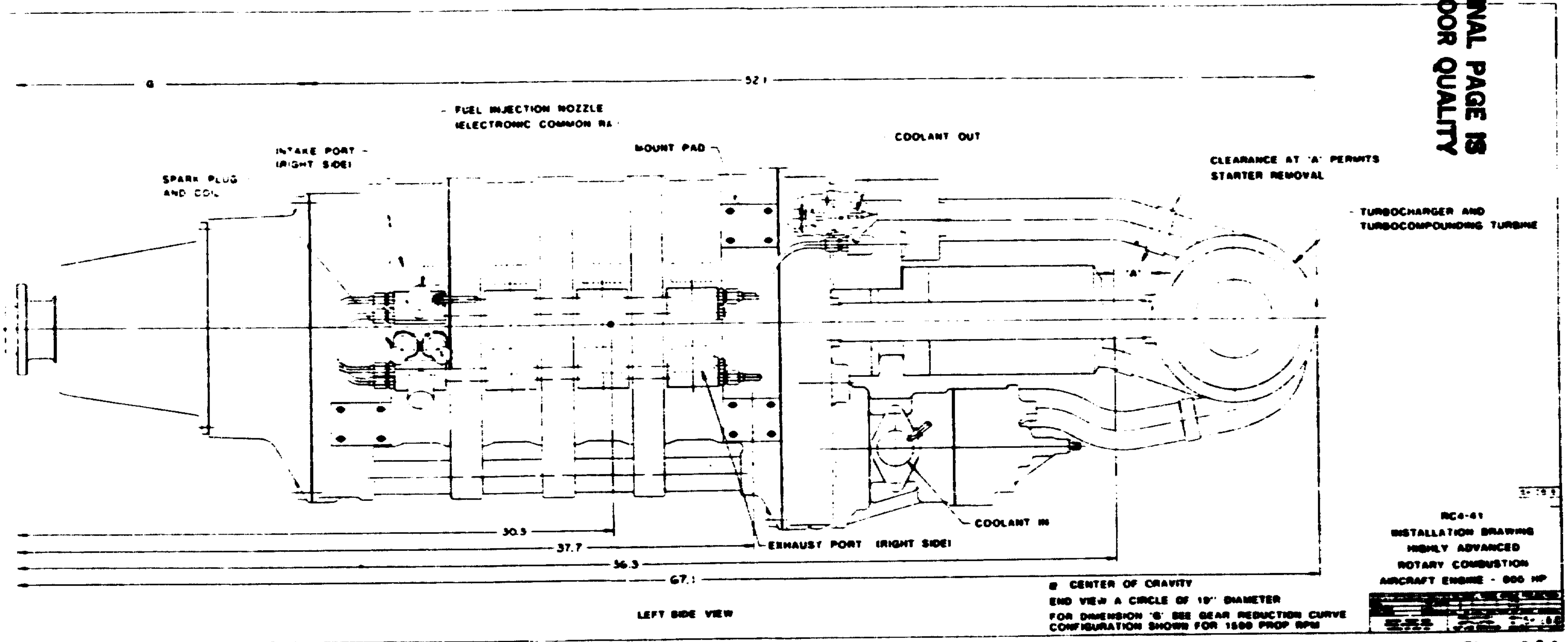

G
52.1
FUEL INJECTION NOZZLE
(ELECTRONIC COMMON RA
INTAKE PORT
(RIGHT SIDE)
SPARK PLUG
AND COIL
MOUNT PAD
COOLANT OUT
CLEARANCE AT 'A' PERMITS
STARTER REMOVAL
TURBOCHARGER AND
TURBOCOMPOUNDING TURBINE
'A'
COOLANT IN
EXHAUST PORT (RIGHT SIDE)
30.3
37.7
36.3
67.1
LEFT SIDE VIEW
⊕ CENTER OF GRAVITY
END VIEW A CIRCLE OF 19" DIAMETER
FOR DIMENSION 'G' SEE GEAR REDUCTION CURVE
CONFIGURATION SHOWN FOR 1500 PROP RPM
RC4-41
INSTALLATION DRAWING
HIGHLY ADVANCED
ROTARY COMBUSTION
AIRCRAFT ENGINE - 800 HP

Figure 2.0.1

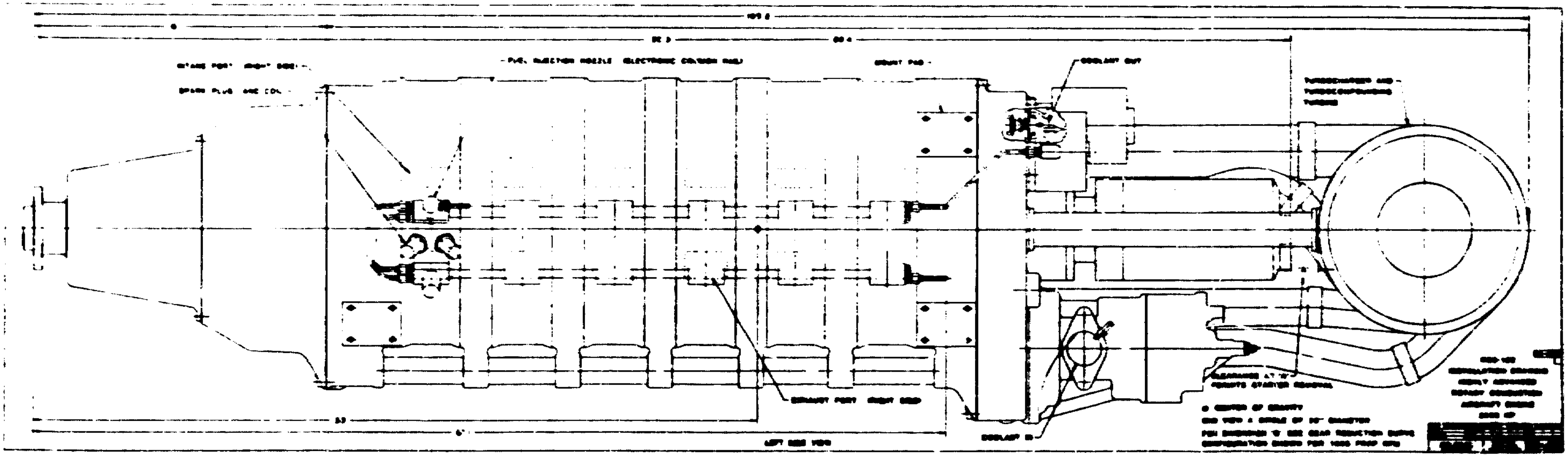

INTAKE PORT (RIGHT SIDE)
SPARK PLUG AND COIL
FUEL INJECTION NOZZLE (ELECTRONIC CONTROL RAIL)
MOUNT PAD
COOLANT OUT
TURBOCHARGER AND
TURBOCOMPOUNDING
TURBINE
EXHAUST PORT (RIGHT SIDE)
COOLANT IN
LEFT SIDE VIEW
CENTER OF GRAVITY

Figure 2.0.2

The internal structure includes a central web and radial ribs, designed to carry differential thermal and pressure loads and to effectively circulate internal oil for cooling. The sealing elements, consisting of apex, side, corner and oil seals, as well as timing gear and bearing, are all part of the rotor assembly. The rotor assembly also includes an inertial mechanism, shown just under the apex seal, to reduce apex seal loading at high operating speeds.

The rotor housings include integral coolant inlet, outlet, and bypass manifolds in a design which allows commonality for engine families of from 1 to 6 rotors. The exhaust gas passage through the rotor housing is provided with an insulating sleeve. This minimizes the heat rejection to the engine coolant. Local housing temperatures are reduced, coolant heat exchanger requirements and cooling drag are reduced, and exhaust energy for turbocharging and turbocompounding is increased.

Oil scavenge is via drain tubes connecting the intermediate and end housings. This dry sump engine has separate scavenge and pressure pumping elements with pressure oil supplied to the end housings and main bearings and then to the rotor journals by drilled holes in the crankshaft. The commuter aircraft engines will have a main bearing in each of the end and intermediate housings while the two rotor engine in Figure 2.0.0 omits the bearing in the intermediate housing.

The torsional isolator shown on the propeller shaft will not be needed on the commuter aircraft engines, which will have 4 to 6 rotors.

The new technology approaches incorporated in the "Highly Advanced" engines presented in this study are as follows:

ORIGINAL PAGE IS
OF POOR QUALITY

Increased IMEP and speed

Turbocharging with intercooling

Turbocompounding

Higher hot strength aluminum casting alloy

Composite lightweight housing materials

Lightweight rotor

Exhaust port thermal liner

Variable displacement pressure oil pump

Provision for counter-rotating propellers

On-board diagnostics

Alternate apex seal/trochoid coating materials

Turbocharger with variable turbine area

Retracting apex seals

Rotor combustion flank insulation

Reduced friction horsepower

Solid-state ignition trigger

Electronic ignition schedule

Independent dual ignition

Multiple power source for ignition

Electronic fuel ignition

Computer timing

Detailed descriptions of these approaches can be found in Reference 3, except for turbocompounding which is described in this report.

Assembly and Internal Engine Differences

One significant respect in which the commuter aircraft engines differ from the general aviation engine in Figure 2.0.0 is that, having more than 2 rotors, the commuter engines' stationary timing gears or the shafts have to be built up from more than one piece for assembly.

The geometry of the 2 rotor engine is such, as can be seen from Figure 2.0.0, that the bore of the timing gear is less than the shaft eccentric O.D. In that case, the gears can be installed at opposite ends of the engine, with both shaft and gear intact, but this is not possible with 3 or more rotors. There are other solutions, such as the internal shaft coupling arrangement used to join two 2-rotor engines, applied in the RC4-350, but this is too heavy an approach for an aircraft engine.

Curtiss-Wright, having built composite shafts for the radial reciprocating engines, has chosen historically to split the gear with their single shaft multi-rotor engines. The most advanced evolution of the split gear approach to be evaluated by test is shown in Figure 2.0.3. The gear halves (either by fracturing after manufacture or splitting before machining the gear teeth), are firmly clamped together by axial wedge segments which simulate an interference fit in the aluminum side housings of as much as .001-.002" per inch of diameter. This system has proven effective, but requires close tolerances.

A lower cost approach consists of replacing the wedges by an actual shrink fit of a sleeve element (Figure 2.0.4). While these cylindrical sections would require machining to remove, this would rarely be required and, in any event, would be less expensive in total. This concept was included in the commuter aircraft engines.

CONE-CLAMPED TWO PIECE GEAR AND BEARING SUPPORT

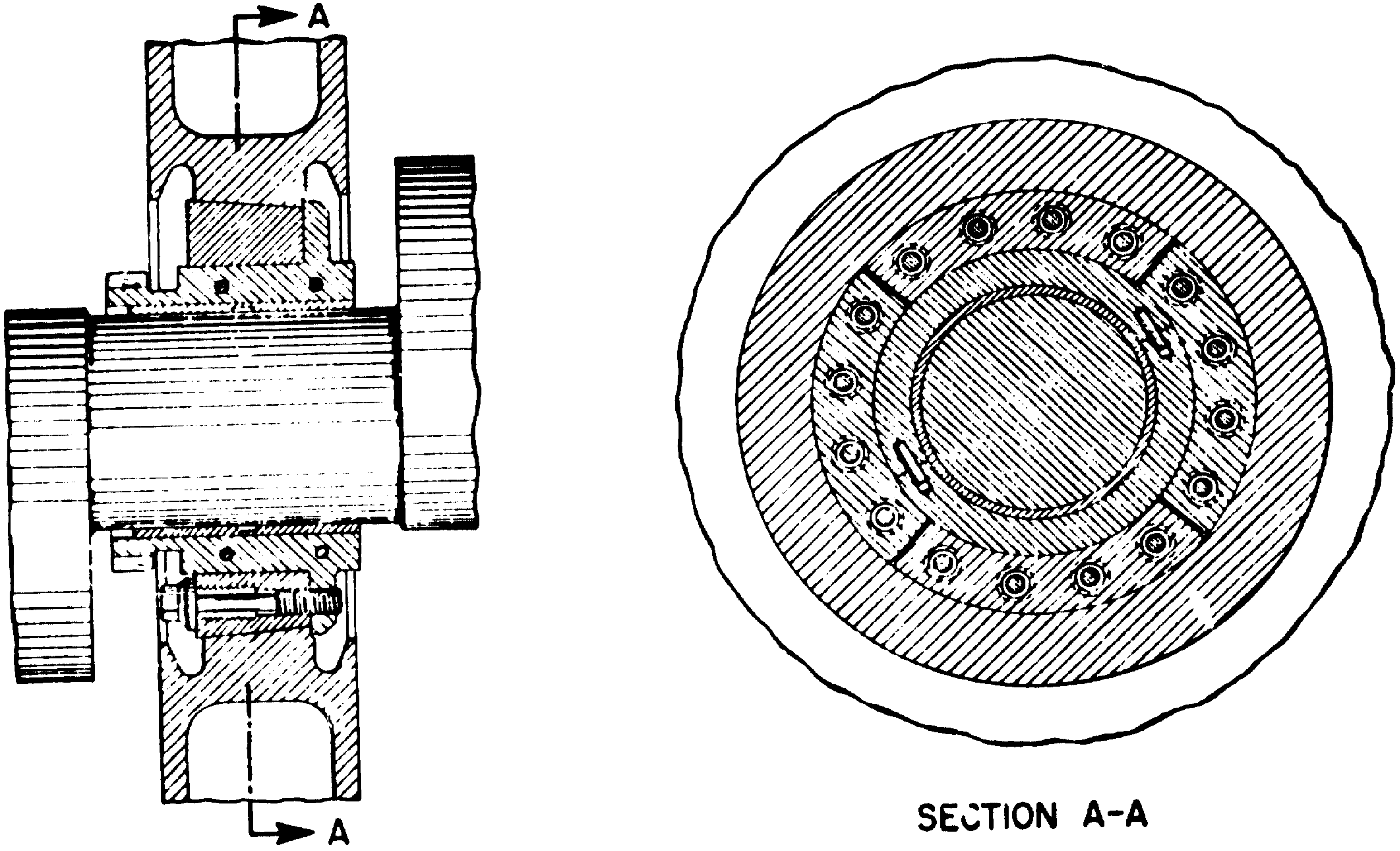
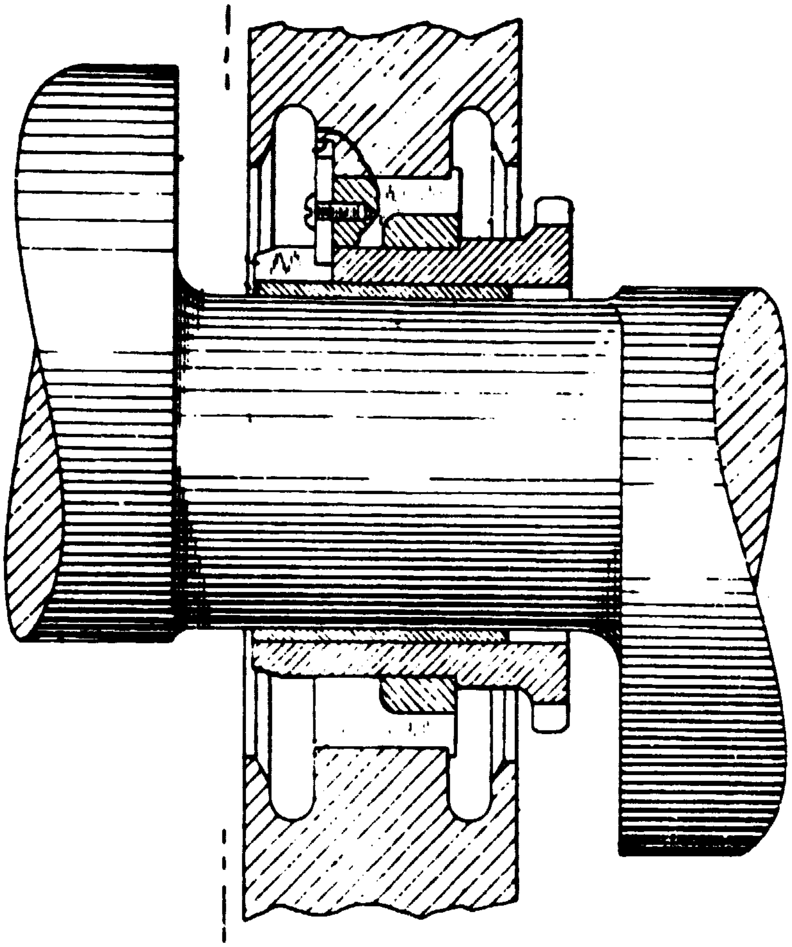


Figure 2.0.3

ORIGINAL PAGE IS
OF POOR QUALITY



REDUCED COST PRESS-FIT SPLIT GEAR AND BEARING SUPPORT

Figure 2.0.4

Except as described above, the engine power section internal configuration is similar to the RC2-32 general/aviation design shown in Figure 2.0.0. The accessory drive and installation arrangement differences are apparent from inspection of the installation drawings, Figures 2.0.1 and 2.0.2, for the RC4-41 and RC6-122 respectively.

