NASA CR-165398
CW-WR-81.021B
Job Number 3291

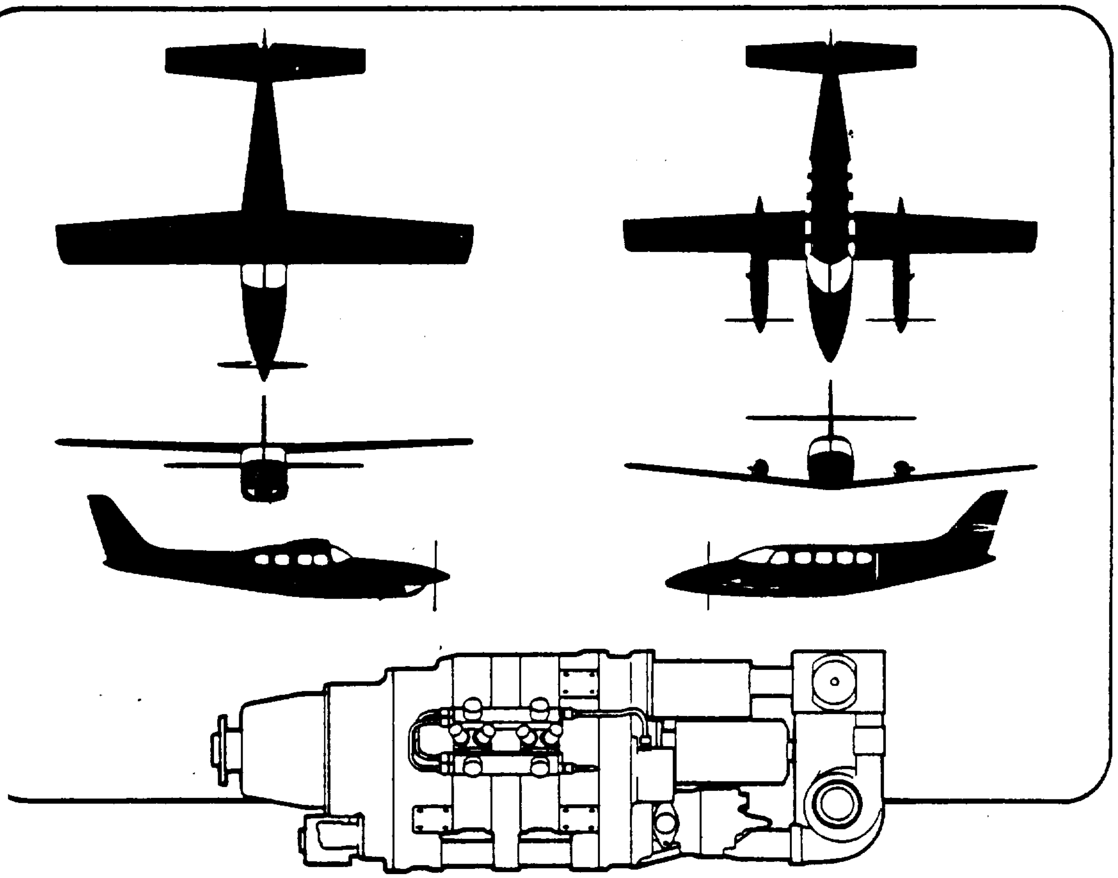
ADVANCED STRATIFIED CHARGE ROTARY AIRCRAFT ENGINE DESIGN STUDY

Final Report

By

CURTISS-WRIGHT CORPORATION:
P. Badgley, M. Berkowitz, C. Jones, D. Myers, E. Norwood and W. B. Pratt

CESSNA AIRCRAFT CORPORATION:
D. R. Ellis, G. Huggins, A. Mueller and J. H. Hembrey



Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA Lewis Research Center

Contract NAS 3-21285

January 29, 1982

CURTISS WRIGHT
Rotary Engine Facility • Wood-Ridge, New Jersey 07075

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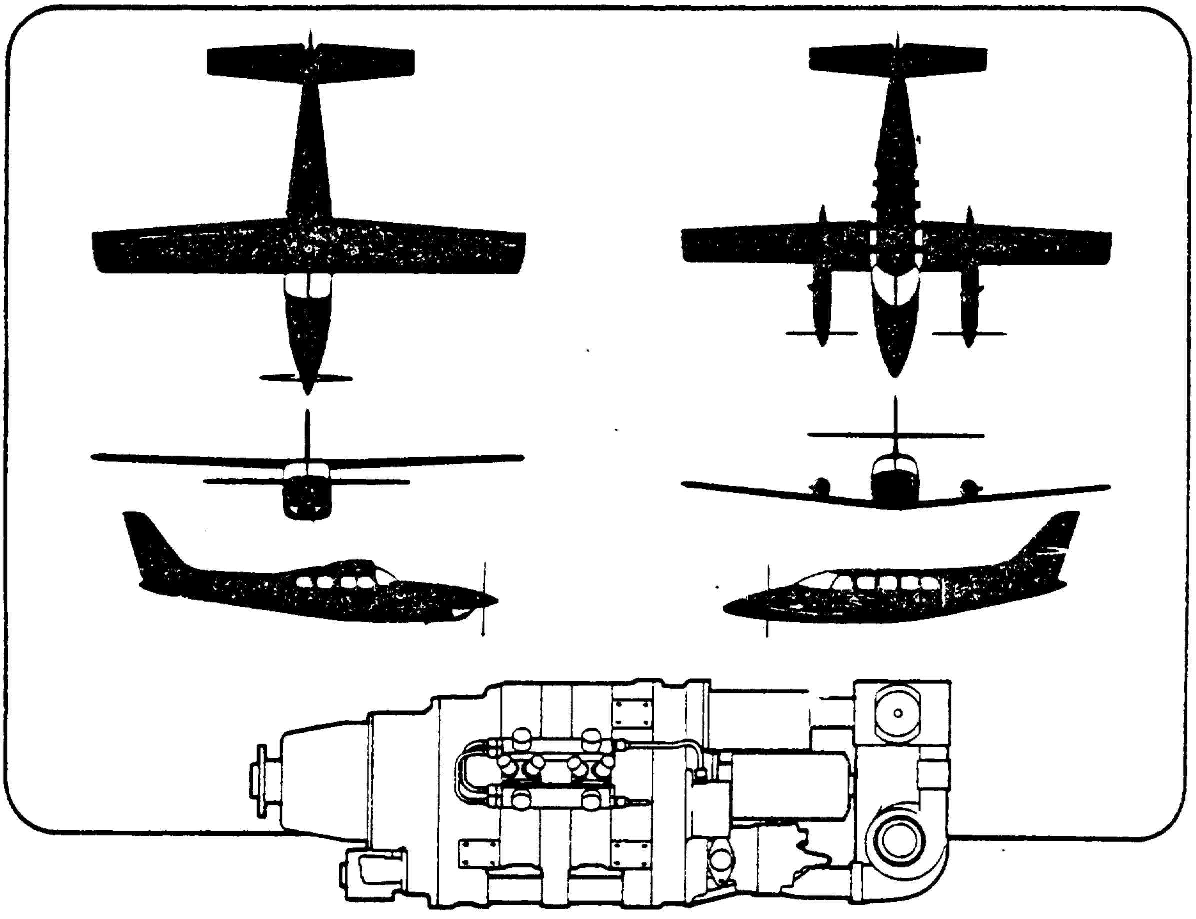

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16. Abstract The needs for future general aviation engines with improved fuel economy, multi-fuel capability, high specific power, and economic viability stimulated this design study of advanced and highly advanced stratified charge rotary combustion engines.

A technology base of new developments which offered potential benefits to a general aviation engine was compiled and ranked. Using design approaches selected from the ranked list, conceptual design studies were performed of an advanced and a highly advanced engine sized to provide 186/250 shaft Kw/HP under cruise conditions at 7620/25,000 m/ft altitude. These are turbocharged, direct-injected stratified charge engines intended for commercial introduction in the early 1990's.

The engine descriptive data includes tables, curves, and drawings depicting configuration, performance, weights and sizes, heat rejection, ignition and fuel injection system descriptions, maintenance requirements, and scaling data for varying power.

The following is a summary of the comparative size, weight, and fuel economy.

BASIC ENGINE DATA
186 Kw (250 HP) Cruise @ 7620m (25,000 ft) Altitude

	TS10-550 (Baseline)	Advanced RC2-47	Highly Advanced RC2-32
Length cm/inches	150.5/59.3	132/52	123/48.6
Width	84.8/33.4	41.9/16.5	40.6/16
Height	48.9/19.3	41.9/16.5	40.6/16
Weight-Flyable Kg/lb	265/585	158/348	116/255
SFC $\frac{g}{Kw\text{-}Hr}$ / $\frac{Lb}{HP\text{-}Hr}$	271/.446	226/.371	216/.355

The Cessna Aircraft Company performed an engine-airframe integration study of the resulting engines in advanced airframes on a comparative basis with current production type engines. The results include comparisons of airplane performance, costs, noise & installation factors. The rotary-engined airplanes showed substantial improvements over the baseline, including 30 to 35% lower fuel usage.

For all items of new technology used in the engine designs, development schedules were prepared showing the sequential actions required to advance the technologies sufficiently to make them available for designs initiated in 1985 or 1986.

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Aircraft Engines
Stratified Charge Engines
Stratified Charge Rotary Combustion Engines
Adv. Aircraft Engines
Rotary Combustion Engs.
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I-a

TABLE OF CONTENTS

Page No.

LIST OF FIGURES iv

LIST OF TABLES vi

INTRODUCTION 1.0.0

TECHNOLOGY ANALYSIS & DESIGN CANDIDATE EVALUATION (TASK I) 1.1.0

- Improved Combustion Efficiency Through Turbocharging 1.1.0
- General Conclusions and Technical Evaluations (Task I) 1.1.1
- Appendix - Technology Descriptions 1.2.0
  - Induction Air Intercooler 1.2.0
  - High Speed Sealing Grids 1.2.0
  - Turbocharger - Variable Inlet Area Turbine 1.2.1
  - Controlled Rotor Oil Cooling 1.2.2
  - Turbo-Compounding 1.2.4
  - Nasvytis Speed Reducer 1.2.5

ENGINE CONCEPTUAL DESIGNS (TASKS II AND VI) 2.0.0

- Design Considerations 2.0.0
- New Technology Assumptions 2.0.0
  - Apex Seal Wear Rate and Trochoid Coating Durability . . . 2.0.0
  - Sealing Effectiveness 2.1.1
  - Metal Temperatures/Cooling 2.1.1
  - Fuel Injection 2.1.2
  - Turbocharging 2.1.2
  - Aluminum Casting Alloy AMS 4229 . . . . 2.1.3
  - Lightweight Rotor 2.1.3
  - Varied Displacement Pressure Oil Pump 2.1.4
  - Rotor Thermal Insulation 2.1.4
- Engine Description - Highly Advanced Engine 2.2.0
  - Table of Geometric Data 2.2.2
  - Operating Data Summary, Metric 2.2.3
  - Operating Data Summary, Inch-Lb - °F 2.2.4
  - Reduction Gear 2.2.5
  - Torsional Vibration Control 2.2.5
  - Ignition System 2.2.7
  - Diagnostics 2.2.8
  - Fuel Injection System 2.2.8
  - Accessories 2.3.0
  - Weight, Size, and Scaling 2.3.0
  - Engine Cooling 2.4.0
  - Coolant and Oil Heat Rejection Rates 2.4.1

3

TABLE OF CONTENTS (Continued)

Page No.

Coolant and Oil Heat Rejection Rates 2.4.1
Time Between Overhaul and Maintenance Schedule 2.5.0
Type of Fuel 2.5.2
Bearing Capacity 2.5.4
Stress Level Criteria 2.5.5

Performance 2.6.0

Power 2.6.1
Fuel Consumption 2.6.1
Efficiency 2.6.2
Mechanical Efficiency 2.6.3
Emissions 2.6.3

Engine Description - Advanced Engine 2.7.0

ENGINE/AIRFRAME INTEGRATION (TASK III) 3.0.0

Introduction 3.1.0

Description of Baselines and Methods 3.1.0

The Sizing Process 3.3.0

Discussion of Results, Single Engine Airplanes 3.4.0

Performance & Weight Comparisons 3.4.1
Cooling Drag Considerations 3.4.3
Cost Considerations 3.4.3
Flyover Noise Levels 3.4.4

Discussion of Results, Twin-Engine Airplanes 3.4.4

Summary and Conclusions 3.5.0

Appendix I - Airplane Weight Breakdowns 3.6.0

Appendix II - Costing Information 3.7.0

TECHNOLOGY ENABLEMENT DEVELOPMENT PLAN (TASK IV) 4.1.0

Related Non-Aviation Technology Enablement 4.2.0

SUMMARY AND CONCLUSIONS 5.0.0

Advantages of the Rotary Stratified Charge Aircraft Engine . . 5.1.0

REFERENCES 6.0.0

BIBLIOGRAPHY 6.1.0

4

LIST OF FIGURES

Figure No.	
1.1.1	ISFC vs F/A Ratio, RC1-350, 8.5:1 Compression Ratio
1.1.2	Theoretical Turbocharging Effect on BSFC
1.1.3	Test Results - BSFC Improvement from Turbocharging
1.1.4	SFC Improvement from Turbocharging
1.1.5	Measured Reduction in Thermal and Pressure Loads from Lower Compression Ratio and Higher Air/Fuel Ratio
1.2.0	Intercooling Effects
1.2.1	High Speed Sealing Grid Drawings
1.2.2	Turbo-Compound Turbine Cutaway
2.1.0	Ferro-Tic Apex Seal Height Wear Against Plasma Sprayed Ferro-Tic Trochoid Coating
2.1.1	Stratified Charge Configuration, BTC Pilot Tandem Dual
2.2.0	RC2-32 Longitudinal Section
2.2.1	Dual Spark Plugs/Fuel Injectors Arrangement
2.2.2	Study - Pilot Injector, Dual Spark Plugs, With Coils
2.2.3	Final Accessory Arrangement Study - End Views
2.2.4	Internal Gear Prop Reduction Drive
2.2.5	Initial Accessory Arrangement Study - End Views
2.2.6	Preliminary Arrangement for Oil and Coolant Pumps on Same Shaft
2.2.7	RC2-32 Installation Drawing
2.2.8	Planetary Prop Gear Reduction
2.2.9	RC2-32 Reduction Gear Torque at Input
2.3.1	Take-Off Power vs Engine Size, (Two Rotor Engines)
2.3.2	Dimensions vs Displacement per Rotor (Two Rotor Engines)
2.4.0	High MEP Diesel Piston Temperatures and Block Strain
2.4.1	Combustion Gas Temperature vs Volume, RC2-32
2.4.2	RC2-32 Engine Coolant and Oil Heat Rejection
2.5.0	Apex Seal Wear, RC2-60
2.5.4	RC2-32 Estimated Indicator Card
2.5.5	Stress Level vs Life Cycles, AMS 4229 and AMS 4220
2.6.0	Effect of Size and Speed on 186 kw/250 HP Cruise BSFC

LIST OF FIGURES (Continued)

Figure No.

2.6.1 Effect of RPM and Displacement on F/A Ratio, Volumetric Efficiency, and IMEP Requirements for 186 kw (250 BHP) and .38 BSFC
2.6.2 Estimated Altitude Performance, RC2-32
2.6.3 RC2-32 Estimated Performance
2.6.4 RC2-32 Estimated Friction Characteristics
2.7.0 RC2-47 Estimated Friction Characteristics
2.7.1 Estimated Altitude Performance, RC2-47
2.7.2 RC2-47 Estimated Performance
2.7.3 RC2-47 Coolant and Oil Heat Rejection
3.2.1 Three-View, Single-Engine Baseline Airplane
3.2.2 Three-View, Twin-Engine Baseline Airplane
3.3.1 Typical Sizing Output, Carpet Plot
3.4.1 Comparative Layout RC2-32 and Baseline Singles
3.4.2 Single Engine RC2-32 Installation Concept
3.4.3 Cooling Drag Considerations
3.4.4 Comparative Layout, RC2-32 and Baseline Twins
3.4.5 Twin Engine, RC2-32 Installation Concept
4.1.1 RC1-60T Technology Enablement Development Plan
4.1.2 RC1-75T Technology Enablement Development Plan
4.1.3 RC1-XT Technology Enablement Development Plan

LIST OF TABLES

Table No.	Title	Page No.
1.1.0	Candidate Technologies Considered	1.1.3
1.1.1	New Technology Evaluation Criteria	1.1.4
1.1.2	Ranking of Technologies	1.1.6
2.2.2	Table of Geometric Data, Highly Advanced RC2-32	2.2.2
2.2.3	Operating Data Summary, RC2-32, Metric	2.2.3
2.2.4	Operating Data Summary, RC2-32, Inch-Lb-°F	2.2.4
2.2.9	Fuel Injection Systems Evaluation	2.2.10
2.3.1	Weights, Rotary Combustion Engine and Accessories	2.3.1
2.5.1	Estimated Wear Out Rate Data - Curtiss-Wright Experience	2.5.1
2.5.3	Preventive Maintenance Frequencies - Hours	2.5.3
2.6.3	RC2-32 Estimated Fuel Consumption	2.6.2
2.6.5	Estimated Emissions Characteristics	2.6.4
2.7.0	Table of Geometric Data, Advanced RC2-47	2.7.0
2.7.1	Operating Data Summary, RC2-47, Metric	2.7.1
2.7.2	Operating Data Summary, RC2-47, Inch-Lb-°F	2.7.2
2.7.3	RC2-47 Estimated Fuel Consumption	2.7.3
3.4.1	Single-Engine Airplane Summary	3.4.1
3.4.2	Comparative Mission Performance - Single-Engine Airplanes.	3.4.2
3.4.3	Acquisition and Direct Operating Costs - Single-Engine Airplanes	3.4.3
3.4.4	Estimated Flyover Noise Levels - Single-Engine Airplanes	3.4.4
3.4.5	Twin-Engine Airplane Summary	3.4.5
3.4.6	Comparative Mission Performance - Twin-Engine Airplanes.	3.4.6
3.4.7	Acquisition and Direct Operating Costs - Twin-Engine Airplanes	3.4.7
3.4.8	Estimated Flyover Noise Levels - Twin-Engine Airplanes	3.4.7
3.7.1	Factors Used in Computing Aircraft Price	3.7.2
3.7.2	Direct Operating Costs for General Aviation Aircraft	3.7.3
3.7.3	Factors Used in Computing Direct Operating Cost	3.7.2
3.7.4	Insurance Rates Applicable to 1981 Cessna Models	3.7.5
3.7.5	Direct Operating Cost	3.7.6
5.1.0	Basic Engine Data, Inch-Lb-Hp	5.0.1
5.2.0	Basic Engine Data, cm-kg-kw	5.0.2

INTRODUCTION

CURTISS-WRIGHT has been actively engaged in research and development of rotary combustion engines for 23 years.

A description of the Rotary Engine Development activity at Curtiss-Wright from 1958 to 1971 may be found in Reference 1. It includes information on design features, apex seal development, testing, and application of the Rotary Engine to automotive, aircraft, and small air-cooled engines. Reports giving more details of the aircraft-related testing are listed in the Bibliography.

Curtiss-Wright's flight experience with the RC2-60 (an automotive prototype) led to the development of a liquid-cooled, gasoline fueled rotary engine, in the 300 horsepower class, the RC2-75, for application to military and commercial light aircraft. This engine was tested under NAS contract Nos. NAS3-20030 and NAS3-20808. NASA reports covering this work are included in the Bibliography.

Over the last several years Rotary (Wankel-type) engine technology research at Curtiss-Wright has been directed at stratified charge direct chamber injection. During this period, successive improvements (Reference 2) have resulted in an efficient multi-fuel combustion configuration which is incorporated in a relatively large displacement military vehicle powerplant now being developed for the USMC. This engine, the RC2-350, with two rotors of 350 cubic inches each, can produce over 750 HP naturally aspirated. It will serve as the technology baseline for the advanced engines described in this report.

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 design studies performed under this contract, which are supplemented by C-W research testing using the RC1-60, growth directions have been defined.

The key elements for advanced aircraft engines are reduced fuel consumption and higher power density through increased BMEP and operation at very lean mixtures by turbocharging to high engine airflow rates. The object of this study is to define what these growth directions mean in terms of small aircraft engines and performance of the aircraft as a total system. The aircraft system segments of this paper have been analyzed by the Cessna Aircraft Company.

The Rotary Stratified Charge Engine offers high power density because of its 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 past the stationary location of the spark plug as an inherent function of its geometry. In stratified charge engines 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. Multi-fuel capability is obtained by 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.

In addition, the stratified charge version 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, power, and emissions) on gasoline, jet engine fuel (JP-4 and JP-5), Diesel fuel, and methyl alcohol, without a hardware configuration change.

The objectives of this contract are to define and conduct a design study of advanced and highly advanced engines for the 1990 time period. They will satisfy the following goals and criteria:

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

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

3. Emissions that meet the previously proposed EPA 1979 piston aircraft standards.

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

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

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

This study contract effort was to make maximum use of new technologies and design approaches. The effort was divided into the following tasks:

Task I: A technology base was established which involved screening numerous sources for applicable new technologies and design approaches, evaluating them, and making selections for inclusion in the Task II conceptual design. A Task VI conceptual design was added as a contract extension to insure equally comprehensive evaluations of both the Advanced and Highly Advanced designs. The use of the Curtiss-Wright stratified charge combustion approach and turbocharging were early basic selections due to their high return in meeting the aforementioned goals. At the end of Task I design approach selections were made to be used in the conceptual designs to follow. They were the approaches estimated to be the most advanced technologies sufficiently proven and highly ranked to be available to an engine design initiated in 1985 or 1986. It is estimated commercial introduction would take place in the early 1990's.

Tasks II and VI: Conceptual designs of Advanced and Highly Advanced engines were made which included data on sizes, stress levels, cooling, weights, scaling with horsepower variation, drawings and performance. The "highly advanced" selections were higher risk approaches which would require a more extensive development program and/or a later introduction to the commercial market.

Task III: The resulting designs were matched by the Cessna Aircraft Corporation with appropriately sized and designed aircraft and engine-airframe integration studies performed on a comparative basis with a "top of the line" current reciprocating engine in a matched aircraft. The comparisons included aircraft performance, mission capability, installation arrangements and aircraft costs.

Task IV: A potential development schedule was prepared for the items of new technology used in the conceptual designs. The schedule indicates the work necessary to advance the new technologies sufficiently for their inclusion in a new design in the 1985 or 1986 time period. In addition an estimate was made of the extent to which the new approaches might be addressed by other research and development sources such as the automotive industry.

Task V: Various reports were made including progress reports, the previously submitted Task I and II reports, and this Final Report.

The detailed results of these tasks are included in the main text which follows.

TECHNOLOGY ANALYSIS & DESIGN CANDIDATE EVALUATION (TASK I)

Based on a review of related technical literature, supplier data and research and development activity at several engine companies, a number of candidate technologies were identified as offering potential benefits to a General Aviation Rotary Engine.

The technologies eventually used in the contract engine designs are discussed in the engine design section (Engine Conceptual Designs - Tasks II and VI, pages 2.0.0 to 2.4.1). The candidate technologies not described there are discussed in an appendix to this section (page 1.2.0).

The following section describes corporate IR&D efforts in the area of turbocharging performed after Task I was completed. The results provide a firmer basis for the SFC projections in this report.

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 1.1.1, 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 1.1.2. 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 1.1.3 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 N.A. 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 outputs, 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 1.1.4, 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 limits. Figure 1.1.5 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.

General Conclusions and Technical Evaluations

The candidate technologies selected for evaluation in Task I are listed in Table 1.1.0. The criteria by which the design approaches and technology candidates were evaluated are listed and defined in Table 1.1.1. In order to introduce differences in importance between the criteria weighted values are shown for each criterion.

The numerical evaluation procedure used made it possible to rank the technologies in a general order of merit regardless of category. Table 1.1.2 shows the ranking of the candidate technologies for both the advanced and highly advanced engines. Since the assessments are obviously far from exact, the strict order should not be taken too seriously. It is probably reasonable to speak of high, middle, and low ranges, however, with the technologies in each group having similar potential and priority. (Paraphrased from SAE Paper No. 790613, "New Technologies for General Aviation Aircraft," by Karl H. Bergey, School of Aerospace, Mechanical and Nuclear Technology, University of Oklahoma.)

On the basis of the methods described above the following design approaches were recommended for inclusion in the overall conceptual design of the advanced engine:

- Increased IMEP and speed
- Turbocharging with intercooling
- Higher hot strength aluminum casting alloy
- 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

The more advanced technology of the "Highly Advanced" engine includes the following additional features:

- Turbocharger with variable turbine area
- Retracting apex seals
- Rotor combustion flank insulation
- Further increases in IMEP and RPM

As described above, when selecting the design approaches used in the engine conceptual designs, engineering judgement was applied rather than a strict observance of the ranking order in Table 1.1.2. There are limitations to the formal evaluation procedure used since it does not include trade-off analyses or systems analyses.

The usefullness and status of some of the new technologies will be a function of the state-of-the-art developed by the major suppliers at the time a design and development program is initiated. Examples of these are: improved lubricants, low pressure drop heat exchangers, and alternate cooling fluids.

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ISFC VS. F/A RATIO FOR 5 SEPARATE RC1-350
ENGINE BUILDS OF THE
SAME CONFIGURATION, 8.5:1 COMPRESSION RATIO

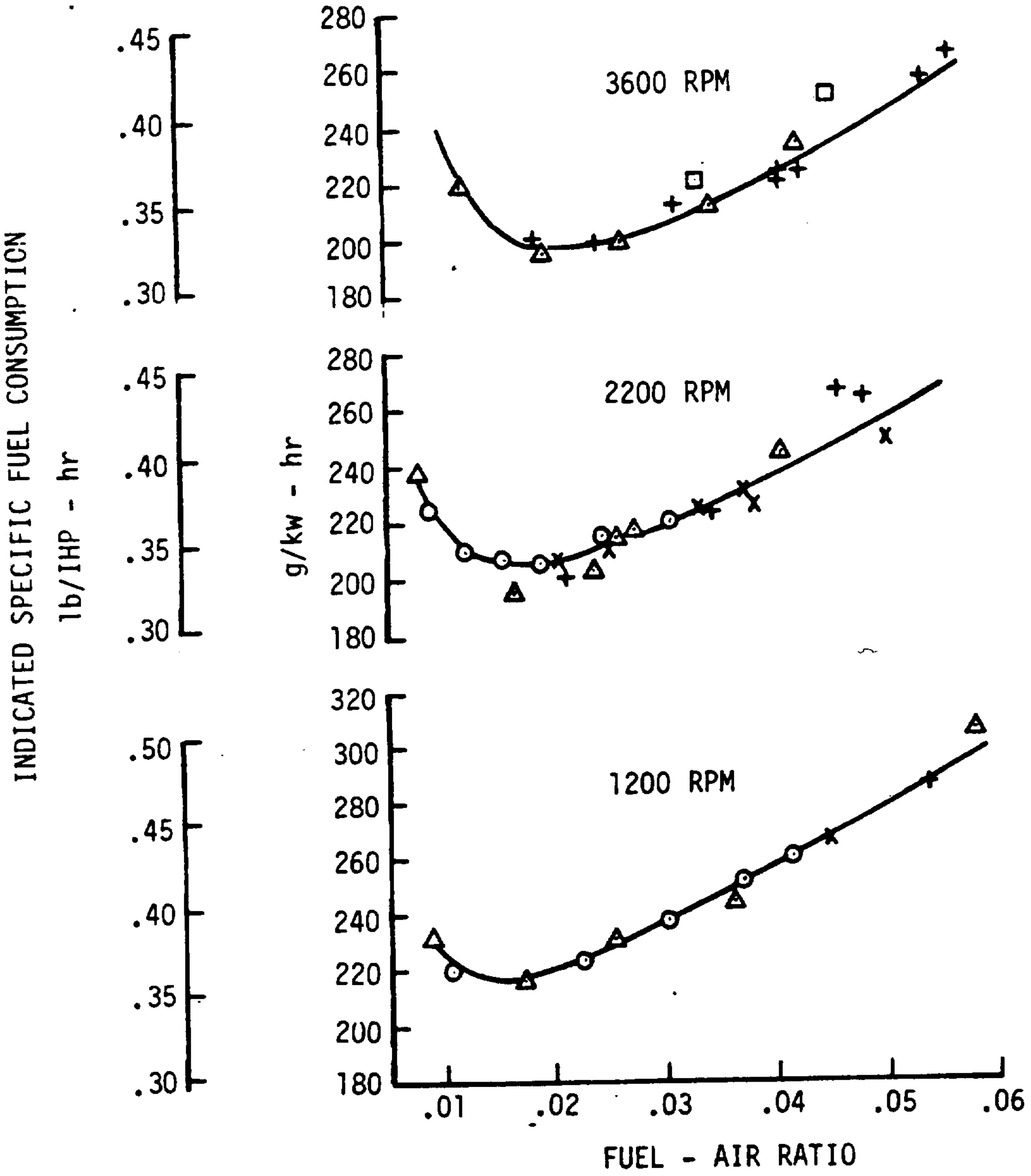


Figure 1.1.1

THEORETICAL TURBOCHARGING EFFECTS ON BSFC

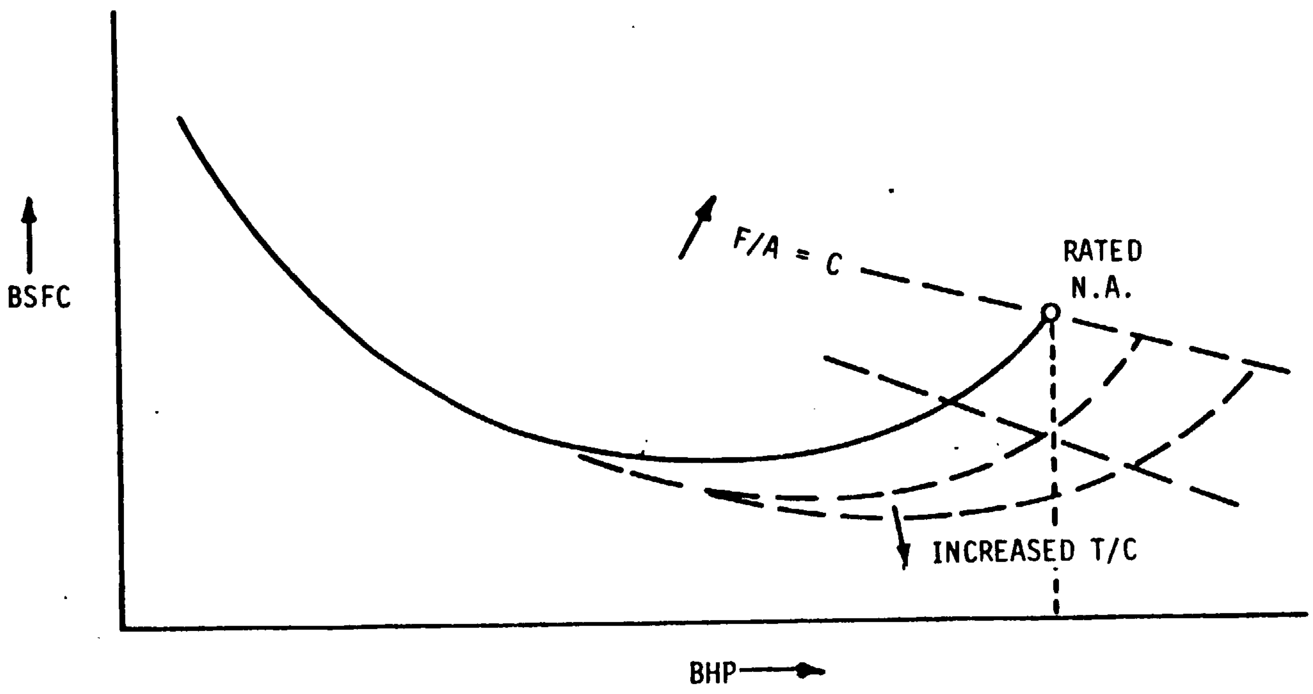


Figure 1.1.2

BSFC IMPROVEMENT FROM TURBOCHARGING

RC1-60 STRATIFIED CHARGE

4000 RPM

PERIPHERAL INTAKE PORTS

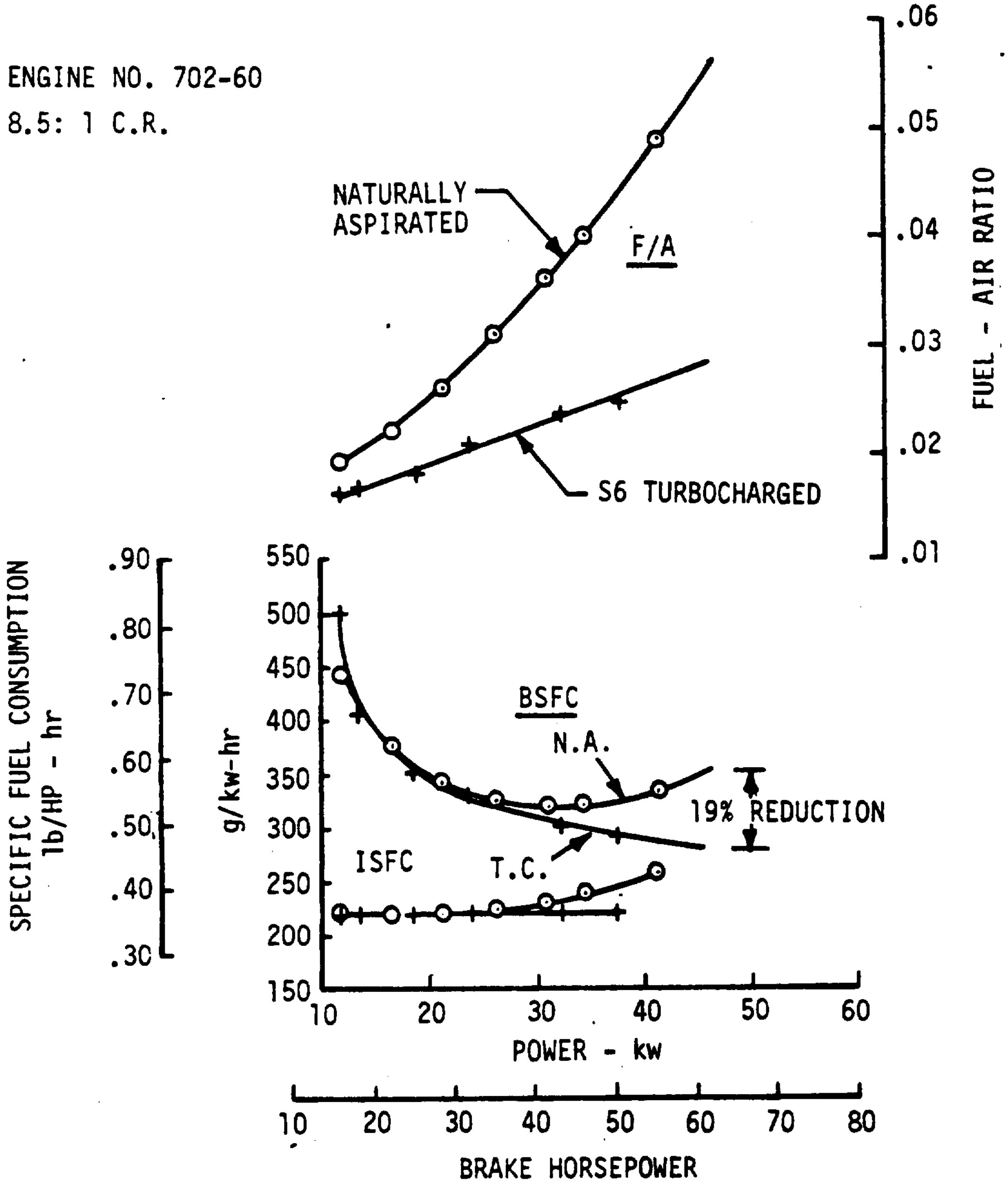


Figure 1.1.3

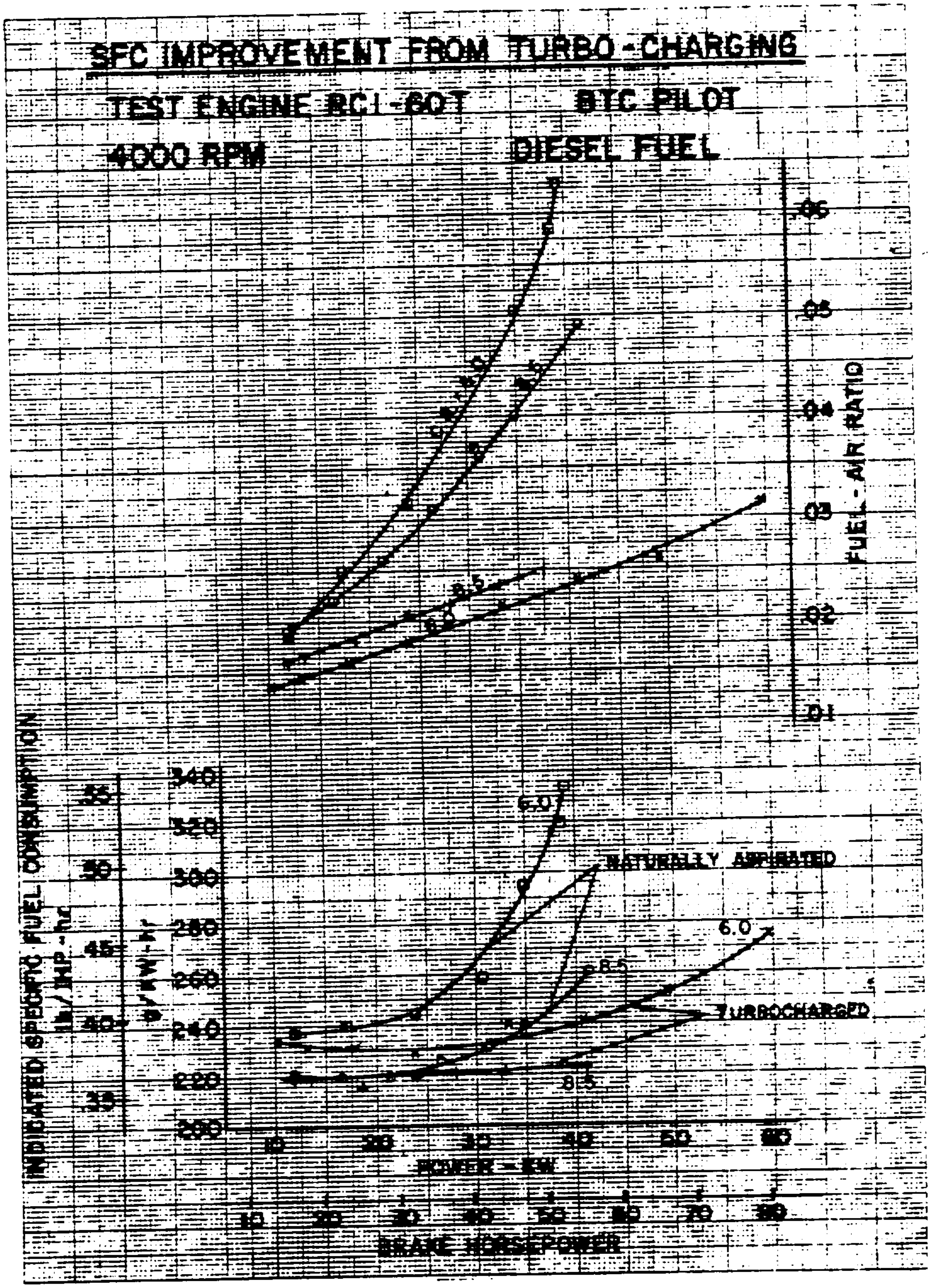

SFC IMPROVEMENT FROM TURBO-CHARGING
TEST ENGINE RC1-60T
BTC PILOT
4000 RPM
DIESEL FUEL
FUEL - AIR RATIO
.06
.05
.04
.03
.02
.01
6.0
8.5
INDICATED SPECIFIC FUEL CONSUMPTION
lb/IHP-hr
g/KW-hr
55
50
45
40
35
340
320
300
280
260
240
220
200
6.0
NATURALLY ASPIRATED
6.0
8.5
TURBOCHARGED
8.5
10
20
30
40
50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

Figure 1.1.4

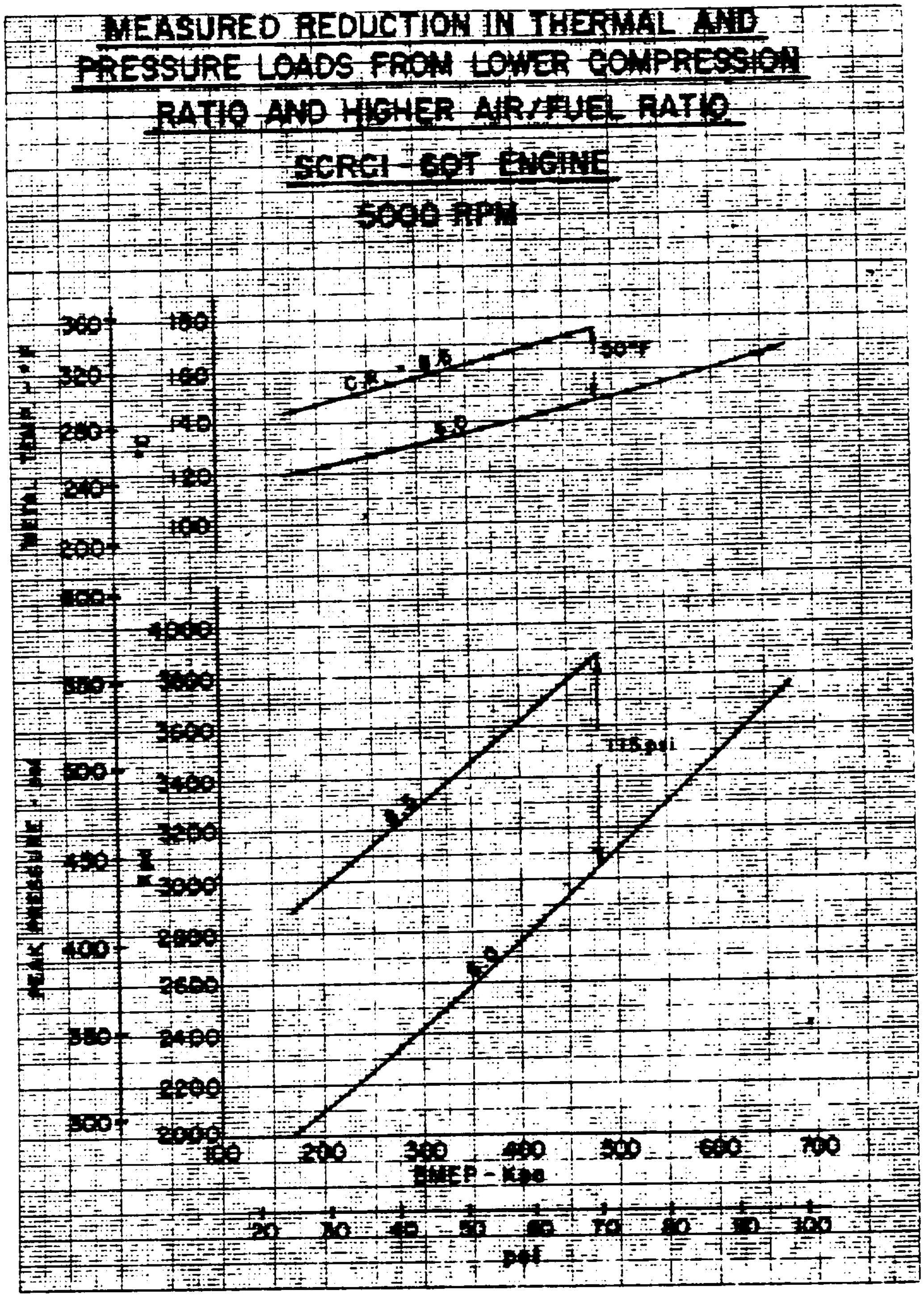

MEASURED REDUCTION IN THERMAL AND PRESSURE LOADS FROM LOWER COMPRESSION RATIO AND HIGHER AIR/FUEL RATIO
SCRCI 60T ENGINE
5000 RPM
METAL TEMP - °F
°C
360
320
280
240
200
180
160
140
120
100
C.R. = 8.5
5.0
30°F
PEAK PRESSURE - psi
KPa
600
550
500
450
400
350
300
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
8.5
5.0
135psi
100
200
300
400
500
600
700
BMEP - Kpa
20
30
40
50
60
70
80
90
100
psi

Figure 1.1.5

TABLE 1.1.0 - CANDIDATE TECHNOLOGIES CONSIDERED

Solid-State Ignition Trigger Vs Mechanical Trigger

Plasma Jet Ignition System

Eliminating Pilot Injector

High Temperature Aluminum Castings

Turbocharger

Thin Wall (Iron) Rotor

Exhaust Port Thermal Liner (Metallic)

Improved Lubricants

Multiple Power Source for Ignition

Induction Air Intercooler

Variable Displacement Pressure Oil Pump

Provision for Counter-Rotating Propellers

Total Diagnostics

Electronic Ignition Schedule

Computer Vs Mechanical Timing

Fiber Optics Data Bus

Low Pressure Drop Heat Exchangers

NASVYTIS Traction Speed Reducer (Prop)

Alternate Cooling Fluid

Composite Rotor Housing (Wear Resistant Liner)

Wing Leading Edge with Integral Coolant Cooler

Alternate Materials Seals

Retracting Apex Seals

Thermostatically Controlled Rotor Oil Cooling

Turbocharger with Variable Area Turbine

Spark Ignition Start/Auto-Ignition Run

Aluminum Rotor (Reinforced Lands)

Insulated Rotor - Thermal Barrier Coating

Independent Dual Ignition

Variable Compression Ratio

Insulated Rotor - Inserts on Metallic Pad Insulator

Adiabatic Engine Ceramic End Walls

Composite Rotor (Reinforced Apex Seal Land)

Electronic Injection (Fuel)

Adiabatic Engine Ceramic Rotor Inserts

Turbocompound

Adiabatic Engine - Ceramic Rotor Housing Liner

Pilot Nozzle Trigger for Ignition System

High Speed Propeller (No Reduction Gear)

NASVYTIS Traction Speed Reducer (Turbocompound Drive - If Used)

Adiabatic Engine - Ceramic Rolling Element Bearings

TABLE 1.1.1 - NEW TECHNOLOGY EVALUATION CRITERIA

CRITERION	DEFINITION	WEIGHTING
Safety	Protection against danger of personal injury and property loss.	8
Reliability	Relative assurance against failure. Minimum "down" time.	8
Fuel Consumption	Engine efficiency as expressed in pounds of fuel consumed per brake horsepower - hour at specified ambient and flying conditions (for example cruise @ 75% power).	7
Weight	Engine weight with defined accessories.	7
Cooling	Effect on aircraft performance of loss due to engine cooling air drag.	7
Initial Cost	Cost of acquisition. Affected by producibility.	7
Multi-Fuel Capability	Ability to operate on alternate fuels such as 100/130 octane aviation fuel, jet, diesel, low octane unleaded automotive fuel, or low octane middle distillate.	7
Performance	Fuel consumption, cooling and multi-fuel capability being separate criteria, this covers primarily the power and altitude capability.	7
Technological Uncertainty	Likelihood of successful development in desired time frame and within appropriate cost restraints.	6
Life Cycle Costs	Total costs over useful life. Affected by durability, fuel consumption, required maintenance, TBO, etc.	6
Size & Shape	Cubic volume occupied by engine. Affects air frame designs, arrangement options.	6
Operational Characteristics	Various items including starting, throttle response, smoothness, forces at engine mounts.	6
Durability	Ruggedness - Life of the engine parts, affects safe time between overhauls.	5

TABLE 1.1.1 - (Continued)

CRITERION	DEFINITION	WEIGHTING
Maintainability	Ease of access for repairs. Use of wear elements, stability of engine settings.	5
Materials	Availability to producers, quantity of strategic types	3
Noise	Degree of undesirable sound levels for individuals inside and outside of the aircraft.	3
Emissions	Contribution to known air pollution contaminants (EPA 1979 piston aircraft standards).	2

TABLE 1.1.2 - RANKING OF TECHNOLOGIES

ADVANCED ENGINE			HIGHLY ADVANCED	
SCORE	ORDER	ITEM	ORDER	SCORE
131	1	Solid State Ignition Trigger vs Mechanical Trigger	1	144
76	2	Plasma Jet Ignition System Eliminating Pilot Injector	2	102
74	3	High Temperature Aluminum Castings	6	80
65	4	Turbocharger	12	65
63	5	Thin Wall (Iron) Rotor	14	62
60	6	Exhaust Port Thermal Liner (Metallic)	9	67
55	7	Improved Lubricants	15	57
53	8	Multiple Power Source for Ignition	11	66
47	9	Induction Air Intercooler	16	53
43	10	Variable Displacement Pressure Oil Pump	17	43
42	11	Provision for Counter Rotating Propellers	18	42
40	12	Total Diagnostics	10	66
39	13	Electronic Ignition Schedule Computer vs. Mechanical Timing	5	85
38	14	Fiber Optics Data Bus	3	86
35	15	Low Pressure Drop Heat Exchangers	19	41
32	16	Nasvytis Traction Speed Reducer (Prop)	20	38
30	17	Alternate Cooling Fluid	22	36
27	18	Composite Rotor Housing (Wear Resistant Liner)	23	33
26	19	Wing Leading Edge with Integral Coolant Cooler	7	77
25	20	Alternate Materials Seals	24	32
20	21	Retracting Apex Seals	8	70

TABLE 1.1.2 - (Continued)

ADVANCED ENGINE			HIGHLY ADVANCED	
SCORE	ORDER		ORDER	SCORE
13	22	Thermostatically controlled rotor oil cooling	30	13
12	23	Turbocharger with Variable Area Turbine	21	36
9	24	Spark Ignition Start/Auto-Ignition Run	27	15
8	25	Aluminum Rotor (Reinforced Lands)	32	8
2	26	Insulated Rotor-Thermal Barrier Coating	26	22
0	27	Independent Dual Ignition	25	27
-1	28	Variable Compression Ratio	No Rating on Highly Advanced	
-5	29	Insulated Rotor-Inserts on Metallic Pad Insulator	28	15
-15	30	Adiabatic Engine Ceramic End Walls	29	15
-17	31	Composite Rotor (Reinforced Apex Seal Land)	37	-11
-17	32	Electronic Injection (Fuel)	4	85
-23	33	Adiabatic Engine Ceramic Rotor Inserts	31	12
-28	34	Turbocompound	38	-28
-34	35	Adiabatic Engine-Ceramic Rotor Housing Liner	36	-10
-44	36	Pilot Nozzle Trigger for Ignition System	35	-10
-45	37	High Speed Propeller (No Reduction Gear)	33	-2
		Nasvytis Traction Speed Reducer (Turbo-compound Drive - if used)	13	64
		Adiabatic Engine - Ceramic Rolling Element Bearings	34	-5

APPENDIX

DESCRIPTIONS OF TASK I CANDIDATE TECHNOLOGIES NOT DESCRIBED IN SECTION ON TASKS II AND VI

Induction Air Intercooler

Intercooling of the charge air between the turbocharger and the engine effectively represents an improvement in compressor efficiency and in a given size engine can result in improved fuel economy, lower mechanical and thermal loadings, lower emissions, lower exhaust gas temperatures, less smoke, and reduced cooling requirements. It permits down sizing on an engine due to better charging capabilities resulting in a smaller lighter package.

Figures A and B of Figure 1.2.0 are based on information from the Institute of Mechanical Engineers Publication "I Mech E Conference Publications 1978-2" entitled "Turbocharging and Turbochargers" and indicate the beneficial effects on Diesel engines of intercooling. Figure A illustrates incremental decreases in fuel consumption, NO_x emissions and peak combustion pressure with increase in intercooler effectiveness (the ratio of actual to possible temperature decrease). Figure B indicates that with the Diesel engine under consideration, an SFC improvement of 3 to 4% was attributable to the intercooler.

High Speed Sealing Grids

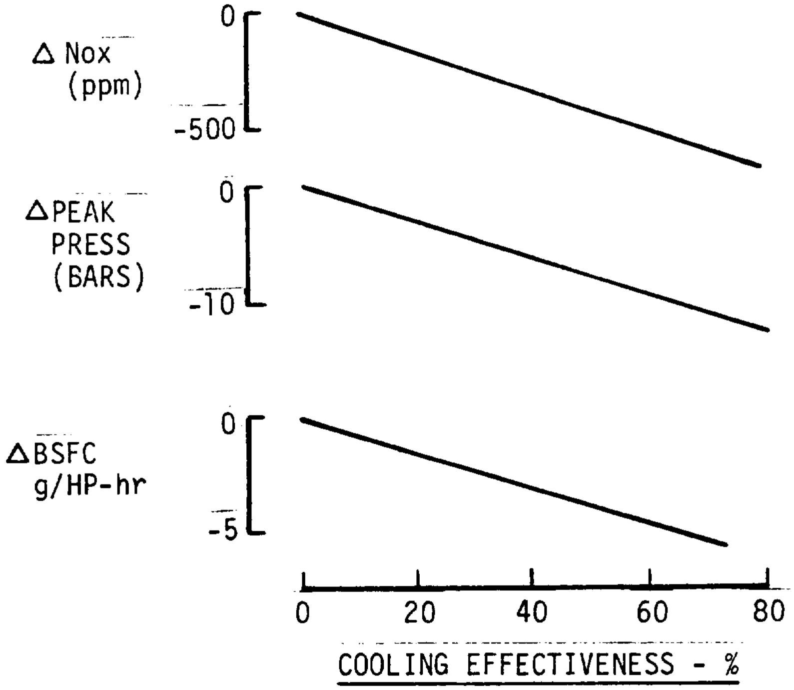
The RC2-75 aircraft rotary engine was conservatively designed and rated to provide a specific output of 1 HP/lb at a speed of 6000 RPM which prior Curtiss-Wright development work has shown to be readily achievable. However, there is a potential for a considerable increase in power output at higher operating speeds.

Testing of the RC2-75 has shown that with the conventional seal configuration, friction mean effective pressure increases exponentially with speed. At speeds above 7000 RPM limiting factors precluded any further increase in power output. Analysis of available test data, however, indicates that a substantial further increase in specific power output could be achieved if seal friction could be reduced or eliminated, ports modified, and a larger capacity fuel system used, permitting the inherent high speed capability of the rotating combustion engine to be more fully exploited (reference 1, page 1.2.1). The potential increase in power density has been estimated as two times for an air cooled engine and three times for a liquid cooled engine, the latter having less limitations from a cooling standpoint. Such large gains in power to weight ratio are particularly attractive for advanced aircraft applications.

In general, higher speed trades-off higher output, and resultant improved specific weight, against poorer specific fuel consumption as a consequence of higher friction. The goal is to either reduce friction at higher speeds or else devise an arrangement which operates at high speed for only peak power output conditions.

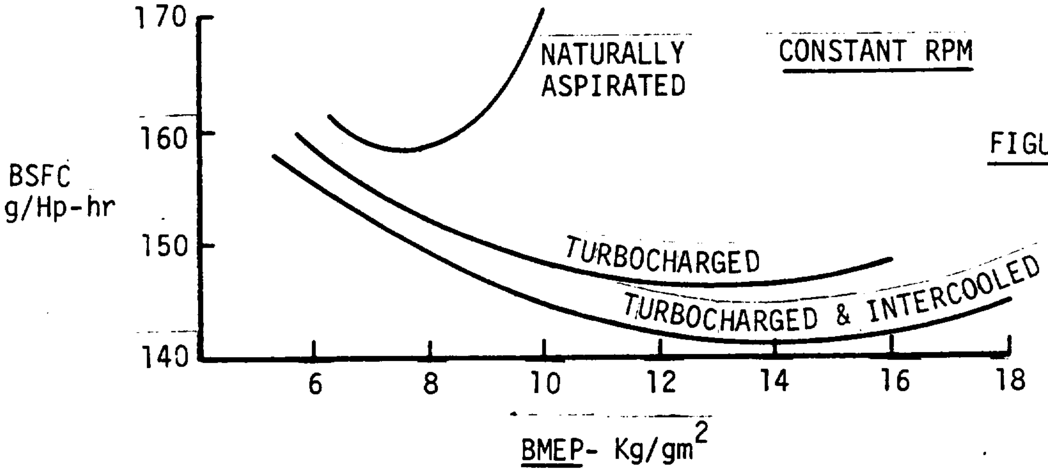
OF POOR QUALITY

INTERCOOLING EFFECTS



CONSTANT BMEP & RPM

FIGURE A



CONSTANT RPM

FIGURE B

Figure 1.2.0

In 1965, tests were conducted with apex seals locked in place to prohibit contact with the trochoid surface. These tests demonstrated that eliminating the friction between the apex seals and trochoid surface at high speed could provide a large gain in total engine output (Reference 2). Friction mean effective pressure was shown to remain constant with speed above 7000 RPM (in the 60 cubic inch size), indicating that seal leakage losses, which are a time-dependent function, become minimal above that speed range. Had the seals not been retracted, FMEP would have continued to increase exponentially with speed.

A number of mechanical configurations for reducing apex seal friction at high speeds have been conceived by Curtiss-Wright (Reference 3-6) (Figure 1.2.1). An alternate approach based on use of the hydrodynamic film between the seal and trochoid surface to achieve increased separation at high speed was conceived in 1969 (Reference 7).

High Speed Sealing Grid References

1. "RC-60 RHP Evaluation - Preliminary Breakdown of Sources of Friction", C-W Memo Report, H. Bachman to C. Jones, June 19, 1963.

2. "Results of High Speed Evaluation of Fixed Apex Seals - RC Engine", C-W Memo Report, R. Leisenring to J. P. Grandfield, March 8, 1965.

3. "Compensated Seal Structure for Rotating Mechanism", Patent #3,456,625, July 1969.

4. "Compensated Seal Structure", Patent #3,456,626, July 1969.

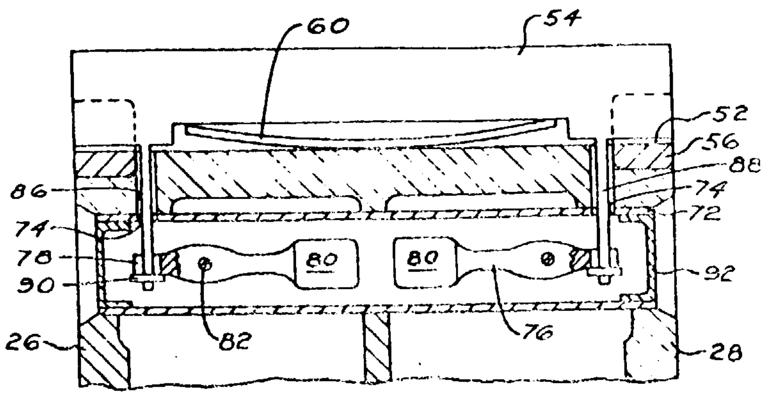
5. "Seal Structure for Rotary Mechanisms", Patent #3,482,550, December 1969.

6. "Seal Control Structure for Rotary Mechanisms", Patent #3,496,916, February 1970.

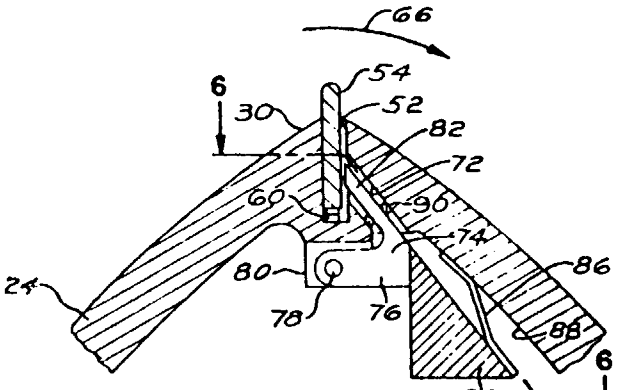
7. "Feasibility Study of an Improved Apex Seal for RC2-60 Rotating Combustion Engines", Batra, S. K. and Hamilton, D. B., Battelle Memorial Institute, November 13, 1969, (For Curtiss-Wright).

Turbocharger - Variable Inlet Area Turbine

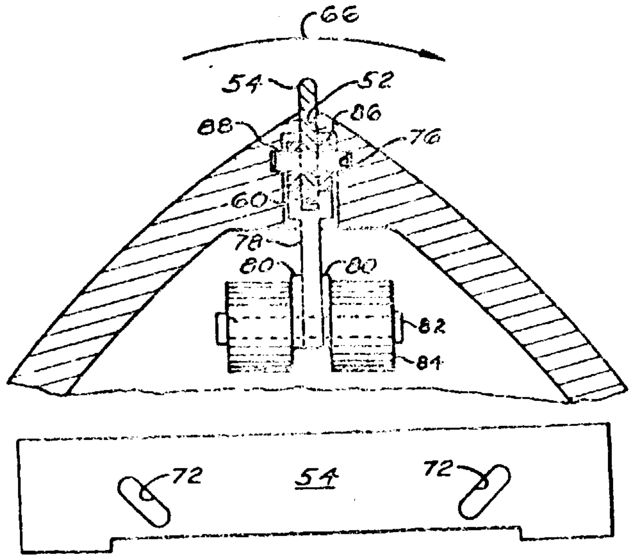
The sole function of the turbine is to meet the power requirements of the turbocharger compressor. Some method of power control must be applied to the turbine to meet these requirements. Normally a waste gate is utilized and alters turbine power by varying its mass flow. With the bypass of exhaust gas around the turbine significant exhaust gas energy losses occur. With a variable turbine inlet area, compressor and turbine flows differ only by the fuel added. This provides a turbine-compressor matching over the engine speed range and results in the ability to provide a positive pressure ratio across the engine for improved volumetric efficiency, faster accelerations and reduced transient smoke. The improved volumetric efficiencies, when not used to reduce engine size, can provide leaner mixture strengths, resulting in reduced fuel consumption by improving cycle efficiency.



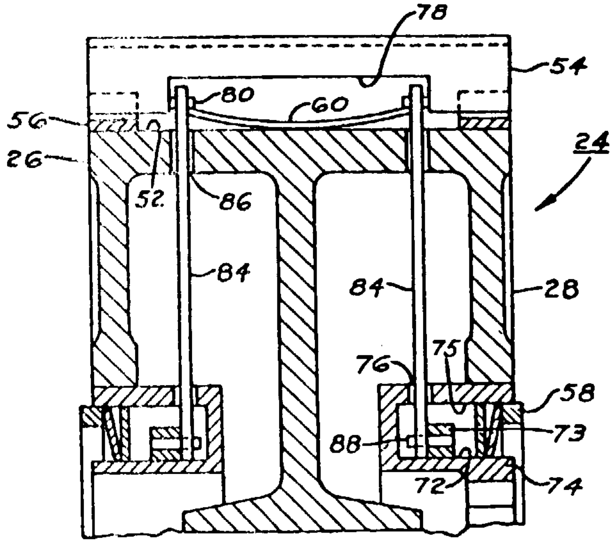
PATENT #3,456,625



PATENT #3,456,626



PATENT #3,482,551



PATENT #3,496,916

HIGH SPEED SEALING GRID DRAWINGS

Figure 1.2.1

The approach involves adjustment of the turbine stator (nozzle) flow area as a function of engine speed. In this way it is possible to maintain a high turbine speed at low engine speeds by closing down on the nozzle area. As engine airflow rate comes up with engine speed, the nozzle area is opened up to prevent overboosting. Via this technique it should be possible to maintain a constant turbo speed (and thus constant intake manifold pressure) regardless of engine speed.

In the case of the diesel, it is evident that, due to the variable nozzle, steady-state smoke should be improved throughout the operating range. Also, "turbocharger lag" on acceleration is virtually eliminated, and with it transient acceleration smoke. The increased air/fuel ratio should also result in more efficient engine operation by improving the basic cycle efficiency and thereby lowering fuel consumption.

There are numerous ways to achieve the required flow control. Variable iris valves, inducer guide vanes, movable sidewalls, individually-pivoted diffuser vanes, and other techniques can be used to vary flow areas. In a recent study by Teledyne Continental Motors and the U.S. Army Tank Research and Development Command, pivoted wedge-shaped compressor diffuser vanes were eventually selected for this application, based on their relative simplicity and durability.

Based on Article, "Turbocharging: What Does the Future Hold?", Automotive Engineering, June 1979, Volume 87, Number 6.

Controlled Rotor Oil Cooling

For faster warm-up of the rotor and for maintaining a higher temperature level on the rotor flank and rotor recess, the NSU KKM 871 is provided with thermostatically controlled rotor cooling. This is a measure to improve the mixture preparation in the combustion chamber and to decrease the friction losses. The function of this control is to have different areas depending on speed and load in which the oil jet, located in the intermediate housing and injecting from the side into the rotor, will be always open, always closed, or regulating. These areas are plotted in the figure below and represent a warm engine.

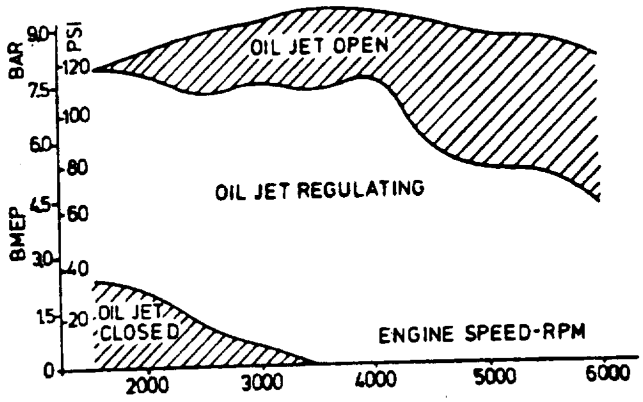
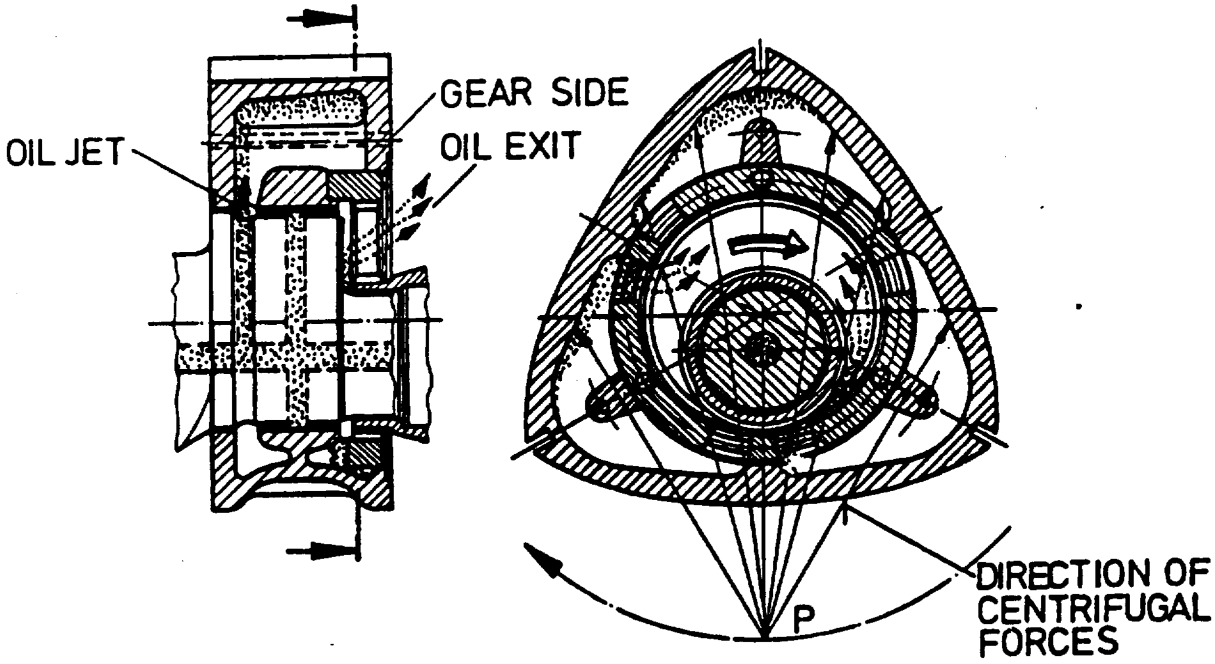


Chart of oil jet control for rotor cooling

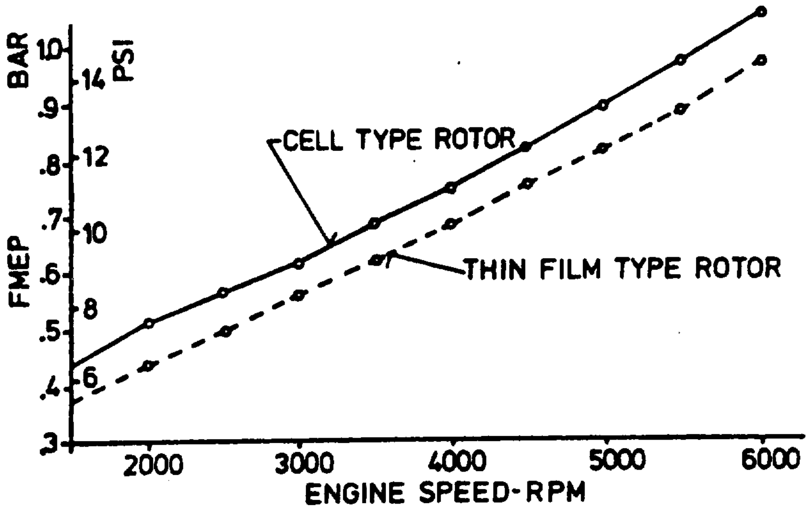
(From Reference: Richard van Basshuysen and Gottlieb Wilmers, "An Update of the Development on the New Audi NSU Rotary Engine Generation," SAE Paper No. 780418.)

The cooling oil flow in the rotor has been changed, too, of which the principle is drawn up in the figure below. Via an oil jet (here located in the eccentric shaft) the cooling oil is injected into the rotor on the opposite side of the synchronizing gear and is circulating there. In the areas below the apex seal groove the oil will flow over to the synchronizing gear side and, by way of ribs in the center of the outer wall, the oil will be forced out of the rotor. Since with this system the cooling oil will pass the areas of the sealing elements with a thin oil film (therefore called "thin film rotor") the cooling effect is concentrated on the critical places. The oil movement demonstrated in the figure refers to a rotating rotor in the drawn up position. The arrows indicate the direction of the centrifugal forces originating from the rotating center of acceleration.

In comparison to the NSU rotor with an interior cell structure used so far there is a reduction of friction mean effective pressure with the thin film rotor by the reduction of shaker losses. The next figure shows that the improvement covers the whole speed range.



Principle of cooling oil flow in the rotor



Comparison of friction mean effective pressure
between different rotor designs

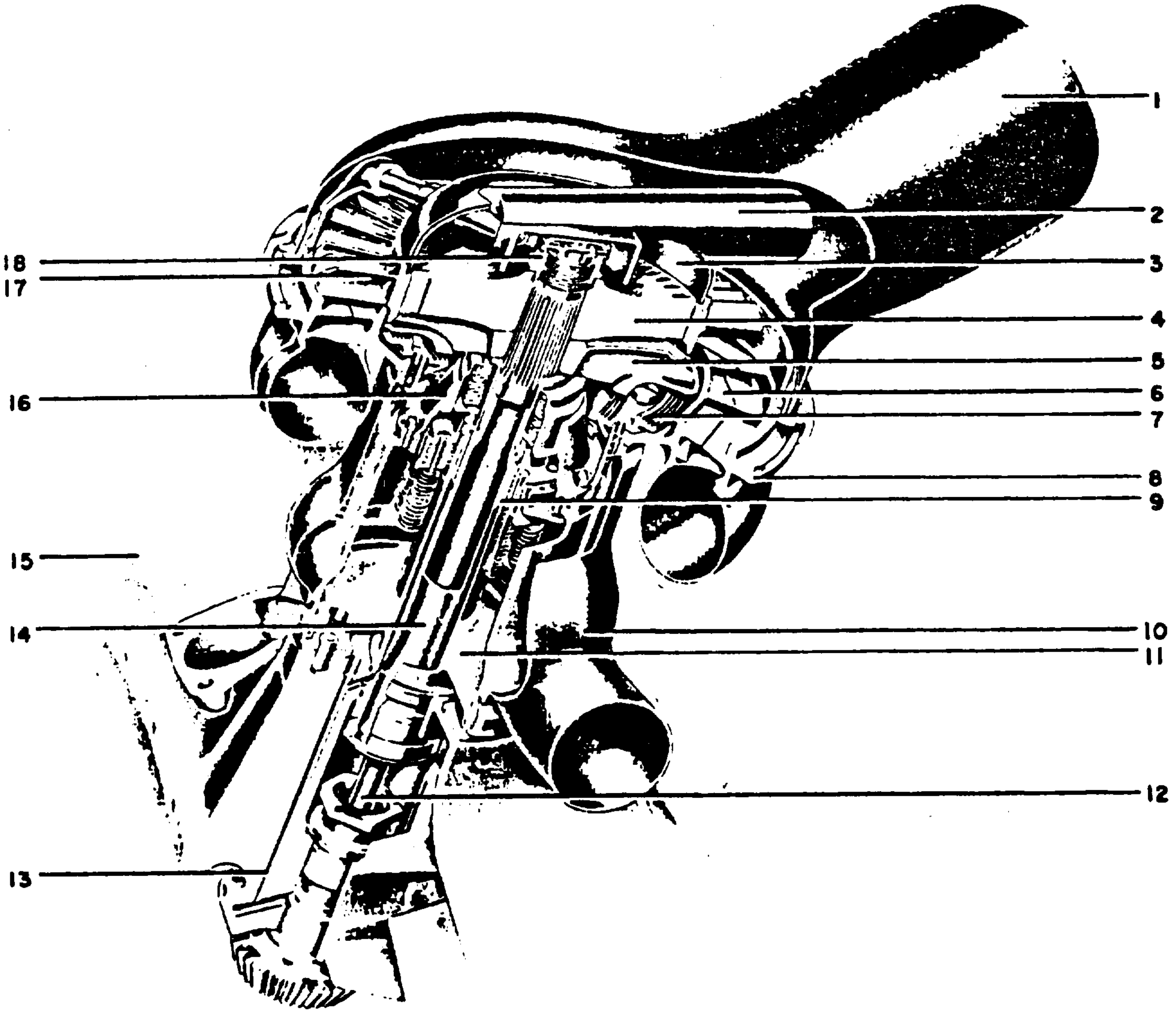
Turbo-Compounding

The Curtiss-Wright TC18 turbo-compound engine went into production early in 1950, and saw long service as an efficient aircraft powerplant. The highly developed and dependable basic 18 cylinder Cyclone engine was supplemented with a second power producer, consisting of three interchangeable "blow-down" turbines. These turbines were geared to the crankshaft and utilized the velocity energy of the exhaust gas, which was normally wasted. The use of these gases by blow-down turbines does not reflect appreciably on the power output of the normal reciprocating engine cycle.

Figure 1.2.2 shows a recovery turbine cutaway.

The consideration here was that the power recovery turbine would be used in conjunction with turbocharging, otherwise a gear driven supercharger must be applied to the engine to obtain altitude requirements, which would not be satisfied. Since in this application the turbine of the turbocharger is using the exhaust energy to a great extent little is left to be gained by adding the weight and complexity of the power recovery turbine which must be connected to the engine output shaft by a fluid coupling to obtain optimum performance.

TURBINE CUTAWAY



1. Hood
2. Cooling air aspirator
3. Cooling cap
4. Turbine wheel
5. Cooling air impeller
6. Nozzle guide vane
7. Labyrinth seal of air deflector
8. Nozzle assembly
9. Lateral vibration damper
10. Cooling air shield
11. Turbine shaft support
12. Quill shaft
13. Lubricating oil passage
14. Turbine drive shaft
15. Supercharger front housing
16. Bellows oil seal
17. Turbine buckets
18. Turbine wheel nut

Figure 1.2.2

Nasvytis Speed Reducer

This development is called the Nasvytis Multiroller Traction Drive.

NASA Lewis reports its new drive is able to transmit high power loads at high speed ratios without the use of toothed gears and, further, that it could replace gearing operations in a broad range of applications.

Instead of gears the Nasvytis traction drives are composed of a planetary cluster of smooth rollers, bearing directly against one another. This configuration includes a "sun" roller in the center, two rows or more of "planet" rollers surrounding the sun roller and a "ring" roller enclosing the total complex at the perimeter.

By introducing power to either the outer ring or to the central sun roller, one creates, in the former case a speed increaser and, in the latter, a speed reducer.

For many applications the new drives would be simpler and less expensive to manufacture because they require no gear tooth design or cutting. In fact, the tolerances for their roller components are well within ordinary machine grinding limits.

Because of their unique load balance geometry, they are lighter and smaller than conventional gear boxes and speed changers. A Nasvytis drive can easily be built to handle more than 500 HP and yet weigh only between 80 and 400 pounds depending on speed ranges and duty cycles.