Engine Cooling

During the take-off and climb phase of flight, the ability of the cooling system to reject heat and properly cool the engine is most critical. The engine is rejecting heat at close to its maximum rate (near full fuel flow) while the aircraft is at a relatively low air speed. Maximum coolant and oil temperatures will occur during this flight phase. On a standard 60°F day, these maximum temperatures will be at or near the temperature levels maintained by thermostatic controls in both systems. As a result, once the engine is warmed up, both the coolant and the oil temperatures into the engine will stabilize at levels corresponding to normal development engine experience through all phases of flight and ground operation. Limiting oil and coolant temperatures will occur during hot day operation. The coolers will be sized to meet the hot day requirements.

Based on analytic studies of structural, combustion, and durability factors, it has been projected that engine operation with a maximum coolant out temperature of 250°F and a maximum oil in temperature of 260/265°F will prove feasible. It is intended that these maximum temperatures would occur only at "hot day" conditions during the climb-out phase of flight. For such a system, the cruise temperatures would be well below the maximum temperature limits. With the use of cowl flaps it may be possible to raise the cruise temperatures somewhat. Surveys of major oil companies indicated that sump temperature peaks of 300°F would be permissible. From trends of similar engines, the higher oil and coolant temperatures should lead to improvements in fuel economy and HC emissions.

The proposed temperatures will reduce the heat rejection to the oil and coolant and increase the driving temperature differential at the oil and coolant coolers, thereby permitting the use of coolers that are smaller, lighter, and less costly. A specific example of the benefits resulting from higher coolant temperatures is shown by the following tabulation, in which the relative cooler size is shown for systems having maximum coolant out temperatures of 230°F and 250°F.

Relative Cooler Size

Maximum Coolant Out Temperature °F	For Same Cooling Drag	For Same Cooling Air Pressure Drop
230	1.22	1.17
250	1.0	1.0

Compact aluminum construction was indicated over steel and brazed copper designs on the basis of size and weight considerations.

Type of Fuel

The proposed rotary aircraft engines are multi-fuel engines capable of operating on a wide range of fuels including gasoline, diesel and jet fuels.

The method for introducing and igniting fuel in the combustion chamber makes the engine insensitive to either cetane or octane characteristics. Injected pilot nozzle fuel is ignited as it is introduced into the chamber. Additional fuel is introduced from the main nozzle as required to obtain the desired power level. The rate of fuel injection matches the rate of combustion. As a result, the engine will operate on a variety of fuels, including middle distillates that represent the maximum yield from a barrel of crude.

Based on results obtained with the military RC2-350 engine, now being developed under contract to the USMC, the engine is not sensitive to timing variations when changing fuels. This means that if the settings are optimized for a specific fuel, operation on a different fuel at the same settings introduces only small performance changes as a function of volumetric heat content. Since the RC2-350 represents the most developed form of the planned combustion system, its ease of interchangeability of jet fuel or gasoline from its reference diesel fuel, is considered to be characteristic.

A partial listing of the specifications covering the fuels which can be burned appear below.

Diesel Fuel	MIL-F-16684
Diesel Fuel	VVF 800
Jet Fuel	MIL-T-5624
Aviation Fuel	100
Aviation Fuel	100 LL

Mixed Flow Turbosupercharger and Power Recovery Turbine

While General Aviation engine sizes permit the use of truck diesel production turbochargers, equivalent low cost high production supply sources do not exist for engines in the 800 to 2500 SHP range. Conceptual designs were therefore carried out using single stage centrifugal compressors driven by axial flow turbines for contract engines of 800 and 2500 horsepower. Since performance analysis had indicated the desirability of turbocompounding, it was decided to add a free wheeling second stage axial flow turbine which would deliver power to the output shaft. The turbocharger and power recovery turbine are close-coupled in one housing with a single shaft centerline for the two shafts.

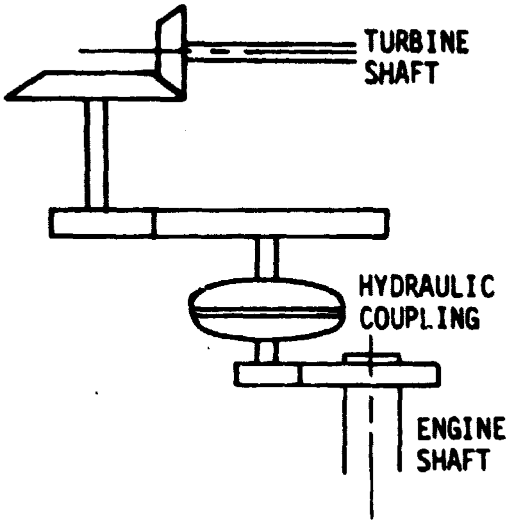
For purposes of effective matching it was assumed that variable inlet turbine nozzle area would be used. This eliminates the need for a waste gate.

Axial flow power recovery turbines were successfully used in the Curtiss-Wright TC18 production reciprocating engines, providing 450 horsepower in engines with 3200 shaft horsepower.

It was found that for effective blowdown turbine action, the exhaust pipes should have individual runs from the exhaust ports, with two half cycle phased ports being joined near the turbine to provide one connection to its own part of the turbine nozzle ring. For a six rotor engine this means three exhaust pipes connect to the turbine housing, each feeding its own 120° of the nozzle ring. The exhaust pipe diameters are controlled to achieve the maximum blowdown effect.

The turbocharger-turbocompounding devices have been installed aft of the accessories with a transverse shaft orientation, (Figures 2.0.1 and 2.0.2).

The power recovery turbine energy is delivered to the engine shaft by (1) a bevel gear take-off from the transverse turbine shaft, (2) the bevel gear shaft lies in an axial direction with its output end in the accessory gear housing, (3) speed reduction gears feed into a hydraulic coupling, and (4) the hydraulic coupling acts as a vibration isolator.



POWER RECOVERY TURBINE
DRIVE - SCHEMATIC DIAGRAM

A summary of the turbocharger-turbocompounder design data for the two engines shown in the installation drawings is shown in Table 2.1.2.

TABLE 2.1.2

TURBOCHARGER-TURBOCOMPOUNDER DESIGN DATA

	RC6-122 2500 HP	RC4-41 800 HP
Compressor Tip Diameter, Inches	12.35	7.00
Compressor, RPM	19,100	33,900
Compressor Flow, Lb/Sec	5.83	1.86
First Turbine Tip Diameter, Inches	11.52	6.49
Second Turbine Mean Blade Diameter, Inches	9.24	5.2
Turbine Flow, Lb/Sec	6.08	1.94

Propeller Gear Box Parametrics

The size and weight of an integral propeller reduction gear box is given in Figure 2.2.0 as a function of an output shaft torque parameter. The gear box weights are based on weight estimates presented in Reference 9 and subsequent studies which indicated that weights could be lowered by 10% with the application of lightweight construction materials such as a graphite fiber composite for the housings and covers. For gear box size, only the axial length of the gear box is defined as the width and height dimensions will fit within the engine envelope dimensions. All weights shown are "wet" weights.

Physical Characteristics and Scaling

Simplified installation drawings for the RC4-41 (800 SHP) and the RC6-122 (2500 SHP) are shown in Figures 2.0.1 and 2.0.2. The drawings show the locations of the coolant connections, the centers of gravity, significant dimensions, engine features and arrangement, and mounting pads. Housing pads are provided to permit either bed mounting or cantilevered dynafocal mounting.

Curves of engine weight vs. horsepower for four and six rotor engines are shown in Figures 2.2.1 (a) and (b). Since the integral propeller gear reduction weight and size has been presented in a form to permit varied speed ratios, to find an engine "wet ready to fly" total weight, it is necessary to add the weights from Figure 2.2.0 and 2.2.1 (b). A curve showing total weight, including the gear box,vs. horsepower for 1500 RPM propeller shaft speed is shown in Figure 2.2.1 (a).

The following items are included in the weights shown in Figures 2.2.1 (a) and (b):

- Coolant in Engine
- External Cooling System (Wet)
- Oil Cooler and Tank (Dry)
- Engine Oil
- Starter
- Generator
  - Part of Alternator/Generator
- Power Section
  - Including Accessory Drives
- Flywheel
- Ignition System
- Fuel System
- Engine Cooling System
- Turbocharger-Turbocompounder and Controls
- Charge Air Cooler
- Exhaust Piping
- Intake Cleaner and Pipe
- Engine Mounts

The weight data has been provided for 4 and 6 rotor engines since these are the indicated selections for the engine sizes required to cover the range from 800 to 2500 SHP. At the 800 horsepower size the 6 rotor engine weight is 23 pounds (4.7%) lighter than the 4 rotor engine weights. The added cost complexity, and small part size for the 6 rotor engine make the small weight improvement unattractive. At the 2500 horsepower size the 6 rotor engine weight is 150 pounds (8.5%) lighter than the 4 rotor engine weight. In this case the weight saving and the larger part size do indicate the use of 6 rotors. The specific weight of the 4 rotor 800 horsepower engine is .68 lb/HP and that of the 6 rotor 2500 horsepower engine .75 lb/HP. This reflects the 122 cubic inches pwer rotor of the RC6-122 compared to the 41 cubic inches per rotor of the RC4-41. In order to maintain proven apex seal linear speeds, when displacement is increased, the RPM is decreased linearly. This results in higher specific weight for larger sized combustion chambers.