They are as efficient as gear systems. In a recent NASA test, they performed at a measured efficiency of more than 95 percent at speeds to 73,000 RPM for 15-to-1 ratio.

They are more reliable and less susceptible to breakdown and wear. Through the use of special traction fluids, their rollers never actually touch each other - the fluid provides a miniscule separation - which serves to virtually eliminate roller wear in addition to dampening out drive line vibrations.

This type of drive was considered for a propeller reduction gear and for a turbocompound reduction gear.

The rating as a propeller reduction gear is not strongly favorable because the device lends itself to large reduction ratios; and in lesser reduction requirements, the unit would be heavier than conventional gearing.

If turbocompounding is used on the highly advanced engine, the large reduction ratio required is very favorable to the Nasvytis system and it will be substantially more favorable than conventional gearing.

In either application, the traction drive would be more attractive if it did not require a special traction fluid. The question of compatibility with lubricating oil and the effects of seal leaks require that the device be considered to slightly reduce reliability.

Engine Conceptual Designs (Tasks II and VI)

The Task II work effort, as originally performed against contract milestones, emphasized the simplicity, cost, and BSFC advantages of larger single rotor engines (reference 8). The Cessna system studies subsequently indicated that the smaller and lighter 2 rotor engines were superior on a total aircraft systems basis.

Accordingly, a Task VI phase was added to this contract for the purpose of further examining a more highly advanced technology engine. The intent was to examine the "Highly Advanced" engines as the principal engine choice, with the "advanced models" considered as a backup position in the event that the required technology advances prove more formidable than predicted.

DESIGN CONSIDERATIONS

New Technology Assumptions

The defined engines are based on the assumption that the state-of-the-art of Rotary Engine technology will be significantly advanced by 1985 when the design and development program would be started. The increased speed and IMEP levels chosen represent a large increase in the loading which affects engine component wear and stress levels. For the engine to function efficiently and provide an adequate service life while running at 7000 to 9400 RPM and IMEPs of 220-245, a number of new approaches will require research and technology test evaluation prior to undertaking an engine design and development program. Otherwise the overall engine development effort might not proceed at a reasonable pace, or might include less new approaches.

These engines will probably use JP-5 or "Jet A" fuel but would show only minor, if any, degradation of performance on gasoline or diesel fuel. The most important supporting parallel technology gains that are required are high speed electronic diesel level fuel injection, seal/coating materials, and improved strength aluminum alloys. Further gains in turbocharging technology will prove particularly rewarding, but are not absolutely essential.

Apex Seal Wear Rate and Trochoid Coating Durability

While the current design approaches are considered satisfactory for the state-of-the-art loading (175 IMEP), past testing indicates that as IMEP rises, apex seal wear rates increase and thermal loading (heat flux) rises. The assumed increase in loading makes it probable that the present seal/coating approach will not be adequate, although it may be possible to achieve satisfactory durability with only substitution of a lower wear apex seal material with the "advanced" technology. The "highly advanced" levels of seal speed and IMEP will almost certainly require both coating and apex seal improvements over current practice. Curtiss-Wright's development experience makes it clear that a seal/trochoid material development effort should precede the full scale engineering development program requiring improved materials.

Current thinking regarding candidate seal/coating materials likely to have sufficient durability for the increased severity represented by the advanced and highly advanced engine applications is as follows:

Coatings

Improvements over the current carbides would ideally include a better match to the base aluminum of thermal coefficients of expansion, thermal shock, and brittleness, as well as superior wear resistance. An increase in hardness, wear resistance, ductility, and thermal shock resistance over present coatings may result from a continuously graded cermet/metallic coating. such a coating would have the mixture ratio of the cermet and the metal gradually varying through the thickness of the coating. It can be applied with a high velocity-energy vacuum chamber plasma system. The process might make use of hot isostatic pressing. Possible coating systems are:

(a) Dispersion of hard phase particles in a sulfamate nickel matrix. The particles could be silicon or carbides and the nickel would be approximately Rockwell C45, a relatively hard matrix.

(b) Dispersion of hard phase particles in chromium, or chrome over nickel for more compatible coefficients of thermal expansion.

(c) Vapor deposition of ceramic/cermet type materials such as titanium nitride, Boron nitride, titanium carbide, silicon carbide, titanium carbonitride or electrodeposition of titanium diboride.

(d) Plasma sprayed or sputtered ceramic coatings, in layers or continuously varying mixtures.

Somewhat less exotic, but very possibly adequate, is exploitation of the advances in plasma spray technology over the past few years, particularly as related to increased bond strength and density, to use Ferro-tic coating with Ferro-tic apex seals. This combination showed potential in C-W testing (Figure 2.1.0) with wear rates about half that of the "standard" C-W configuration (Ref. 6). In fact, recent adaptation of Ferro-tic (titanium carbide in a hardened steel matrix) apex seals with the "standard" D-gun tungsten carbide/cobalt has shown a reduction in wear on the current military engine program.

Seals

New apex seals should combine good wear resistance, high impact strength, low density, and low coefficient of friction. Candidates are:

(a) Pure ceramic (hot pressed silicon nitride or dense silicon carbide).

(b) Metal seals with ceramic inserts.

(c) Coated seals (sputtered, chemical vapor deposited, or electron beam vapor deposited using titanium, tungsten, or boron compounds).

FERRO-TIC APEX SEAL HEIGHT WEAR AGAINST PLASMA SPRAYED FERRO-TIC TROCHOID COATING

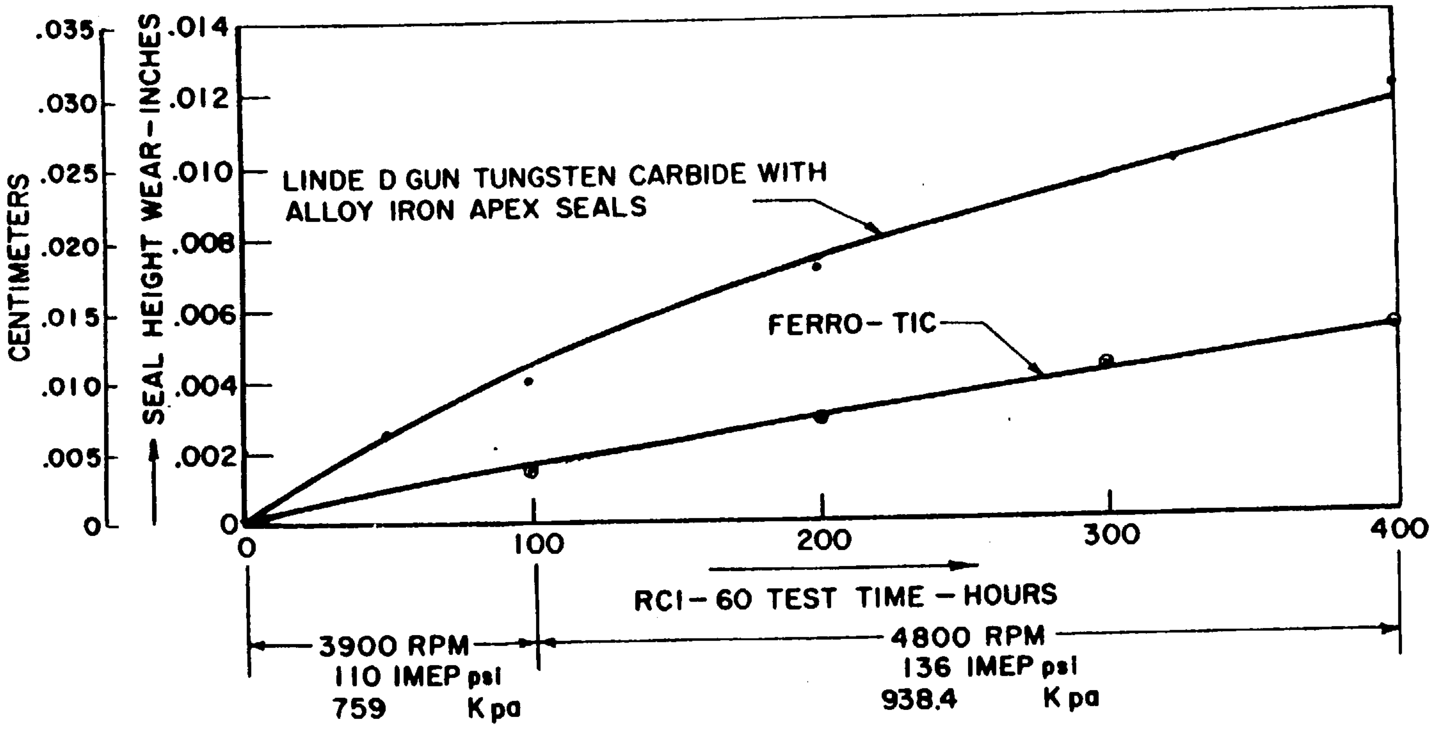


Figure 2.1.0

(d) A new hard alloy with some ductility.

(e) Laser or electron beam hardened cast iron.

There are a number of promising seal/coating combinations which have shown screening rig indications of low wear rates. These, together with newly developed candidates from the above-mentioned possibilities, indicate a high probability of a satisfactory solution. While a friction rig is used to screen candidate seal/coating combinations, final adequacy must be determined by engine testing.

Sealing Effectiveness

Under the increased thermal loading bound to occur in the advanced engine, the housing and apex seal thermal distortions may differ from the current engine. Curtiss-Wright's sealing grids have been among the most effective of the various rotary engine developers, and it is felt that design consideration of the rotor housing thermal distortion is an important part of the reason. A different distortion pattern could alter the ability of the seal to "follow" the housing. Using low compression ratios to try to lower the peak pressures while achieving increased IMEP levels will result in a longer duration per cycle of the higher pressure portion of the cycle. This could alter the cycle pattern of pressure difference across the apex seal, which affects wear and "spit back" aspects.

A variation on the theme of improved apex seals and coatings has to include recognition of the higher speed directions envisioned for the future aircraft engines. At high speeds the sealing leakages of one piece seals become more acceptable.

The previously discussed use of cermets as trochoid coatings could prove particularly significant for ultra-high speed engines where the apex seals need not contact the trochoid surface. Thus, without the need to provide lubrication, the allowable surface temperature limits could be increased to whatever limits the material could withstand. Another variation of the same approach would be use of gas-lubricated apex seals, which like the non-contacting seals mentioned above, provide a unique advantage to the Rotary for an "adiabatic" or reduced heat rejection engine.

Metal Temperatures/Cooling

The rotary combustion engine characteristically has had maximum local heat fluxes in the rotor housing "hot spot" (immediately after the housing top dead center location) that significantly exceed those in comparable reciprocating engines. These higher heat fluxes have been successfully cooled by convective cooling as well as the nucleate boiling effect. The peak heat fluxes of the proposed engine may be significantly higher based on past test developed parametric relations.

It may be necessary to investigate plating the water side of the hot zones with brass or copper to increase their wettability. This enhances the cooling effectiveness of nucleate boiling. The high air/fuel ratios possible in stratified charge engines, with lower compression ratios, may alter for the better the relationships affecting the maximum local heat flux that Curtiss-Wright has found in its carbureted engine testing. It has been assumed that means will be found to achieve operating metal temperatures in the housings which will permit engine oil to lubricate the seals, and are consistent with structural adequacy.

As in the case of the seal/coating choice, the technology development required calls for activity prior to a full scale new engine design and development, particularly since development of (carbureted) engines over a size range of about 500:1 has shown the heat flux to be scaleable.

Fuel Injection

High pressure fuel injection systems characteristically require development of adequate mixing to achieve efficient combustion of the injected fuel in the short time available in each cycle. The stratified charge engine, in addition, requires a particular spray pattern to be found which, in combination with the rotor pocket shape and the injection timing and duration, yields good thermal efficiency. A separate pilot nozzle with relatively small fuel flow is used to trigger combustion. A multi-hole main nozzle, located close to the trochoid surface is used to supply fuel flow in response to power demand (Figure 2.1.1). The fuel injection pump and its system hardware will require a rigorous test program to be sure that the system dynamics cause no problems.

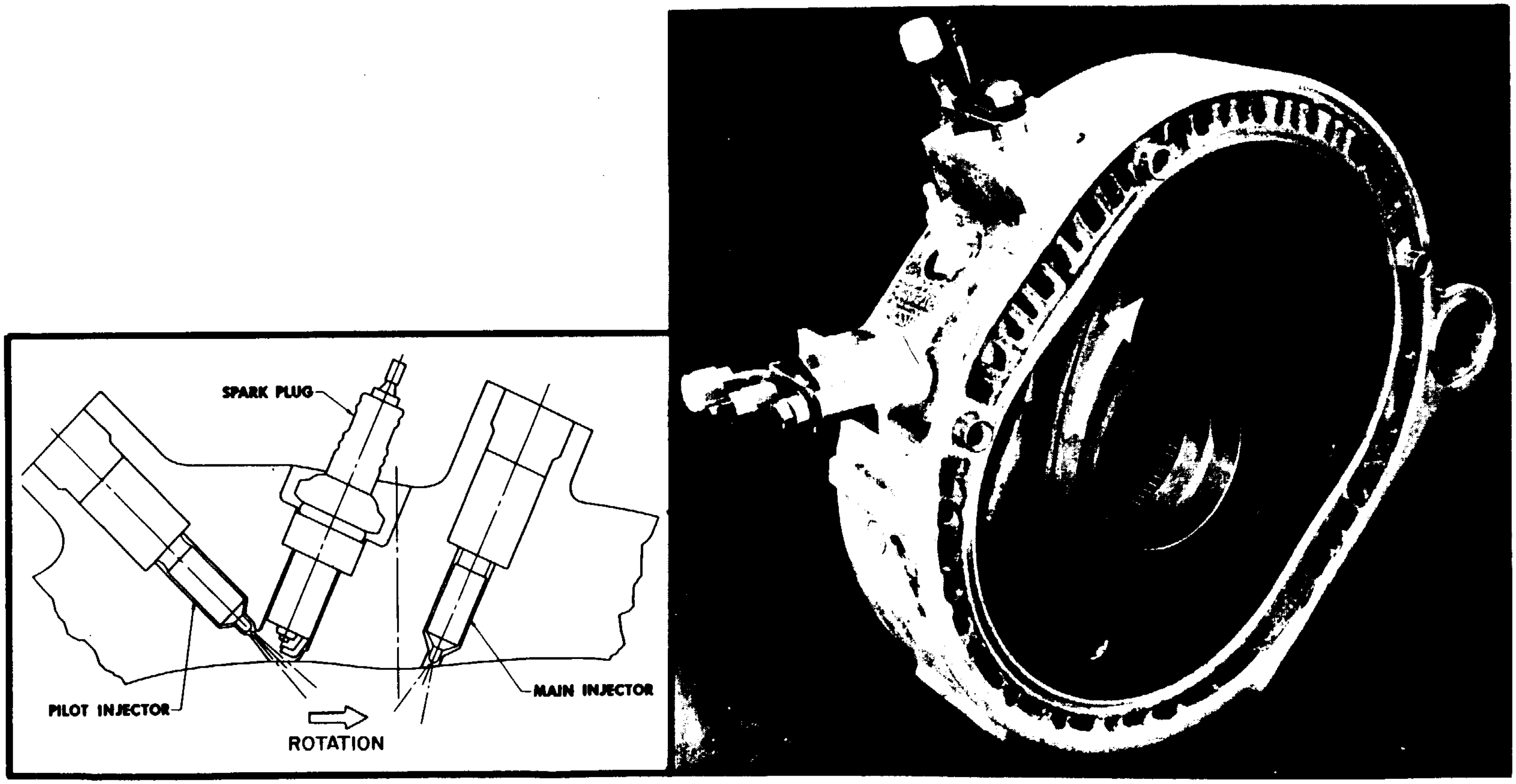
All of the above are made more difficult by virtue of the increased shaft speed. However, the developing field of small high speed diesel automotive engines has provided the required impetus for active electronic fuel injection development by a number of major manufacturers in the field. Experimental and limited production (for a military 8000 RPM application) units are already operational and there are many indications to believe that the additional developments to reduce cost and improve reliability will be forthcoming.

Turbocharging

The turbocharger assumptions used to predict engine performance were relatively conservative. This is discussed on page 4.2.2 in the section on expected non-aviation new technology activity.

While turbocharging is not considered a new technology, the optimum integration of an advanced turbocharger with a highly advanced Stratified Charge Rotary Engine will require the determination of system relationships to a degree which warrants being described as a new technology advancement. The following tabulation presents the spectrum of areas to be effectively balanced to achieve the full potential of turbocharging for the General Aviation application.

STRATIFIED CHARGE ROTARY ENGINE



RC-351

Figure 2.1.1

TURBOCHARGING CONSIDERATIONS

1. Turbocharger

   Pressure Ratio
   Surge Line Limitations
   Efficiency (Compressor and Turbine)
   Variable Geometry
   RPM
   Weight/Inertia

2. Engine Performance Interface

   Compression Ratio
   Porting - Shape and Timing

   a. Intake
   b. Exhaust

   Fuel/Air Ratio as Function of Thermal Efficiency
   Combustion Configuration
   Manifolding/Waste Gating
   Charge Air Cooling

The feasibiilty of improving BSFC, as well as output, by turbocharging to permit engine operation at the most efficient mixture strengths has been recently demonstrated on the RC1-60, and is discussed on page 1.1.0. Variable inlet area turbines are discussed on page 1.2.1.

Aluminum Casting Alloy AMS 4229

It has been assumed that the improved strength properties at high temperature levels will be available for rotor housings in the RC2-47. There is a risk that the hot short properties, which make this alloy a difficult one to cast successfully, could lead the commercial foundries to be unwilling to quote on orders. This was experienced with the present alloy (AMS 4220), but Curtiss-Wright's own foundry (no longer functioning) pursued a process development activity which resulted in many foundries being willing to provide housings. A similar casting development sequence may well be required to support suppliers of rotor housings in AMS 4229.

Lightweight Rotor

High speed engines demand light strong rotors. Advances in powder metal and sintering technology, as well as electron and laser beam welding open up whole ranges of new possibilities. Improvements here too have been spurred on by the increasing use of aluminum, including eutectic alloys for passenger car engines both here and in Europe. Rotor fabrication material technologies, other than the nodular cast iron approach currently used, will be re-examined in light of latest developments.

The rotor, as currently envisioned, is considered to be a "thin walled" nodular iron casting with rib thicknesses as low as 0.125". Thin wall castings require a more sophisticated approach than the sand casting process generally used for rotary engine rotors. The hot ceramic mold process is capable of thin walls and was used successfully in procuring 90 cubic inch rotors for Curtiss-Wright's engine test program.

In subsequent experimental/development programs, we have been unable to interest qualified suppliers. It is assumed that sufficient program activity in this area will take place to make thin wall castings available.

Varied Displacement Pressure Oil Pump

In Curtiss-Wright's RC-350 test activity, a potential fuel saving has been noted in the energy required to drive the pressure oil pump. The volume output of the positive displacement pumps generally used matches the low speed condition and at higher speeds, much of the pressurized oil is bypassed by a spring loaded pressure control valve. By making the proportions of a gear or Gerotor pump such that the element that forms the pump chambers is relatively wide, at low speeds there is time to fill the suction chamber, but at high speeds, the oil cannot solidly fill the pump chamber, providing an automatic self regulating effect which more closely matches the engine needs. This is a potential savings at the present time.

Rotor Thermal Insulation

It has been assumed that a durable surface thermal insulation will become feasible in the four to five year time interval available. While work is in progress on this objective, it is felt that a parallel program should be undertaken to add a thin metal shield over the ceramic insulating layer to enhance its durability, reliability and safety aspects.

The remaining new technology items are felt to be sufficiently matured to be included in designs to be initiated in 1985.

ENGINE DESCRIPTION - HIGHLY ADVANCED ENGINE

The "Highly Advanced" engine that has been conceptually designed is a turbocharged twin rotor Stratified Charge Rotary Combustion Engine with a swept volume of 31.9 cubic inches per rotor. At the 320 brake horsepower take-off rating the engine shaft speed is 9420 RPM; the IMEP is 244.6 psi, and the FMEP is 33.4 psi.

For comparison of thermal and mechanical loading, the current state-of-the-art for a naturally aspirated carbureted gasoline rotary aircraft engine is a twin rotor engine with a swept volume of 76.2 cubic inches per rotor. At the same brake horsepower take-off rating the engine shaft speed is 6000 RPM; the IMEP is 175, and the FMEP is 32.

The arrangement of major components is shown in the longitudinal section drawing, Figure 2.2.0. The crankshaft is supported on two main bearings. This eases alignment requirements, and reduces manufacturing costs, assembly time, and weight. The geometric proportions, particularly width to eccentricity ratio (w/e) were selected to permit high speed operation without detrimental shaft deflection or stresses above the elastic limit; however, a relatively light rotor is a requirement.

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.

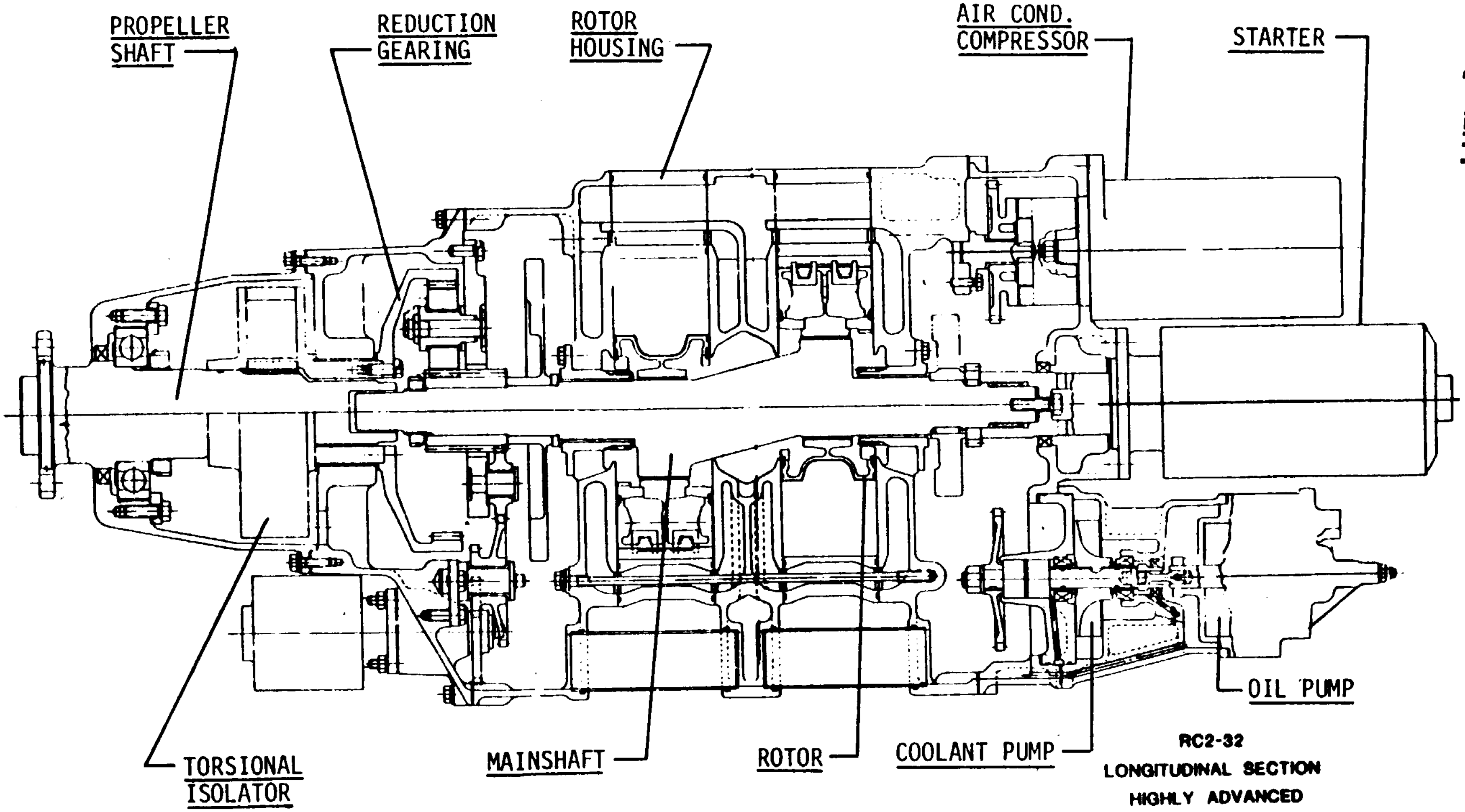
A torsional isolator is blocked out on the propshaft between bearings. The propshaft and bearings have been sized on the basis of assumed asymmetric aerodynamic load and gyroscopic couples.

The rotor shown is a thin-walled nodular iron casting, with thermally insulated combustion chamber faces to reduce heat loss to the oil. 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 is increased.

Oil scavenge is via drain tubes connecting the intermediate and both 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.



RC2-32
LONGITUDINAL SECTION
HIGHLY ADVANCED
ROTARY COMBUSTION AIRCRAFT ENGINE

Figure 2.2.0

To establish that a rotor housing of this size could physically accommodate the required injection nozzles and spark plugs without detrimental influence on either cooling or structural adequacy, a number of supporting layout studies were completed. Representative drawings are reproduced in Figures 2.2.1 and 2.2.2.

Figure 2.2.1, "Dual Spark Plugs/Fuel Injectors Arrangement" indicates that the current pilot and main injection system, in this case shown with dual ignition, can be accommodated in the 32 cubic inch rotor housing. This is considered a worst case evaluation, since test work at C-W, which has been duplicated by other investigators, indicates that a single nozzle arrangement in this sized engine may be suitable for the higher speed range emphasis of the General Aviation engine. If this turns out to be the case, it would simplify the fuel injection system development.

Figure 2.2.2 shows a variation of the pilot injector/ignitor configuration where close-coupled screw-in coils are used. Again, the arrangement is shown to be feasible.

The intent of this study was to determine the configuration feasibility of a housing as small as 32 cubic inches displacement.

The propeller shaft, which is co-linear with the engine shaft shows an integral mounting flange. The driving connection between the two shafts is via an internal spur gear. Counter-rotating propellers for twin engine installations are achieved by installation of appropriate idler gears. The gearing arrangement is shown on Figure 2.2.3. An intershaft sleeve bearing is used where the crankshaft enters the propshaft (Figure 2.2.4).

An initial accessory arrangement study using an external propeller shaft spur gear resulted in an excessive frontal area (Figure 2.2.5).

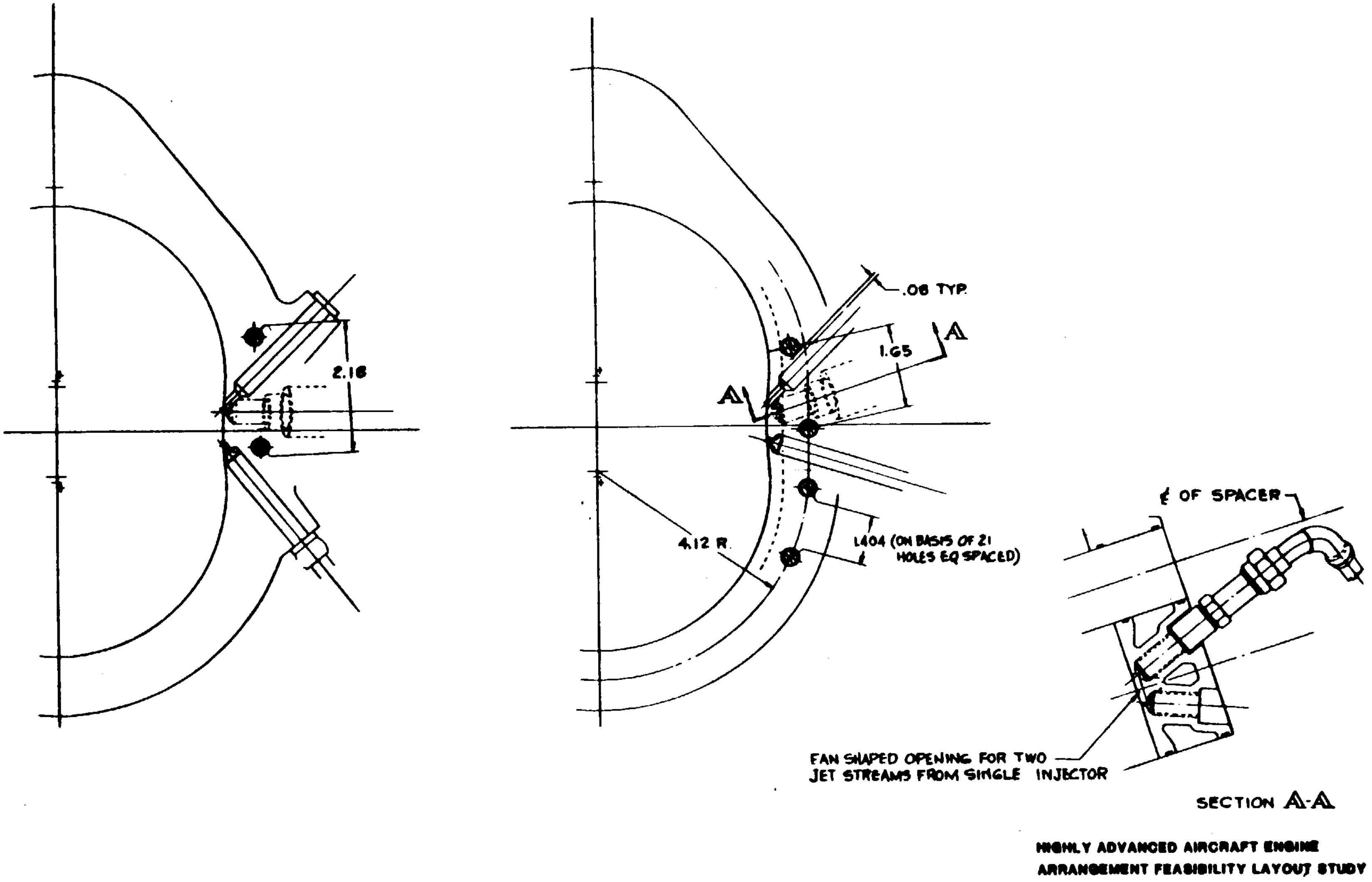
The accessory drives and location have been chosen to minimize frontal area to improve twin engine installations. The vacuum and hydraulic pumps are mounted at the prop end of the engine, driven by external spur gears meshing with the crankshaft reduction gear pinion.

To maintain the compact arrangement, the remaining accessories are grouped at the anti-propeller end, as shown in Figure 2.2.3, and driven by external spur gears with input from a crankshaft pinion. The starter, which includes an integral planetary gear reduction, drives directly through the crankshaft.

The water pump and oil pump are mounted on the same shaft. A sketch of the drive arrangement is shown on Figure 2.2.6.

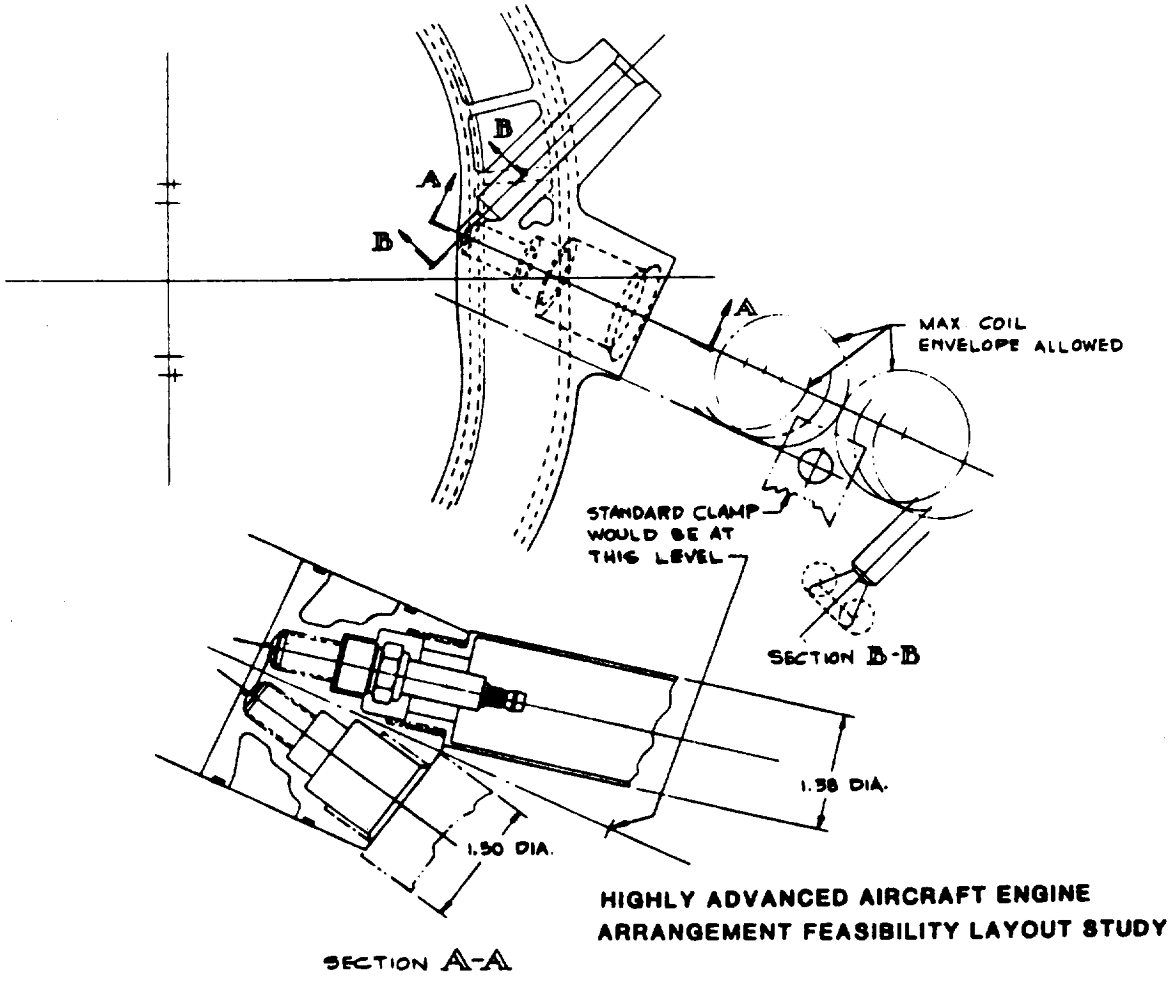
The function and drive arrangement for the remainder of the accessories is apparent from Figure 2.2.3.

The turbocharger is mounted aft behind the starter and accessories, along with the charge air cooler. The arrangement, as well as other external features is shown on Figure 2.2.7.



DUAL SPARK PLUGS/FUEL INJECTORS ARRANGEMENT

Figure 2.2.1



STUDY - PILOT INJECTOR, DUAL SPARK PLUGS, WITH COILS

Figure 2.2.2

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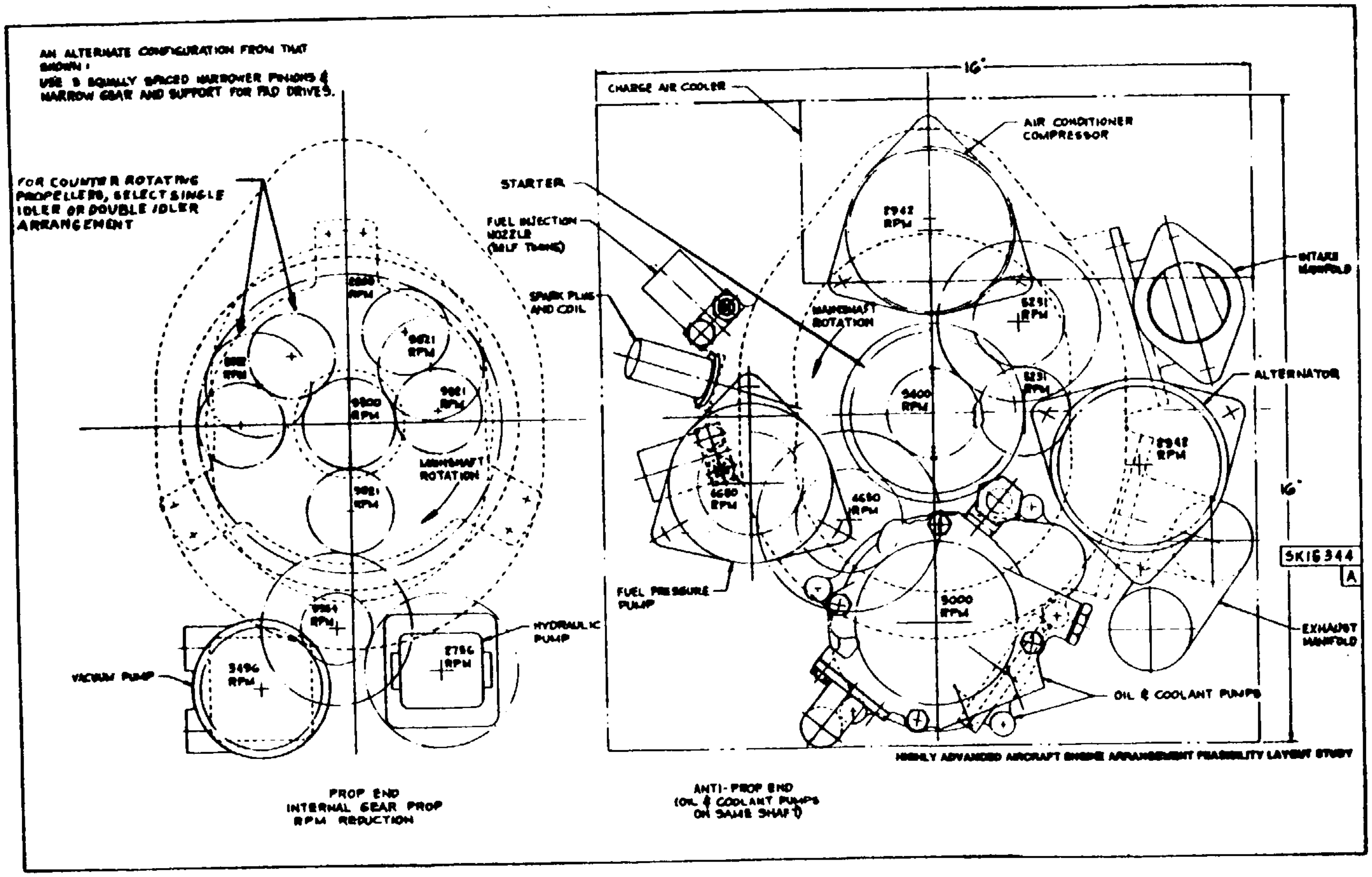
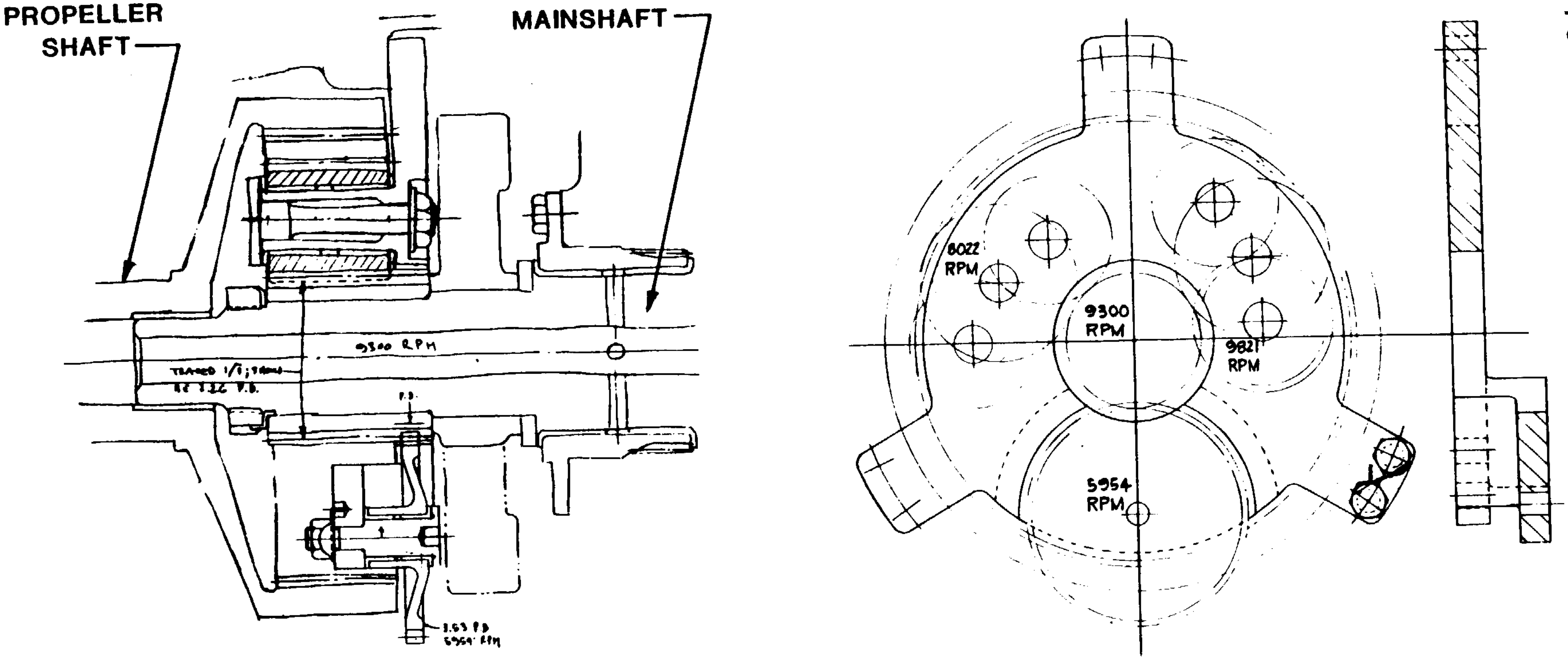


FINAL ACCESSORY ARRANGEMENT STUDY-END VIEWS

Figure 2.2.3



INTERNAL GEAR PROP REDUCTION DRIVE

AN ALTERNATE CONFIGURATION FROM THAT SHOWN:
USE 3 EQUALLY SPACED NARROWER PINIONS & NARROW GEAR AND SUPPORT FOR PAD DRIVES.

HIGHLY ADVANCED AIRCRAFT ENGINE ARRANGEMENT FEASIBILITY LAYOUT STUDY

Figure 2.2.4

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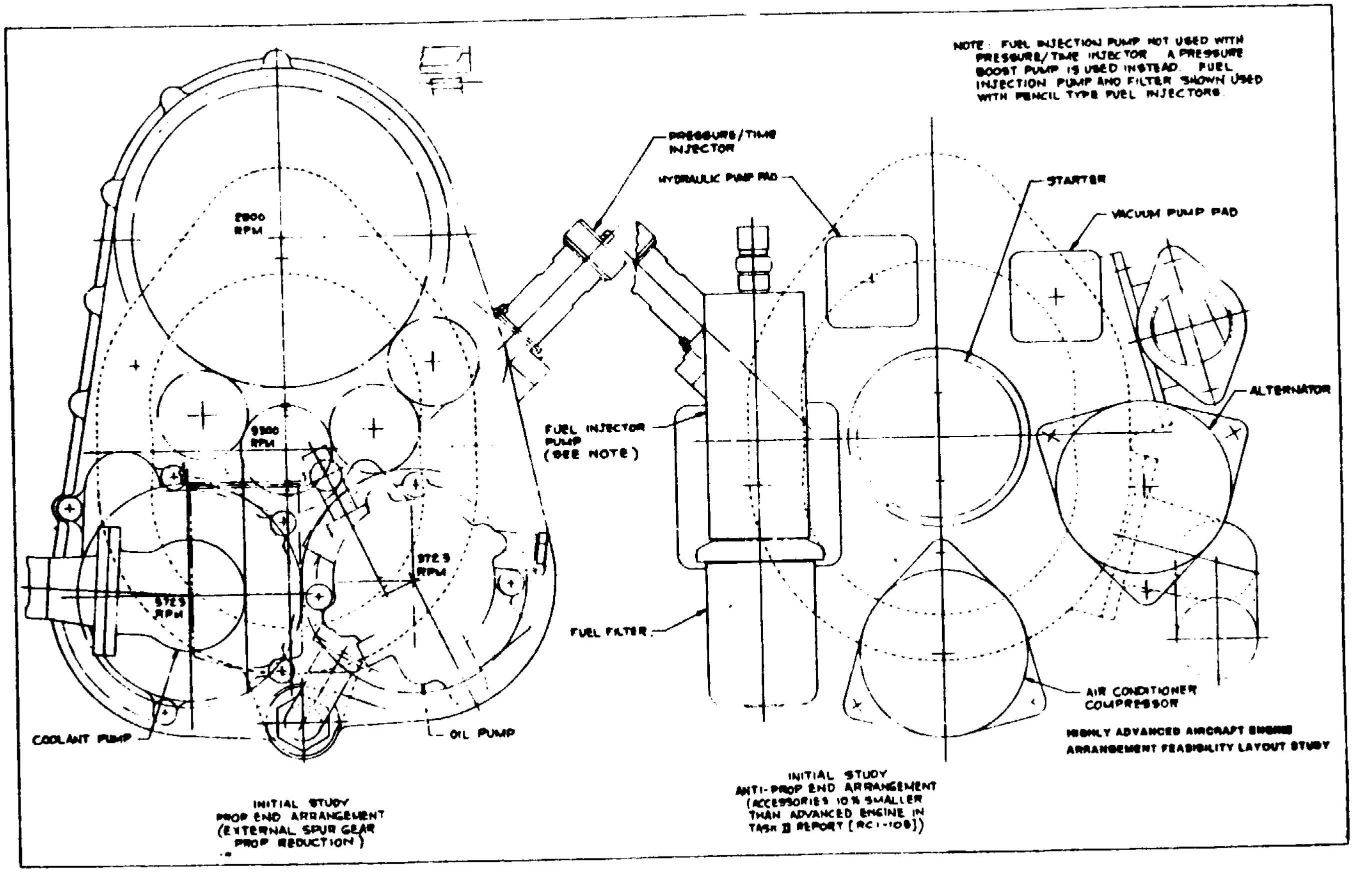
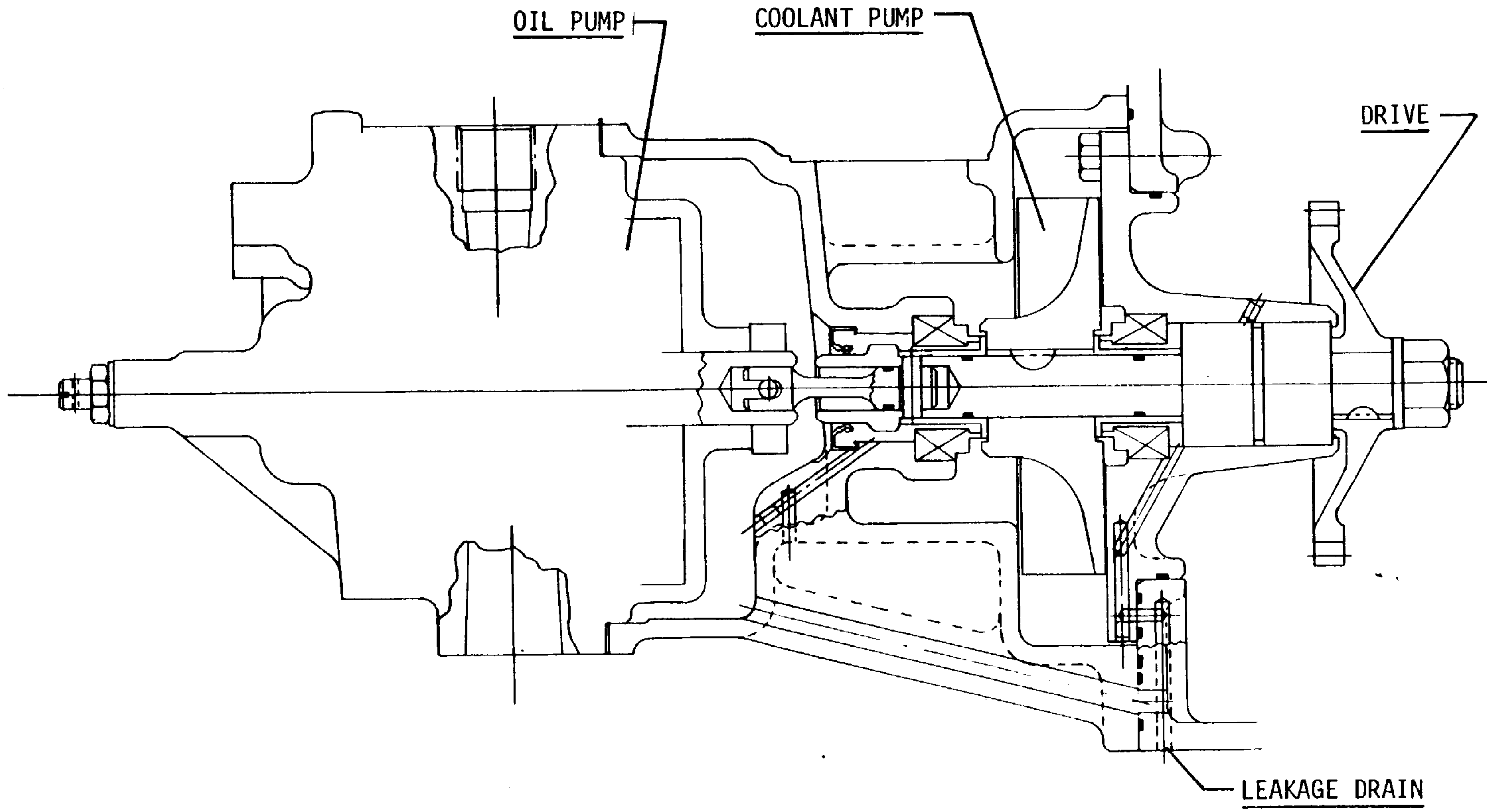


INITIAL ACCESSORY ARRANGEMENT STUDY-END VIEWS

Figure 2.2.5



PRELIMINARY ARRANGEMENT FOR OIL AND COOLANT PUMPS ON SAME SHAFT

HIGHLY ADVANCED AIRCRAFT ENGINE
ARRANGEMENT FEASIBILITY STUDY

Figure 2.2.6

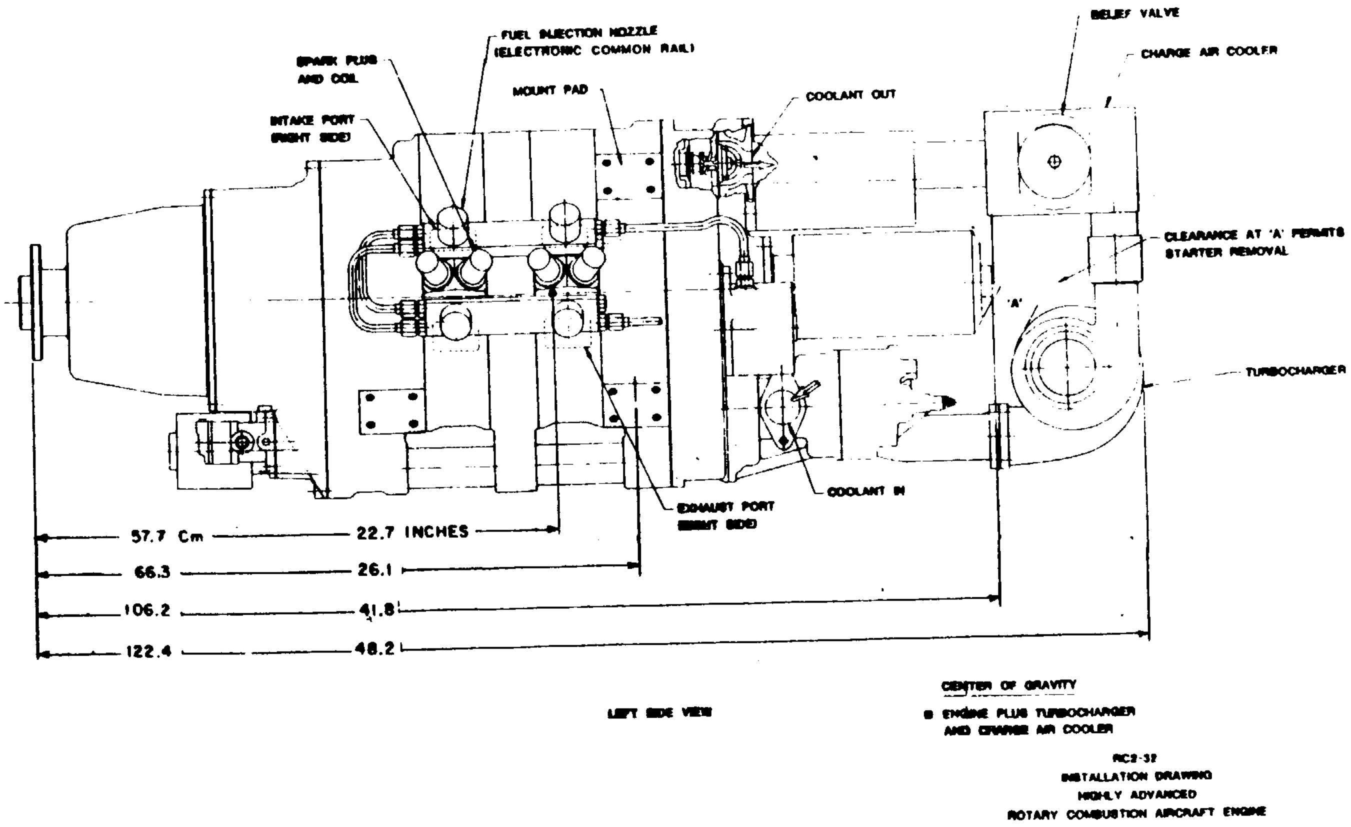

SPARK PLUG AND COIL
FUEL INJECTION NOZZLE (ELECTRONIC COMMON RAIL)
MOUNT PAD
INTAKE PORT (RIGHT SIDE)
COOLANT OUT
RELIEF VALVE
CHARGE AIR COOLER
CLEARANCE AT 'A' PERMITS STARTER REMOVAL
'A'
TURBOCHARGER
COOLANT IN
EXHAUST PORT (RIGHT SIDE)
57.7 Cm
22.7 INCHES
66.3
26.1
106.2
41.8
122.4
48.2
LEFT SIDE VIEW
CENTER OF GRAVITY
⊕ ENGINE PLUS TURBOCHARGER AND CHARGE AIR COOLER
RC2-32
INSTALLATION DRAWING
HIGHLY ADVANCED
ROTARY COMBUSTION AIRCRAFT ENGINE

Figure 2.2.7

Table of Geometric Data

TABLE 2.2.2

HIGHLY ADVANCED RC2-32

Number of Rotors	2
Displacement - Cubic Inches/Cubic cm	31.9/523
Shaft Eccentricity, e - Inches/mm	.56/14.2
Generating Radius, R - Inches/mm	3.89/98.8
Combustion Chamber Width, W - Inches/mm	2.8/71.1
R/e	6.9
W/e	5
Trochoid Major Axis - Inches/mm	8.9/226
Trochoid Minor Axis - Inches/mm	6.6/167.6

The data above shows that the power section size and proportions are close to that of the Mazda RX-7 12-B engine, which has developed approximately the same take-off powers and speeds quoted here, on gasoline as a homogeneous charge engine, for racing purposes. Obviously such racing engines are not designed for extended use and have unacceptably brief life spans, but the reference does serve to provide a perspective.

Operating Data Summary

TABLE 2.2.3 - HIGHLY ADVANCED ROTARY COMBUSTION AIRCRAFT ENGINE
RC2-32 (31.9)

OPERATING DATA SUMMARY - METRIC
STANDARD DAY - NO RAM

	Take-Off	186.4 Kw Cruise Sea Level	186.4 Kw Cruise 7620 m
BKw	238.6	186.4	186.4
RPM	9420	7850	7850
RPM (Equivalent)	7050	5875	5875
IMEP, Kpa	1686.5	1556.2	1556.2
IKW	276.4	212.5	212.5
FMEP, Kpa	230.3	189.6	189.6
FKW	37.7	26.1	26.1
BMEP, Kpa	1456.2	1366.6	1366.6
Fuel/Air Ratio	.045	.04	.04
Airflow Kg/hr	1218.8	1007.0	1007.0
*Blower Ratio	1.94	1.96	5.47
P_2 (At Engine Inlet) Kpa	193.1	194.4	201.3
Engine Inlet Temp. °C	56.3	58.0	87.3
Fuel Flow Kg/hr	54.1	40.3	40.3
Ambient Temp. °C	15.0	15.0	-34.4
Ambient Pressure Kpa	101.4	101.4	36.7

*Before 2% Pressure Loss in Intercooler

Assumes (1) Intercooler Effectiveness = 50%

(2) 70% Compressor Efficiency

Operating Data Summary

TABLE 2.2.4 - HIGHLY ADVANCED ROTARY COMBUSTION AIRCRAFT ENGINE RC2-32 (31.9)

OPERATING DATA SUMMARY - (INCH-LB-°F UNITS)
STANDARD DAY - NO RAM

		250 HP Cruise	
	Take-Off	Sea Level	25,000 Ft
BHP	320	250	250
RPM	9420	7850	7850
RPM (Equivalent)	7050	5875	5875
IMEP, psi	244.6	225.7	225.7
IHP	370.6	285.0	285.0
FMEP, psi	33.4	27.5	27.5
FHP	50.6	35.0	35.0
BMEP, psi	211.2	198.2	198.2
Fuel/Air Ratio	.045	.04	.04
BSFC, lb/BHP-hr	.372	.355	.355
Airflow lb/hr	2687	2220	2220
*Blower Ratio	1.94	1.96	5.47
P_2 (At Engine Inlet) psi	28.0	28.2	29.2
Engine Inlet Temp. °F	133.4	136.4	159.2
Fuel Flow lb/hr	119.2	88.8	83.8
Ambient Temp. °F	59	59	-30
Ambient Pressure psi	14.7	14.7	5.45

*Before 2% Pressure Loss in Intercooler
Assumes (1) Intercooler Effectiveness = 50%
(2) 70% Compressor Efficiency

The "RPM" (equivalent) is the engine speed the Curtiss-Wright RC2-75 Engine would have for its rotor apex seal linear velocity to be the same as the RC2-32 at its listed speeds. This provides a direct comparison to the RC2-75 operating experience. The RC2-75 take-off RPM is 6000 RPM but the engine has been run to 7000 RPM W.O.T. without any signs of distress, although the maximum speed limits were not examined in depth on the test stand.

It should be noted that the cruise F/A ratio is .04. If further improvements in turbocharging allowed operation at a pressure ratio higher than 5.5, the engine could run with a leaner fuel-air ratio and realize further reductions in BSFC.

Reduction Gear

The nose section houses a coaxial gear reduction drive for the propeller shaft. The selected ratios are approximately 4 to 1 for the RC2-32 and approximately 3 to 1 for the RC2-47. The consequent propeller speeds for both engines are 2400 RPM at take-off rating and 2000 RPM at cruise rating.

A crankshaft driven pinion drives an internal propeller shaft gear through multiple idler gears on fixed trunnions. The direction of propeller rotation can be reversed by alternate idler gear arrangements, thus permitting counter-rotation in a twin engine installation (Figure 2.2.3).

Alternate Reduction Gear

A conventional planetary reduction gear is considered to be a potentially desirable alternate. The sun gear is driven by the engine's crankshaft. The planet gears are carried on trunnions on the propeller shaft. A stationary internal gear provides for reaction loads (see Figure 2.2.8).

Detail design may show that this type of reduction gear results in a weight saving. This advantage would then have to be balanced against various disadvantages. An important negative consideration is the difficulty of reversing the direction of propeller rotation with this type of reduction gear. Major modifications would be required to provide counter-rotation for a twin engine installation.

A possible approach would be to provide "universal" flange attachments at both ends of the power section, which would permit the engine to be installed with either end driving the propeller. Curtiss-Wright's RC2-350 prototype military engine has this capability.

This would obviate the need for extra idlers in the reduction gear or would permit the use of one design of planetary gear.

Some negative aspects would be (1) the need for two accessory drive arrangements or accessories that could rotate in either direction, (2) the added size and weight for making each end housing capable of attaching to either a propeller drive cover housing or an accessory drive cover housing and, (3) design restrictions such as a vertical major axis, coolant and manifold entrances and exits at either end of the engine.

Torsional Vibration Control

The propeller shaft can be provided with a torsional isolator to minimize the effects of torsional vibration. The isolator is a spring drive connecting the reduction gear to the propeller shaft. As a result, torsional oscillations of the crankshaft result in reduced variation of torque. Fatigue loads on the reduction gear and propeller are reduced. A flywheel is provided on the crankshaft to limit acceleration of the crankshaft and consequent loading of the rotor gears.

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PLANETARY PROP GEAR REDUCTION

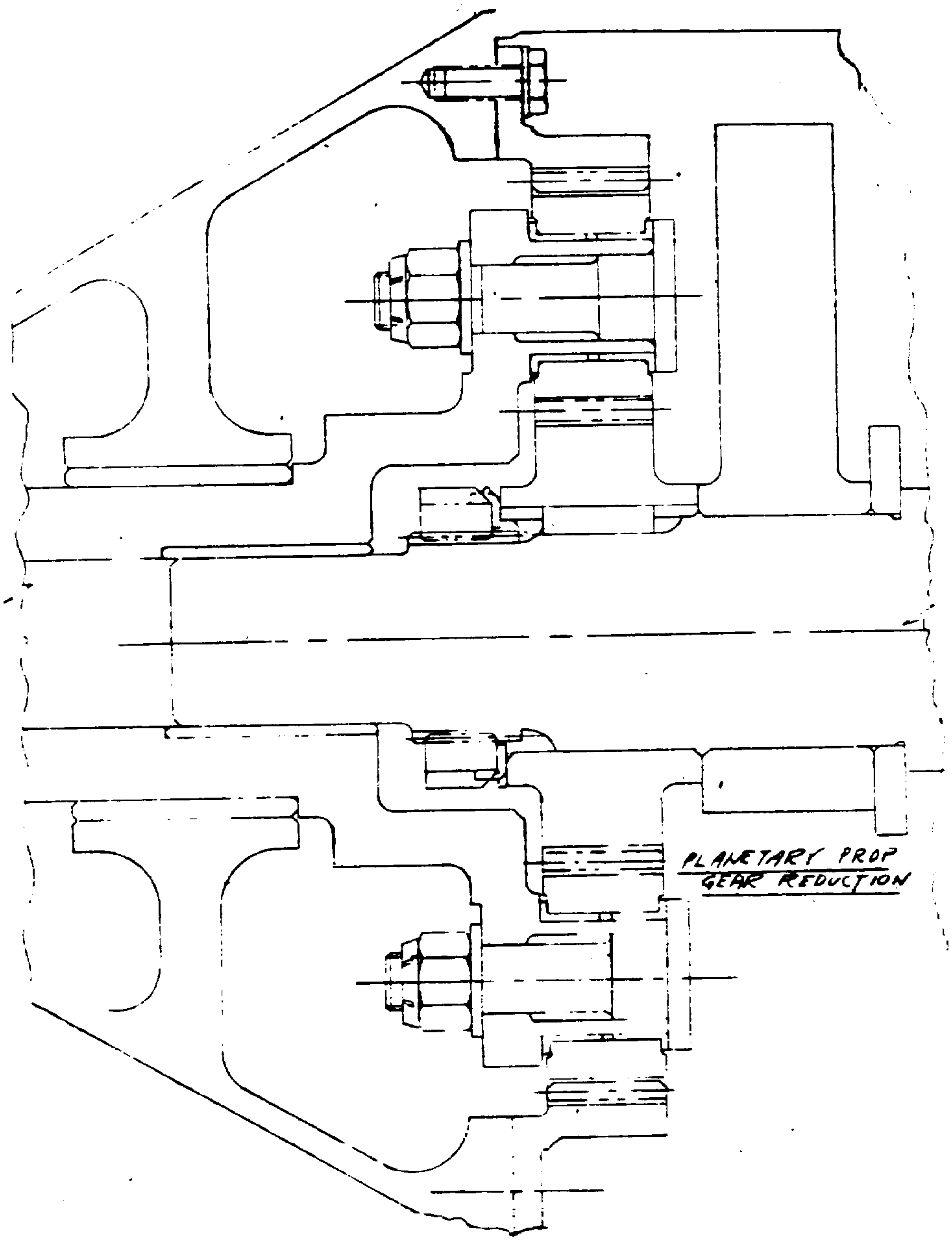

Figure 2.2.8

At some intermediate speed, a torsional resonance of the engine versus the propeller will be encountered. This critical speed has been placed at 1800 RPM by selecting the spring rate of the torsional isolator.

The response of the system over the operating speed range has been estimated (Figure 2.2.9) and is discussed below.

Based on rotary engine test data, the excitation torque at low speed is assumed to be one-third of full output excitation, whether firing or motoring, since this is an unthrottled engine operating largely on a prop load curve.

For two rotor engines the full output excitation is 82% of the full output mean torque. The above relationships, with a magnification at resonance of five, result in a peak vibratory torque at 1800 RPM of 3000 in.-lb.

Now consider the reduction gear input torque at take-off and at 1800 RPM resonance. (Torque values in in.-lb.)

	Mean Torque	Vibratory Torque	Peak Torque
Take-Off	2200	0	2200
Resonance	0	3000	3000

It should be noted that vibratory torque exceeds the mean torque below 3000 RPM so that the reduction gear is subject to reverse loading except at the higher powers. This may result in some noise but is not expected to seriously affect gear strength. A particular gear tooth on the crankshaft pinion always is loaded by the maximum mean plus vibratory torque as a cyclic loading from zero to the maximum. Reverse loading occurs on a different tooth.

Alternate Torsional Systems

The torsional system described above has been selected for the preliminary design. As part of a final design, various alternate systems can be investigated to minimize weight and engine complexity. The following possibilities exist:

	Isolator Coupling	Flywheel
1. Flexible System	Yes	Yes
2. Stiff System	No	No
3. Variable Stiffness	Yes	Yes
4. Tuned Pendulum	No	No

1. Flexible System

This is the selected preliminary design. As described earlier it isolates the reduction gear from vibratory torques at the high output conditions. This desirable result must be balanced against its complexity, weight and low speed resonance characteristics.

RC2 - 32

REDUCTION GEAR TORQUE

AT INPUT

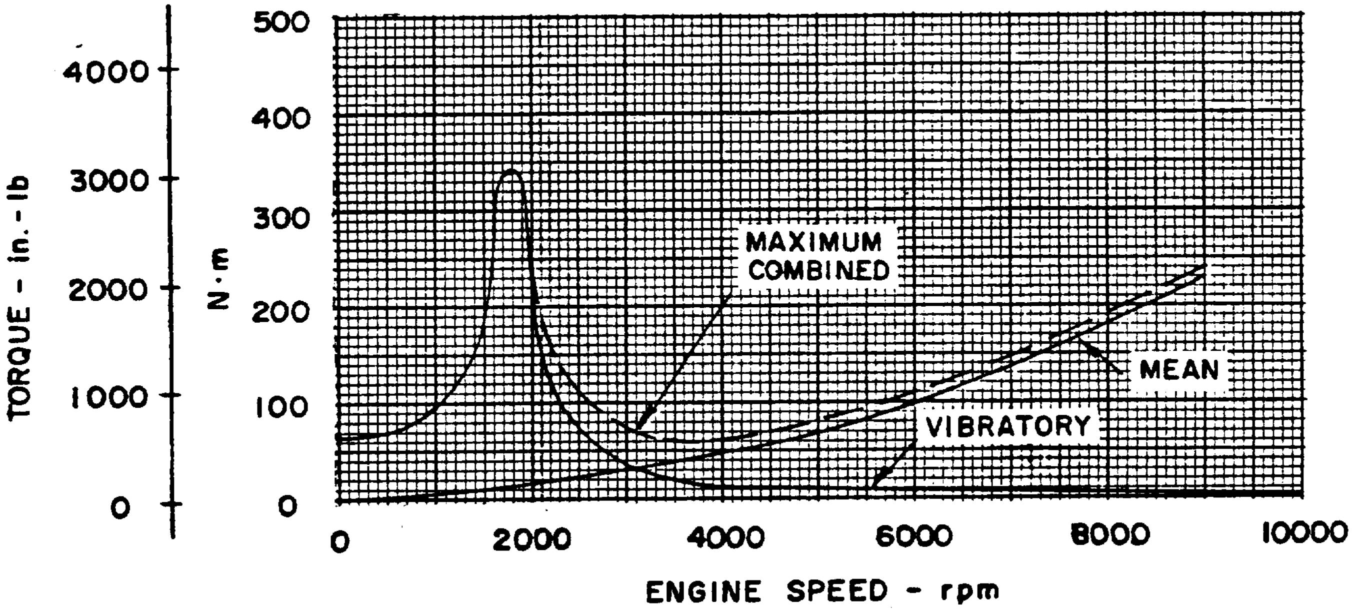

Figure 2.2.9

2. Stiff System

If the torsional spring between the crankshaft and the propeller can be made high enough, then the engine can avoid major torsional resonances in the operating speed range. Past attempts to accomplish this have been unsuccessful since propeller shaft and related flexibilities have been too large. However, this possibility should be investigated for this particular set of design circumstances.

3. Variable Stiffness

The spring drive of the flexible system can be provided with a clutch that locks out the flexibility at low engine speeds. At a selected speed, the clutch is disengaged to permit isolation at high speeds. With this system, low speed resonance is avoided, yet the advantages of the flexible system are retained.

4. Tuned Pendulum

The crankshaft can be equipped with a torsional pendulum that is tuned to the firing order. This is the approach that has been used successfully on large reciprocating aircraft engines. The tuned pendulum effectively nullifies response to the firing frequency excitation. Complexity and cost are the prime negative considerations.

Ignition System

The ignition requirements of the Rotary Stratified Charge Engine are basically the same as for any homogeneous charge Otto cycle engine of Rotary or reciprocating design. The major difference is that whereas the overall air-fuel ratio of the stratified charge engine is lean, the local area around the spark plug is constantly changing, going from lean to rich as the pilot fuel injects into its cavity which is common with the spark plug. In order to provide for dependable ignition, a very high frequency, long duration, multiple sparking ignition system with high spark energy and rapid rise time is shown on this engine. This type of system allows the spark to be turned on prior to pilot injection and thus negates the need for an accurate timing relationship between pilot - injection and initiation of spark. The long duration also facilitates relighting the pilot if for any reason it should extinguish.

The ignition system shown on Figure 2.2.7 is totally electronic with no moving or rubbing parts. There are four independent systems with two spark plugs per rotor in keeping with FAA practice. The ignition trigger system employes a magnet or ferrous vane on one of the engine's rotating components which passes by a solid-state sensor of either Hall-Effect or Weigand Wire construction. Using today's miniaturization techniques each of the four ignition triggers can be made up of multiple redundant sensors all constructed on a single silicon chip along with the logic elements necessary to isolate failed components. This same redundancy technique can also be used in the ignition control units timing computation circuits, pulse shaping circuits, and output stages. The ignition system would be of the low tension type which has no high voltage cables, instead the four ignition coils are shown mounted onto the rotor housings enclosing the spark plugs thus providing an excellent environmental sealing of the spark plug - ignition coil interface.

Power for this system can be generated by separate generators (magnetos) for each system or pair of systems or can be provided by the airframe batteries or the airframe alternator. Different combinations can be explored and used to optimize size, weight and cost while providing for extreme safety of operation.

A combustion augmentation device can also be employed which provides a combustion heated hot spot in the vicinity of the pilot nozzle which can ignite the mixture once the engine is up to operating temperature thus providing independence from the ignition system once the take-off procedure is initiated.

Diagnostics

In this age of the microprocessor it will be conceivable to have an onboard diagnostics computer which can monitor the engine, airframe and avionics and result in greater convenience, safety and a reduced life cycle cost. Reduced maintenance costs would result from a reduction in troubleshooting time and increased convenience and safety from the computer's ability to predict failures based on statistically monitoring the systems. The diagnostics would have the largest payoff on those systems which are totally electrical in nature such as the avionics, the electrical charging and storage system, the starting system and the ignition system. The remainder of the systems require that transducers be used to obtain signals for the computer. Obvious transducers to be fitted are lube system pressure and temperature sensors, an exhaust temperature sensor and a coolant temperature sensor. Other likely monitoring points include the intake air temperature and absolute pressure, the turbocharger speed, the oil metering flow, and engine airframe interfaces such as cabin pressurization and prop beta angle. Integration of the diagnostics with the ignition system, fuel control system, and vehicle power control is discussed in the section on the Fuel Injection System which follows.

Development of the components for this diagnostic system is presently taking place at an extremely rapid pace for a variety of uses including automotive, military and aerospace applications.

Fuel Injection System

The fuel injection equipment of the study engine (high pressure rail) is of the type developed for reciprocating Diesel engines. The design embodied on the RC2-32 Installation Drawing, Figure 2.2.7 employs two injectors per rotor. One called the pilot injector injects a constant fuel quantity per engine revolution and the second termed the main injector injects varying quantities of fuel depending on the power and speed demanded of the engine. Three types of systems were examined for use in this design - they are as follows:

1. Conventional "Jerk" pump-line-injector system using either in-line or distributor type pumps.

2. Unit Injectors Combine the pump and injector into one unit driven by an external camshaft and push type linkage.

3. High Pressure Common Rail This type system uses an untimed pressure generating system with a timed valve to provide fuel to the injector.

These three systems were evaluated on the following criteria:

1. Injection quality - including turn down ratio (ratio of maximum fuel per stroke to minimum fuel per stroke), freedom from secondary or pre-injection, injection pressure versus speed and load.

2. Timing control - timing range available and timing algorithms realizable.

3. Packaging - size, weight, configuration.

4. Cost - both development and production.

5. Reliability - part count, loadings, redundancy.

6. Maintainability - modular, calibration and adjustment requirements, airframe interface.

7. Availability - for both development and production.

Table 2.2.9 is a compilation of the results of this evaluation. The high pressure common rail system was chosen for use in this design because of its overwhelming superiority on this high technology engine. Availability of prototype systems is excellent and such a system would be used for even the early stages of engine development. Since the control of the injection timing and fuel flow is totally electronic it would be possible to integrate the ignition system, fuel control system, diagnostics and vehicle power control into a single flight engine control package thus minimizing interconnections and the cost and reliability penalties associated with them. This system can have control over the redundant power sources and thus ensure the safety of the fuel and ignition systems.

TABLE 2.2.9 - FUEL INJECTION SYSTEMS EVALUATION

	CONVENTIONAL - PUMP, LINES, NOZZLES SYSTEM	UNIT INJECTORS	HIGH PRESSURE COMMON RAIL (SYSTEM CHOSEN)
1. INJECTION QUALITY	Poorest of all systems, tuning of lines will allow secondaries at some points, pressure will vary with speed. Limited turn down ratio.	Free of secondaries and line dynamics, pressure varies with speed.	Best of all systems, free of secondaries, pressure controllable.
2. TIMING CONTROL	Very difficult - requires bulky mechanical timing device.	Timing and quantity can be controlled electronically.	Fully electronic, no timed drives required.
3. PACKAGING	Overall the largest, heaviest system, timed drive required.	Must be integral part of engine, intermediate size and weight. Camshaft required.	Smallest and lightest overall.
4. COST	High to moderate for development and production. Difficult to make changes.	High for development, moderate for production.	Low for development, production cost low if used on automotive diesels.
5. RELIABILITY	Lowest part count.	Moderate part count.	Very low part count.
6. MAINTAINABILITY	Difficult to adjust.	Electrical adjustments.	Adjustments all electronic.
7. AVAILABILITY	Existing pumps can be modified.	Electronic control concepts bench tested successfully, large units in production, design and development for application required.	Development systems available now running at our specifications. Production dependent on automotive diesels.

Accessories

Pads have been provided at the rear of the engine to permit installation of the following accessories:

- Starter
- Fuel Pressure Pump
- Alternator
- Air Conditioning Compressor
- Single Shaft Oil and Water Pump

Pads at the front are provided for possible aircraft needs:

- Vacuum Pump
- Hydraulic Pump

Contacts with vendors indicated some reductions in weight and size were probable. A 10% reduction compared to current sizes was used to estimate the weights of the study engines.

Weight, Size, and Scaling

The pertinent data for both the Advanced (RC2-47) and Highly Advanced (RC2-32) engines will be provided in this section.

Table 2.3.1 provides a detailed weight breakdown for both engines. For the items with weight values not listed, the values are either included in the first item, Basic Engine, or provided by the aircraft manufacturer.

Scaling For ± 25% of Horsepower

The displacement and engine shaft speed vs. prop shaft take-off horsepower are shown in Figure 2.3.1 for both technology levels. The engine dimensions vs. displacement are shown in Figure 2.3.2.

TABLE 2.3.1

WEIGHTS

ROTARY COMBUSTION ENGINE & ACCESSORIES

(NOTE: Items Included in Basic Engine Weight listed as "Incl.")