ORIGINAL PAGE IS
OF POOR QUALITY

INTEGRAL PROP REDUCTION GEAR BOX LENGTH AND WEIGHT VS. OUTPUT TORQUE

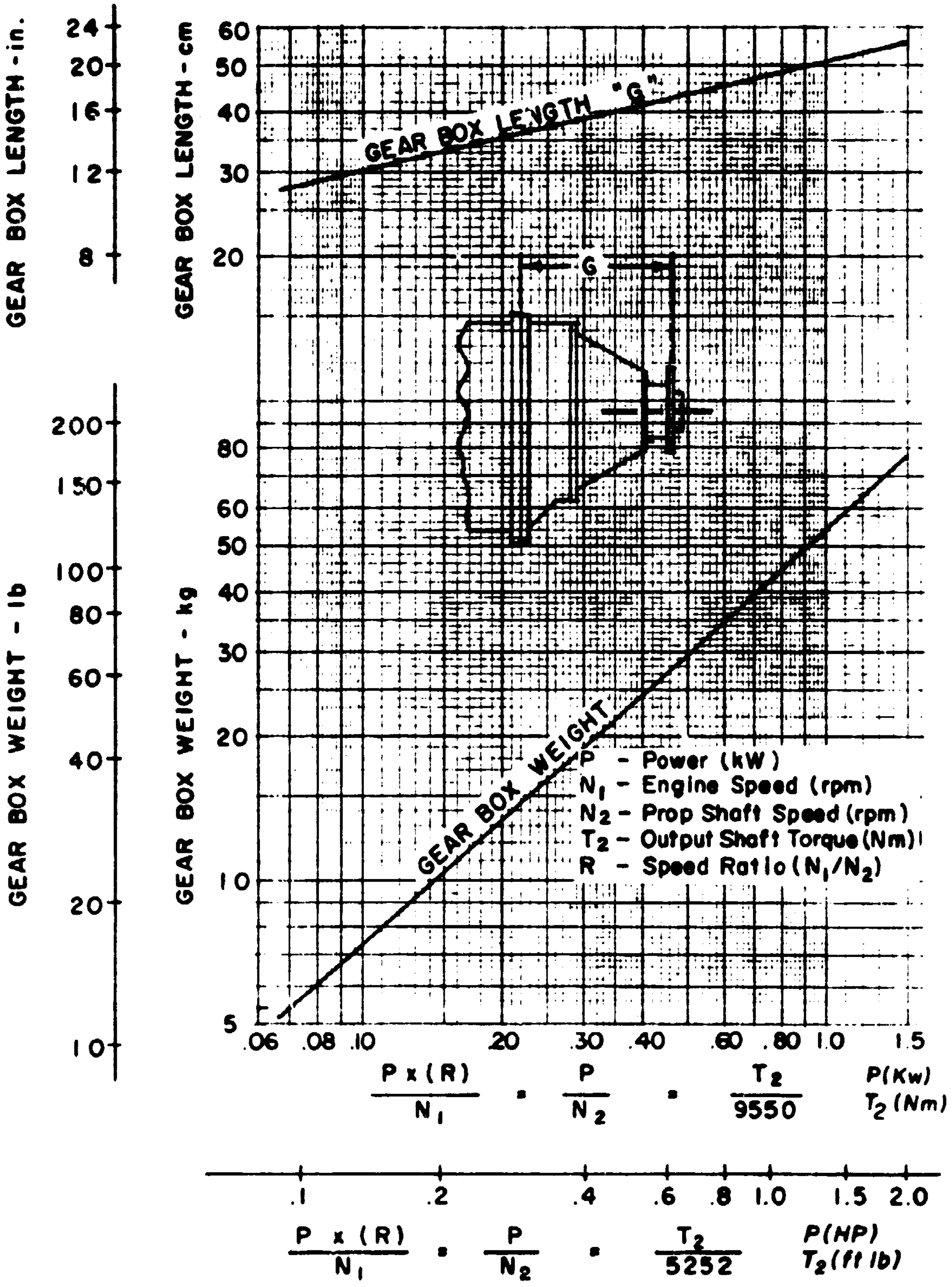


Figure 2.2.0

ORIGINAL PAGE IS
OF POOR QUALITY

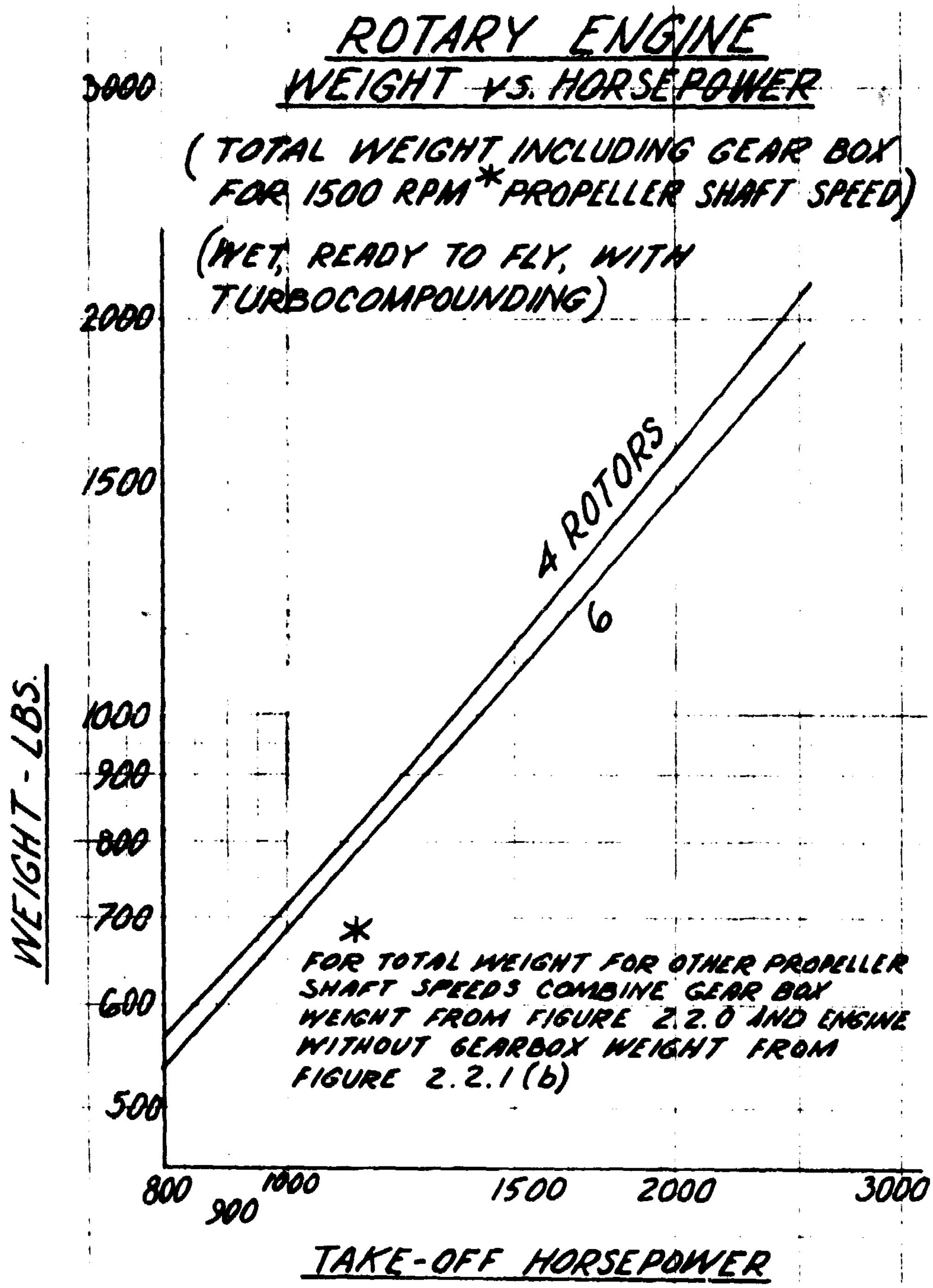
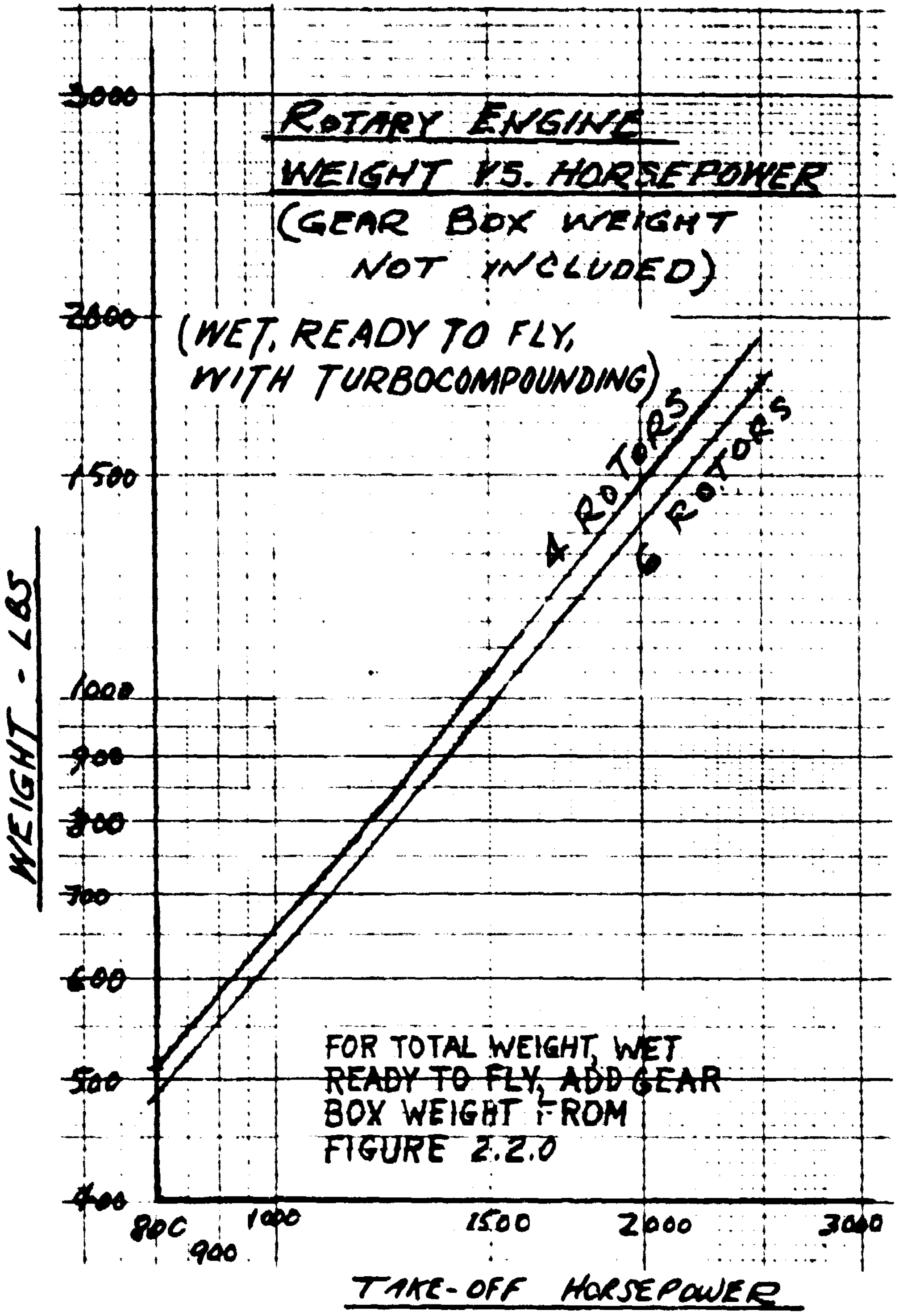


Figure 2.2.1(a)



FOR TOTAL WEIGHT, WET
READY TO FLY, ADD GEAR
BOX WEIGHT FROM
FIGURE 2.2.0

Figure 2.2.1 (b)

Figure 2.2.2 presents the variation in the take-off power with displacement per rotor for two, four and six rotors. The curve also shows the relationship between take-off shaft speed and displacement per rotor.

Figure 2.2.3 shows the engine dimensions vs. displacement per rotor for four and six rotor engines. Again, to determine the complete engine length to the propeller flange, it is necessary to refer to Figure 2.2.0 for the length of the propeller gear reduction portion.

It can be seen from Figure 2.2.2 that an 800 horsepower engine will be an RC4-41. From previous studies (Reference 9) the trend that a higher number of rotors yields a lighter engine for the same horsepower was well established. A 41 cubic inch displacement rotor is practical in terms of spark plug and injector arrangement and fuel injection requirements. As discussed earlier, the weight savings for a 6 rotor 800 horsepower engine were not attractive. In sizing a 2500 horsepower engine on Figure 2.2.2 it can be seen that a 122 cubic inch rotor displacement results for a six rotor engine. The size is practical and the weight gain is significant. An eight rotor engine is not considered as attractive a solution. In the middle range between 800 and 2500 horsepower the decision between four and six rotors may depend on aircraft system evaluations.

Tables 2.2.2 and 2.2.3 present the means of scaling BSFC (Brake Specific Fuel Consumption) with horsepower. Table 2.2.2 covers four rotor engines from 900 to 1500 horsepower, and Table 2.2.3 covers six rotor engines from 1500 to 2500 horsepower. The tables also contain expression for determining displacement per rotor, take-off RPM, idle fuel flow, and idle RPM as a function of take-off horsepower and RPM.

The performance and heat rejection data is presented for 1200 and 2000 horsepower engines, while the installation drawings show 800 and 2500 horsepower engines. In order to complete the engine data for 1200 and 2000 horsepower engines, the engine scaling curves previously mentioned have been used to provide the data shown in Table 2.2.4.

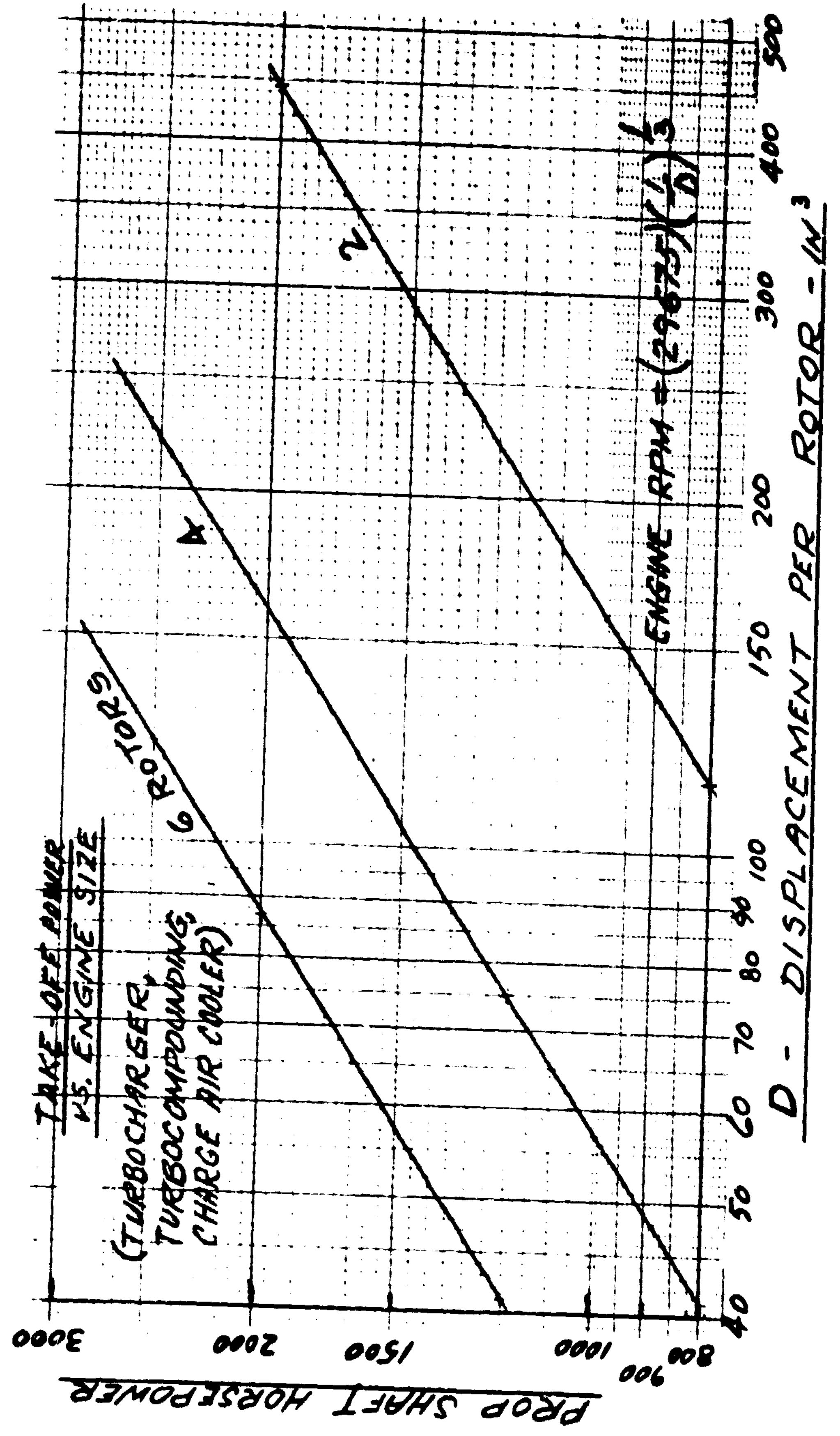

TAKE-OFF POWER
vs. ENGINE SIZE
(TURBOCHARGER,
TURBOCOMPOUNDING,
CHARGE AIR COOLER)
6 ROTORS
4
2
ENGINE RPM = (29675)(1/D)^1/3
D - DISPLACEMENT PER ROTOR - IN^3
40
50
60
70
80
90
100
150
200
300
400
500
PROP SHAFT HORSEPOWER
800
900
1000
1500
2000
3000

Figure 2.2.2

ORIGINAL PAGE IS
OF POOR QUALITY

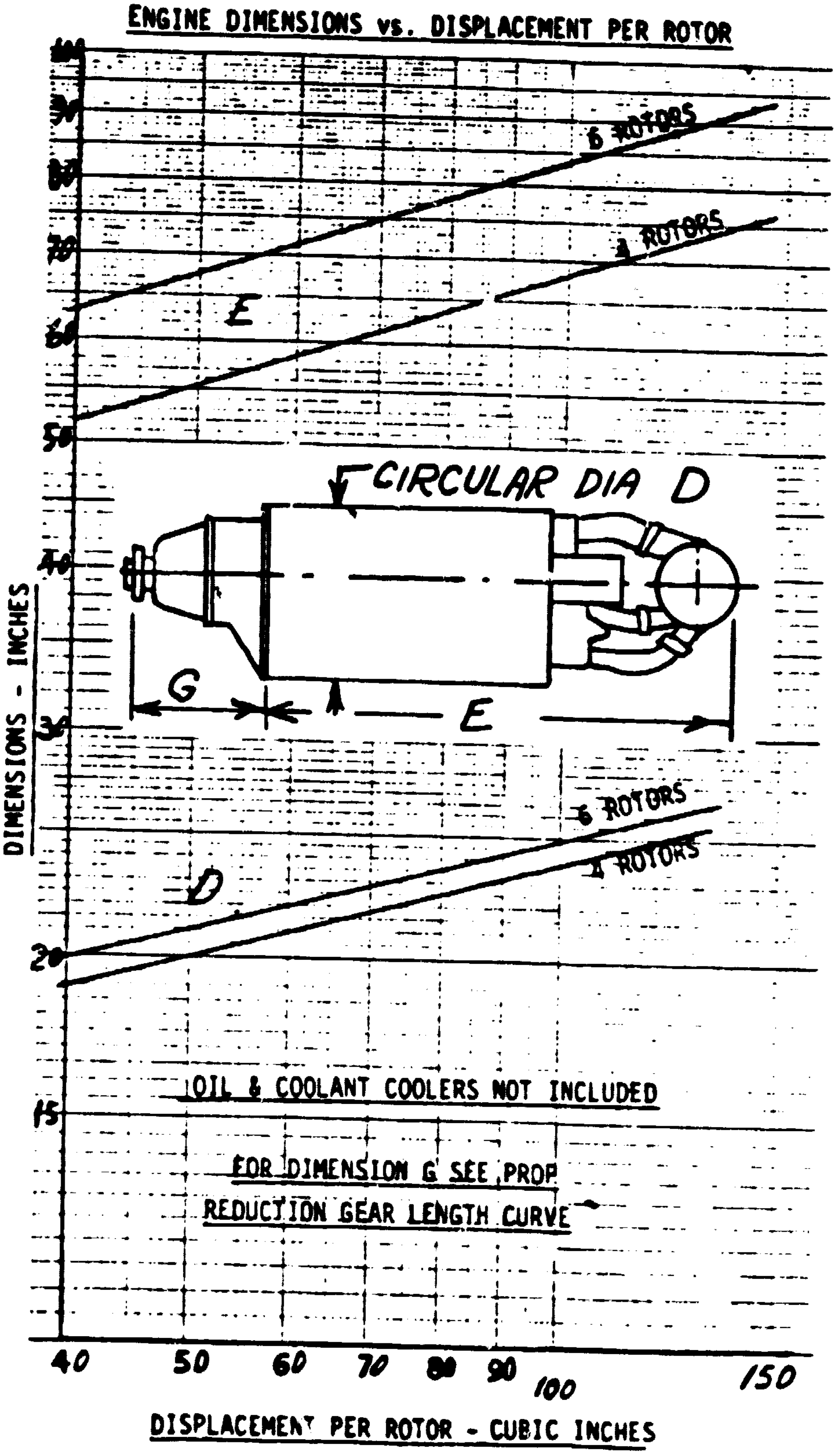


Figure 2.2.3

TABLE 2.2.2

POWER SECTION SCALING

APPLICABLE TO 1200 BHP ± 25%

FOR 4 ROTORS

BSFC

0.25% INCREASE IN BSFC FOR 25% POWER DECREASE

0.20% DECREASE IN BSFC FOR 25% POWER INCREASE

DISPLACEMENT PER ROTOR

$$\text{DISP. IN.}^3 = .0019825\ (\text{BHP})^{1.4850}$$

TAKE-OFF RPM

$$\text{T.O. CRANKSHAFT RPM} = 237923\ (\text{BHP})^{-.4950}$$

IDLE FUEL FLOW

$$\text{FUEL FLOW, LB/HR} = (\text{BHP})^{1.5}/6508$$

IDLE RPM

IDLE CRANKSHAFT RPM = 0.20 X TAKE-OFF CRANKSHAFT RPM

NOTE: (BHP) = TAKE-OFF HORSEPOWER OF SCALED ENGINE

ENGINE WEIGHT

SEE FIGURES 2.2.0, 2.2.1(a), and 2.2.1(b).

TABLE 2.2.3

POWER SECTION SCALING

APPLICABLE TO 2000 BHP ± 25%

FOR 6 ROTORS

BSFC

0.25% INCREASE IN BSFC FOR 25% POWER DECREASE

0.20% DECREASE IN BSFC FOR 25% POWER INCREASE

DISPLACEMENT PER ROTOR

$$\text{DISP. IN.}^3 = .0010847\ (\text{BHP})^{1.4851}$$

TAKE-OFF RPM

$$\text{T.O. CRANKSHAFT RPM} = 290893\ (\text{BHP})^{-.4951}$$

IDLE FUEL FLOW

$$\text{FUEL FLOW, LB/HR} = (\text{BHP})^{1.5}/9161$$

IDLE RPM

IDLE CRANKSHAFT RPM = 0.20 X TAKE-OFF CRANKSHAFT RPM

NOTE: (BHP) = TAKE-OFF HORSEPOWER OF SCALED ENGINE

ENGINE WEIGHT

SEE FIGURES 2.2.0, 2.2.1 (a), and 2.2.1 (b)

TABLE 2.2.4

SIZE AND WEIGHT OF 1200 AND 2000 BHP ENGINES

(WITH TURBOCOMPOUNDING)

	RC4-74 1200 BHP	RC6-87 2000 BHP
Total Weight (including gear box), lb. (Wet, Ready to Fly)	876	1488
Partial Engine Length, E, Inches	62.5	80
Gear Box Length, G, Inches	17.8	20
Total Engine Length, Inches	80.3	100
Engine Envelope Diameter, Inches	22.1	24

(Based on 1500 RPM Propeller Take-Off Speed)

PERFORMANCE

Improved Combustion Efficiency Through Turbocharging

The stratified charge engine air utilization resembles a diesel more closely than it does a conventional carbureted engine because of its ability to 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 higher power density, but offered potential for significant improvement in fuel economy.

The theory that turbocharging could improve combustion efficiency was predicated on the characteristic ISFC vs. F/A curve shapes shown in Figure 3.0.1, which is representative for both the RC1-60 and RC-350 engines. Since ISFC is inversely proportional to thermal efficiency, it can be seen that the engine cannot only 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 3.0.2. As output is increased (higher BMEP), the mechanical efficiency improves and this gain is additive to the improvements in thermal efficiency through leaner mixture strengths.

Based on this trend it was predicted that high power BSFC could be reduced approximately 17% by driving the BSFC curve "hook" out beyond the "normal" naturally aspirated range. Although the NASA study engines were based on this approach, there was no test data on stratified charge Rotary Engines to support the predictions, prior to testing conducted late in 1980.

All engine builds utilized the BTC pilot configuration rotor housing with available rotors which did not represent an "optimized" system match of rotor combustion pocket, main nozzle spray pattern and rotor housing. The tests were run nonetheless because performance trends were expected to be applicable to later configurations.

The results plotted in Figure 3.0.3 show that as additional air is supplied by turbocharging, bringing the F/A ratio at 50 HP from .044 to .025, the ISFC remains at the same minimum value that was obtained at 20 HP. Accordingly, the BSFC curve, instead of "hooking" up in the customary curve shape, continues to decrease, showing an improvement of 19% at an assumed limiting .055 fuel-air ratio naturally aspirated, both test curves extrapolated to this point. The BSFC improvement related to best BSFC naturally aspirated, at approximately 3/4 naturally aspirated power is 11% on the same basis. Therefore, it is considered that the basic theoretical contention that the Indicated Specific Fuel Consumption (ISFC) would remain essentially at its optimum value for higher output power, if the corresponding F/A ratio was maintained, has been demonstrated.

The testing at 6.0:1 compression ratio, shown compared to the 8.5:1 C.R. results in Figure 3.0.4, is particularly instructive because, despite anticipated poorer performance when naturally aspirated, the data shows:

ORIGINAL PAGE IS OF POOR QUALITY

ISFC VS. F/A RATIO FOR 5 SEPARATE RC1-350 ENGINE BUILDS

SAME CONFIGURATION, 8.5:1 COMPRESSION RATIO

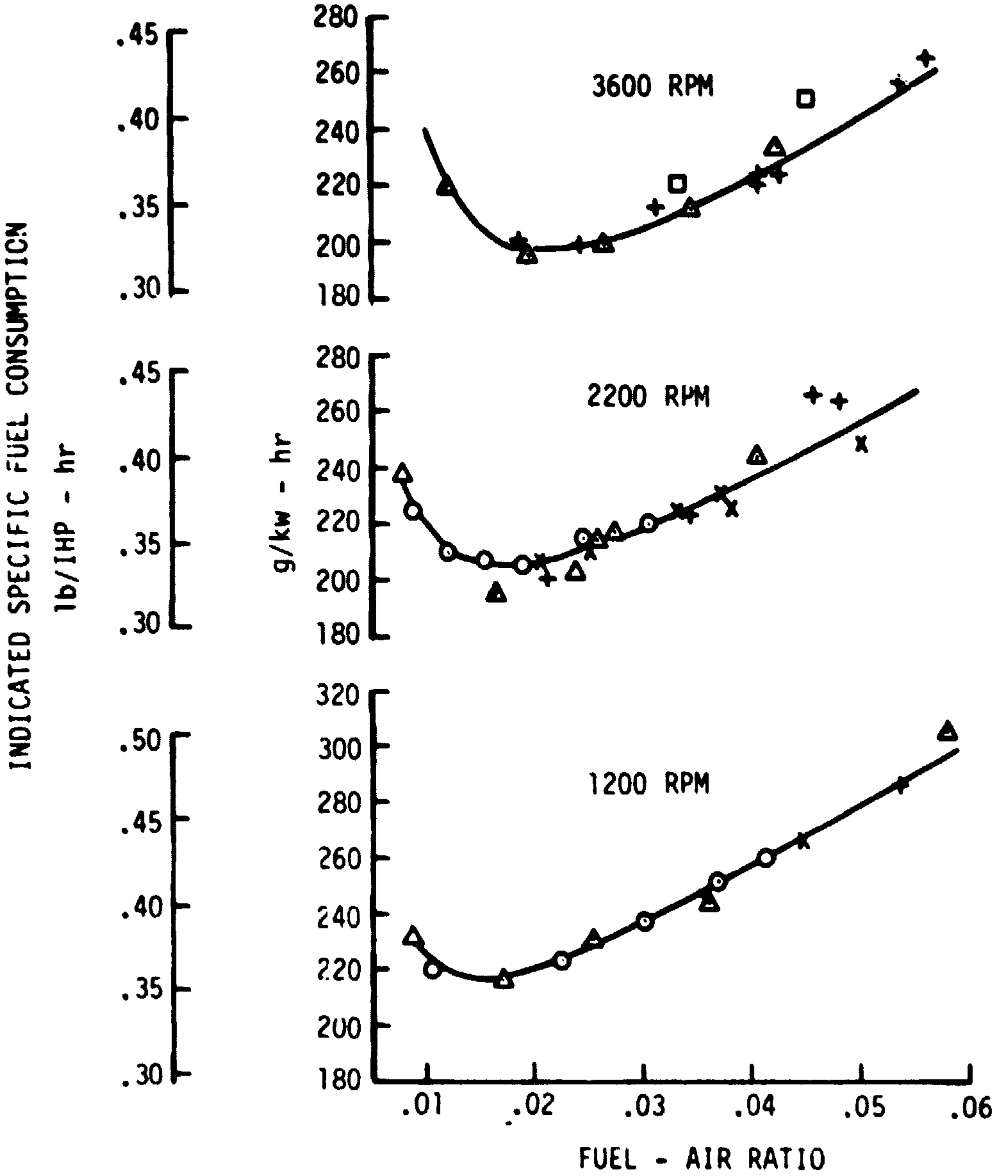


Figure 3.0.1

THEORETICAL TURBOCHARGING EFFECTS ON BSFC

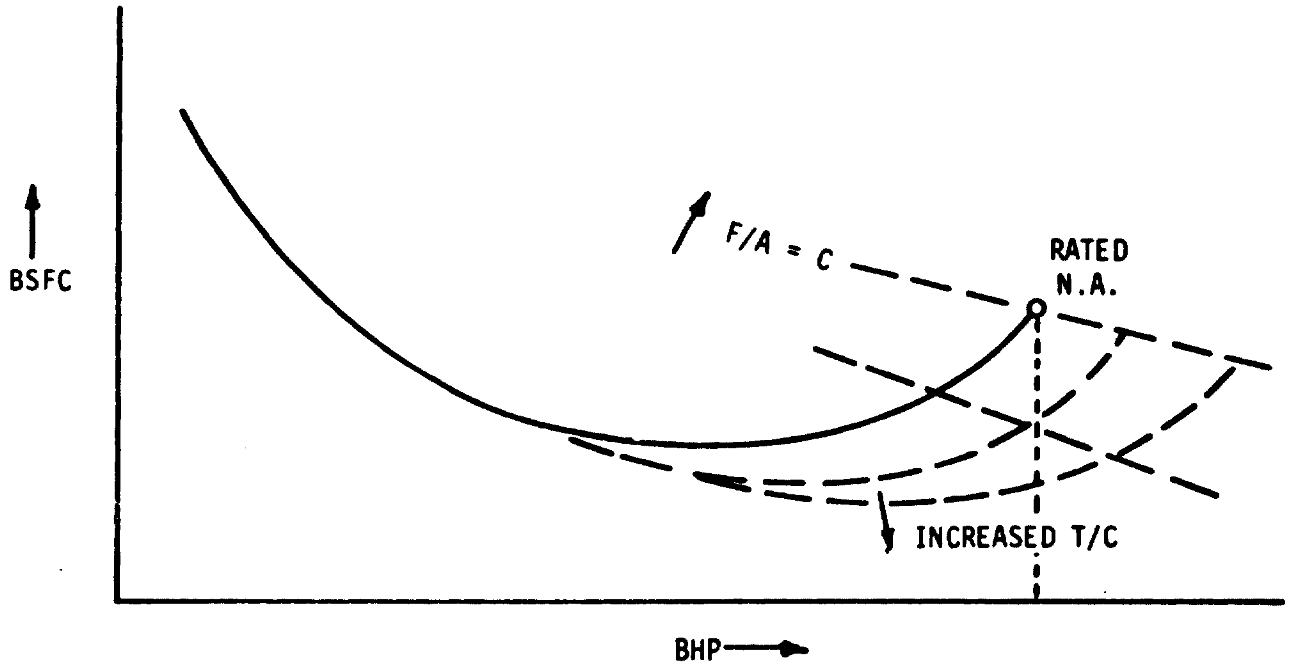


Figure 3.0.2

ORIGINAL PAGE IS
OF POOR QUALITY

BSFC IMPROVEMENT FROM TURBOCHARGING
RC1-60 STRATIFIED CHARGE
4000 RPM
PERIPHERAL INTAKE PORTS

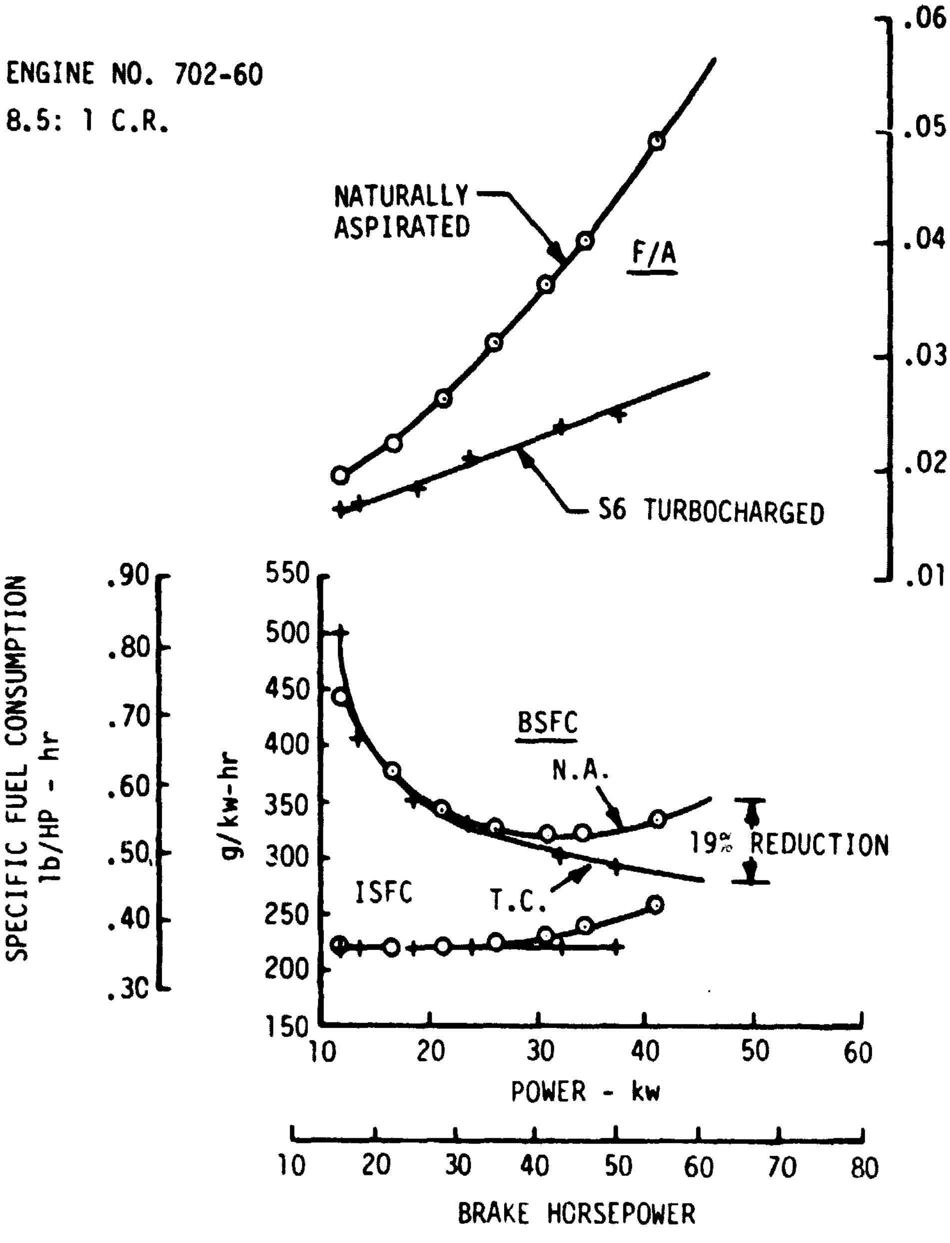


Figure 3.0.3

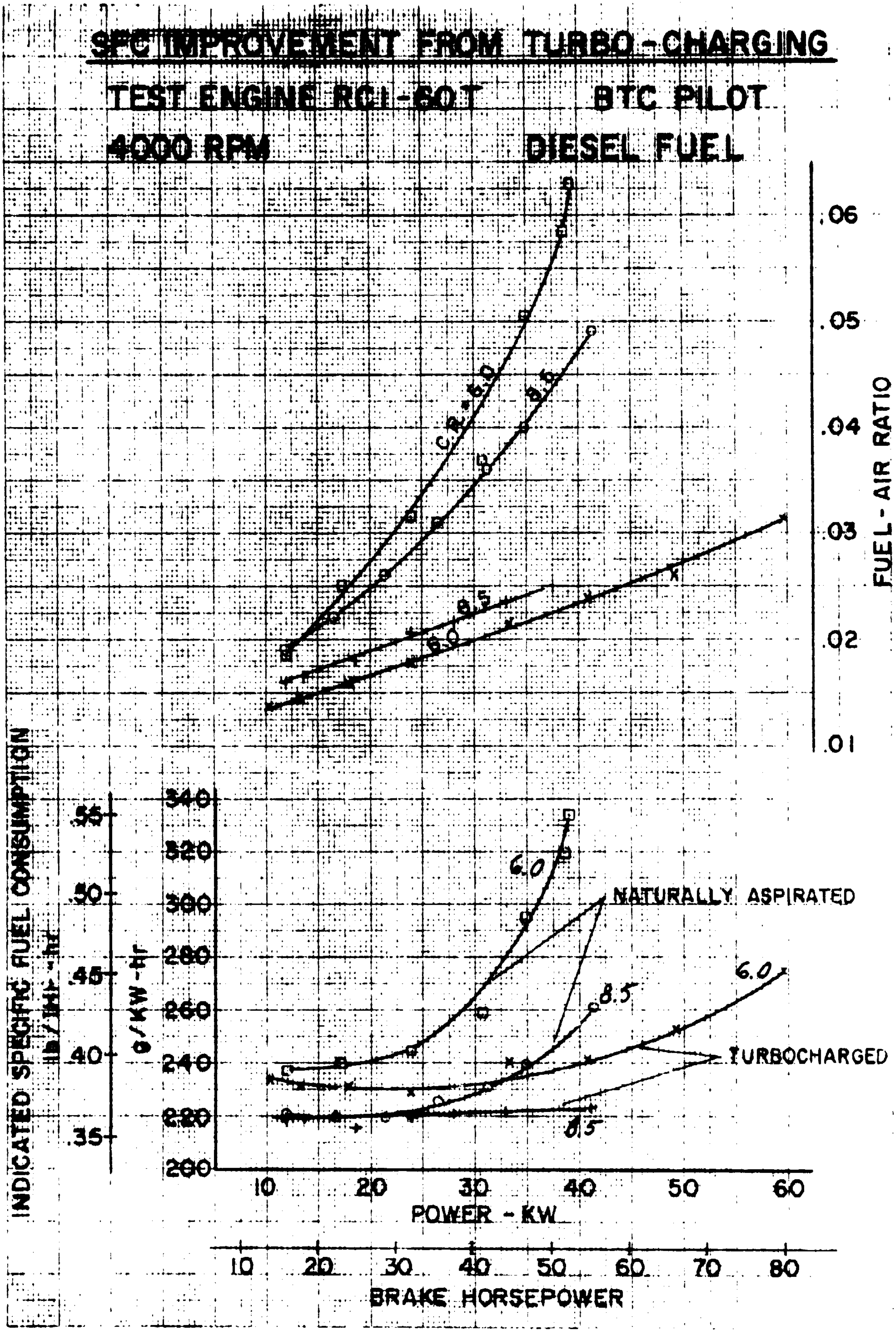

SFC IMPROVEMENT FROM TURBO-CHARGING
TEST ENGINE RC1-60T
BTC PILOT
4000 RPM
DIESEL FUEL
FUEL-AIR RATIO
.06
.05
.04
.03
.02
.01
C.R.=6.0
8.5
8.5
6.0
INDICATED SPECIFIC FUEL CONSUMPTION
lb/IHP-hr
.55
.50
.45
.40
.35
g/KW-hr
340
320
300
280
260
240
220
200
6.0
NATURALLY ASPIRATED
8.5
6.0
TURBOCHARGED
8.5
10
20
30
40
50
60
POWER - KW
10
20
30
40
50
60
70
80
BRAKE HORSEPOWER

Figure 3.0.4

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 limits. Figure 3.0.5 shows these effects more clearly, plotted here for 5000 RPM.

The test results indicate that a lower compression ratio is desirable, and this will be a fruitful area for further effort.

As would be expected at the test operating mixture strengths, for the most part without a wastegate, the excess airflow keeps turbine entry temperatures in the same general moderate range as turbocharged diesels. Future testing with variable geometry (turbines and compressors) will be of interest to the extent they can provide improvements over a broader range with surge-free compressors of high efficiency, higher pressure ratios, and high efficiency turbines which can approach constant speed operation. The rotary engine requirements in this regard are not essentially different from those of reciprocating piston engines.

The fuel economy values predicted in the tabulated data were limited by the turbocharger pressure ratios expected to be achieved in the time-frame for the study engines. For 4570m (15,000 feet) cruise performance, the maximum practical (i.e., good efficiency and wide range) pressure ratio was assumed to be 3.4, which limits sea level ratios to 2.2:1. This does not permit sufficient excess air to be supplied to the stratified charge rotary to permit it to operate at best thermal efficiency, which occurs at .02-.03 fuel-air ratio at the present state of development. Therefore, if turbocharger improvements exceed those estimated for the subject time-frame, this will permit higher rates of airflow and thus further improve BSFC predictions over the study estimated values.

The contract describes the commuter application as follows:

Engine/Aircraft Operational Characteristics

The engines shall be flat rated to 15,000 ft altitude. Operational altitude is 10,000 - 15,000 ft. Operational aircraft speed is .4 - .6 Mach at cruise conditions with a minimum speed of 290 knots at 10,000 ft altitude. A typical engine operational cycle (included for reference) is 30-35 minutes as follows:

ORIGINAL PAGE IS
OF POOR QUALITY

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

SCRCI - 6CT ENGINE

3000 RPM

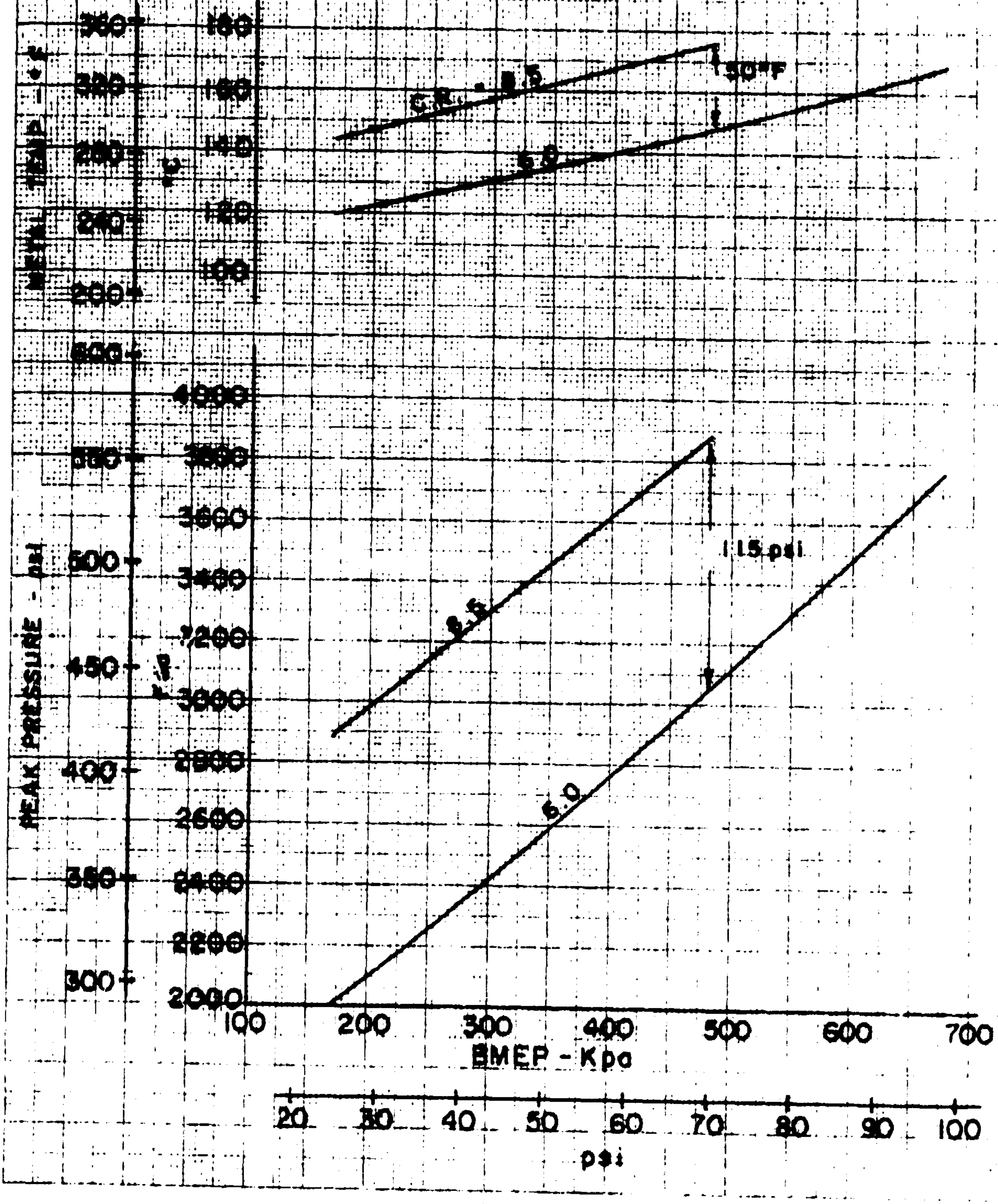


Figure 3.0.5

Idle Taxi	3 Minutes
Take-Off	1 Minute (Full Power)
Climb	10-11 Minutes (80% to Full Power)
Cruise	7-8 Minutes (55% to 75% Power)
Descent and Approach Maneuvers	6-7 Minutes (30% to 40% Power)
Idle Taxi	3 Minutes

Tables 3.0.3, 3.0.4, 3.0.5, and 3.0.6, provide a summary of operating data at sea level take-off and 70% power cruise at 4572m (15,000 feet) altitude for the 895 Kw (1200 BHP) and 1490 Kw (2000 BHP) engines. These tables are based on engine configurations which have turbocompounding after the turbocharger to extract additional work from the exhaust gas to increase efficiency. The Note (In Chamber) in the tables indicates the values shown are based on the engine power section horsepower, and do not include the turbocompounding power. Separate tables provide the data in metric and conventional British units.

Figures 3.0.6 and 3.0.7 show the projected altitude performance and specific fuel consumption for the two engines. Figure 3.0.8 shows the power contribution from turbocompounding vs. altitude and RPM. Figures 3.0.9 and 3.0.10 show the part load fuel consumption at sea level.

Coolant and Oil Heat Rejection Rates

Coolant and oil heat rejection rates for the 895 Kw engine (RC4-74) and the 1490 Kw engine (RC6-87) are given by Figures 3.0.11 and 3.0.12. These rates represent an upperbound estimate of coolant and oil heat rejection and are based on test data from a current RC1-350 stratified charge engine (naturally aspirated). The data was scaled to commuter engine operating conditions using heat rejection scaling factors for fuel/air ratio, RPM, turbo boost, and IMEP as determined from carbureted and stratified charge rotary engines. The lower bound estimate of coolant and oil heat rejection would result in a 33% reduction of the rates given by Figures 3.0.11 and 3.0.12.

The heat rejection shown is occurring within the engine envelope. Previous analyses have shown that natural cooling over the engine outer surface and the coolant hoses can reduce the heat load on the coolant cooler by up to 10%. The oil cooler load may also vary depending on how close coupled the oil cooler is to the engine.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 3.0.3

(895 Kw)

RC4-74 (74.12)

TURBOCHARGED TURBOCOMPOUNDED ENGINE

OPERATING DATA SUMMARY

STANDARD DAY - NO RAM

	TAKE-OFF SEA LEVEL	70% CRUISE 4572m ALTITUDE
BKw	895	626.4
RPM (CRANKSHAFT)	7116	5436
IMEP, Kpa (IN CHAMBER)	1683.1	1497.0
IKw (IN CHAMBER)	970.1	659.2
FMEP, Kpa	221.9	169.5
FKw	127.9	74.6
BMEP, Kpa (IN CHAMBER)	1461.2	1327.5
FUEL/AIR RATIO	.04	.04
BSFC, g/Kw-HR	205.2	200.2
AIRFLOW, Kg/HR	4593.5	3136.6
COMPRESSOR PRESSURE RATIO *	2.17	3.39
ENGINE INLET TEMPERATURE, °C	65.4	61.4
ENGINE INLET PRESSURE, Kpa	215.1	190.0

* BEFORE 2% INTERCOOLER PRESSURE DROP. ASSUMES INTERCOOLER EFFECTIVENESS OF 50% AND COMPRESSOR EFFICIENCY OF 70%.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 3.0.4

(1200 BHP)

RC4-74 (74.12)

TURBOCHARGED TURBOCOMPOUNDED ENGINE

OPERATING DATA SUMMARY

STANDARD DAY - NO RAM

	TAKE-OFF SEA LEVEL	70% CRUISE 15000 FT ALTITUDE
BHP	1200	840
RPM (CRANKSHAFT)	7116	5436
IMEP, PSI (IN CHAMBER)	244.11	217.12
IHP (IN CHAMBER)	1300.40	883.69
FMEP, PSI	32.19	24.58
FHP	171.48	100.04
BMEP, PSI (IN CHAMBER)	211.92	192.54
FUEL/AIR RATIO	.04	.04
BSFC, LB/BHP-HR	.3375	.3293
AIRFLOW, LB/HR	10127	6915
COMPRESSOR PRESSURE RATIO *	2.17	3.39
ENGINE INLET TEMPERATURE, °F	149.8	142.6
ENGINE INLET PRESSURE, PSI	31.2	27.55

* BEFORE 2% INTERCOOLER PRESSURE DROP. ASSUMES INTERCOOLER EFFECTIVENESS OF 50% AND COMPRESSOR EFFICIENCY OF 70%.

TABLE 3.0.5

(1490 Kw)

RC6-87 (86.67)

TURBOCHARGED TURBOCOMPOUNDED ENGINE

OPERATING DATA SUMMARY

STANDARD DAY - NO RAM

	TAKE-OFF SEA LEVEL	70% CRUISE 4572m ALTITUDE
BKw	1491.4	1044
RPM (CRANKSHAFT)	6754	5848
IMEP, Kpa (IN CHAMBER)	1683.1	1497.0
IKw (IN CHAMBER)	1615.1	1097.7
FMEP, Kpa	220.4	168.3
FKw	211.5	123.4
BMEP, Kpa (IN CHAMBER)	1462.7	1328.7
FUEL AIR RATIO	.04	.04
BSFC, g/Kw-HR	205.0	200.0
AIRFLOW, Kg/HR	7647.6	5221.8
COMPRESSOR PRESSURE RATIO *	2.17	3.39
ENGINE INLET TEMPERATURE, °C	65.4	61.4
ENGINE INLET PRESSURE, Kpa	215.1	190.0

* BEFORE 2% INTERCOOLER PRESSURE DROP. ASSUMES INTERCOOLER EFFECTIVENESS OF 50% AND COMPRESSOR EFFICIENCY OF 70%.