ITEM	ADVANCED RC2-47 Pounds	ADVANCED RC2-47 Kg	HIGHLY ADVANCED RC2-32 Pounds	HIGHLY ADVANCED RC2-32 Kg
Basic Engine	257	116.6	170	77
Carburetor	None	None	None	None
Fuel Injectors	Incl.	Incl.	Incl.	Incl.
Magnetos	None		None	
Ignition System, Spark Plugs	Incl.	Incl.	Incl.	Incl.
Battery	Cessna	Cessna	Cessna	Cessna
Drives				
Starter	Incl.	Incl.	Incl.	Incl.
Alt.	Incl.	Incl.	Incl.	Incl.
Vac. Pump	Incl.	Incl.	Incl.	Incl.
Prop. Gov.	Incl.	Incl.	Incl.	Incl.
Fuel Pump	Incl.	Incl.	Incl.	Incl.
Compressor	Incl.	Incl.	Incl.	Incl.
Tach.	Incl.	Incl.	Incl.	Incl.
Propeller	Cessna	Cessna	Cessna	Cessna
Spinner	Cessna	Cessna	Cessna	Cessna
Governor	Cessna	Cessna	Cessna	Cessna
Starter Switch	Cessna	Cessna	Cessna	Cessna
Transistor Volt Reg.	Cessna	Cessna	Cessna	Cessna
Overvoltage Relay	Cessna	Cessna	Cessna	Cessna
Vacuum Pump	1.4	.6	1.2	.5
Fuel Pump	None for engine		None for engine	
Primer System	Cessna	Cessna	Cessna	Cessna
Starter	25	11.3	22	10

TABLE 2.3.1 (Continued)

ITEM	ADVANCED RC2-47		HIGHLY ADVANCED RC2-32	
	Pounds	Kg	Pounds	Kg
Alternator Ø	Cessna	Cessna	Cessna	Cessna
Turbocharger*	Incl.	Incl.	Incl.	Incl.
Baffles ☐	See Note		See Note	
Air Filter	Cessna	Cessna	Cessna	Cessna
Oil Filter	Incl.	Incl.	Incl.	Incl.
Oil Filler Ext.	None	None	None	None
Thermostatic Oil Bypass, Oil Cooler, and Tank, Dry	12.1	5.49	12.1	5.49
Thermocouple	Cessna	Cessna	Cessna	Cessna
Exhaust System	Incl.	Incl.	Incl.	Incl.
Dynafocal Mounts	4	1.81	3	1.36
Engine and Prop. Attach.	Cessna	Cessna	Cessna	Cessna
External Coolant System (wet)	19.1	8.66	19.1	8.66
Coolant in Engine	9.7	4.40	6.6	2.99
Lubricating Oil	21.6	9.80	21.6	9.80

NOTES

Ø (1) Self excited generator
(2) Alternator sized for aircraft requirements

☐ No baffles or reduced baffles with air to liquid coolant cooler

* Complete installation including intercooler

TAKE-OFF POWER VS. ENGINE SIZE
(TWO-ROTOR ENGINES)

ENGINE RPM		
ENGINE	D(cm^3)	D(in.^{3})
HIGHLY ADVANCED	$75375/D^{1/3}$	$29675/D^{1/3}$
ADVANCED	$64610/D^{1/3}$	$25437/D^{1/3}$

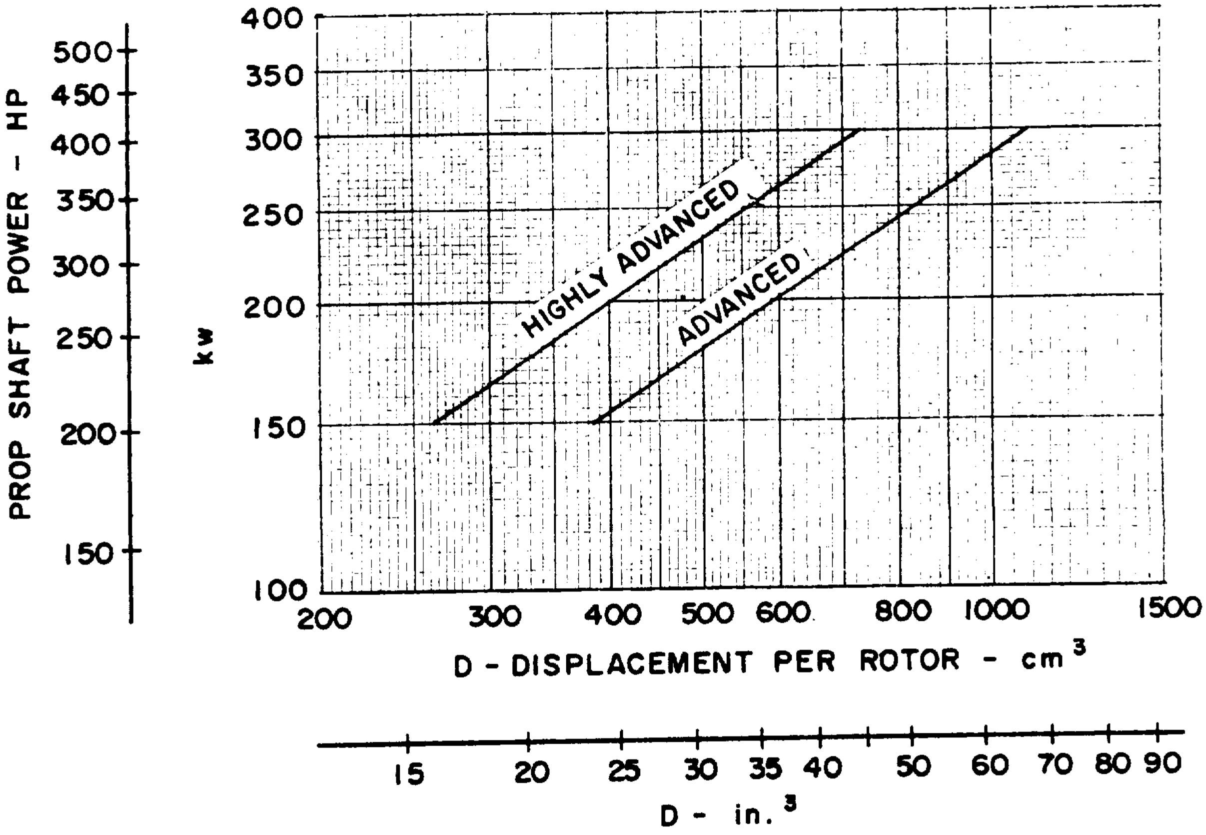

Figure 2.3.1

ADVANCED AND HIGHLY-ADVANCED ROTARY COMBUSTION AIRCRAFT ENGINES

ENGINE DIMENSIONS VS. DISPLACEMENT PER ROTOR

TWO-ROTOR ENGINES

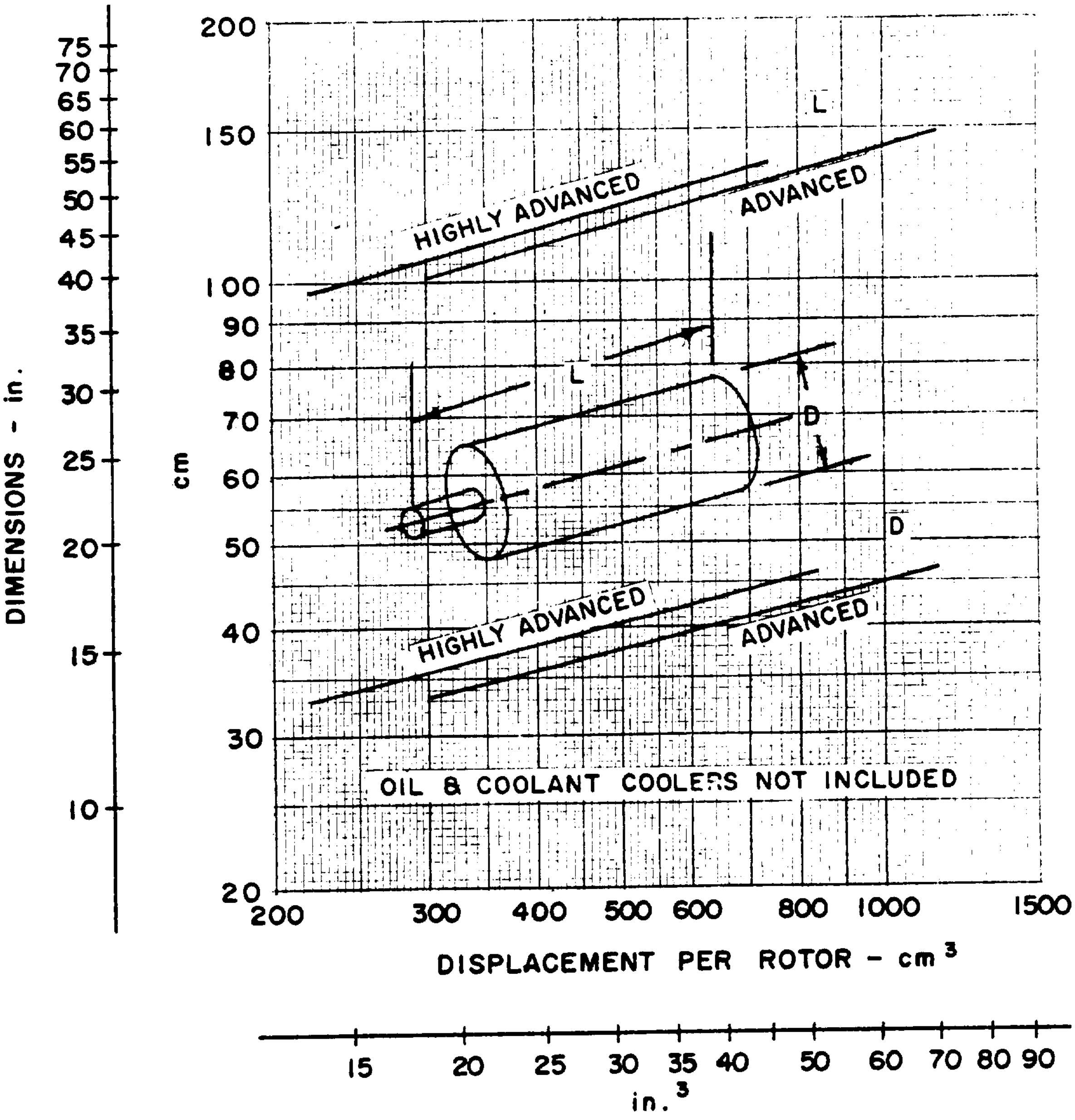

Figure 2.3.2

The engine weight scales as follows:

WEIGHT SCALING FACTORS

HIGHLY ADVANCED ENGINE

Weight, Kg = 115.7 + .32 (T.O. Bkw -238.6)

Weight, Lb = 255 + .53 (T.O. BHP -320)

ADVANCED ENGINE

Weight, Kg = 157.8 + .487 (T.O. Bkw -238.6)

Weight, Lb = 348 + .8 (T.O. BHP -320)

These weights are "wet, ready to fly".

The following items are included in the weights shown above:

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

ENGINE COOLING

Estimates of the maximum local heat flux were made for the RC2-32 engine using parametric relationships determined from carbureted gasoline rotary combustion engine test programs. The predictions indicate an increase in the maximum local heat flux (at a point typically located slightly after top dead center in the rotor housing).

It is highly likely, however, that the relationships do not apply to a stratified charge engine operating with air/fuel ratios in the 22 to 25 range. In fact, the indications are that for stratified charge engines and for diesels, the expected increases in mechanical and thermal loading due to turbocharging may be avoided by the use of low compression ratios and high air/fuel ratios. Figure 2.4.0 shows two figures from an article by Roy Kamo, "Higher BMEP Prospect for Vehicular Diesels" (Reference 7). The test data shown illustrates the above mentioned means of avoiding increased stresses and temperatures while substantially increasing BMEP level and the output horsepower.

Figure 2.4.1 shows the variation in combustion chamber temperature throughout the operating cycle. This data is used in evaluating the effect of the rotor insulating coating on heat rejection. Cooling risks and assumptions are discussed on page 2.1.1.

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 rack setting) while the aircraft is at a relatively low airspeed. 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 a possibility 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.

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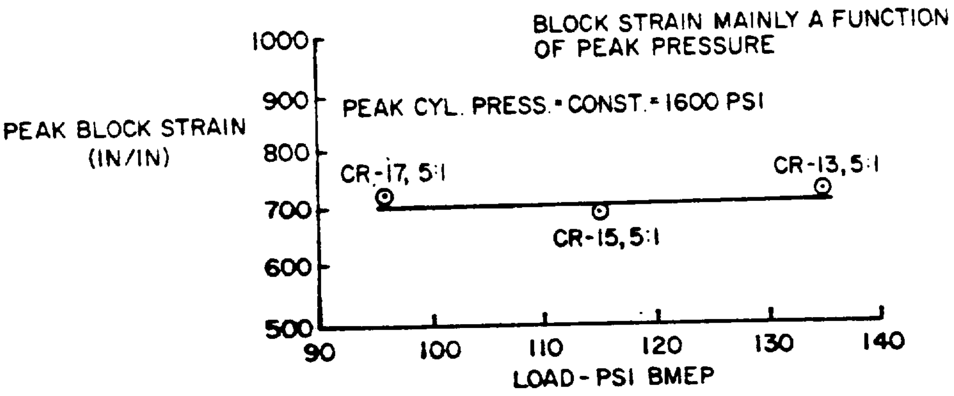
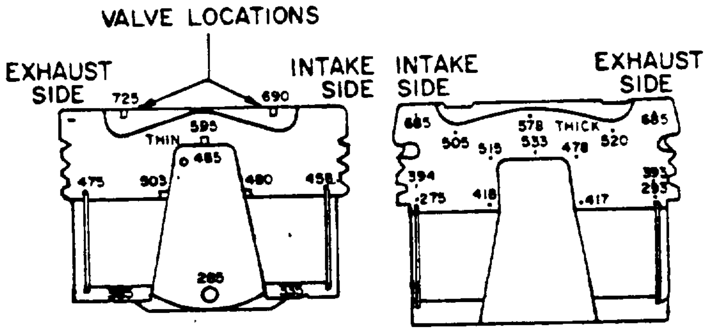
HIGH MEP DIESEL PISTON TEMPERATURES AND BLOCK STRAIN



(a) Effect of BMEP Level on Peak Block Strain for Constant Peak Cylinder Pressure and Varied Compression Ratio.



HIGH COMPRESSION RATIO PISTON:

C.R.	15.5:1
BHP	400
A/F	25.5:1
RPM	2600

LOW COMPRESSION RATIO PISTON:

C.R.	10.8:1
BHP	600
A/F	31:1
RPM	2600

(b) Piston Temperature Distribution in the Same Engine. Thermal Load From 50% Higher BMEP Compensated by Lower Compression Ratio and Higher Air/Fuel Ratio

(Reference 7)

Figure 2.4.0

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COMBUSTION GAS TEMPERATURE VS VOLUME

RC2-32

(TAKE-OFF POWER & RPM)

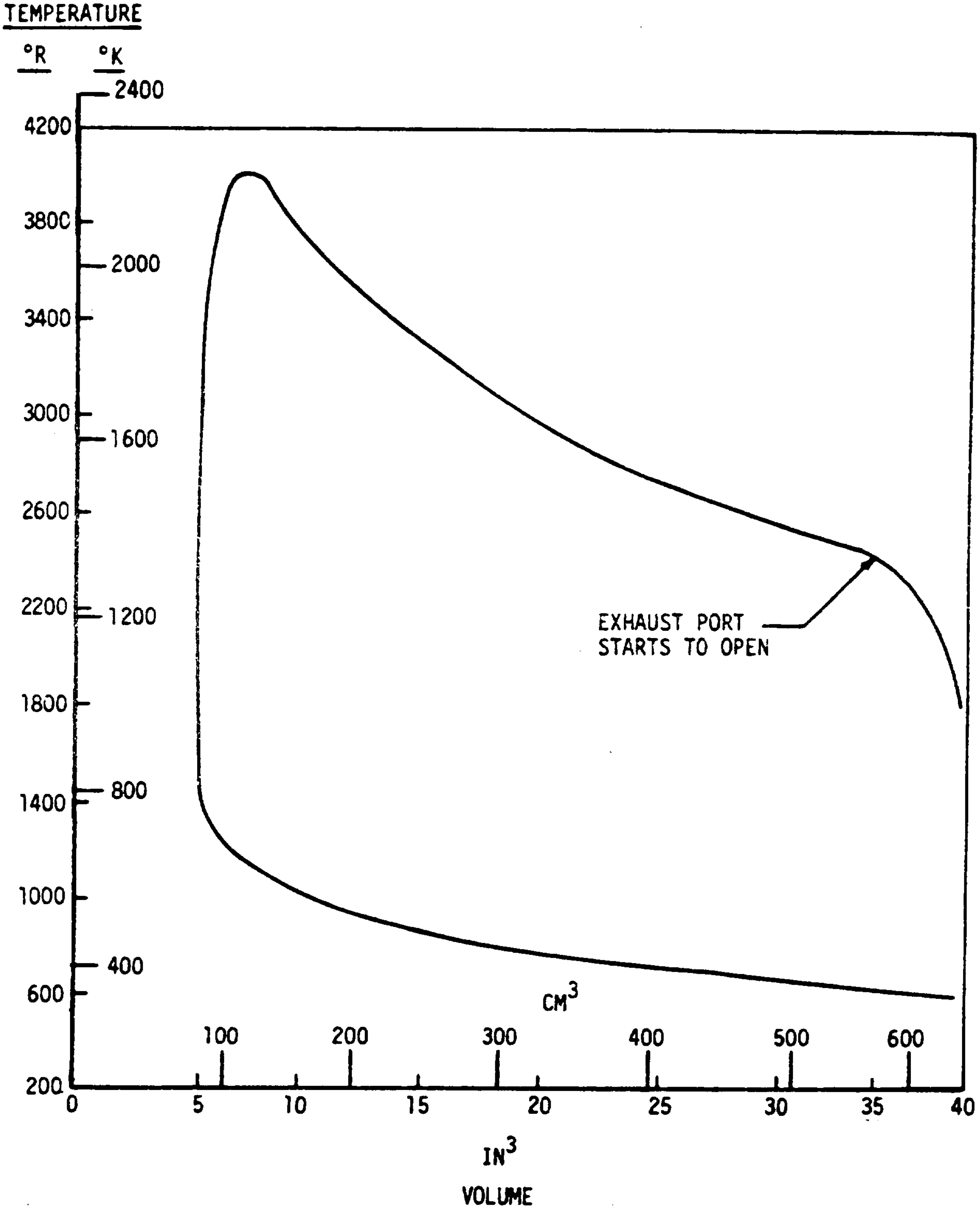


Figure 2.4.1

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 110°C/230°F and 121°C/250°F.

Relative Cooler Size

Maximum Coolant Out Temperature °C/°F	For Same Cooling Drag	For Same Cooling Air Pressure Drop
110/230	1.22	1.17
121/250	1.0	1.0

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

Coolant and Oil Heat Rejection Rates

Coolant and oil heat rejection rates for the highly advanced engine (RC2-32) are given by Figure 2.4.2. These rates represent an upper bound 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 RC2-32 engine operating conditions using heat rejection scaling factors for F/A, 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 Figure 2.4.2.

RC2-32 ENGINE 238.6 KW (320 BHP)

COOLANT AND OIL HEAT REJECTION

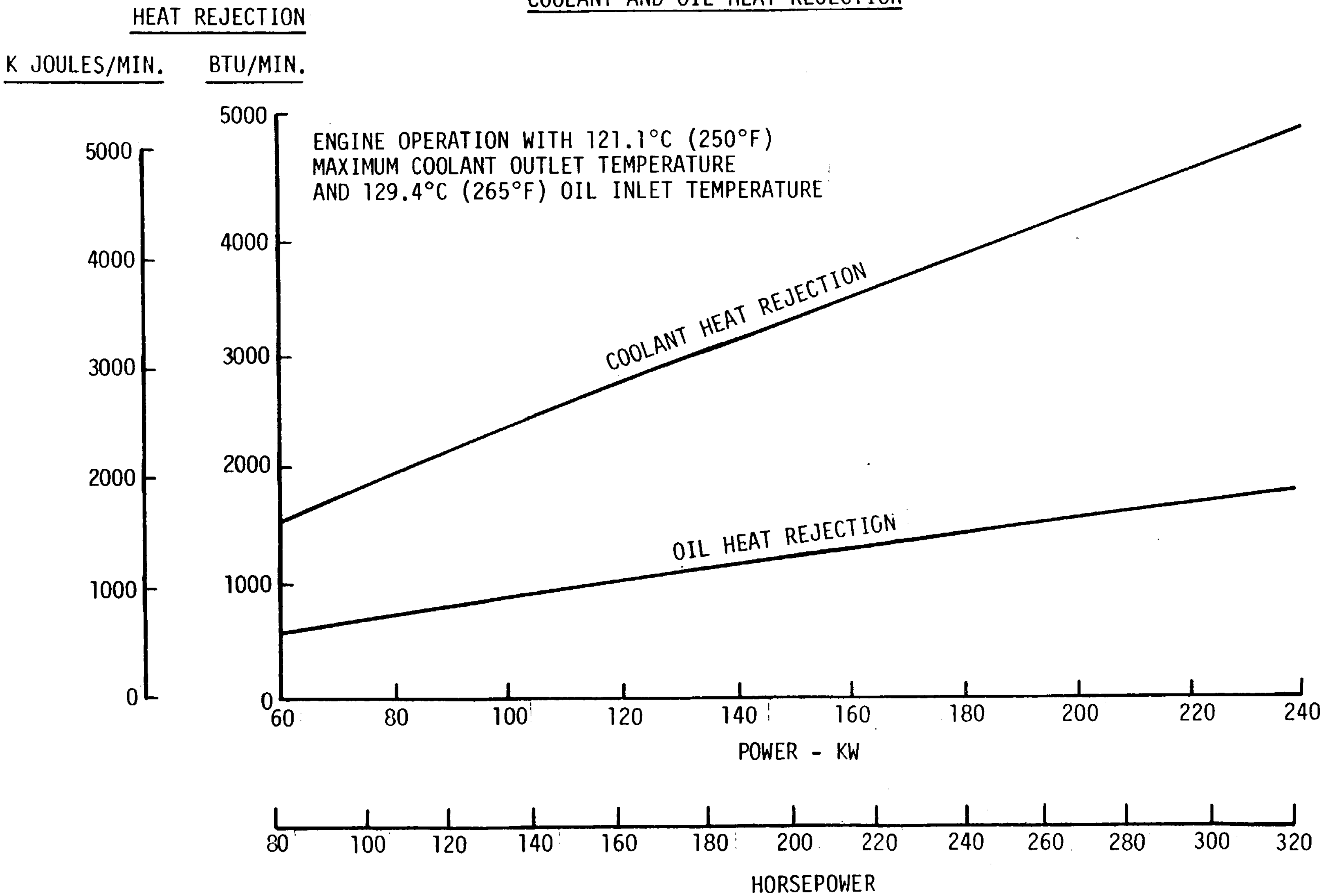


Figure 2.4.2

TIME BETWEEN OVERHAUL AND MAINTENANCE SCHEDULE

The time between overhaul (TBO) for the "advanced" and "highly advanced" rotary aircraft engines is anticipated to be 2000 hours or greater.

The estimate is based upon known wear rates of critical internal components 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.

In the 23 years Curtiss-Wright has been developing its rotary engines, it has investigated engines with displacement ranging from 4.3 to 2500 cubic inches per chamber, but the predominant amount of 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, which represents the same basic design approaches planned for the general aviation engines. Wear data for the principal components in this engine, for current state-of-the-art loading, appear on Table 2.5.1 and for apex seals in Figure 2.5.0.

Among the components whose wear rates influence engine performance and life, the apex seal is the most critical and it is obvious from Figure 2.5.0 that the current useful life of this seal far exceeds the predicted 2000 hour TBO in the RC2-60 engine.

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

- 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 (through increased wear rates) and trochoid coating life.

It is assumed that sufficient testing activity can occur in the next five years to result in the introduction of improved seal and rotor housing wear surface materials. This should permit the 2000 hour TBO to be realized and possibly extended. Candidate materials are discussed elsewhere in this report.

Based upon diesel truck experience, the life of the fuel injection equipment and turbochargers is expected to extend well beyond 2000 hours.

APEX SEAL WEAR
RC2-60

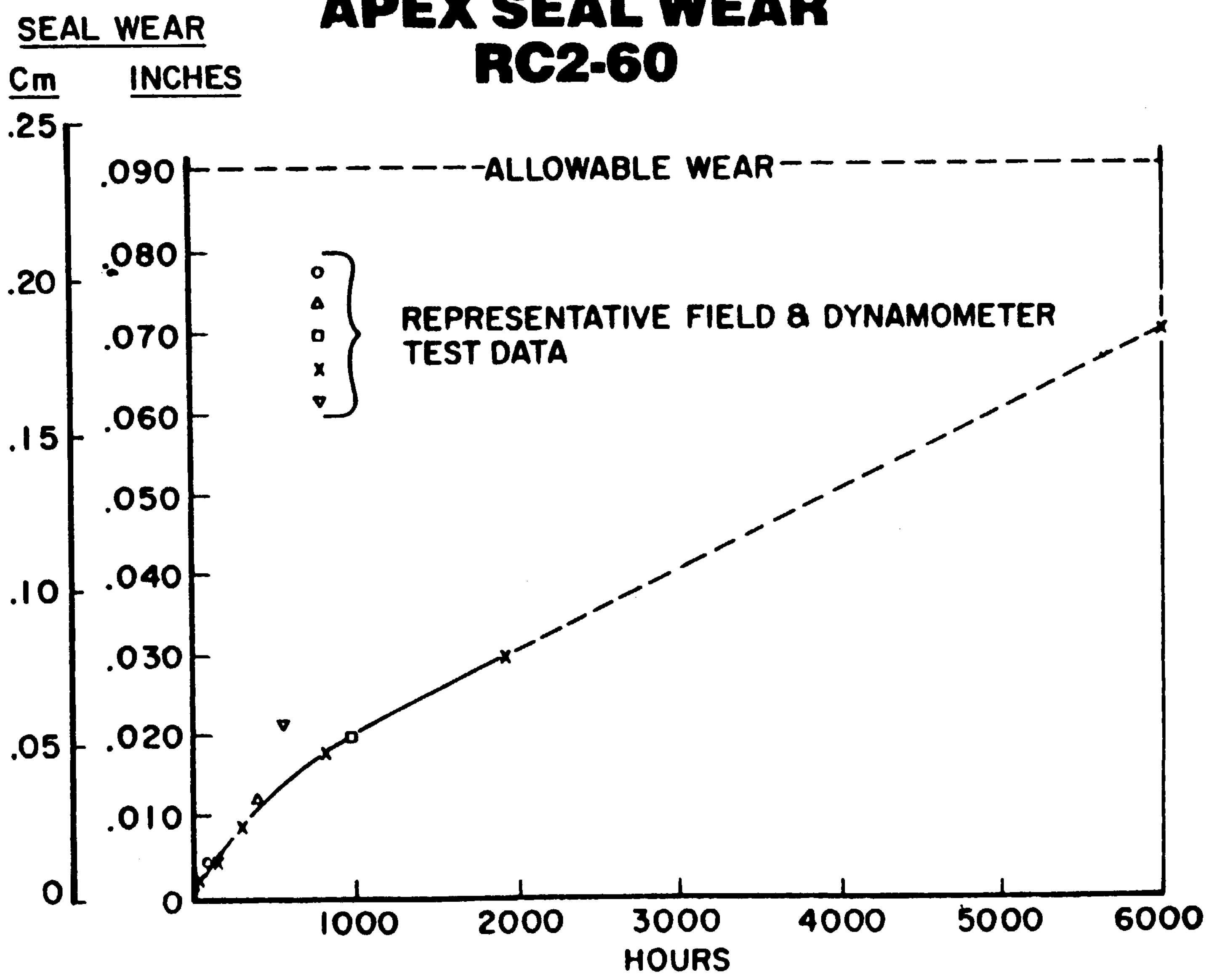


Figure 2,5.0

TABLE 2.5.1

ESTIMATED WEAR-OUT RATE DATA FOR 350 IN^3 U.S. MARINE CORPS PROGRAM, BASED ON CURTISS-WRIGHT ROTARY ENGINE DEVELOPMENT EXPERIENCE

Item	Allowable Wear	Minimum Wear-Out Life-Hrs	Field and Development Background
Apex Seals	.090" Height	2400	.013" in 1973 Hrs at C-W
Side Seals	.015" End	2400	.008" in 1093 Hrs at C-W
Oil Seals (Inner or Outer)	.020" Flat Width Increase	2400	Ingersoll-Rand experience and Sealed Power recommendation - Mazda allows almost 300% increase
Rotor Bearings	.001" Local Material Removal at Loaded Zone	4800	.0002" in 1922 Hrs at C-W (Mazda allows .0008" on dia.)
Main Bearings	To Be Determined	4800	(Mazda allows .0011" wear on diameter) - No measurable wear in 1950 Hrs at C-W
Stationary Gears	.004" Decrease in Over Pins Measurement	4800	Negligible wear in 2012 Hrs at C-W
Rotor Gears	.005" Increase in between Pins Measurement	4800	Negligible wear in 2200 Hrs at C-W
Rotor Housing: Low Cycle Thermal Fatigue	Assumes Typical Duty Cycle for Low Cycle Thermal Fatigue		T-K Rotor Housings can sustain at least 6000 extreme thermal cycles
Rotor Housing Surface Coat.	.002" on Sliding Surface	4800	Negligible wear in 2000 Hrs at C-W
End/Intermediate Housing Surface Coat.	.004" on Sliding Surface	2400	Mazda uses .0039" before grinding

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 2.5.3 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 other engines designed for aircraft use, it is assumed the cost of corrective maintenance would be comparable to other aircraft engines.

Type of Fuel

Both the "advanced" and "highly advanced" 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 referee 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

Automotive fuel presents no problem regarding combustion in the engine, however, its vapor pressure characteristics make it necessary to have a resealed pressurized tank for operation at altitudes. The vapor pressures required to permit starting in carbureted engines in cold climates would otherwise cause excessive evaporation at the higher altitudes.

96

TABLE 2.5.3 - PREVENTATIVE MAINTENANCE FREQUENCIES - HOURS

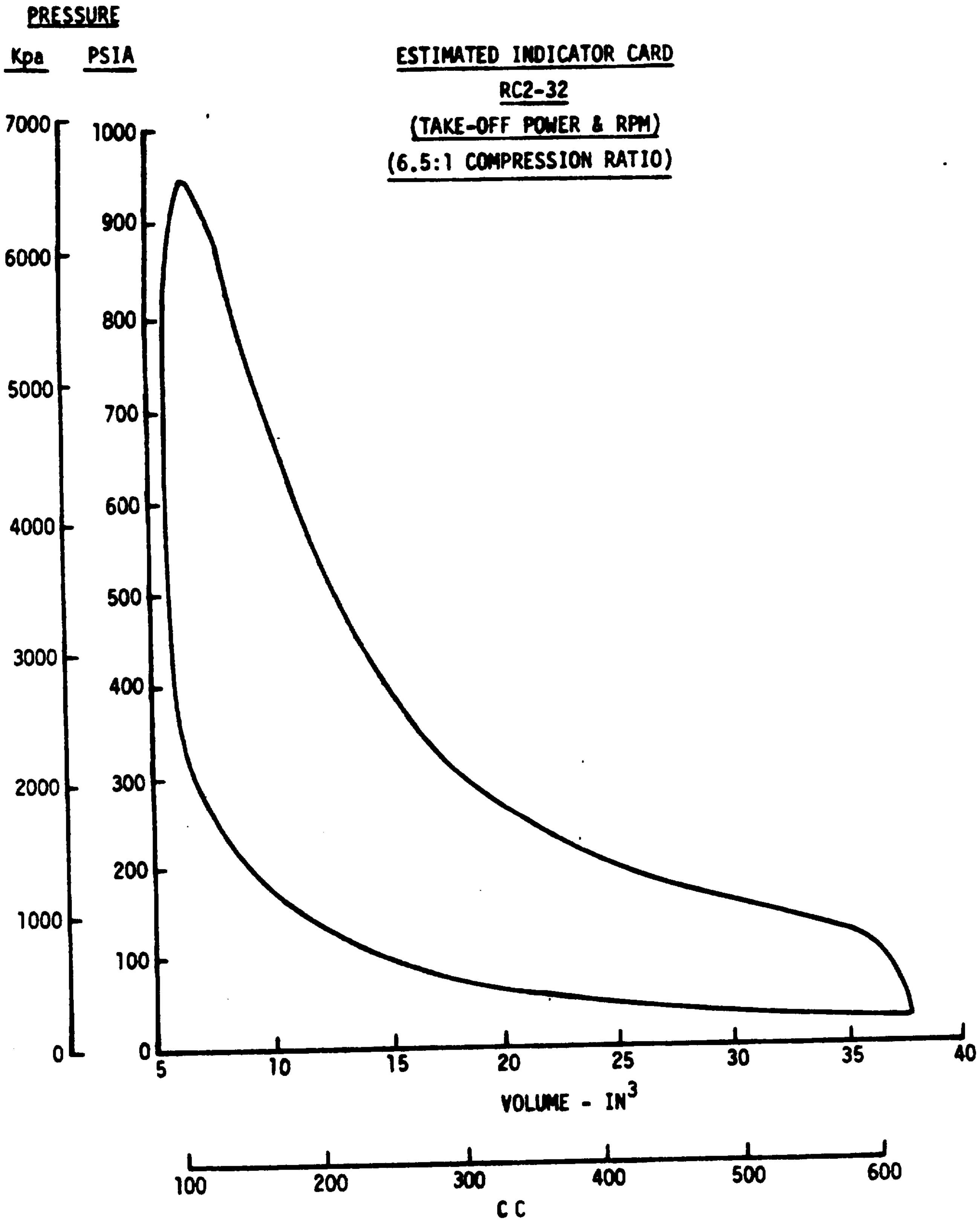
		FREQUENCY*
1.	Change Oil	250
2.	Replace Oil Filter	100
3.	Replace Spark Plugs	100
4.	Drain and Refill Coolant System	500
5.	Replace Fuel Filter	50

*Or once per year at annual inspection, whichever comes first. The once per year requirement may be revised for the coolant system after FAA coordination. No liquid cooled engines are currently in use and standards have not been set. It is possible that in cases of substantially less than 500 hours, the once per year frequency will not apply.

Bearing Capacity

The increased IMEP levels will increase the peak chamber pressure, notwithstanding the mitigating affects of lower compression ratio. In addition to undetermined wear and structural consequences these higher pressure peaks result in increased bearing loads. In a two rotor, two bearing engine of the type being proposed, the main bearings are normally loaded only as a function of gas pressure whereas the rotor bearing experiences a resultant loading from both gas pressure and inertia forces.

On the basis of simplified comparative analyses at the anticipated pressure peaks for the estimated indicator card, Figure 2.5.4, the bearings will not be limiting at the speeds and loads projected. A condition which could prove critical, that of extreme high speed without gas loading, is not likely to occur with normal propeller loading.



ESTIMATED INDICATOR CARD
RC2-32
(TAKE-OFF POWER & RPM)
(6.5:1 COMPRESSION RATIO)

Figure 2.5.4

STRESS LEVEL CRITERIA

The critical items affected by the increased mechanical and thermal loading of the advanced and highly advanced engines are the rotor housings and the rotors.

The mainshaft configurations in Curtiss-Wright's rotary combustion engines are characteristically governed by stiffness requirements rather than stress levels. The mainshafts, rotor gears and stationary gears are made of AMS 6260, a carburizing steel. The rotor and stationary gears are not in the power train. They basically enforce the "circle rolling on a circle" rotor motion that generates the geometric definition of the trochoidal machine. The gear loads that do occur are due to (1) inertia forces accompanying engine speed changes, (2) frictional drag of the rotor seals against the housings and at the journal bearing, and (3) cyclic loading due to the torque variation of the crank effort diagram and any torsional vibrations. The flywheel has been sized to limit the gear tooth force felt due to the crank effort variations. Since the loading of the gear teeth is not a direct function of the increased pressures and speeds, and the design latitude permits choosing to have relatively low gear tooth stresses (350 in.^{3} rotor gear stresses are about half of those in the earlier Curtiss-Wright engines) it is felt the gears are not critical items relative to the advanced and highly advanced engine loading. It is recognized that the higher speeds tend to cause higher gear tooth inertia loading due to tolerance variations.

Rotor Housings

The criteria for the stress levels are based on two kinds of failure modes.

1. Low Cycle Thermal Fatigue

The point of maximum compressive stress at the trochoid surface generally occurs close to the point of maximum metal temperature. Spark plugs or injector holes in the trochoid surface at the same location add stress concentration factors to raise the maximum compressive stress. Both thermal gradients and pressure loading contribute to a system of steady-state plus cyclic stresses. The calculated stresses are converted to strains and a prediction of the number of life cycles is made. Curves of cyclic stress vs. life cycles are shown for AMS 4229 and AMS 4220 at 400°F in Figure 2.5.5. The design stress level is selected to be enough below the knee of the curve to provide a predicted thermal fatigue life with a safe margin compared to the desired part life and expected duty cycles. For example, if the peak temperature was 400°F, for AMS 4229 a peak cyclic stress of 50,000 psi would be permitted, and for AMS 4220 the peak cyclic stress could be 30,000 psi. The material properties utilized in predicting the thermal fatigue life cycles at 400°F are:

80

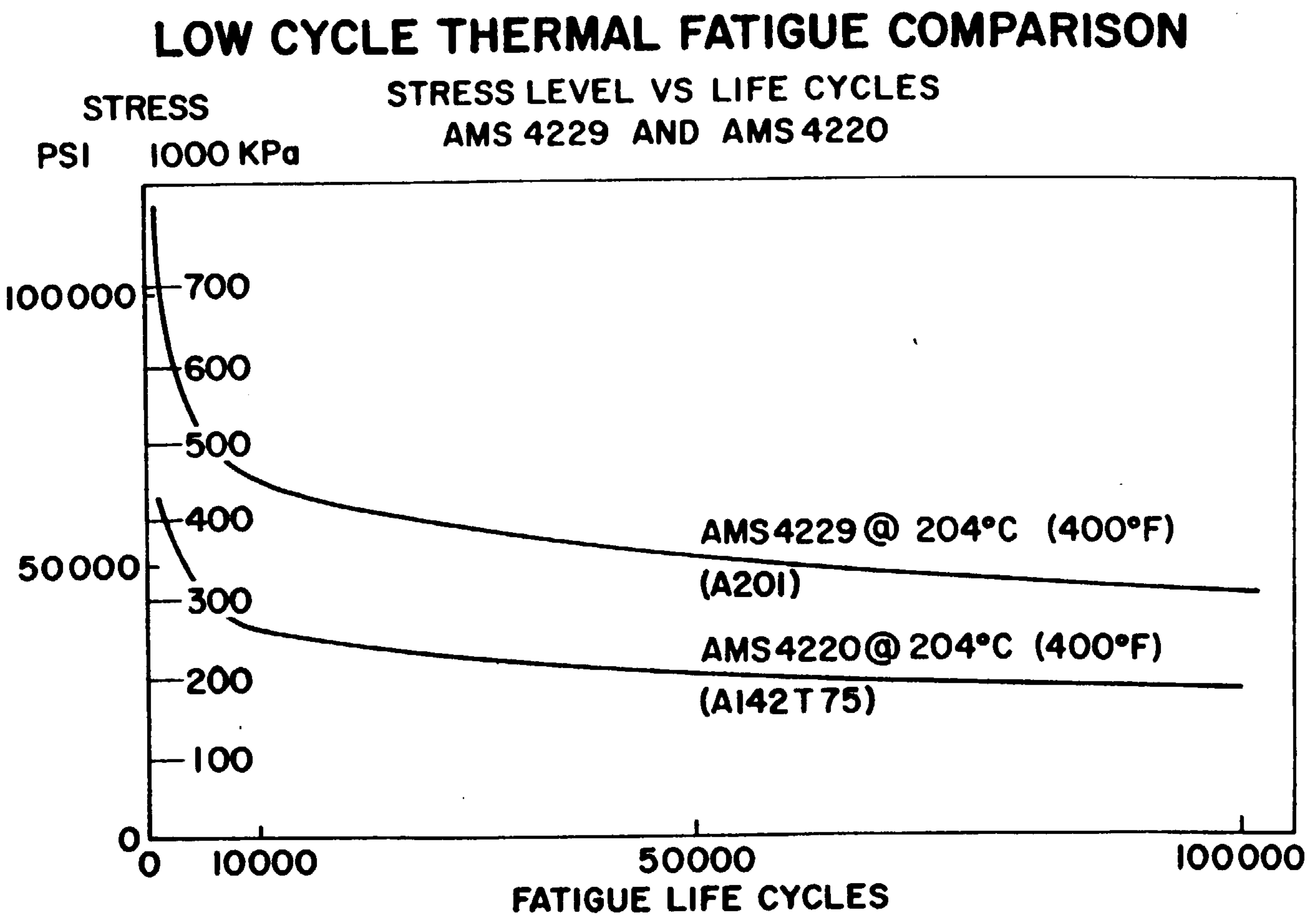
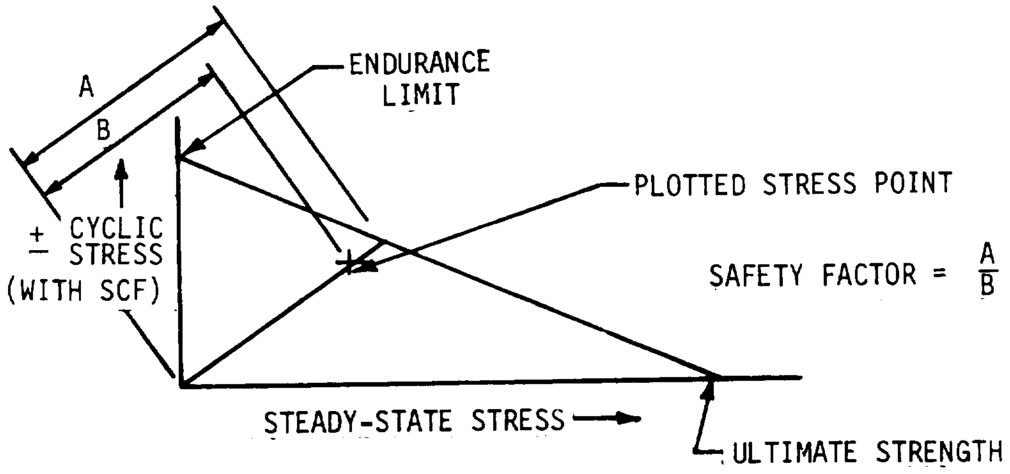

LOW CYCLE THERMAL FATIGUE COMPARISON
STRESS LEVEL VS LIFE CYCLES
AMS 4229 AND AMS 4220
STRESS
PSI
1000 KPa
100000
50000
0
700
600
500
400
300
200
100
0
10000
50000
100000
FATIGUE LIFE CYCLES
AMS4229 @ 204°C (400°F)
(A201)
AMS4220 @ 204°C (400°F)
(A142T75)

Figure 2.5.5

	AMS 4229	AMS 4220
Ultimate strength, 1000 Kpa/Ksi	325/47	200/29
Room temperature ductility in % reduction in area	4.5	3
Modulus of elasticity, Kpa/psi	$6.9(10)^7/10^7$	$6.9(10)^7/10^7$

2. Conventional Fatigue Failure

In this case, the thermal stress is considered to be a steady-state stress and the pressure induced stress is the cyclic stress. With a combustion cycle occurring in the rotor housing with each shaft revolution, the high number of cycles required to reach the endurance limit of a material occur easily. The condition of safety in this regard is evaluated on a modified Goodman Diagram.



The diagram is plotted as shown using the endurance limit and the ultimate strength at temperature. The stresses at critical points are found in terms of the steady-state stress and the fully reversing cyclic stress. Any stress concentrations present are included with the cyclic stress only. The stresses are plotted on the modified Goodman Diagram, and a safety factor is found by drawing a line from the origin to the allowable stress line through the plotted point. The safety factor is determined as shown in the sketch. In order to increase its validity the stress analysis and plotting procedure is also applied to baseline hardware with proven durability and the safety factors of the new design and the baseline compared. An example of the material properties applicable follows:

	AMS 4229 at 204°C/400°F	AMS 4220 at 177°C/350°F
Ultimate Strength, 1000 Kpa/Ksi	325/47	219/31.7
Endurance Limit, 1000 Kpa/Ksi	83/12	50.3/7.3

Rotors

The rotor in the present engine is a nodular cast iron alloy.

The primary potential failure mode is high cycle fatigue. The safety margin is established on a modified Goodman diagram, with the thermal stress and half the pressure stress considered the steady-state stress and half the pressure stress factored by a stress concentration factor, the cyclic stress.

Another stress consideration is the outer flank bending as an unsupported plate between the radial ribs and the side walls and mid-plane web. Comparative evaluations are made of these stresses also. By relating the calculation to parts of proven durability, the stress values are treated as indexes, and aspects which may have been omitted analytically are automatically compensated for.

Performance

The highly advanced RC2-32 turbocharged stratified charge Rotary combustion engine and the RC2-47 advanced engine are based on the following:

1. Contract Goals
    - a. 186.425 KW (250 BHP) Cruise Power at 8202.1 M (25,000 feet) Altitude
    - b. BSFC 231.15 g/KW-hr (.38 lb/BHP-hr at 75% Cruise)
    - c. Specific Weight .608 Kg/Rated KW (1.0 lb/Rated HP)
2. Engine Performance Variables
    - a. IMEP Levels and Speeds
    - b. Combustion Characteristics
    - c. Friction Characteristics
    - d. Turbocharger Requirements

The RC2-32 (two rotors of 32 cubic inch (522.75 cc) displacement per rotor) Rotary engine described is a highly advanced turbocharged stratified charge engine utilizing new technology to the fullest degree considered reasonable.

The configuration chosen results from parametric analysis of contract goals and criteria, Curtiss-Wright developed test data relative to stratified charge engine friction, airflow and combustion characteristics and improvements resulting from the new approaches in the design.

For an operating data summary for the take-off, sea level and 8202.1 M (25,000 feet) maximum cruise conditions, see Tables 2.2.3 and 2.2.4.

With an established take-off IMEP the engine size was determined by satisfying the following considerations:

- a. Engine Friction versus RPM
- b. Turbocharger Compressor Pressure Ratio Limits
- c. Desired Cruise Fuel Consumption
- d. Critical Altitudes

Figure 2.6.0 illustrates graphically two elements of the sizing trade-off process, namely the effects of displacement and shaft speed on the relative fuel consumption at maximum cruise for the advanced technology engine of 1517.5 Kpa (220.1 psi) take-off IMEP. Disregarding the size and weight differences which result from displacement variations, it is evident that the larger slower engines produce the lowest fuel consumption. The primary variable affecting the differences in BSFC values is the increase in FMEP with decreasing displacement at constant equivalent speed and increasing speed at fixed displacement. Noted on the figure are the advanced technology RC1-105 and RC2-47. A higher relative speed was selected for the single rotor engine at a sacrifice in fuel consumption to minimize engine size and weight.

Figure 2.6.1 illustrates on the advanced technology base the effect of the additional trade-off relationships of fuel-air ratio, volumetric requirement and IMEP level on selecting shaft speed and displacement. The example is for the 186.425 KW (250 HP) cruise rating and 231.15 g/KW-hr (.38 lb/BHP-hr) BSFC.

Power

The "highly advanced" Rotary stratified charge engine, if naturally aspirated at sea level, is limited in power output by its volumetric efficiency and air utilization. Turbocharging at sea level has been incorporated to provide the airflow required to achieve the sea level take-off power of the engine when rated at 1548.56 Kpa (244.6 psi) IMEP. All other aspects being equal, brake efficiency would be improved by the increased power capability alone. While the pressure ratio of a typical compressor would easily satisfy the sea level requirements, additional capability of the turbocharger compressor is required for the altitude operation. Page 2.2.3 shows the compressor requirements at sea level for take-off and sea level and 8202.1 M (25,000 feet) for the 186.425 KW (250 HP) maximum cruise. With the defined compressor efficiency and the intercooler effectiveness and pressure loss as noted, the resultant compressor pressure ratio is 5:1 at maximum cruise at 8202.1 M (25,000 feet). Current activity indicates the probable availability of a single stage turbocharger within the proposed time frame.

The projected altitude power characteristics of the RC2-32 engine are shown on Figure 2.6.2 indicating a 8202.1 M (25,000 feet) maximum cruise power (186.425 KW - 250 BHP) critical altitude and in excess of 6096 M (20,000 feet) at the 238.6 KW (320 HP) take-off rating.

Due to the effects of speed on fuel economy a lower speed than is compatible with fixed propeller operation has been selected for maximum cruise so that a constant speed propeller is indicated.

Fuel Consumption

Figure 2.6.3 shows the estimated fuel consumption characteristics of the RC2-32 highly advanced engine versus power at constant RPM. Specific fuel consumption at maximum cruise is 215.93 g/KW-hr (.355 lb/BHP-hr), with the minimum of 213.51 g/KW-hr (.351 lb/BHP-hr) occurring over the 55 to 65% power range.

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TURBO-CHARGED
ADVANCED STRATIFIED CHARGE ROTARY ENGINE
EFFECT OF SIZE & SPEED
ON 186 Kw (250 HP) CRUISE BSFC

NOTE: (1) CRUISE RPM = 83% TAKE-OFF RPM
(2) ENGINE POINT PLOTTED HAS ONE PARAMETER VALUE DIFFERING FROM GENERALIZED ONE AND TWO ROTOR CURVES

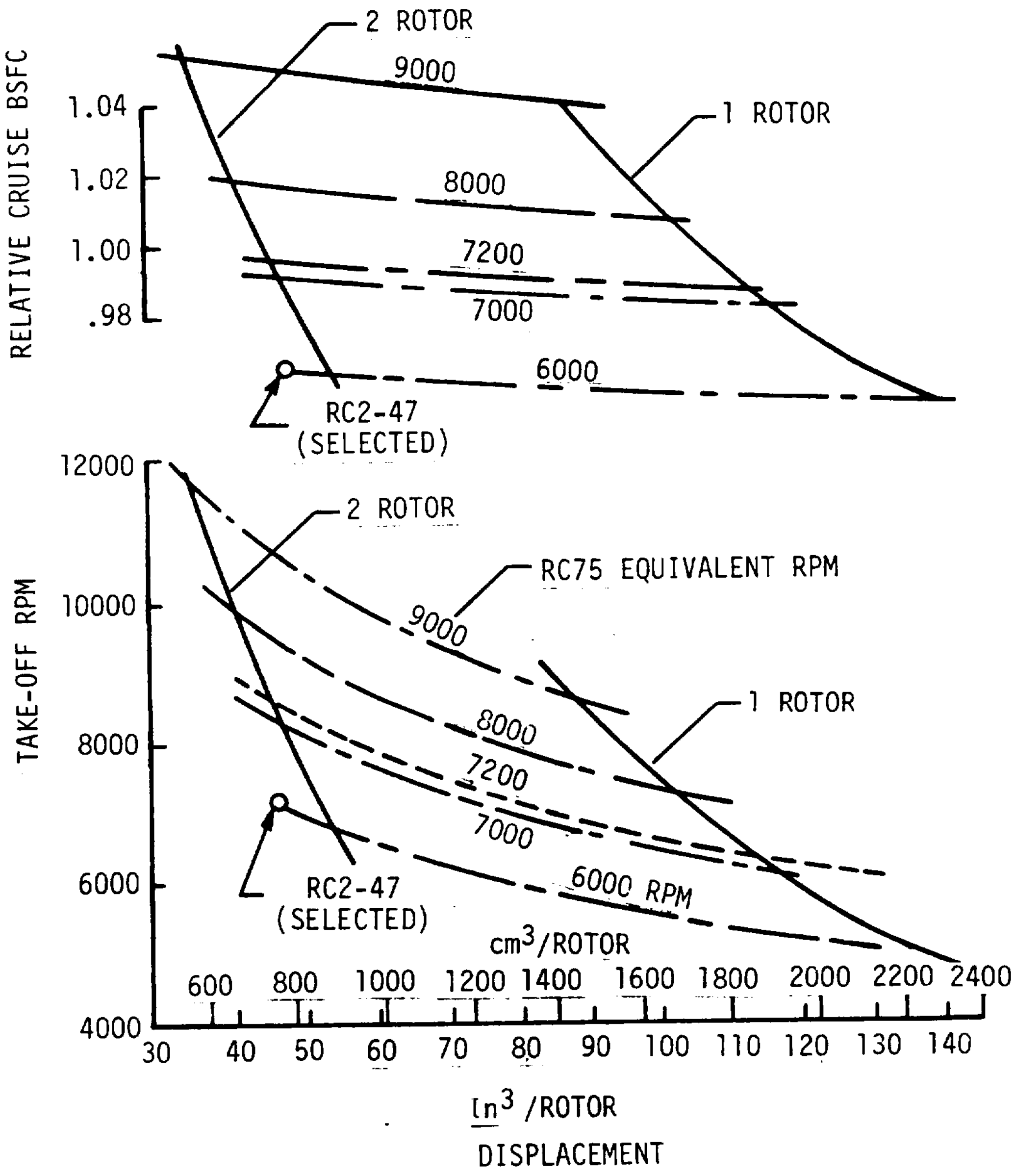

Figure 2.6.0

ADVANCED TURBO-CHARGED - STRATIFIED CHARGE
ROTARY COMBUSTION ENGINE
EFFECT OF RPM AND DISPLACEMENT
ON FUEL-AIR RATIO, VOLUMETRIC EFFICIENCY
AND IMEP REQUIREMENTS FOR
186kw (250 BHP) AND .38 BSFC

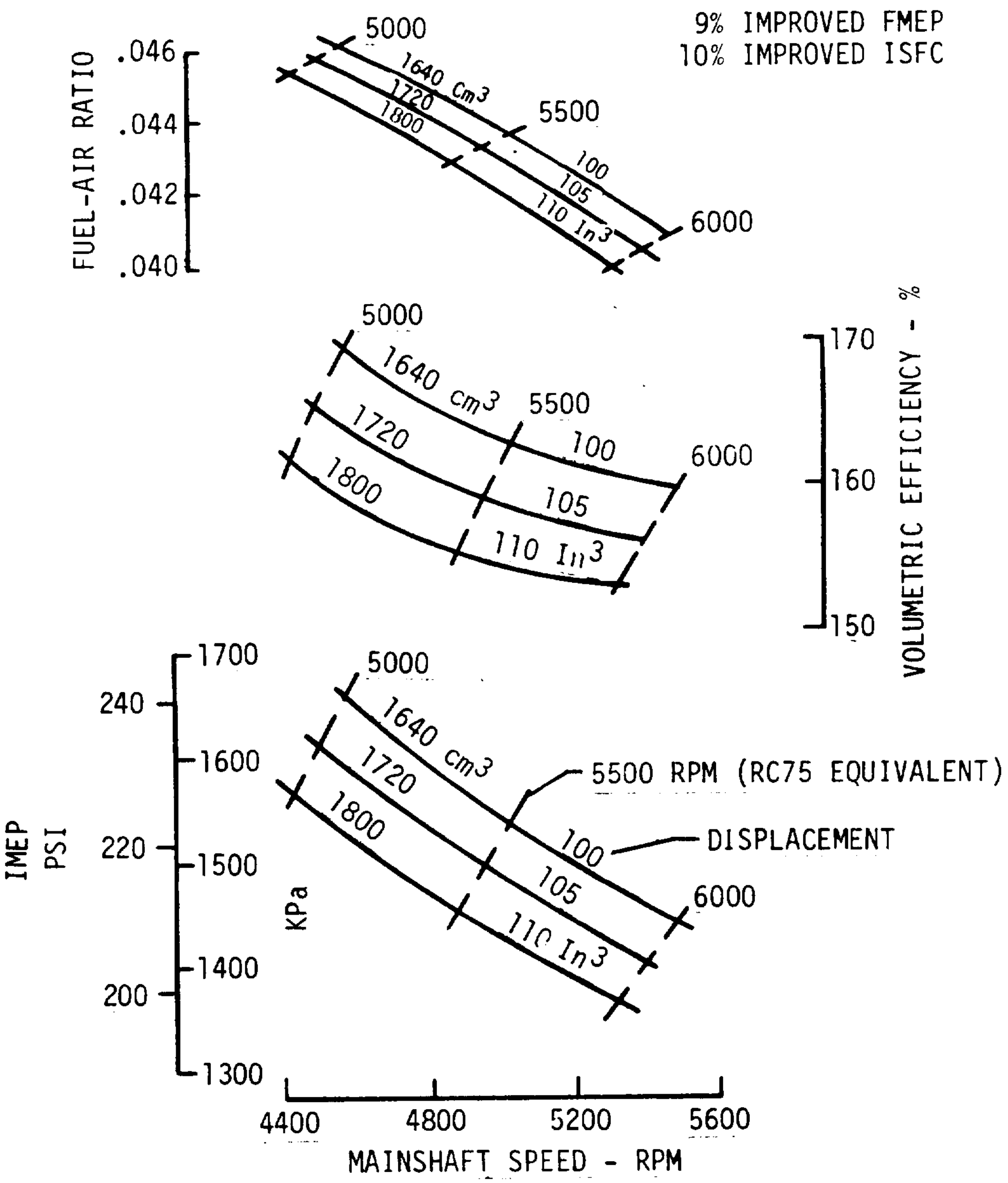

Figure 2.6.1

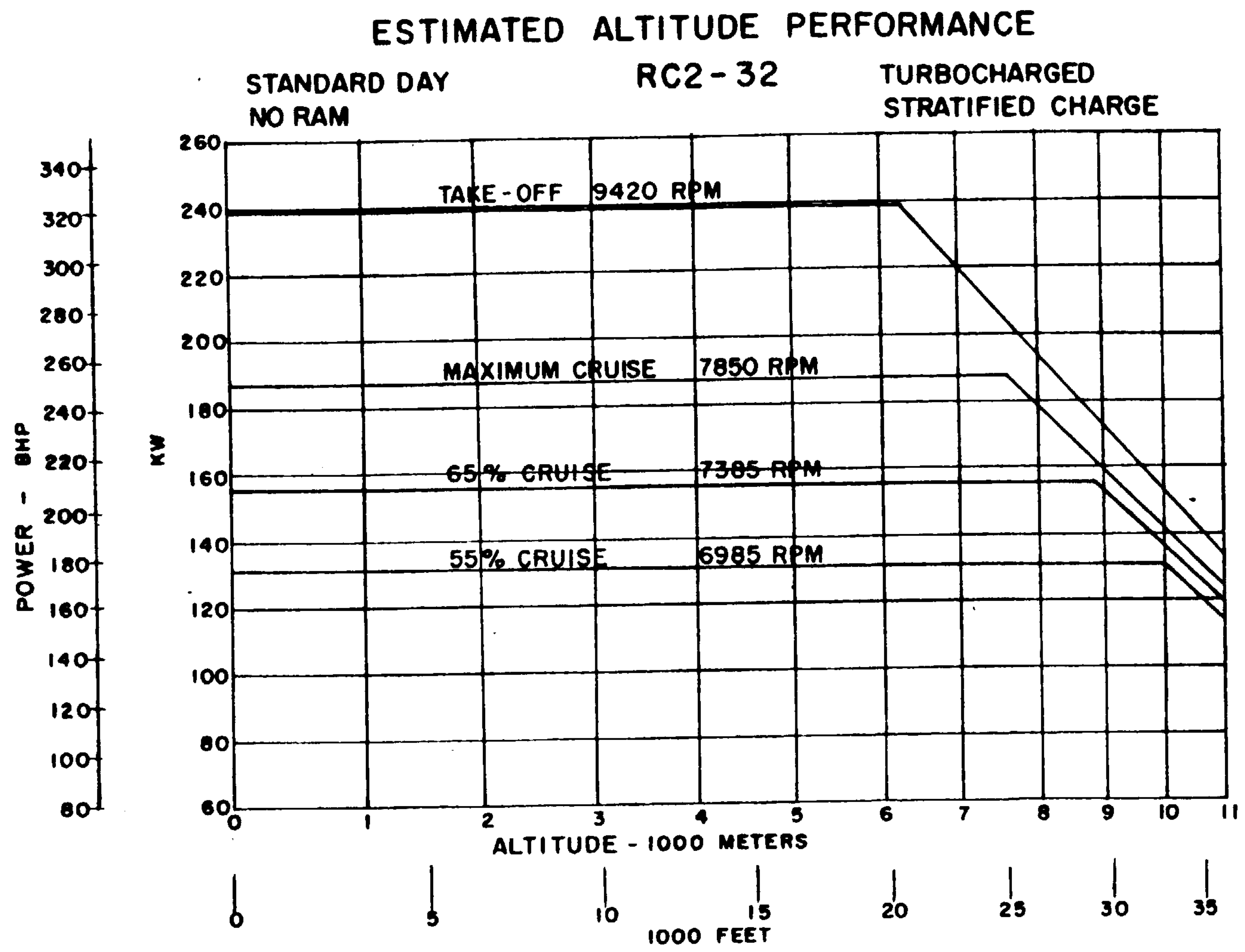
ESTIMATED ALTITUDE PERFORMANCE
STANDARD DAY
NO RAM
RC2-32
TURBOCHARGED
STRATIFIED CHARGE
TAKE-OFF 9420 RPM
MAXIMUM CRUISE 7850 RPM
65% CRUISE 7385 RPM
55% CRUISE 6985 RPM
POWER - BHP
340
320
300
280
260
240
220
200
180
160
140
120
100
80
KW
260
240
220
200
180
160
140
120
100
80
60
0
1
2
3
4
5
6
7
8
9
10
11
ALTITUDE - 1000 METERS
0
5
10
15
20
25
30
35
1000 FEET

Figure 2.6.2

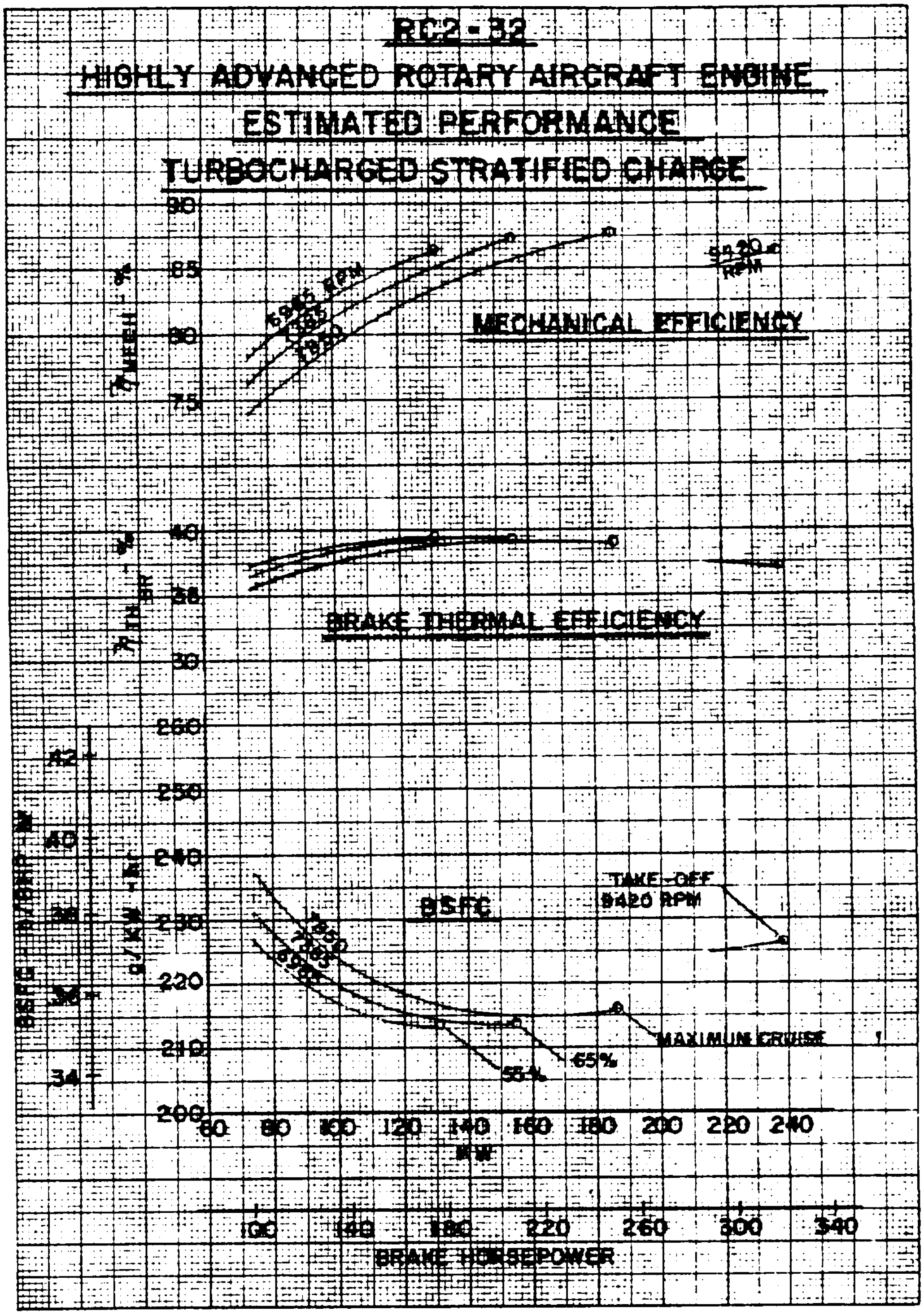
RC2-32
HIGHLY ADVANCED ROTARY AIRCRAFT ENGINE
ESTIMATED PERFORMANCE
TURBOCHARGED STRATIFIED CHARGE
90
85
80
75
η MECH - %
6985 RPM
7385
7850
8420 RPM
MECHANICAL EFFICIENCY
40
35
30
η TH. BR - %
BRAKE THERMAL EFFICIENCY
260
250
240
230
220
210
200
42
40
38
36
34
BSFC - lb/BHP - hr
g / KW - hr
BSFC
7850
7385
6985
TAKE-OFF
8420 RPM
MAXIMUM CRUISE
65%
55%
60
80
100
120
140
160
180
200
220
240
KW
100
140
180
220
260
300
340
BRAKE HORSEPOWER

Figure 2.6.3

TABLE 2.6.3

RC2-32

ESTIMATED FUEL CONSUMPTION

Rating	KW	HP	Crankshaft RPM	BSFC Lb/BHP-HR	BSFC g/KW-Hr
T.O.	238.62	320	9420	.372	226.28
Cruise	186.42	250	7850	.355	215.94
65%	155.11	208	7385	.351	213.51
55%	131.69	176	6985	.351	213.51
Approach	95.45	128	7385	.364	221.41
Taxi	23.86	32	3925	.445	270.68
Idle	2.61	3.5	1875	.925	562.66
Idle	0	0	1875	2 lb/hr*	(.907 Kg/Hr)

*Constant speed propeller set at no load.

The fuel consumptions are applicable at both sea level and altitude. Fuel consumption projections for take-off, cruise, approach, taxi and idle are shown in Table 2.6.3.

Efficiency

Brake thermal efficiency, which is inversely proportional to the fuel consumption, is also shown on Figure 2.6.3 and indicates a peak of approximately 39.5%. The improved thermal efficiency and specific fuel consumption are the result of the following factors:

1. Higher IMEP levels achieved by turbocharging.

2. Additional turbocharging to operate at leaner mixture strengths for improved combustion efficiency. The added turbocharging is over and above that required to obtain the power at altitude. This added turbocharging has a secondary benefit of limiting the turbine inlet temperatures to the 1200-1300°F range and is self-regulating, since when fuel is added above that required for the rated power (maximum cruise, for example) the turbocharger introduces more air into the engine for a minor increase in fuel-air ratio and decrease in exhaust gas temperature.

3. Reduced friction mean effective pressure as projected from reduced coolant and lubricant pump requirements, size effects, etc.

4. Projected improved Indicated thermal efficiency related to:

a. Reduced heat rejection to the coolant as a result of increased coolant temperatures and the exhaust port liner.

b. Reduced heat rejection to the lubricant resulting from the rotor combustion face insulation.

c. Improvements of the basic combustion characteristics, as presently experienced, by further optimization of the combustion pocket geometry and location and the fuel injection system.

Mechanical Efficiency

Figure 2.6.3 (upper curves) indicates the engine mechanical efficiency which is directly related to Items 1 and 3 considered in the discussion of the brake thermal efficiency. Combining the mechanical efficiency (87.7%) and brake thermal (38.9%) efficiency at the 186.42 KW (250 HP) cruise condition produces an indicated thermal efficiency of 44.4%. Naturally aspirated, this size engine with fixed fuel-air ratio, ISFC and friction, would produce approximately 101 KW (136 BHP) at cruise with a mechanical efficiency of about 79.5% and resultant 238 g/KW-hr (.392) brake specific fuel consumption.

The projected friction HP versus shaft speed of the RC2-32 engine is shown in Figure 2.6.4 and includes the estimated losses of the components listed. Losses for fuel injection include only the work required for circulating within the pump (no flow to the injectors). The baseline ISFC versus fuel-air ratio parameter, upon which projections in performance were made, incorporates the change in pump work with variation in flow.

Emissions

Table 2.6.5 presents the projected EPA 5 Mode Cycle emissions characteristics of a turbocharged stratified charge "advanced" technology Rotary combustion engine. Based on the presumed accuracy of the projections and the significant margin within standards of the engine, it has been assumed the RC2-32 emissions projections will also fall within the proposed limits.

The stratified charge engine characteristic operation at overall lean fuel-air ratio, with only the pilot combustion in the stoichiometric range, is conducive to low emissions of unburned hydrocarbons and carbon monoxide. Low oxides of nitrogen result from the lean mixture and the extended combustion period. Results of the analysis show that only the oxides of nitrogen emissions would be any substantial proportion (66%) of the EPA Standard.

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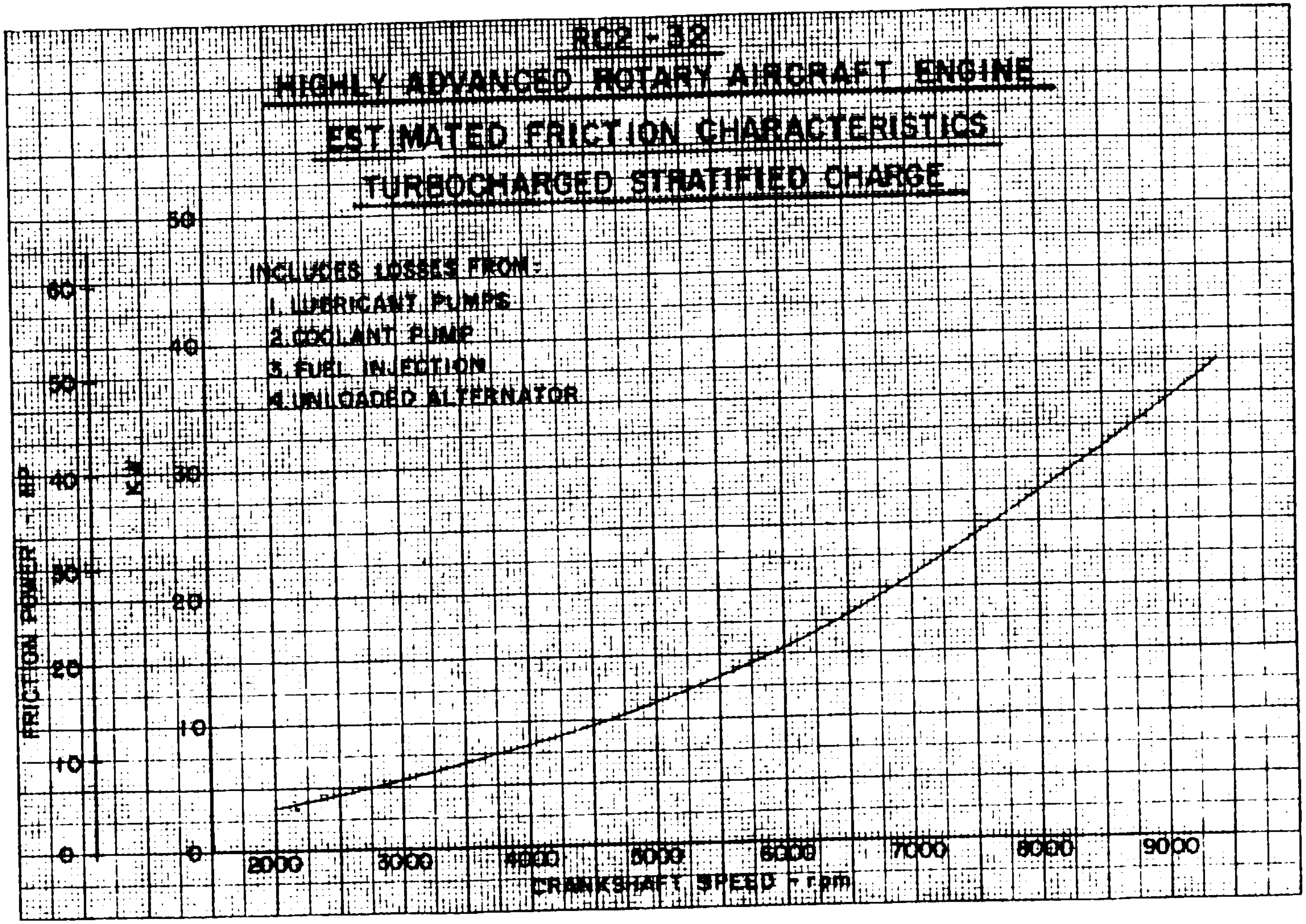

Figure 2.6.4

TABLE 2.6.5

ADVANCED TURBOCHARGED STRATIFIED CHARGE ROTARY COMBUSTION ENGINE

ESTIMATED EMISSIONS CHARACTERISTICS

EPA 5 Mode Cycle

	Idle	Taxi	Take-Off	Climb	Approach
BHP	3.5	32	320	250	128
KW	2.6	23.9	261	186	95
RPM	1300	2700	6470	5390	5070
HC Lb/Cycle	.0035	.0242	.0021	.0320	.0262
CO Lb/Cycle	.0035	.0726	.0067	.1066	.1874
NO_x Lb/Cycle	.0031	.0968	.0100	.1332	.0750

		EPA Standard
HC Emissions Lb/Cycle/Rated HP	.0003	.0019
CO Emissions Lb/Cycle/Rated HP	.0012	.0420
NO_x Emissions Lb/Cycle/Rated HP	.0010	.0015

ENGINE DESCRIPTION - ADVANCED ENGINE (RC2-47)

Two levels of advanced technology were established. The "Advanced" aircraft engine represents improvements from current practice, but not as many as are included for the "Highly Advanced" engine.

In view of the relatively small increase of power section component sizes, the basic arrangement and configuration of the RC2-32 is considered applicable to the RC2-47 as well. The width and height, which were primarily influenced by the accessories, increase only by 12.7mm/.5" over the RC2-32, to 419mm/16.5" for each. The overall length increase is less than 102mm/4", going from 1234mm/48.6" to 1321mm/52".

The means of scaling the weight and size for varying horsepower for both the Advanced and Highly Advanced engines are given on page 2.3.0.

Table of Geometric Data

TABLE 2.7.0

"ADVANCED" RC2-47

Number of Rotors	2
Displacement-cubic inches/cubic cm	47.4/777
Shaft Eccentricity, - in./mm	.64/16
Generating Radius, R - in./mm	4.42/112
Combustion Chamber Width, W - in./mm	3.2/81
R/e	6.9
W/e	5
Trochoid Major Axis - in./mm	10.1/257
Trochoid Minor Axis - in./mm	7.6/193

Operating Data Summary

The operating data for the RC2-47 is shown on Tables 2.7.1 and 2.7.2. The seal velocities, or "equivalent RPM" is maintained at current levels to favor BSFC at the expense of engine power density. The IMEP is roughly one quarter above levels run on the naturally aspirated RC2-75, which puts it in the realm of attainability with only minor changes/improvements to effect satisfactory durability and life requirements. The FMEP shows a modest decrease, on the order of several percent, over the current RC2-75. It is possible that the change to the unthrottled intake induction system will achieve this much improvement and that additional reductions of oil seal friction and apex seal leakage gap will show the target to have been conservative.