ORIGINAL PAGE IS OF POOR QUALITY

TABLE 3.0.6

(2000 BHP)

RC6-87 (86.67)

TURBOCHARGED TURBOCOMPOUNDED ENGINE

OPERATING DATA SUMMARY

STANDARD DAY - NO RAM

	TAKE-OFF SEA LEVEL	70% CRUISE 15000 FT ALTITUDE
BHP	2000	1400
RPM (CRANKSHAFT)	6754	5848
IMEP, PSI (IN CHAMBER)	244.11	217.12
IHP (IN CHAMBER)	2165.00	1471.49
FMEP, PSI	31.97	24.41
FHP	283.52	165.40
BMEP, PSI (IN CHAMBER)	212.14	192.71
FUEL AIR RATIO	.04	.04
BSFC, LB/BHP-HR	.3372	.3289
AIRFLOW, LB/HR	16860	11512
COMPRESSOR PRESSURE RATIO *	2.17	3.39
ENGINE INLET TEMPERATURE, °F	149.8	142.6
ENGINE INLET PRESSURE, PSI	31.2	27.55

* BEFORE 2% INTERCOOLER PRESSURE DROP. ASSUMES INTERCOOLER EFFECTIVENESS OF 50% AND COMPRESSOR EFFICIENCY OF 70%.

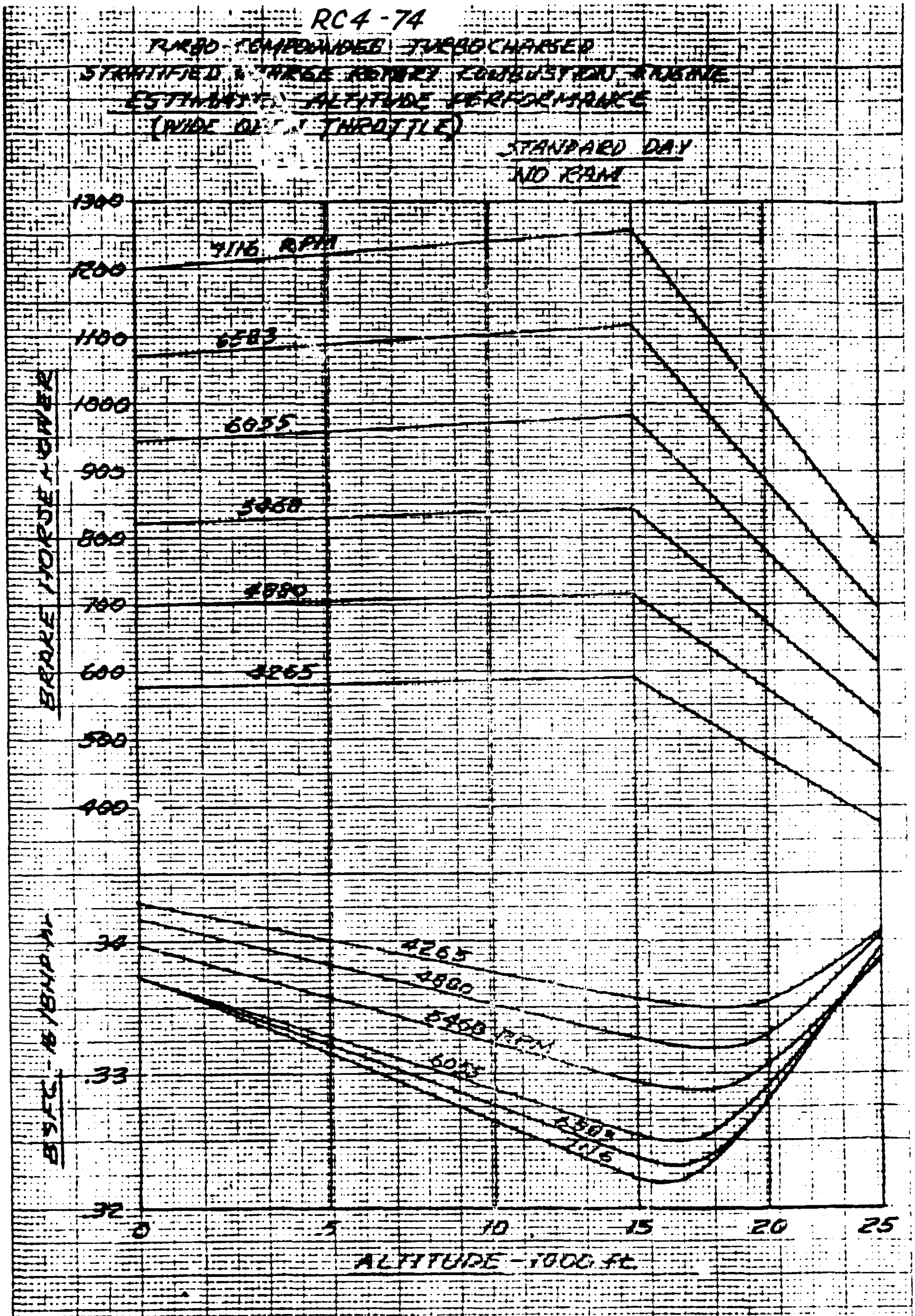

RC4-74
TURBO COMPOUNDED TURBOCHARGED
STRATIFIED CHARGE ROTARY COMBUSTION ENGINE
ESTIMATED ALTITUDE PERFORMANCE
(WIDE OPEN THROTTLE)
STANDARD DAY
NO RAM
BRAKE HORSE POWER
1300
1200
1100
1000
900
800
700
600
500
400
7116 RPM
6583
6035
5468
4880
4265
BSFC - lb/BHP HR
.34
.33
.32
4265
4880
5468 RPM
6035
6583
7116
0
5
10
15
20
25
ALTITUDE - 1000 ft

Figure 3.0.6

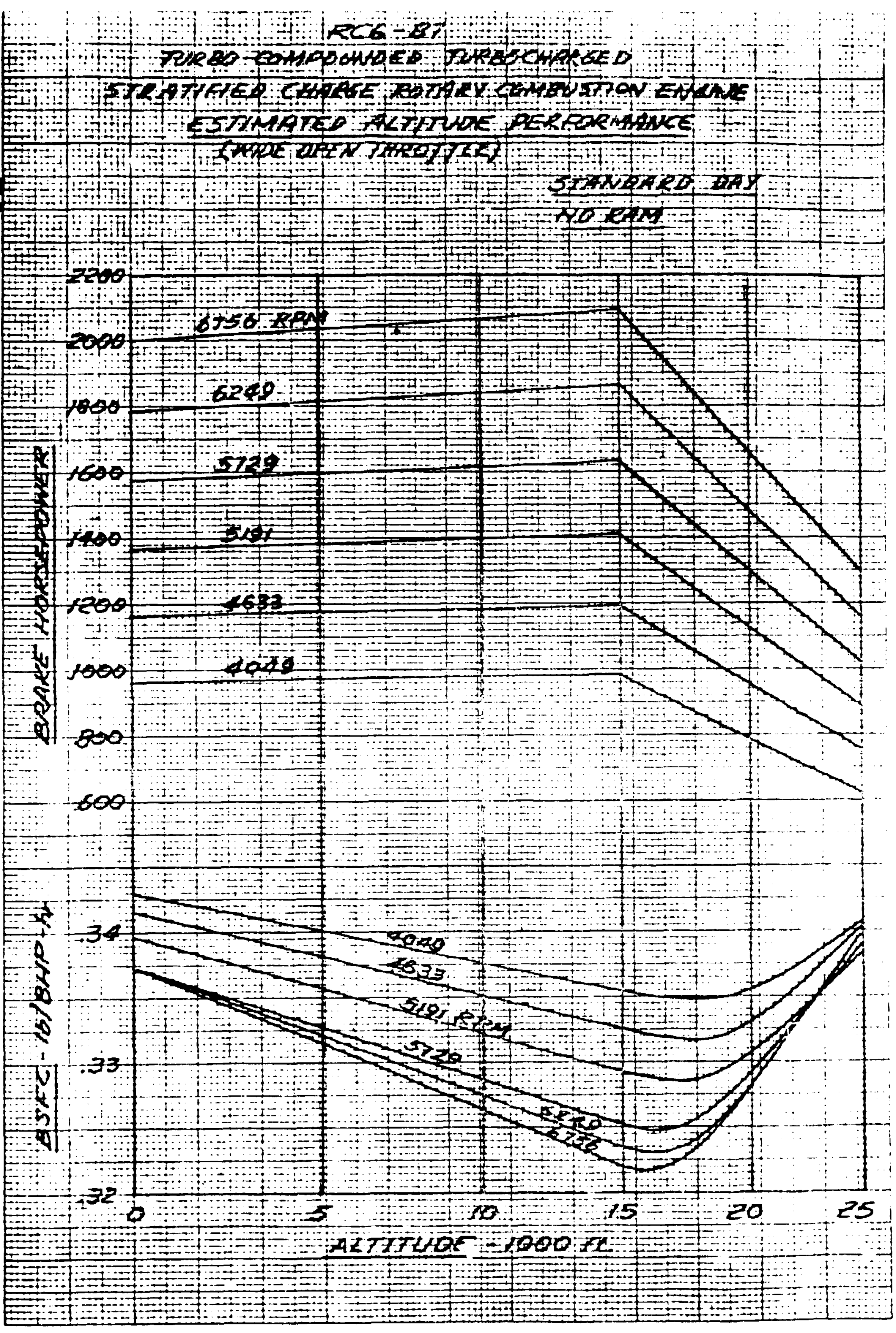

RC6-87
TURBO-COMPOUNDED TURBOCHARGED
STRATIFIED CHARGE ROTARY COMBUSTION ENGINE
ESTIMATED ALTITUDE PERFORMANCE
(WIDE OPEN THROTTLE)
STANDARD DAY
NO RAM
BRAKE HORSEPOWER
2200
2000
1800
1600
1400
1200
1000
800
600
6750 RPM
6249
5729
5191
4633
4049
BSFC - lb/BHP-hr
.34
.33
.32
4049
4633
5191 RPM
5729
6240
6750
0
5
10
15
20
25
ALTITUDE - 1000 FT.

Figure 3.0.7

STRATIFIED CHARGE ROTARY AIRCRAFT ENGINE PERFORMANCE

NOTES:

1. ESTIMATES ARE BASED ON STANDARD ATMOSPHERIC CONDITIONS AND NO RAM.
2. ESTIMATES ARE APPLIED TO ALTITUDE POWER CURVES AT RESPECTIVE SPEEDS TO THE BHP SHOWN.

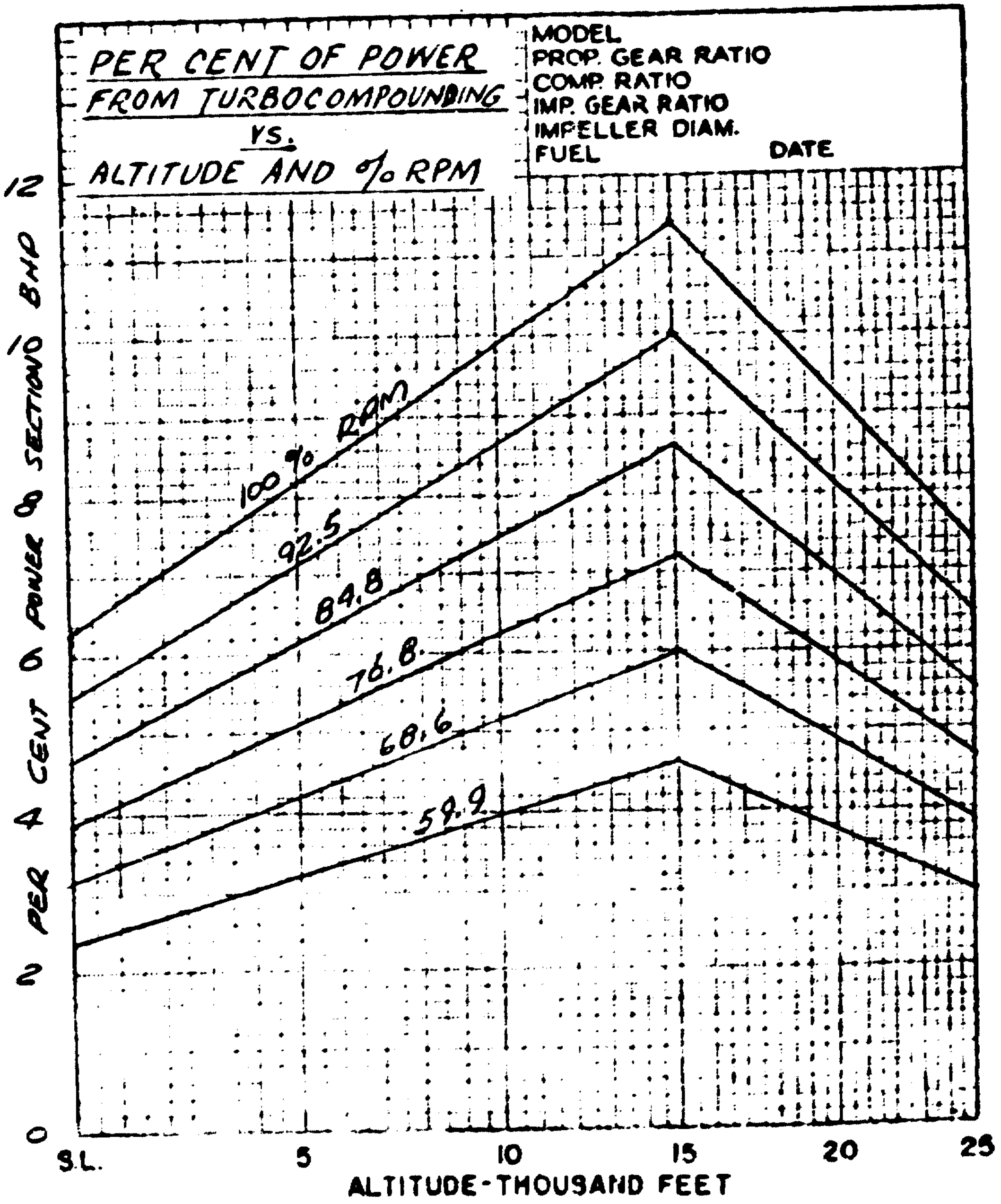


Figure 3.0.8

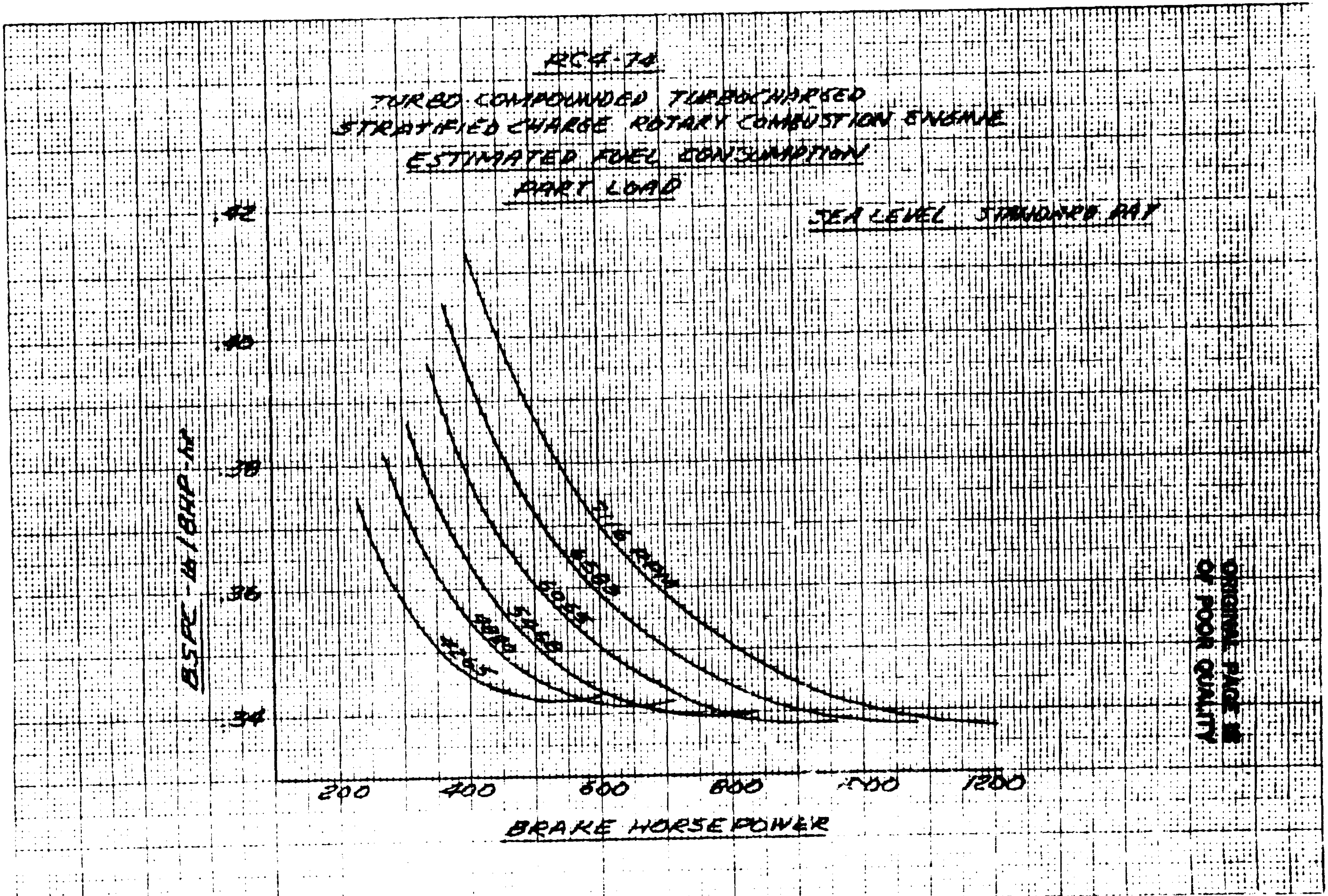

RC4-74
TURBO COMPOUNDED TURBOCHARGED
STRATIFIED CHARGE ROTARY COMBUSTION ENGINE
ESTIMATED FUEL CONSUMPTION
PART LOAD
SEA LEVEL STANDARD DAY
7216 RPM
6589
6063
5468
4885
4265
BSFC - lb/BHP-hr
.42
.40
.38
.36
.34
200
400
600
800
1000
1200
BRAKE HORSEPOWER

Figure 3.0.9

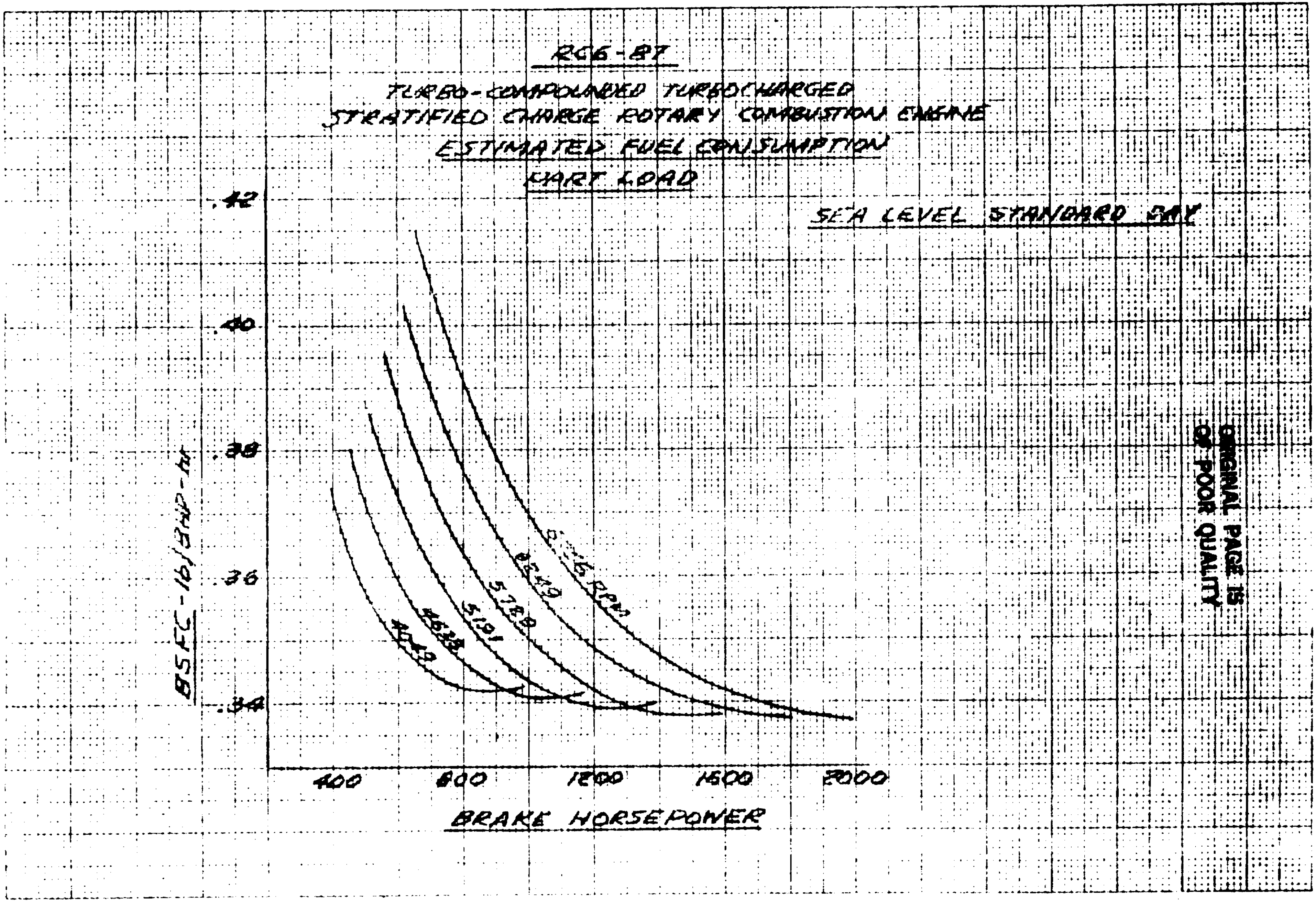

RC6-87
TURBO-COMPOUNDED TURBOCHARGED
STRATIFIED CHARGE ROTARY COMBUSTION ENGINE
ESTIMATED FUEL CONSUMPTION
PART LOAD
SEA LEVEL STANDARD DAY
BSFC - lb/BHP-hr
.42
.40
.38
.36
.34
400
800
1200
1600
2000
BRAKE HORSEPOWER
6[illegible]6 RPM
6349
5788
5191
4633
4049

Figure 3.0.10

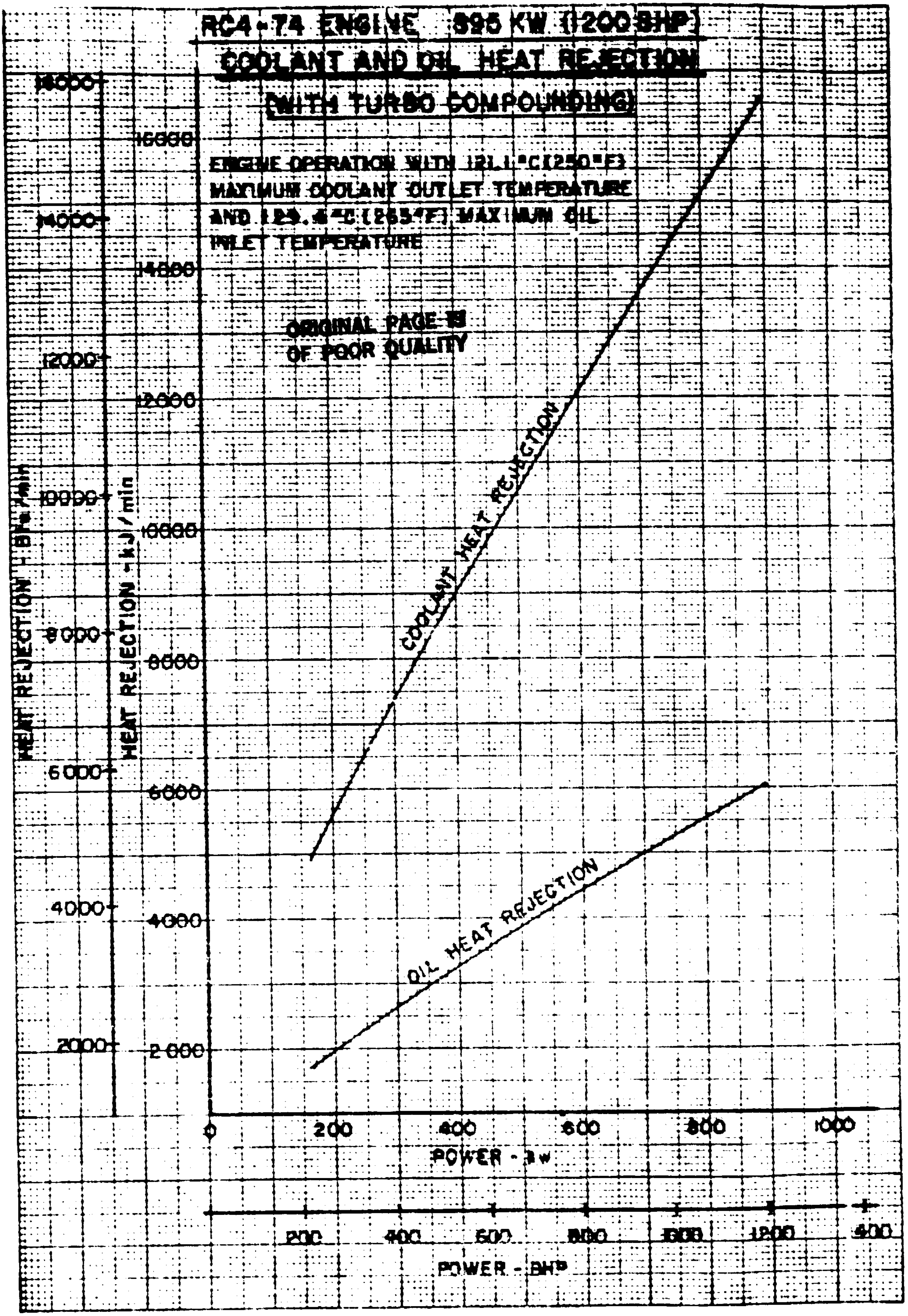

RC4-74 ENGINE 895 KW (1200 BHP)
COOLANT AND OIL HEAT REJECTION
(WITH TURBO COMPOUNDING)
ENGINE OPERATION WITH 121.1°C (250°F) MAXIMUM COOLANT OUTLET TEMPERATURE AND 123.9°C (255°F) MAXIMUM OIL INLET TEMPERATURE
ORIGINAL PAGE IS OF POOR QUALITY
COOLANT HEAT REJECTION
OIL HEAT REJECTION
HEAT REJECTION - BTU/min
HEAT REJECTION - kJ/min
16000
14000
12000
10000
8000
6000
4000
2000
16000
14000
12000
10000
8000
6000
4000
2000
0
200
400
600
800
1000
POWER - kW
200
400
600
800
1000
1200
1400
POWER - BHP

Figure 3.0.11

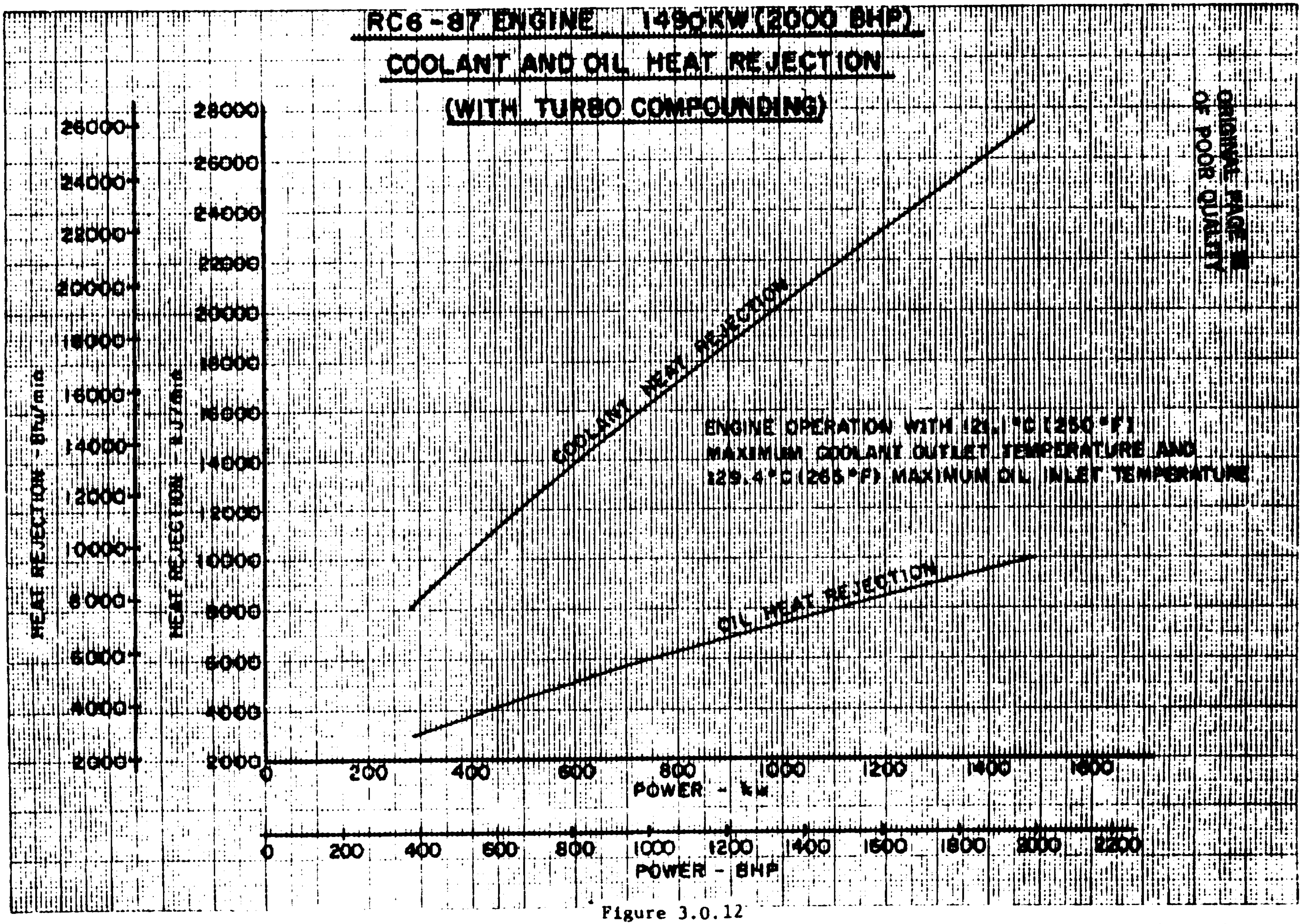

RC6-87 ENGINE 1490KW (2000 BHP)
COOLANT AND OIL HEAT REJECTION
(WITH TURBO COMPOUNDING)
ORIGINAL PAGE IS
OF POOR QUALITY
HEAT REJECTION - Btu/min
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
22000
24000
26000
HEAT REJECTION - kJ/min
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
22000
24000
26000
28000
COOLANT HEAT REJECTION
OIL HEAT REJECTION
ENGINE OPERATION WITH 121.1°C (250°F)
MAXIMUM COOLANT OUTLET TEMPERATURE AND
129.4°C (265°F) MAXIMUM OIL INLET TEMPERATURE
0
200
400
600
800
1000
1200
1400
1600
POWER - kW
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
POWER - BHP

Figure 3.0.12

Time Between Overhaul and Maintenance Schedule

The time between overhaul (TBO) for the commuter aircraft rotary engines is anticipated to be 3000 hours or greater. The estimate is based upon known wear rates of critical internal components (Figure 3.1.0 and Table 3.1.1) in existing engines which are similar in function to those which will be employed in the advanced engines, namely, apex seals, side seals, rotors, bearings, gears, end and intermediate housings, and rotor housings.