64

TABLE 2.7.1 - ADVANCED ROTARY COMBUSTION AIRCRAFT ENGINE RC2-47 (47.4)

OPERATING DATA SUMMARY - METRIC
STANDARD DAY - NO RAM

		186.4 Kw Cruise	
	Take-Off	Sea Level	7620m
Bkw	238.6	186.4	186.4
RPM	7030	5860	5860
RPM (Equivalent)	6000	5000	5000
IMEP, kpa	1518	1402	1402
Ikw	276	212	212
FMEP, kpa	203	170	170
Fkw	37	25.6	25.6
BMEP, kpa	1314	1232	1232
Fuel/Air Ratio	.045	.04	.04
BSFC, g/kw-Hr	238	226	226
Airflow kg/Hr	1265	1051	1051
*Blower Ratio	1.82	1.81	5.09
P_2 (At engine inlet) kpa	181	180	188
Engine Inlet Temp. °C	52.9	52.8	65
Fuel Flow kg/Hr	56.9	42	42
Ambient Temp. °C	15	15	-30
Ambient Pressure kpa	101	101	37.6

*Before 2% Pressure Loss in Intercooler

Assumes (1) Intercooler Effectiveness = 50%
(2) 70% Compressor Efficiency

TABLE 2.7.2 - ADVANCED ROTARY COMBUSTION AIRCRAFT ENGINE RC2-47 (47.4)

OPERATING DATA SUMMARY (INCH - LB - °F UNITS)
STANDARD DAY - NO RAM

	Take-Off	250 HP Cruise Sea Level	250 HP Cruise 25,000 Ft
BHP	320	250	250
RPM	7030	5860	5860
RPM (Equivalent)	6000	5000	5000
IMEP, psi	220.1	203.3	203.3
IHP	369.6	284.4	284.4
FMEP, psi	29.5	24.6	24.6
FHP	49.6	34.4	34.4
BMEP, psi	190.6	178.7	178.7
Fuel/Air Ratio	.045	.04	.04
BSFC, Lb/BHP-Hr	.392	.371	.371
Airflow Lb/Hr	2788	2318	2318
*Blower Ratio	1.82	1.81	5.09
P_2 (at engine inlet), psi	26.2	26.1	27.2
Engine Inlet Temperature, °F	127.3	127.0	149.0
Fuel Flow Lb/Hr	125.4	92.7	92.7
Ambient Temperature, °F	59	59	-30
Ambient Pressure, psi	14.7	14.7	5.45

*Before 2% Pressure Loss in Intercooler
Assumes (1) Intercooler Effectiveness = 50%
(2) 70% Compressor Efficiency

Performance

The performance estimates provided were obtained using the same analytical procedures but with higher friction characteristics (Figure 2.7.0). Pressure ratio characteristics required of the turbocharging system are not reduced compared to the "highly advanced" engine but flow capacity is higher due to the requirements of a larger less efficient engine.

For the RC2-47 engine sea level take-off and sea level and 8202.1 m (25,000 ft) altitude maximum cruise operating data see Tables 2.7.1 and 2.7.2. Notable is the reduced take-off IMEP, 1517 kpa/220 psi versus 1689 kpa/245 psi, of the RC2-47 engine compared to the "highly advanced" RC2-32. The relative engine speeds of the RC2-32 are also higher than for the RC2-47.

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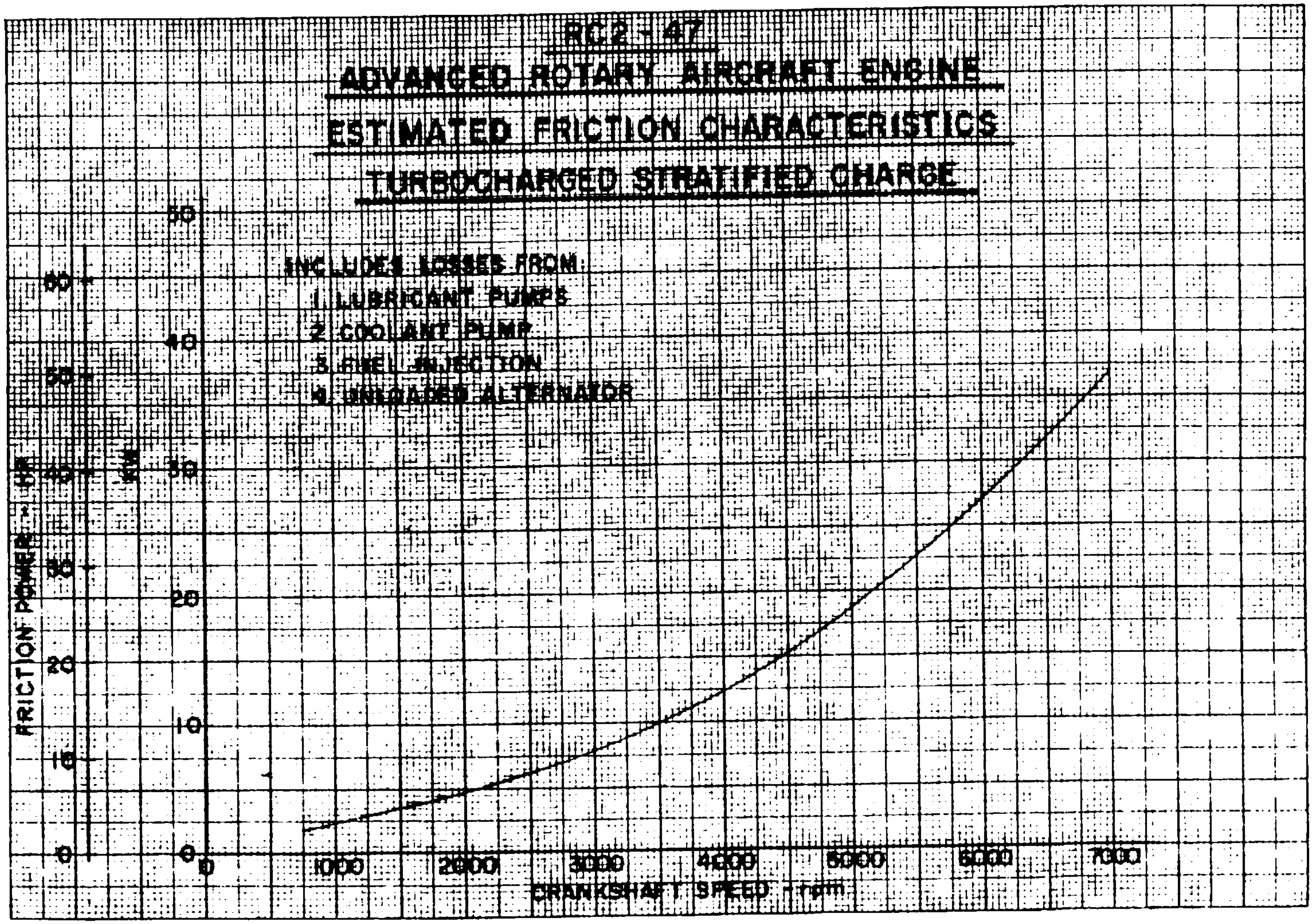

Figure 2.7.0

Power

The RC2-47, as is the RC2-32, is take-off rated at 238.6 KW (320 BHP) with maximum cruise power of 186.4 KW (250 BHP). Projected altitude characteristics shown on Figure 2.7.1 are the same as for the RC2-32.

Fuel Consumption and Efficiency

Figure 2.7.2 defines the fuel consumption and mechanical and thermal efficiencies of the RC2-47 with a maximum cruise of 225.67 g/KW-hr (.371 lb/BHP-hr) compared to the "highly advanced technology" RC2-32 SFC of 215.93 g/kw-hr (.355 lb/BHP-hr). Comparable effects are noted for mechanical and thermal efficiency comparisons.

TABLE 2.7.3

RC2-47

ESTIMATED FUEL CONSUMPTION

				BSFC	
Rating	KW	HP	RPM	#/BHP-Hr	g/KW-Hr
T.O.	238.62	320	7030	.392	238.44
Cruise	186.42	250	5858	.371	225.67
65%	195.11	208	5510	.364	221.41
55%	131.69	176	5210	.361	219.59
Approach	95.45	128	5510	.378	229.93
Taxi	23.86	32	2930	.460	279.81
Idle	2.61	3.5	1400	.959	583.34
Idle	0	0	1400	2 lb/hr*	

*Constant speed propeller set at no load.

Coolant and Oil Heat Rejection Rates

Coolant and oil heat rejection rates for the advanced engine (RC2-47) are given by Figure 2.7.3.

The remarks on page 2.4.1 concerning the Highly Advanced (RC2-32) heat rejection rates also apply to the Advanced engine.

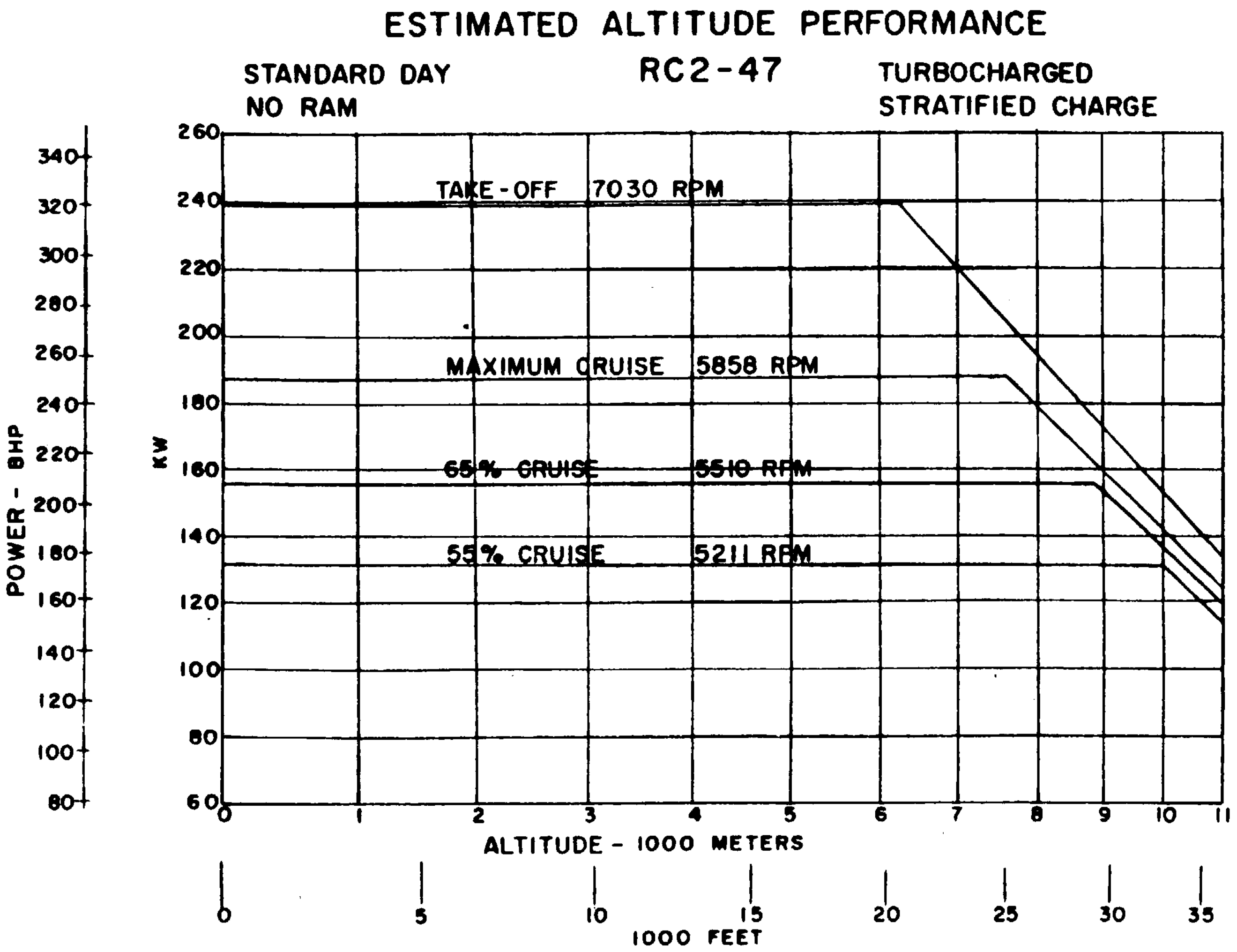
ESTIMATED ALTITUDE PERFORMANCE
RC2-47
STANDARD DAY
NO RAM
TURBOCHARGED
STRATIFIED CHARGE
TAKE-OFF 7030 RPM
MAXIMUM CRUISE 5858 RPM
65% CRUISE 5510 RPM
55% CRUISE 5211 RPM
POWER - BHP
340
320
300
280
260
240
220
200
180
160
140
120
100
80
KW
260
240
220
200
180
160
140
120
100
80
60
ALTITUDE - 1000 METERS
0
1
2
3
4
5
6
7
8
9
10
11
1000 FEET
0
5
10
15
20
25
30
35

Figure 2.7.1

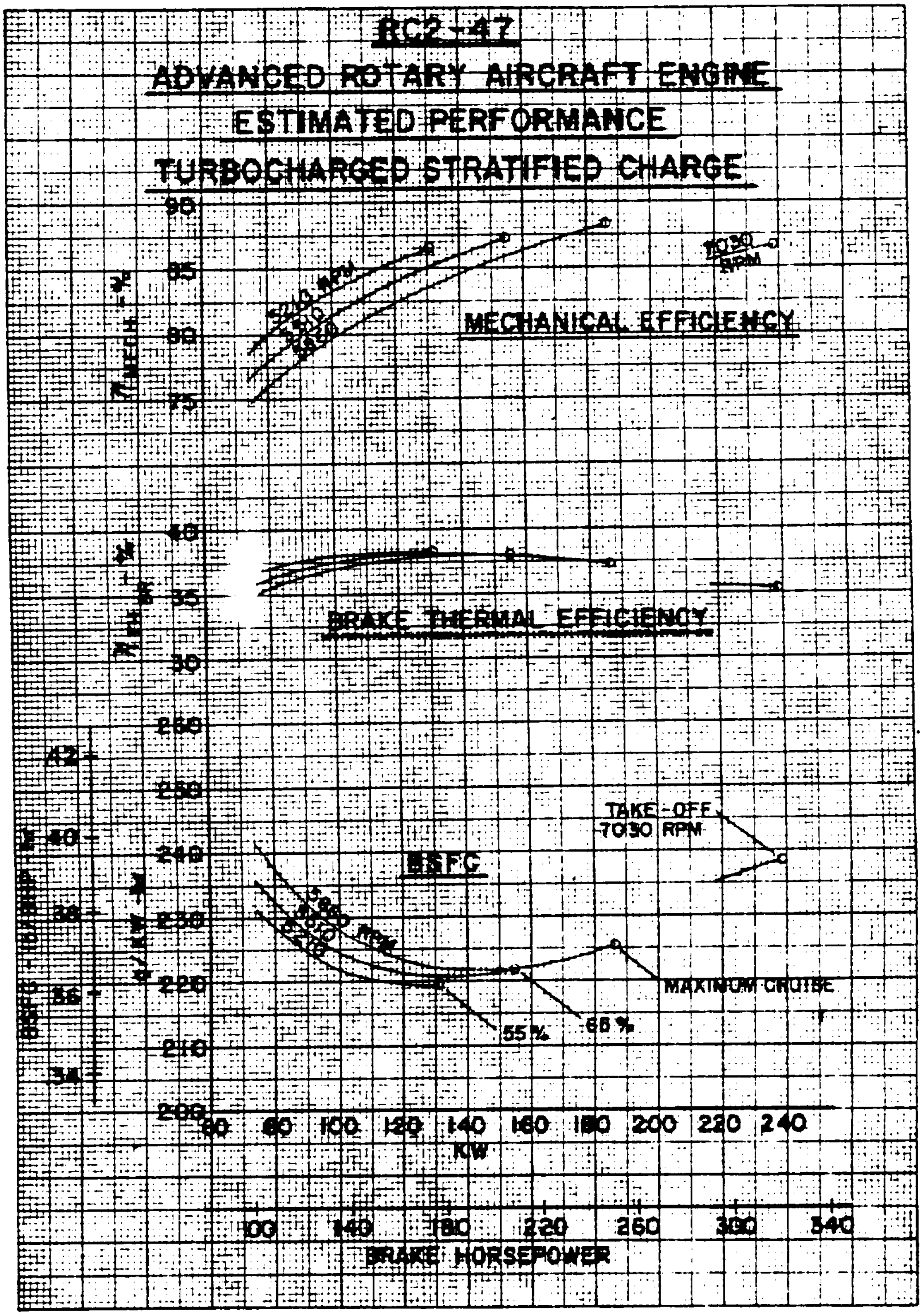
RC2-47
ADVANCED ROTARY AIRCRAFT ENGINE
ESTIMATED PERFORMANCE
TURBOCHARGED STRATIFIED CHARGE
η MECH - %
95
85
90
75
7030 RPM
MECHANICAL EFFICIENCY
η TH - %
40
35
30
BRAKE THERMAL EFFICIENCY
BSFC - LB/BHP-HR
g/KW-HR
42
40
38
36
34
260
250
240
230
220
210
200
BSFC
TAKE-OFF
7030 RPM
RPM
MAXIMUM CRUISE
55%
65%
60
80
100
120
140
160
180
200
220
240
KW
100
140
180
220
260
300
340
BRAKE HORSEPOWER

Figure 2.7.2

RC2-47 ENGINE 238.6 KW (320 BHP)
COOLANT AND OIL HEAT REJECTION

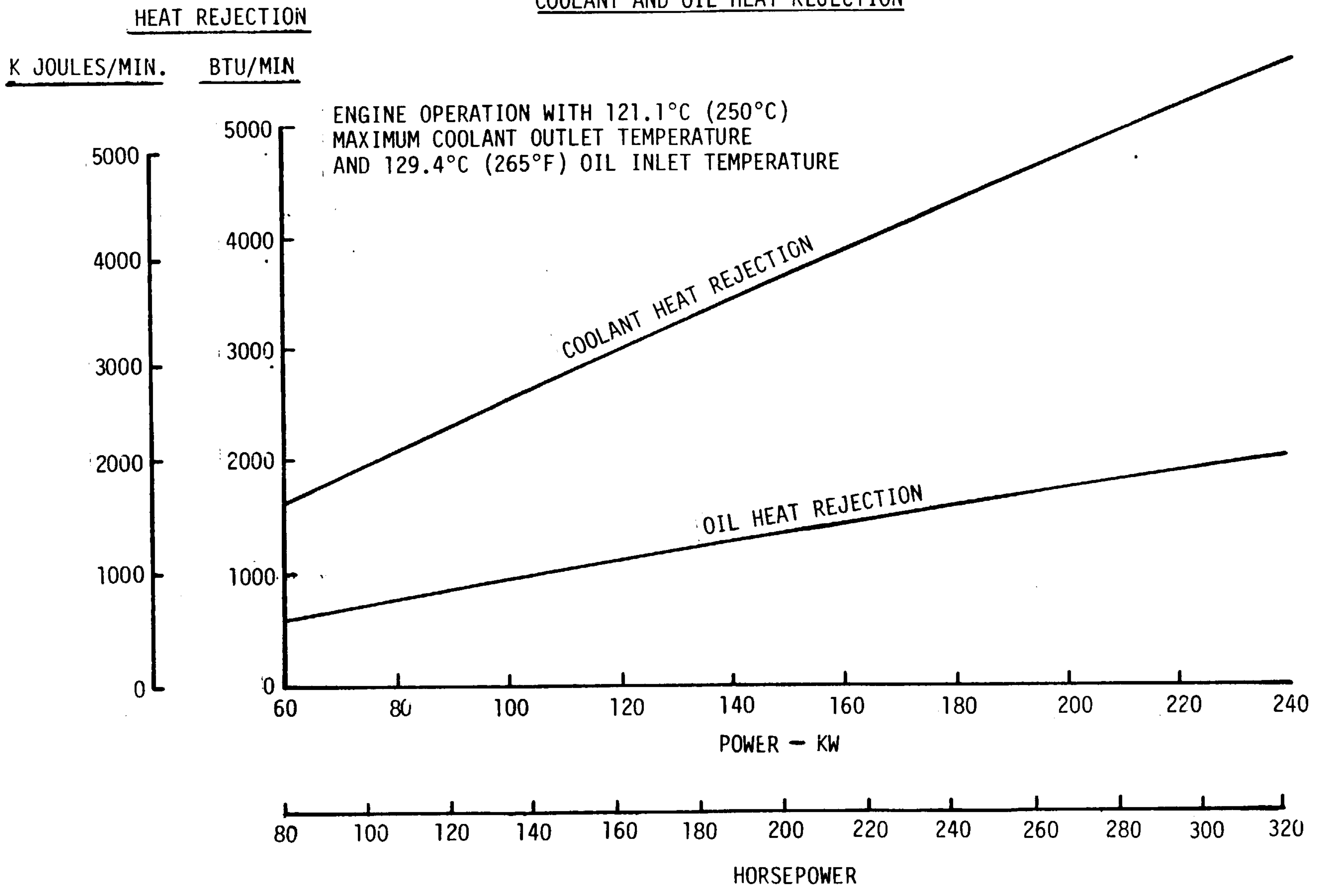

Figure 2.7.3

TASK III

ENGINE/AIRFRAME INTEGRATION
CURTISS-WRIGHT RC2-47 AND RC2-32 ENGINES

A Subcontract Performed under NASA Contract NAS3-21285,
Design Study of Advanced Rotary Combustion Aircraft Engines

Prepared by: D. R. Ellis
G. Huggins
A. Mueller
J. Hembrey
Cessna Aircraft Company

TASK III - ENGINE AIRFRAME INTEGRATION

Introduction

The work reported here represents one phase of a design study of advanced rotary combustion engines for use in general aviation aircraft. This particular effort deals with the integration of such engines with typical airframes, and considers performance, cost, and installation factors; the results are compared with those for a conventional engine.

Brief descriptions of the methods used, including baseline performance and mission criteria and the process used to "resize" the baseline airframes to take advantage of the characteristics of the rotary combustion engine, are covered first. This is followed by a detailed discussion of the results obtained for the single engine and multi-engine designs using the "advanced" RC2-47 and "highly-advanced" RC2-32 powerplants.

Description of Baselines and Methods

Baseline Airplanes and Missions

In general, the baseline airplanes chosen for the study may be considered to be refined versions of typical 1980 technology products, using conventional light metal structures 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, and to focus attention directly on the engine characteristics.

Single Engine Baseline Airplane

The single engine baseline airplane is depicted in three-view form in Figure 3.2.1. It is seen to be a high wing tractor monoplane of conventional layout with retractable tricycle landing gear. The cabin seats six, and is pressurized with bleed air from the engine turbocharger to a differential pressure of approximately 31 kpa/4.5 psi to give a cabin altitude of 3048m/10,000 feet when the airplane is at its maximum operating altitude of 7620m/25,000 feet. The wing employs a long-span single-slotted flap to obtain a lower-than 113 km/Hr-61 knot stall speed (the limit allowed by Federal Air Regulations for single-engined aircraft) with a wing loading which is moderately higher than current practice. A combination of small "feeler ailerons" and spoilers are employed for roll control.

The baseline conventional powerplant is the Teledyne Continental Motors TSIO-550, an air-cooled, six-cylinder, horizontally opposed unit developing 265 kw/350 brake horsepower at 2800 rpm for takeoff and, for the purposes of this study 186 kw/250 BHP at 2300 rpm for cruise at 7620m/25,000 feet altitude (71.4% power). Turbocharging permits takeoff horsepower to be obtained to 4572m/15,000 feet, decreasing thereafter to a maximum of 222 kw/298 BHP at 7620m/25,000 feet.

Takeoff gross weight for the baseline single is 2064 kg/4550 lb (arrived at by the sizing process described subsequently). A weight breakdown for this and the other airplanes in the study is given in Appendix 1, page 3.6.0.

Single-Engine Mission

The mission selected for the analysis is one of basic transportation, calling for a specified payload to be carried at maximum rate of climb to cruising altitude, and then at maximum cruising speed over a specified range, with reserve fuel remaining. The specific requirements are as follows:

Payload: 544 kg/1200 lb (six 77 kg/170 lb people with 13.6 kg/30 lb baggage each)

Distance: 1296 km/700 nautical miles

Cruising Altitude: 7620m/25,000 feet

Reserve Fuel: Sufficient for 45 minutes flight at cruise power

In addition to the above fixed requirements, constraints are specified for other performance parameters in order to insure that contemporary standards of utility are met or exceeded. They are:

Takeoff Distance: 762m/2500 feet or less over a 15m/50 foot obstacle under standard sea level conditions

Time to Climb: 30 minutes or less to 7620m/25,000 feet using maximum climb power

Cruising Speed: 370km/Hr-200 knot true airspeed or more at 7620m/25,000 feet using maximum cruise power

Stalling Speed: 113 km/Hr-61 knot calibrated airspeed or less

Twin-Engine Baseline Airplane

The twin-engine baseline airplane is shown in Figure 3.2.2. It is of conventional low wing layout with engines mounted on the wings in a tractor arrangement. The cabin seats eight and, like the baseline single, is pressurized to a 31 kpa/4.5 psi differential. Again, the combination of long-span flaps with roll control spoilers and small "feeler ailerons" is used.

The baseline twin powerplant is the same as that of the single, the TCM TSIO-550 rated at 261 kw/350 BHP for takeoff and 186 kw/250 BHP at 7620m/25,000 feet altitude for cruise, with 261 kw/350 BHP available to 4572m/15,000 feet and 222 kw/298 BHP available to 7620m/25,000 feet for climb.

Takeoff gross weight is projected to be 3005 kg/6625 lb. A weight breakdown is given in Appendix 1, page 3.6.0.

BASELINE SINGLE ENGINE AIRPLANE

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- SIX-PLACE PRESSURIZED
- CONVENTIONAL METAL STRUCTURE
- ENGINE: TCM TSIO-550
  - 261 KW (350 BHP) @ 2800 RPM TAKEOFF
  - 186 KW (250 BHP) @ 2300 RPM CRUISE AT 7620 m (25000 FT)
- WEIGHT: EQUIPPED AIRPLANE
  - BASIC EMPTY 1280 kg (2822 LB)
  - TAKEOFF GROSS 2064 kg (4550 LB)
- WING
  - SPAN 12.2 m (39.9 FT)
  - AREA 16.4 m^2 (177 FT^2)
  - ASPECT RATIO 9.0

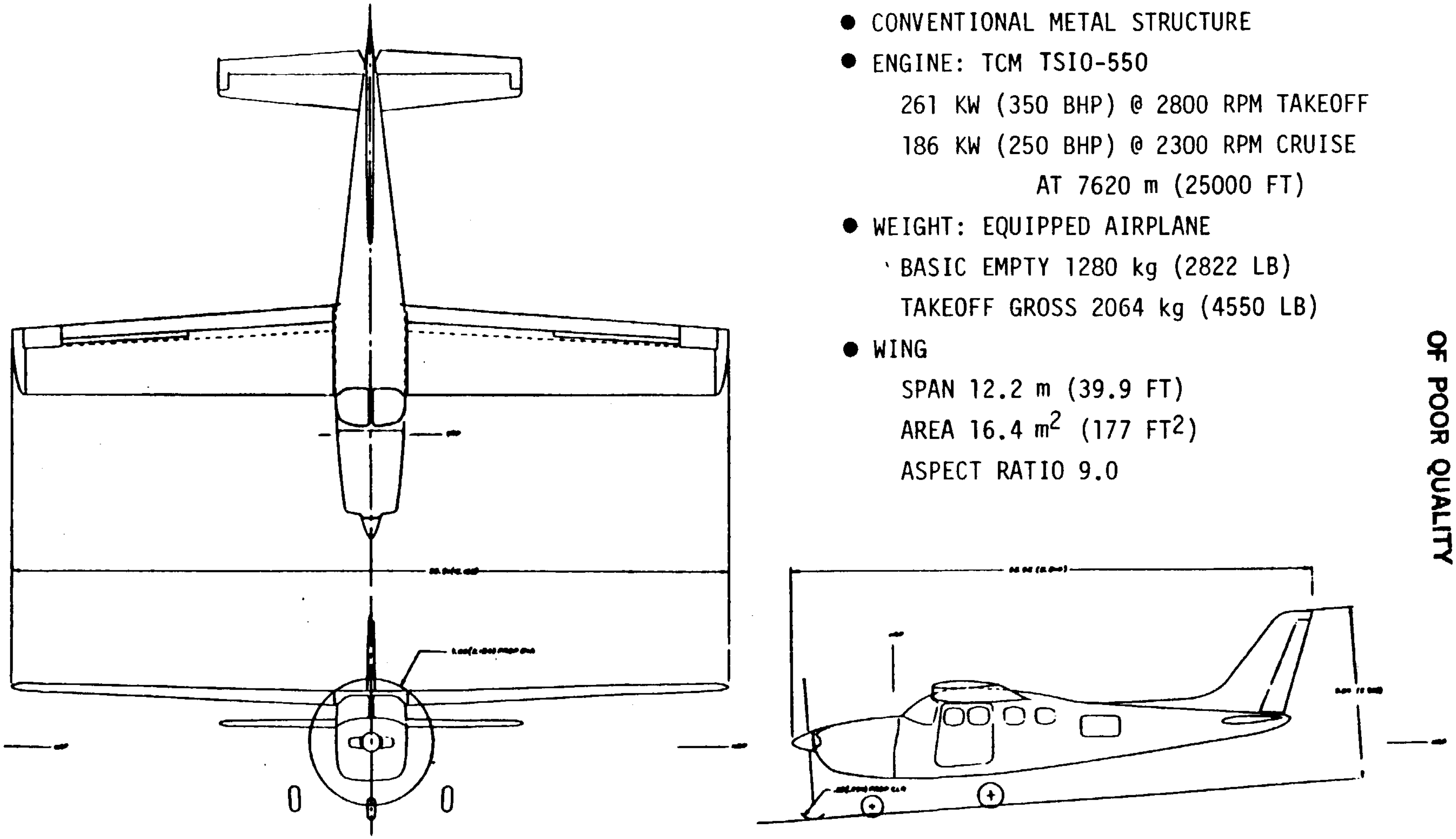
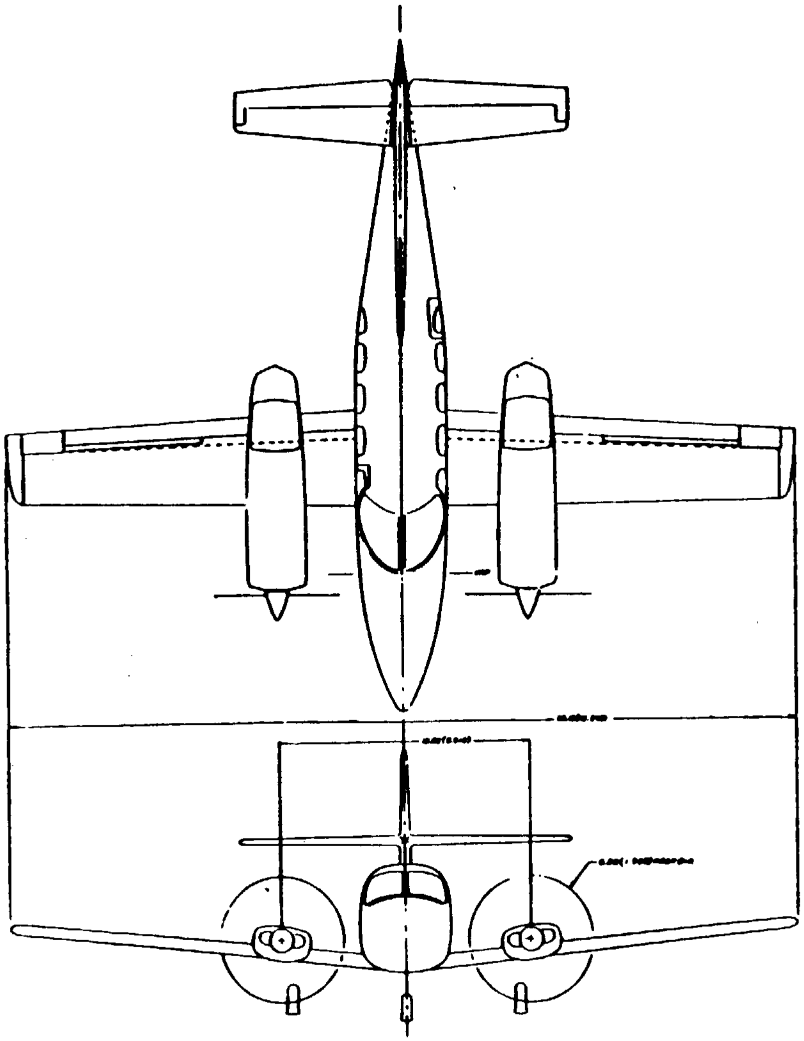


Figure 3.2.1

BASELINE TWIN ENGINE AIRPLANE



- EIGHT-PLACE PRESSURIZED
- CONVENTIONAL METAL STRUCTURE
- ENGINE: TCM TSIO-550

  261 KW (350 BHP) @ 2800 RPM TAKEOFF

  186 KW (250 BHP) @ 2300 RPM CRUISE

  AT 7620 m (25000 FT)
- WEIGHT: EQUIPPED AIRPLANE

  BASIC EMPTY - 1906 kg (4203 LB)

  TAKEOFF GROSS - 3005 kg (6625 LB)
- WING

  SPAN 12.25 m (40.19 FT)

  AREA 15.8 m^2 (170 FT^2)

  ASPECT RATIO 9.5

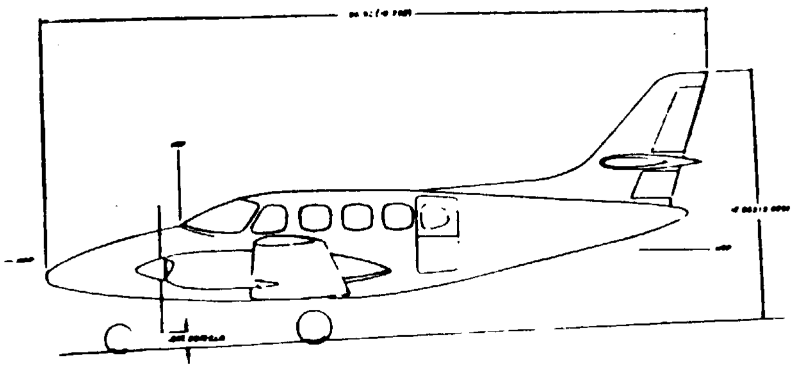


Figure 3.2.2

Twin-Engine Mission

As for the baseline single, the study is organized around a transportation mission profile featuring high altitude cruise. The specific requirements are:

Payload: 635 kg/1400 lb (seven 77 kg/170 lb people with 13.6 kg/30 lb baggage each)

Distance: 1481 km/800 nautical miles

Cruising Altitude: 7620m/25,000 feet

Reserve Fuel: Sufficient for 45 minutes flight at normal cruise speed

The additional performance constraints are the following:

Takeoff Distance: 914m/3000 feet or less over a 15m/50 foot obstacle

Time to Climb: 30 minutes or less to 7620m/25,000 feet using maximum climb power

Rate of Climb at 7620m/25,000 feet: 152m/m-(500 fpm) or more

Cruising Speed: 426 km/Hr-230 knots true airspeed or more at 7620m/25,000 feet using maximum cruise power

Stalling Speed: 139 km/Hr - 75 knots calibrated airspeed or less

The Sizing Process

The objectives of the sizing process are to determine whether or not an airplane can be designed to meet specific performance goals and, within prescribed constraints, to determine the choice of a "best" configuration.

Performance characteristics available for study are:

- Takeoff over an obstacle of prescribed height
- Climb performance at any prescribed altitude
- Payload - range performance at any altitude, and percent of maximum power
- Payload - endurance at any altitude and power
- Cruise speed at any altitude and power
- Stall speed
- Fuel used for the mission

From this list of performance characteristics, one will be selected as a "primary constraint" which will always be met in the sizing calculation; any of the remaining characteristics may be specified as "secondary constraints".

Design variables utilized in the process are:

- Engine power as a function of altitude
- Wing area, span, and planform characteristics
- Lift coefficient as a function of flap deflection
- Propeller characteristics
- Airframe drag characteristics
- Aircraft weight

Normally, two design variables such as wing area and aspect ratio will be treated as independent variables and takeoff gross weight as a dependent variable, with other factors such as drag and propeller performance being specified.

The sizing program performs two basic calculations, the first determining the weight required to meet the primary constraint (such as a specified payload and range), the second giving performance at a specified weight (speed, rate of climb, and takeoff distance for example).

A carpet plot format is used to display the computed performance as a function of the primary and secondary variable. In this case, combinations of gross weight, wing area, and aspect ratio which meet the payload and range requirements are shown. Other performance constraints are then overlayed on this carpet, defining areas wherein the required performance is or is not met. An example is shown in Figure 3.3.1.

If the solution space defined by the constraints is well defined, the normal procedure will be to choose the lightest, smallest airframe since that will be the lowest cost case. Oftentimes, however, few constraints will appear on the carpet, and engineering judgement concerning such matters as practical aspect ratios, off-design operating points, and trades between higher cruise speeds and lower fuel burn must be exercised to make a configuration choice.