The predominant amount of Curtiss-Wright's testing has been done on the 60 cubic inch displacement engine. Approximately 17,000 operating hours have been accumulated on the industrial and vehicular prototypes of the RC2-60 model engine. It's apex seal wear rates are shown in Figure 3.1.0. Wear data from three rotary engine companies, for various engine parts under current state-of-the-art loading, appear on Table 3.1.1.

Rotary engines do not develop sludge, therefore the apex seal wear rate will be the most critical influence on engine performance consistency and life. It is obvious from Figure 3.1.0 that the current useful life of this seal (.090 inch wear) far exceeds the predicted 3000 hour TBO in the RC2-60 engine. The wear data in Table 3.1.1 was also a basis for estimating the TBO.

There are both configuration and operational differences between the RC2-60 baseline engine and the commuter aircraft engines in this design study. These include for the commuter aircraft engines:

Operating at Higher Speeds, Pressures, and Temperatures
Use of "Diesel Type" Fuel Injection Equipment
Use of Turbochargers
Use of Direct Injected Stratified Charge Combustion

The higher loading cited above is expected to have the greatest effect on apex seals and trochoid coating life.

It is assumed that sufficient testing activity can occur in the next five years to result in the introduction of inertia controlled designs or improved seal and rotor housing wear surface materials. This should permit the 3000 hour TBO to be realized and possibly extended.

Based upon diesel truck experience, the life of the fuel injection equipment and turbochargers is expected to extend well beyond 3000 hours.

Maintenance Between Overhauls

Maintenance costs are separated into two categories, namely, preventative and corrective. Corrective maintenance is unscheduled and results from random failure of components.

The maintenance schedule shown in Table 3.1.2 relates only to preventative maintenance. Corrective maintenance is most likely to occur on other than basic engine components, such as starters, ignition system, and the like. Since these components are similar to those found on reciprocating engines designed for aircraft use, it is assumed the cost of corrective maintenance would be comparable to reciprocating aircraft engines.

ORIGINAL PAGE IS
OF POOR QUALITY

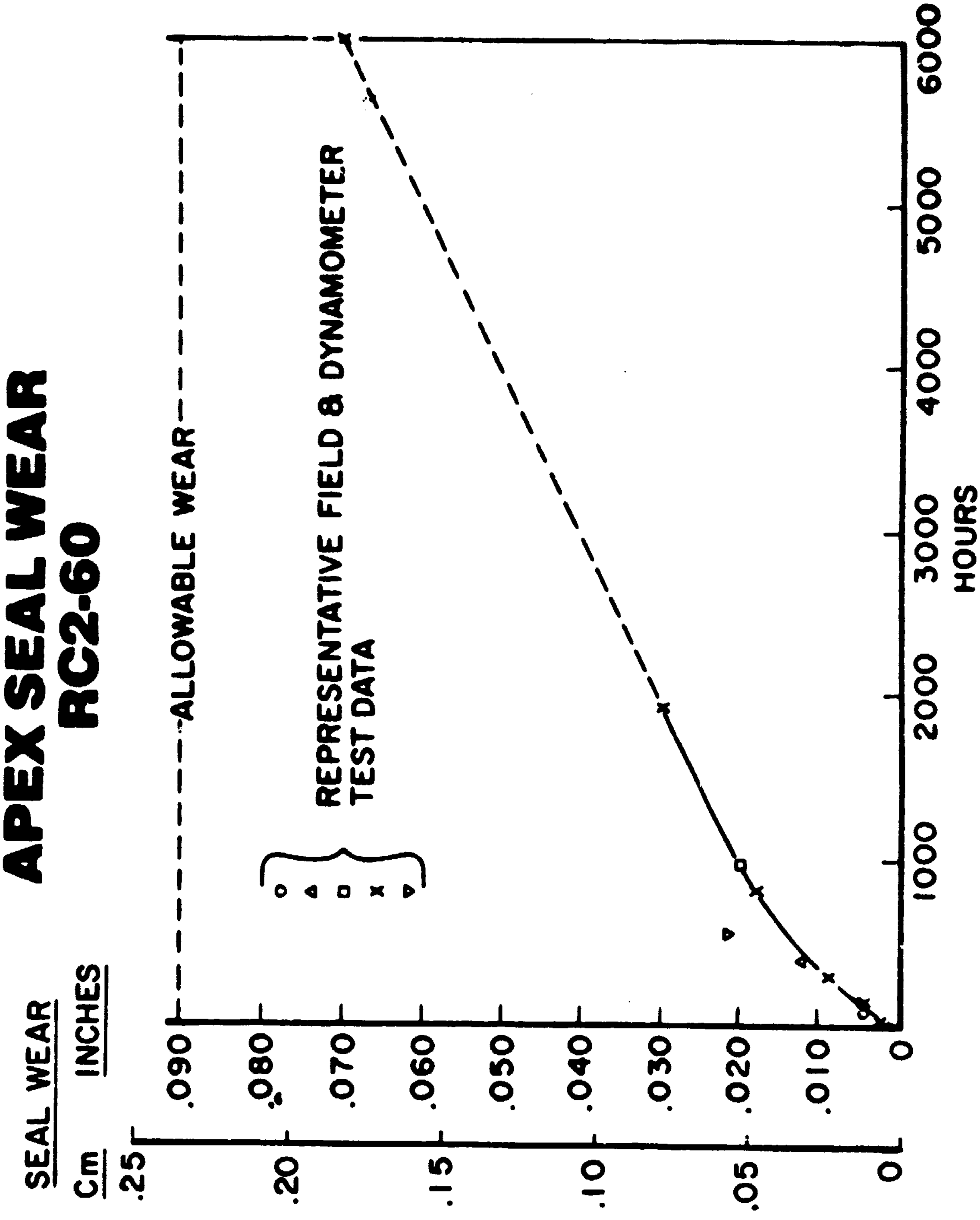


Figure 3.1.0

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 3.1.1

ESTIMATED WEAR-OUT RATE DATA
BASED ON ROTARY ENGINE DEVELOPMENT EXPERIENCE

Item	Allowable Wear	Field and Development Background
Apex Seals	.090" Height	[illegible] in 1973 hours at C-W
Side Seals	.015" End	[illegible] in 1093 hours at C-W
Oil Seals (Inner or Outer)	.020" Flat Width Increase	Ingersoll-Rand experience and sealed power recommendation - Mazda allows almost 300% increase
Rotor Bearings	.001" Local Material Removal at Loaded Zone	.0002" in 1922 hours at C-W (Mazda allows .0008" on diameter)
Main Bearings	To Be Determined	(Mazda allows .0011" wear on diameter) No measurable wear in 1950 hours at C-W
Stationary Gears	.004" Decrease in Over Pins Measurement	Negligible wear in 2012 hours at C-W
Rotor Gears	.005" Increase in Between Pins Measurement	Negligible wear in 2200 hours at C-W
Rotor Housing: Low Cycle Thermal Fatigue	Assumes Typical Duty Cycle for Low Cycle Thermal Fatigue	Mazda rotor housings can sustain at least 6000 extreme thermal cycles
Rotor Housing Surface Coating	.002" on Sliding Surface	Negligible wear in 2000 hours at C-W
End/Intermediate Housing Surface Coating	.004" on Sliding Surface	Mazda uses .0039" before grinding

TABLE 3.1.2

PREVENTATIVE MAINTENANCE FREQUENCIES - HOURS

	FREQUENCY
1. Change Oil	250
2. Replace Oil Filter	100
3. Replace Spark Plugs	100
4. Drain and Refill Coolant System	500
5. Replace Fuel Filter	50

SUMMARY

Hypothetical "Highly Advanced" engines were defined based on new technologies and design approaches. Physical and performance data were generated suitable for computerized comparative aircraft system evaluation studies of alternate engine candidates. The size range spanned from 800 to 2500 shaft horsepower and the market introduction goal was the early 1990's.

The basic combustion system is developed; however, the projected power densities and performance efficiencies require increases in engine internal pressures, thermal loading, and rotative speed. The commensurate technology advances are believed to be attainable with a practical technology enablement activity level.

The results of this study contract, taken together with the current status of demonstrated Stratified Charge Rotary Engine combustion technology, indicate a high potential for achieving an efficient multi-fuel engine well suited for commuter aircraft. A list of the engine's advantages compared to current top of the line air cooled reciprocating aircraft engines is attached.

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

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

LOWER AIRFLOW THAN TURBINE ENGINES

BASE TECHNOLOGY (TURBOCHARGED STRATIFIED CHARGE) DEMONSTRATED

REFERENCES

1. Charles Jones, "A Survey of Curtiss-Wright's 1958-1971 Rotating Combustion Engine Technological Developments", Paper No. 720468, presented at the National Automobile Engineering Meeting, Detroit, Michigan, May 1972.

2. Charles Jones, Harold D. Lamping, David M. Myers, Robert W. Loyd, "An Update of the Direct Injected Stratified Charge Rotary Combustion Engine Developments at Curtiss-Wright". SAE Transactions 1977, Vol. 86, Paper No. 770044.

3. P. Badgley, M. Berkowitz, C. Jones, D. Myers, E. Norwood and W.B. Pratt, "Advanced Stratified Charge Rotary Aircraft Engine Design Study, Final Report", NASA CR-165398 prepared under Contract No. NAS3-21285 by Curtiss-Wright Corporation for NASA Lewis Research Center, January 29, 1982

4. "United Parcel Service Applies Texaco Stratified Charge Engine Technology to Power Parcel Delivery Vans-Progress Report", J.M. Lewis, UPS, W.T. Tierney, Texaco, Inc.. SAE Paper No. 801429.

5. "Performance Evaluation of a Stratified Charge Engine Powered Automobile", Richard N. Wares, U.S. Dept. of Energy, Sept. 23, 1980.

6. "Multi-Fuel Rotary Aircraft Engine", C. Jones and M. Berkowitz, Curtiss-Wright Corp., AIAA-80-1237, Presented at the American Institute of Aeronautics & Astronautics, SAE, and ASME 16th Joint Propulsion Conference, June 30 - July 2, 1980, Hartford, Conn.

7. Roy Kamo, "Higher BMEP Prospect for Vehicular Diesels", Institute of Mechanical Engineers, October 26, 1977.

8. P. Badgley, M. Berkowitz, D. Myers, E. Norwood, W.B, Pratt, W. Silvestri, "Advanced Rotary Combustion Aircraft Engine Design Study, Task II - Engine Conceptual Design", prepared under Contract No. NAS3-21285 by Curtiss-Wright Corporation for NASA Lewis Research Center, January 18, 1980.

9. M. Berkowitz, W. Hermes, H. Lamping, "Rotating Combustion Engine Evaluation for Low Noise Level Aircraft Applications", prepared under Contract No. N00019-69-C-0460 by Curtiss-Wright Corporation for Department of the Navy, Naval Air Systems Command, January 1970.

BIBLIOGRAPHY

A. C.H. Hurkamp, W.M. Johnston, and J.H. Wilson, "Technology Assessment of Advanced General Aviation Aircraft", Report Nos. NASA CR-114338 and NASA CR-114339, prepared under Contract No. NASA 2-5972 by Lockheed-Georgia Company for NASA, June 1971.

B. Charles Jones, "A Review of Curtiss-Wright Rotary Engine Developments with Respect to General Aviation Potential". SAE Paper No. 790621, April 3, 1979.

C. M. Berkowitz, W.L. Hermes, R.E. Mount, and D. Myers, "Performance, Emissions, and Physical Characteristics of a Rotating Combustion Aircraft Engine", Report No. NASA CR-135119, prepared under Contract No. NAS3-20030 by Curtiss-Wright Corporation for NASA Lewis Research Center, December 1976.

D. Bergey, Karl H.: New Technology for General Aviation Aircraft. SAE Paper No. 790613, April 1979.

E. S.S. Manson, "Fatigue: A Complex Subject - Some Simple Approximations". Experimental Mechanics, July 1965, presented at the SESA Annual Meeting, Cleveland, Ohio, October 28 - 30, 1964.

F. Char. Jones, "A Progress Report on Curtiss-Wright's Rotary Stratified Charge Engine Development". SAE Paper No. 741206, presented at SAE International Stratified Charge Engine Conference, October 1974.

G. Charles Jones, "Development of the Rotary Engine", presented at the Rotary Engine Symposium, Detroit, Michigan, November 1973, SME Paper No. MM73-650.

H. Charles Jones and Harold Lamping, "Curtiss-Wright's Development Status the Stratified Charge Rotating Combustion Engine". SAE Transactions 1971, Vol. 80, Paper No. 710582.

I. W.T. Figart, R.L. Leisenring and W.B. Silvestri, "The RC Engine - A New Approach to Reduce Costs". SAE Paper No. 700273, presented at SAE National Air Transportation Meeting, April 1970.

J. David E. Cole and Charles Jones, "Reduction of Emissions from the Curtiss-Wright's Rotating Combustion Engine with an Exhaust Reactor". SAE Transactions 1970, Vol. 79, Paper No. 700074.

K. Charles Jones, "The Rotating Combustion Engine - Compact, Lightweight Power for Aircraft". SAE Transaction 1966, Vol. 76, Paper No. 670194.

L. Charles Jones, "New Rotating Combustion Powerplant Development". SAE Transactions 1966, Vol. 74, Paper No. 640723.

M. Charles Jones, "The Curtiss-Wright Rotating Combustion Engines Today". SAE Transactions 1965, Vol. 73, Paper No. 886d.

BIBLIOGRAPHY - (Continued)

N. W.T. Tierney and R.F. Wilson, "Adequate Future Transportation Demands Vehicle-Fuel-Refinery System Optimization Today", presented at the API Michigan Meeting, January 1976.

O. W.T. Tierney, E.M. Johnson and N.R. Crawford, "Energy Conservation of the Vehicle-Fuel-Refinery System", SAE Paper No. 750673, presented at the Fuels and Lubricants Meeting, June 1975.

P. W.T. Tierney, E. Mitchell, and M. Alperstein, "The Texaco Controlled-Combustion System, A Stratified Charge Concept, Review and Current Status", presented at the Institution of Mechanical Engineers Powerplants and Future Fuels Meeting, January 1975.

Q. R.K. Lamping, I. Manning, D. Myers and B. Tjoa, "Performance, Emissions, and Physical Characteristics of a Rotating Combustion Aircraft Engine", Report No. NASA CR-135119, Supplement A, prepared under Contract No. NAS3-20808 by Curtiss-Wright Corporation for NASA Lewis Research Center, May 1980.

R. Carson, G.H. "Fuel Efficiency of Small Aircraft", AIAA-80-1847.

S. H.D. Lamping, M.W. Galliers, and S.W. Wolosin, "Rotary Combustion Engine Trochoid Coatings and Seals", SAE Paper No. 741043, presented at SAE Automobile Engineering Meeting, October 1974.