Discussion of Results

Single Engine Airplanes

General Features. The single engine configurations powered by the RC2-47 and RC2-32 are typified by the comparison in Figure 3.4.1. Generally similar in layout and appearance to the baseline single, the rotary-powered airplanes are characterized by longer noses reflecting the necessary forward placement of the lighter weight engines for balance purposes. In fact, the forward movement

TYPICAL SIZING OUTPUT

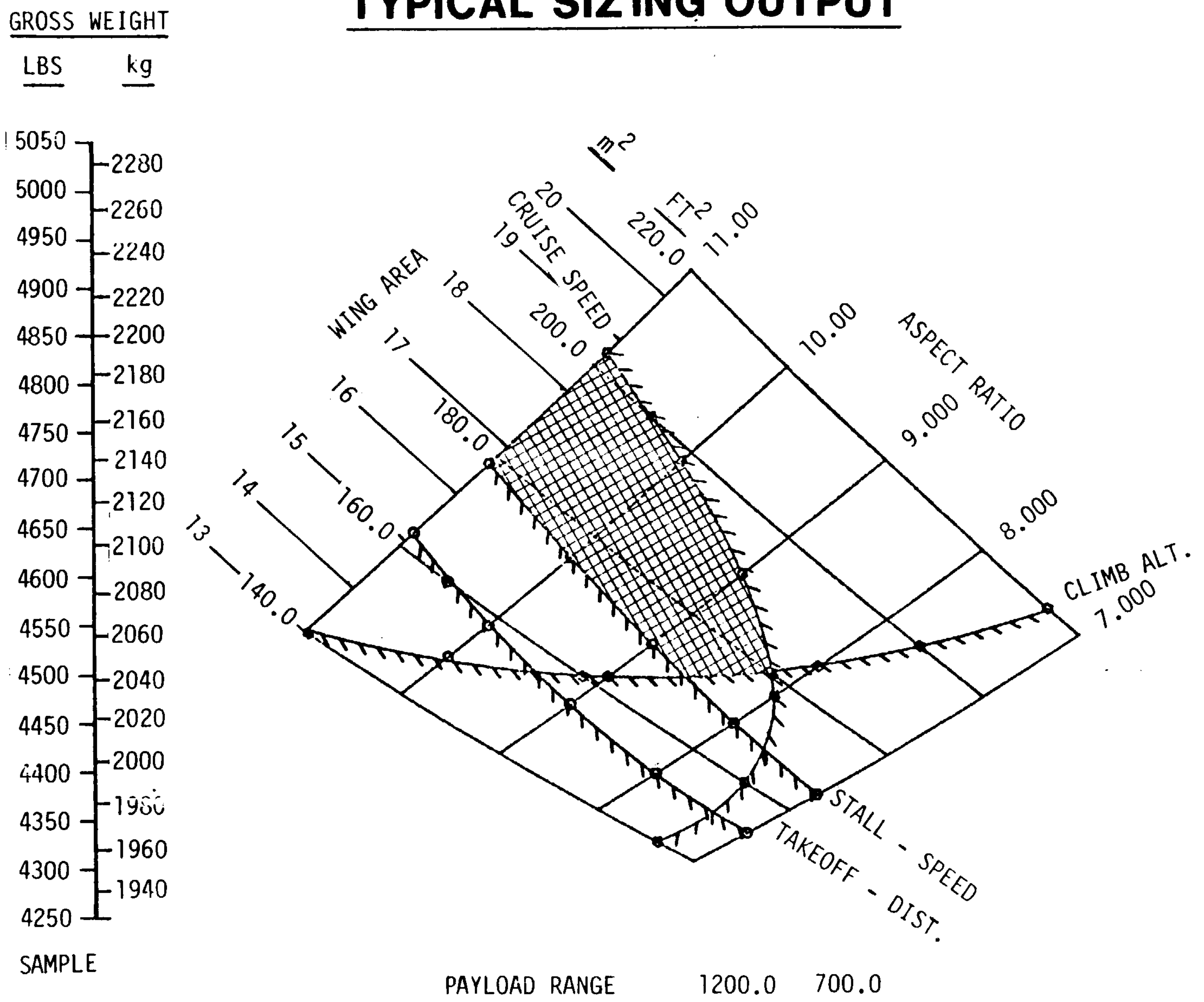
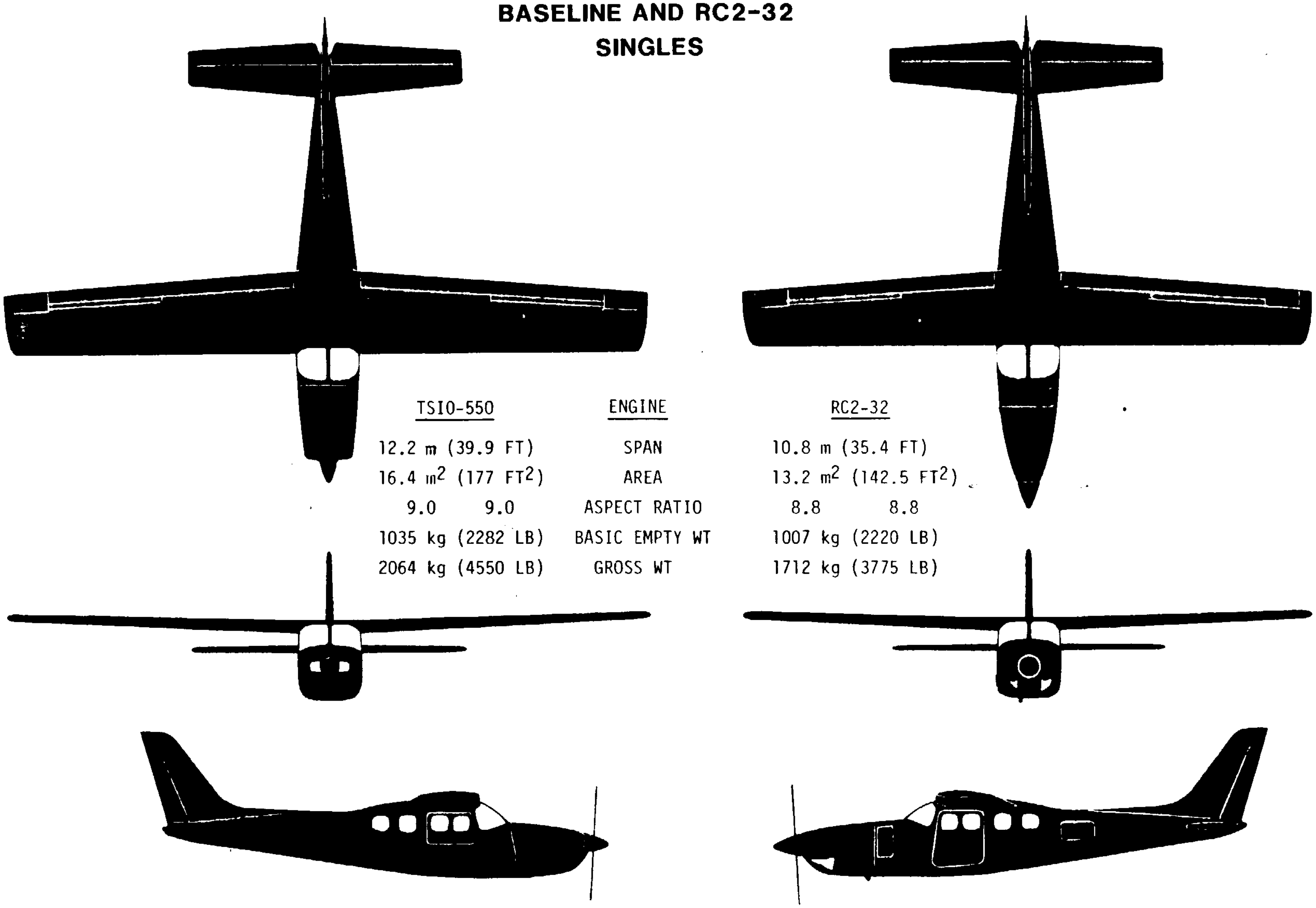


Figure 3.3.1

BASELINE AND RC2-32
SINGLES



TSIO-550	ENGINE	RC2-32
12.2 m (39.9 FT)	SPAN	10.8 m (35.4 FT)
16.4 m^2 (177 FT^2)	AREA	13.2 m^2 (142.5 FT^2)
9.0 9.0	ASPECT RATIO	8.8 8.8
1035 kg (2282 LB)	BASIC EMPTY WT	1007 kg (2220 LB)
2064 kg (4550 LB)	GROSS WT	1712 kg (3775 LB)

RC-451

Figure 3.4.1

of engine and accessories permits a baggage compartment to be located forward of the cabin, giving increased volume and loading flexibility. Other visible differences are in wing size (smaller both in span and area than the baseline).

Figure 3.4.2 shows typical installation features for the rotary engines in the single engine airframes (the outline shown is for the RC2-32, but the RC2-47 would differ only in minor dimensional details). Although not much aerodynamic advantage can be taken of the small physical size of the engine in the single due to the relatively large dimensions of the fuselage, there is considerable volume at the sides to the rear of the engine compartment which is used here for cooling and induction air systems and for the cabin pressurization air system. Flush inlets on the sides of the cowling are suggested to facilitate forward retraction of the nose wheel under the engine; cheek-style inlets would be an alternative, but the flush units have proven very successful in recent powerplant applications.

Performance & Weight Comparisons. Gross weight, dimensions, and performance for the two rotary-engined airplanes and the baseline are summarized in Table 3.4.1.

TABLE 3.4.1

SINGLE ENGINE AIRPLANE SUMMARY

	BASELINE	ROTARY COMBUSTION	
Engine	TSIO-550	RC2-47	RC2-32
Gross Weight, kg/lb	2064/4550	1769/3900	1712/3775
Wing Span, m/ft	12.2/39.9	10.6/34.9	10.8/35.4
Wing Area, m^2/ft^2	16.4/177	13.9/150	13.2/142.5
Aspect Ratio	9.0	8.1	8.8
Wing Loading, kpa (lb/ft^2)	1.23/25.7	1.24/26.0	1.27/26.5
Maximum Speed, km/hr/(kt) (at altitude, m/ft)	387/209 4572(15,000)	463/250 7620(25,000)	469/253 7620(25,000)
Cruising Speed, km/hr/(kt) (at 7620m/25,000 ft)	378/204	431/233	435/235
Stalling Speed, km/hr/(kt)	111/60	111/60	113/61
Rate of Climb, m/min-ft/min (at 7620m/25,000 ft)	194/635	325/1066	354/1160
Time to Climb, min (to 7620m/25,000 ft)	28.4	23.3	21.7

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

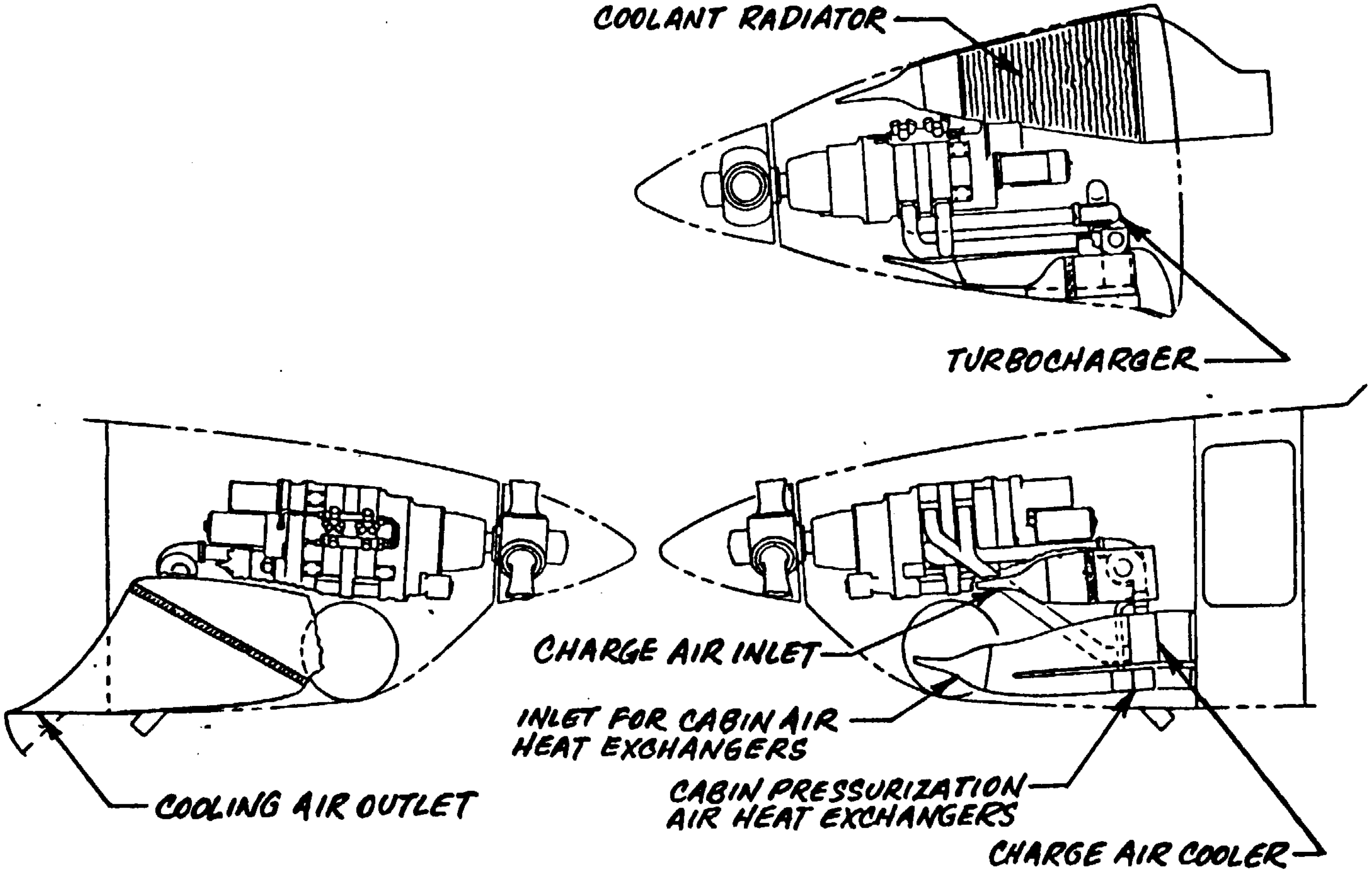


Figure 3.4.2

TABLE 3.4.1 - (Continued)

	BASELINE	ROTARY COMBUSTION	
Takeoff Distance, m/ft (over 15m/50 ft obstacle)	701/2300	619/2030	575/1885
Mission Fuel, kg/lb	201/444	139/307	131/288
Total Fuel Required, kg/lb (accounts for reserves)	205/552	181/400	171/377
Cruise Mileage, km/kg (naut mi/lb)	819/2.18	10.3/2.51	10.8/2.65

It should be noted to begin with that the baseline airplane itself has very impressive capabilities by today's standards. The payload/range criterion picked (1200 lb/700 nm) cannot be achieved by any available single; the only pressurized single in production today is certificated for 23,000 feet rather than 25,000 feet, and its cabin altitude at that height is 12,500 feet rather than 10,000 feet; the time to climb to maximum altitude in today's pressurized single is well over 30 minutes, whereas the baseline airplane reaches 25,000 feet in less than that time; and the baseline airplane's cruising speed, at 204 knots, is nearly 20 knots faster than the contemporary pressurized single.

The two rotary-engined singles are seen to be from 650 to 775 pounds lighter than the baseline single, a result which stems from the engines being 35% to 46% lighter, a lighter structure (principally from the resized wings with 15% to 20% less area and 4 feet less span), and the smaller amount of fuel required to fly the specified mission. Detailed weight breakdowns are given in Appendix I, page 3.6.0.

Table 3.4.1 indicates that takeoff, climb, and cruise performance of the rotary singles substantially exceeds that of the baseline airplane, with the RC2-32 machine being a few percent better in each category than the slightly heavier RC2-47 engined airplane. Comparative performance for the two segments of the mission profile is shown in Table 3.4.2; for the mission as a whole, the rotary-engined airplanes are clearly superior, completing the trip in less time and burning 31% to 35% less fuel.

TABLE 3.4.2
COMPARATIVE MISSION PERFORMANCE
SINGLE-ENGINE AIRPLANES

	CLIMB SEGMENT		CRUISE SEGMENT		TOTAL MISSION		
AIRPLANE	TIME,hr	FUEL BURN,kg/lb	TIME,hr	FUEL BURN,kg/lb	TIME,hr	FUEL BURN,kg/lb	FUEL REQ'RD,kg/lb*
Baseline	.47	44/97	3.12	157/347	3.59	201/444	250/552
RC2-47	.39	22/49	2.78	117/258	3.17	139/307	181/400
RC2-32	.36	19.5/43	2.76	111/245	3.12	131/288	171/377

*Includes reserve

Cooling Drag Considerations. In the above analysis, the liquid-cooled rotary engined airplanes were assumed to benefit from slight negative cooling drag (that is, some net thrust), based on a survey of old data, particularly that of Reference 9. This is admittedly an optimistic viewpoint and one which might be challenged since there are no current production light airplanes flying with such cooling systems, and hence no data base. On the other hand, reliable data on cooling drag of conventional horizontally-opposed air-cooled powerplants is sparse and in fact this is an area of active research (References 10 and 11, for example). About the only safe statement that can be made is that the level of cooling drag is very dependent on the details of the installation regardless of the cooling scheme, and can range from a large percentage of airframe drag to a negligible one.

At any rate, it is fair to ask what impact an optimistic cooling drag assumption has on the performance quoted above, both for purposes of the comparison and to help judge the potential benefits of putting development effort in this area. The results of such an analysis for the RC2-47 single are shown in Figure 3.4.3. Here increments in weight and performance are plotted as a function of an equivalent parasite area which might be attributed to cooling. The differences are not negligible if the cooling drag is increased to the level assumed for the air-cooled baseline engine, but even if that were the case, the RC2-47 airplane would still retain a substantial margin of superiority over the baseline machine in all of the performance and mission parameters (for example, mission fuel required would be 150/330 kg/lb rather than 139/307 kg/lb, still good compared to 200/440 kg/lb for the baseline).

Viewed in another light, it is apparent that close attention to cooling drag reduction will yield performance dividends significant enough to warrant serious development efforts.

Cost Considerations. Comparative acquisition costs and direct operating costs (DOC), computed according to the methods of Appendix II, page 3.7.0 are tabulated in Table 3.4.3.

TABLE 3.4.3

ACQUISITION & DIRECT OPERATING COSTS
SINGLE-ENGINE AIRPLANES

Airplane	BASELINE	RC2-47	RC2-32
Acquisition Cost 1981 Dollars	$215,000	$199,000	$196,000
Direct Operating Cost Per Hour	$127.88	$117.04	$114.89

(Based on 500 hours per year utilization)

COOLING DRAG CONSIDERATIONS

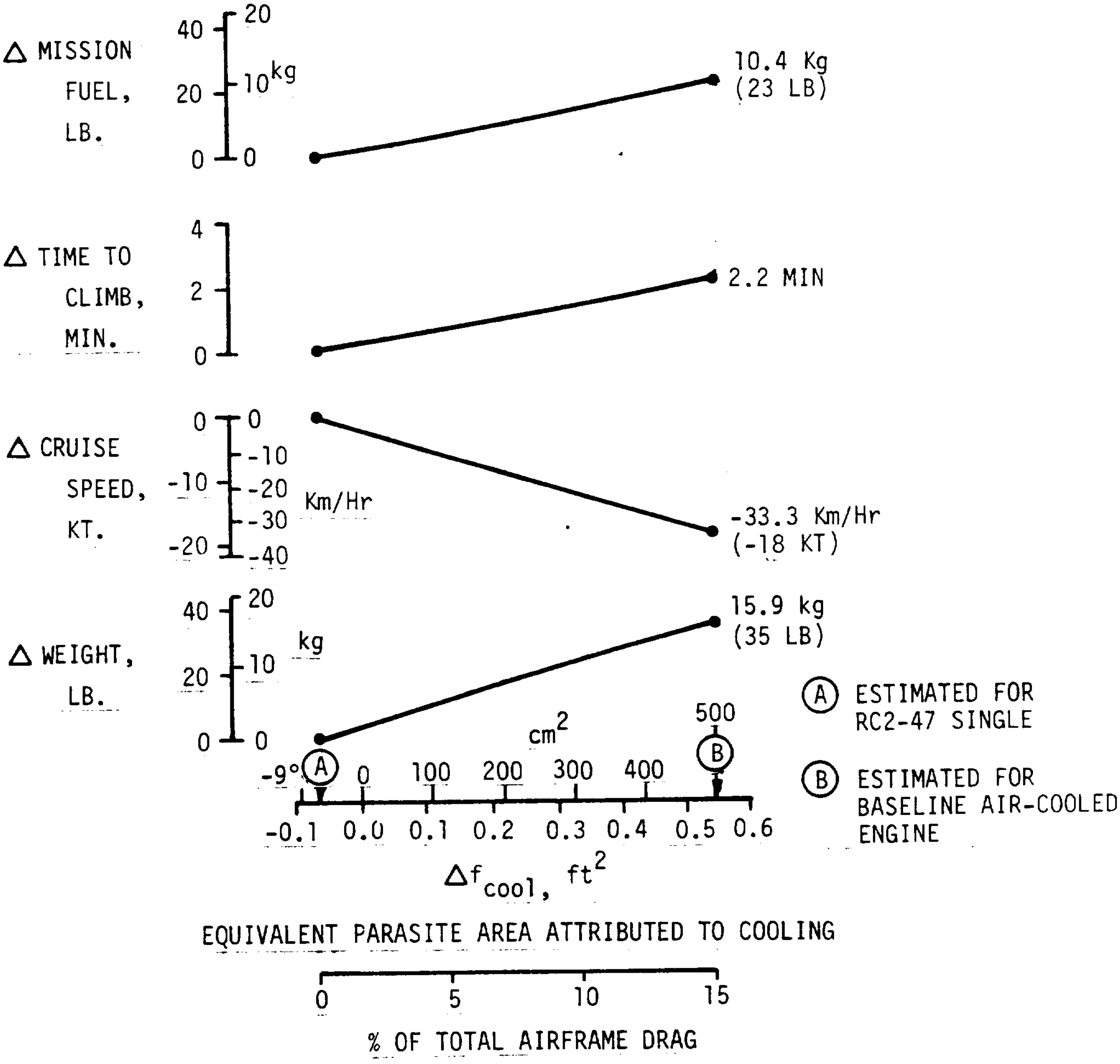


Figure 3.4.3

Because of the many assumptions inherent in such calculations, the above numbers should be considered only indicative of trends; different levels of engine price, assumed here to be equal for all powerplants at $35,000, for example, will give significantly different results.

Direct operating costs are not independent of acquisition cost in the computation method used here, since depreciation is the biggest single factor. (Fuel used is the second largest contributor, followed by engine maintenance and overhaul, insurance, and airframe maintenance).

Flyover Noise Levels. Because of their lower operating speeds (2400 rpm for takeoff, 2000 rpm for cruise versus 2800 and 2300 rpm for the baseline engine) the rotary-engined airplanes will exhibit lower levels of flyover noise, as estimated by Cessna methods. These are tabulated in Table 3.4.4.

TABLE 3.4.4

ESTIMATED FLYOVER NOISE LEVELS
SINGLE-ENGINE AIRPLANES

Airplane	BASELINE	RC2-47	RC2-32
Flyover Noise Level, dB(A)	86.2	80.7	80.1

Other Factors. The rotary-engined airplanes would be expected to show advantages over the baseline in areas other than performance and mission capability. Among the attractive possibilities are the following:

Inherently low vibration levels

More effective, carbon-monoxide free heating of cabin air

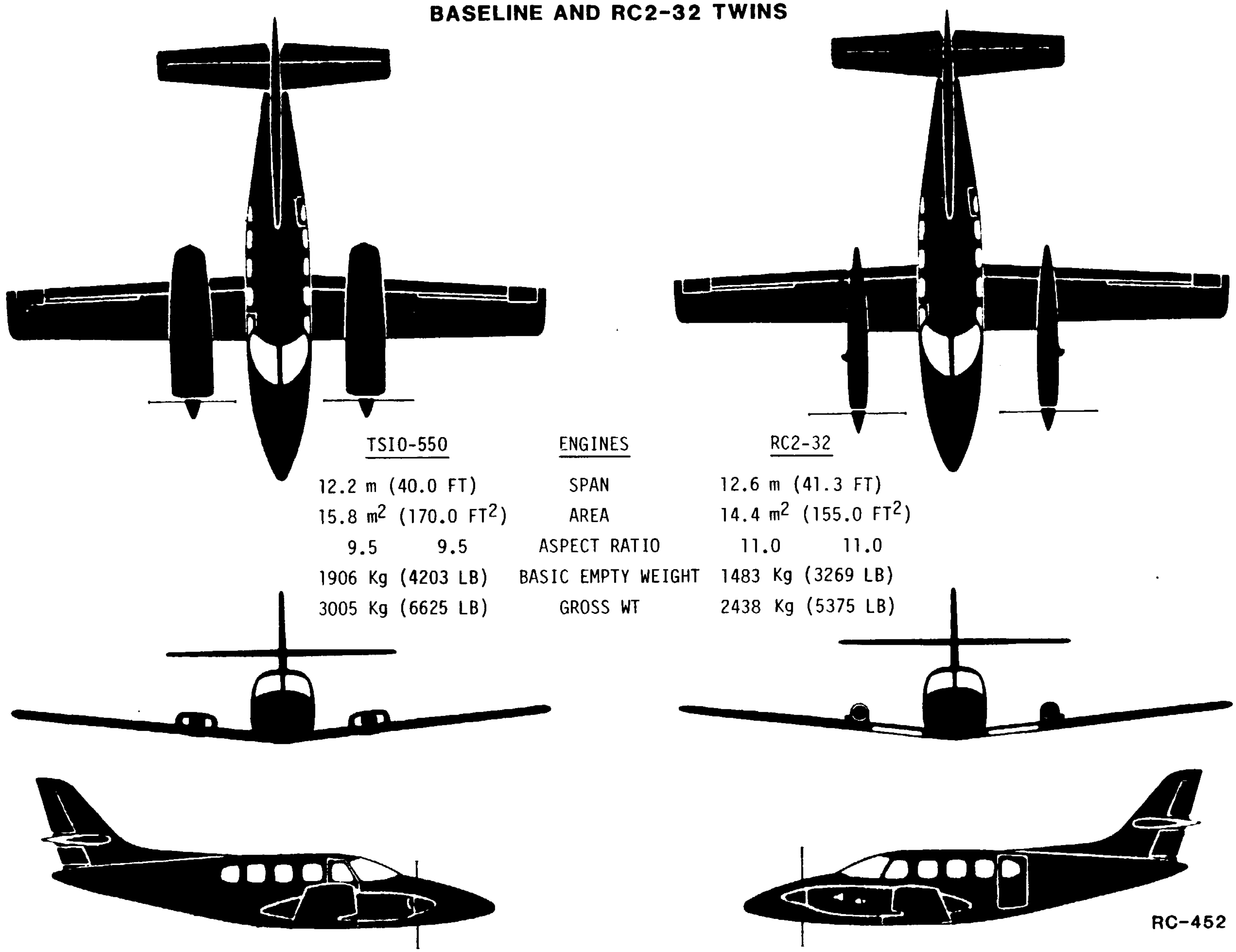
Use of engine coolant for anti-icing purposes, particularly around cowling inlets; further investigation is required.

Better control of engine temperature, particularly for low power descents.

Twin-Engine Airplanes

General Features. The twin-engine airplanes with rotary combustion powerplants are depicted in Figure 3.4.4. Compared to the baseline, these have longer, slimmer nacelles to accommodate the smaller, lighter engines, and larger diameter propellers. Also evident are smaller wings and raised horizontal tail, the latter to maintain clearance from the slipstream with the raised thrustline and larger diameter propeller.

BASELINE AND RC2-32 TWINS



TSIO-550		ENGINES	RC2-32	
12.2 m (40.0 FT)		SPAN	12.6 m (41.3 FT)	
15.8 m² (170.0 FT²)		AREA	14.4 m² (155.0 FT²)	
9.5	9.5	ASPECT RATIO	11.0	11.0
1906 Kg (4203 LB)		BASIC EMPTY WEIGHT	1483 Kg (3269 LB)	
3005 Kg (6625 LB)		GROSS WT	2438 Kg (5375 LB)	

Figure 3.4.4

Figure 3.4.5 shows typical installation features for the twin rotary engines. Unlike single-engine airplanes, the turbocharger and induction air cooler are located behind the engine proper to take advantage of the small engine cross section and minimize nacelle size. The coolant radiator is situated in the inboard wing leading edge in the style of several successful World War II era liquid-cooled twin engine installations. Optionally, a turboprop-style chin inlet under the spinner might be considered.

Performance & Weight Comparisons. Gross weight, dimensions, and performance for the two rotary-engined twins are compared with the baseline in Table 3.4.5.

TABLE 3.4.5

TWIN ENGINE AIRPLANE SUMMARY

	BASELINE	ROTARY COMBUSTION	
Engines (2)	TSIO-550	RC2-47	RC2-32
Gross Weight, lb/kg	6625/3005	5650/2563	5375/2438
Wing Span, ft/m	40/12.19	40.25/12.27	41.3/12.59
Wing Area, ft ^{2}/m^2	170/15.79	162/15.05	155/14.40
Aspect Ratio	9.5	10.0	11.0
Wing Loading, lb/ft^2/kg/m^2	39/190	35/171	35/171
Maximum Speed, kt/kph	243/450	275/509	279/517
(at altitude, ft/m)	(15,000/4572)	(25,000/7620)	(25,000/7620)
Cruising Speed, kt/kph (at 25,000 ft/7620m)	230/426	257/476	260/482
Stalling Speed, kt/kph	74/137	70/130	70/130
Rate of Climb, ft/min/m/min (at 25,000 ft/7620m)	880/268	1820/3371	1990/3685
Time to Climb, min	19.4	13.5	12.8
Takeoff Distance, ft/m (over 50' obstacle)	2525/769.62	1750/533.40	1640/500
Mission Fuel, lb/kg	856/388.28	610/276.70	575/260.82
Total Fuel Required, lb/kg (Accounts for reserves)	1065/483.08	787/356.98	747/338.84
Cruise Mileage, Nautical mi-per lb (km/kg)	1.03/4.21	1.38/5.63	1.46/5.96

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

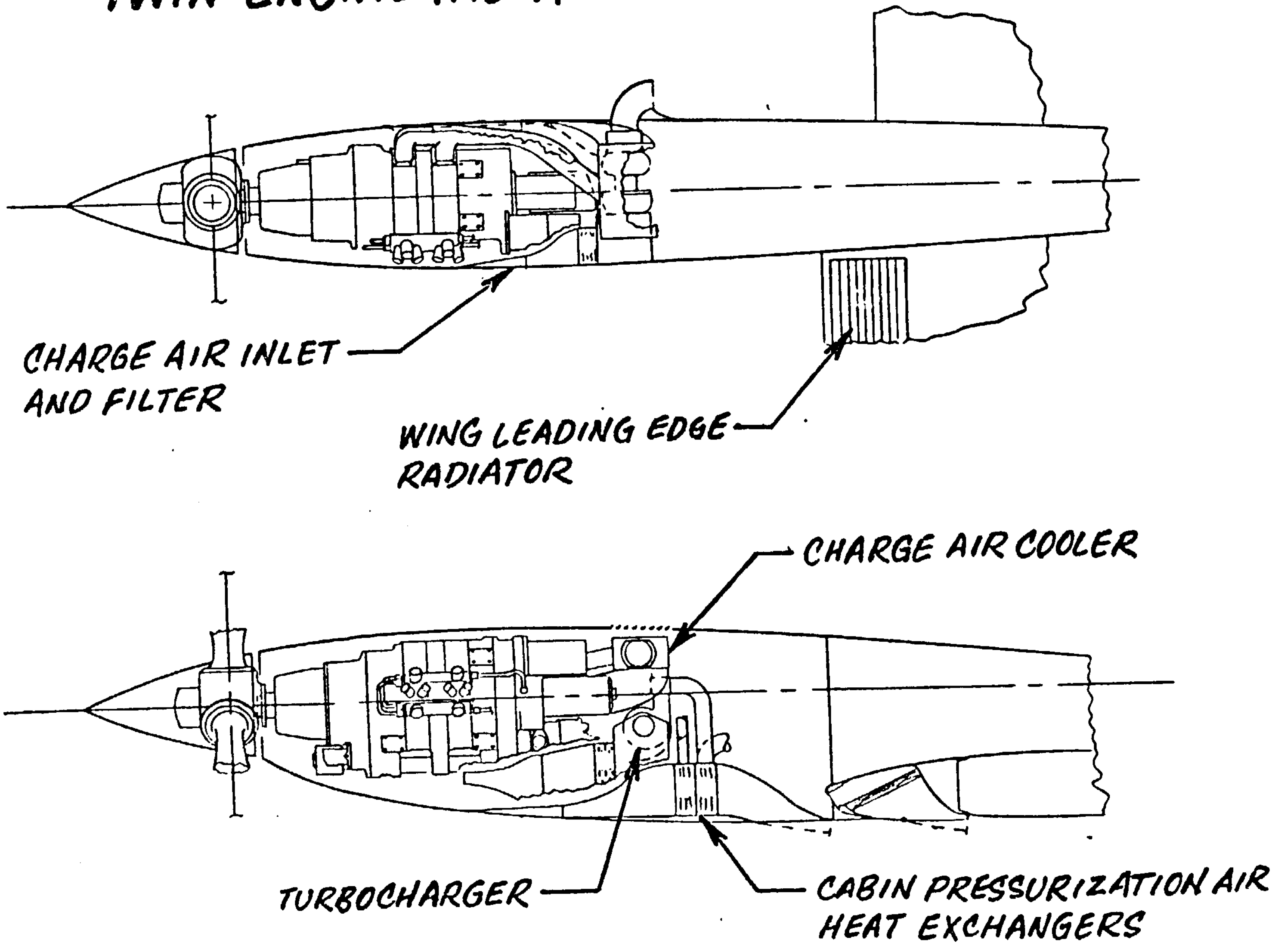


Figure 3.4.5

As in the case of the single-engine airplanes, the baseline twin is a very capable machine in its own right, with a combination of payload, range, and climb performance which are not available in today's market. In particular, the short (less than 20 min.) time to climb to 25,000 makes the use of favorable high altitude winds possible even for relatively short flights.

The two rotary-engined twins are from 975 lb (14.7%) to 1250 lb (18.9%) lighter than the baseline airplane; this results primarily from the engines being 35% to 46% lighter, the smaller wing size, and the smaller amount of fuel (ranging from 28.7% to 32.8% less) required to fly the given mission. Detailed weight breakdowns are to be found in Appendix I, page 3.6.0.

The rotary-engined twins, like their single-engined counterparts, show large improvements in performance over the baseline airplane. Referring to Table 3.4.5, cruising speed is up by 11.7% to 13%, time to climb is decreased by 30% to 34%, and mission fuel lowered by 28.7% to 32.8%. Improvements in cruise mileage range from 34% to 41.7% (this improvement is greater than the mission fuel change because it does not account for the high fuel consumption climb segment; it is essentially independent at altitude).

Comparative performance for the two segments of the mission profile are shown in Table 3.4.6, with the clear superiority of the rotary-engined airplanes again being evident.

TABLE 3.4.6

COMPARATIVE MISSION PERFORMANCE

TWIN-ENGINE AIRPLANES

Airplane	Climb Segment		Cruise Segment		Total Mission		
	Time Hrs.	Fuel Burn lb/kg	Time Hrs.	Fuel Burn lb/kg	Time Hrs.	Fuel Burn lb/kg	Fuel Req'd. lb/kg*
Baseline	0.32	133/60	3.25	723/328	3.57	856/388	1065/483
RC2-47	0.225	58/26	2.98	552/250	3.21	610/217	787/357
RC2-32	0.21	51/23	2.95	524/238	3.16	575/261	747/339

*Includes Reserve

Cooling Drag Considerations. The rotary-engined twins were assumed to have the same advantageous cooling drag situation as the singles, namely, a slight net thrust in cruise. This is probably even more feasible in the twin than in the single, with adequate space being available in the wing leading edge for the large radiator required, and with the active, high velocity portion of the propeller slipstream acting upon most of its surface. Although the computation was not done, an analysis like the one shown in Figure 3.4.3 for the RC2-47 single would be expected to yield very similar results for a rotary-engined twin.

Cost Considerations. Comparative acquisition and direct operating costs (D.O.C.) computed according to the methods of Appendix II, page 3.7.0 are tabulated in Table 3.4.7.

TABLE 3.4.7

ACQUISITION & DIRECT OPERATING COST
TWIN-ENGINE AIRPLANES

Airplane	BASELINE	RC2-47	RC2-32
Acquisition Cost 1981 Dollars	$356,000	$344,000	$355,000
Direct Operating Cost, $/hr. (500 hr/yr utilization)	$226.42	$210.39	$205.08

Flyover Noise Levels. As with the single engined airplanes, the rotary-powered twins will exhibit lower flyover noise levels from the baseline due to lower propeller operating speeds (2400 rpm vs 2800 rpm for takeoff). These are tabulated in Table 3.4.8.

TABLE 3.4.8

ESTIMATED FLYOVER NOISE LEVELS
TWIN-ENGINE AIRPLANES

Airplane	BASELINE	RC2-47	RC2-32
Flyover Noise Level, dB(A)	91.2	79.1	78.9

Other Factors. The rotary twins would be expected to have the same advantages as the singles with respect to low vibration levels, ease of cabin heating, possible anti-icing functions, and engine temperature control which permits more rapid low power descents.

Summary and Conclusions

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 with those obtained for similar baseline airplanes powered with a conventional horizontally-opposed air cooled engine, the TCM TSIO-550.

The basic approach involved designing all of the airplanes to perform a typical transportation mission consisting of climb and cruise phases with a specified payload. Airframes were "sized" to meet these requirements using computerized design routines. A general framework of traditional aerodynamic layout and conventional light metal riveted and bonded structure was adhered to in order to permit use of well-documented methods of weight and drag estimation, and to focus attention on powerplant rather than airframe characteristics.

The baseline airplanes which resulted are very capable machines, 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 category due to lower engine weight and fuel consumption. Some of the important differences are listed below, the spread resulting from the further advantages in weight and fuel efficiency of the RC2-32 over the RC2-47.

Improvement Over Baseline

Item	Singles	Twins
Gross Weight	14% to 17% Lighter	15% to 17% Lighter
Cruise Speed	14% to 15% Higher	12% to 13% Higher
Time to Climb to Cruising Altitude	18% to 24% Shorter	30% to 34% Shorter
Mission Fuel Burn	31% to 35% Less	29% to 33% Less

Flyover noise for the rotary-engined airplanes is estimated to be about 5 dB(A) lower for the singles and 12 dB(A) for the twins compared to the baseline due mainly to lower propeller speed at maximum power (2400 vs 2800 RPM).

Acquisition costs and amortized operating costs (including depreciation, maintenance, and overhaul) are projected to be slightly lower for the rotary engined airplanes.

In addition, the rotary-engined airplanes are expected to offer advantages in smoothness of operation; in effective, carbon-monoxide-free cabin heating; and in better control over engine temperatures.

To summarize, the rotary-engined airplanes show substantial improvements over the baseline in all performance areas, and accomplish the demanding design mission with 30 to 35% smaller fuel usage. Other factors, including noise, cost, and installation features, also favor the rotary combustion powerplant.

APPENDIX I

Curtiss-Wright Subcontract

Single-Engine Designs
Weight Breakdowns

Engine	TSIO-550	RC2-47	RC2-32
Gross Weight	4550/2064 lbs/kg	3900/1769 lbs/kg	3775/1712 lbs/kg
Wing Area	177/16.4 ft^2/m^2	150/13.9 ft^2/m^2	142.5/13.2 ft^2/m^2
Aspect Ratio	9.0	8.1	8.8
Wing Span	39.91/12.2 ft/m	34.86/10.6 ft/m	35.41/10.8 ft/m
Mean Aerodynamic Chord	53.76/1366 in./mm	52.20/1326 in./mm	48.84/1241 in./mm
Wing c.g. - L.E.	24.19/614 in./mm	23.49/597 in./mm	21.98/558 in./mm
Weight Item	**lbs/kg**	**lbs/kg**	**lbs/kg**
Wing	565.1/256.33	411.6/186.70	419.2/190.15
Fuselage	565.3/256.42	484.6/219.81	469.0/212.74
Vertical Tail	25.7/11.66	19.0/8.62	18.3/8.30
Horizontal Tail	61.2/27.76	55.7/25.27	55.5/25.17
Powerplant	686.0/311.17	467.0/211.83	373.0/169.19
Main Landing Gear	124.5/56.47	112.1/50.85	109.7/49.76
Nose Landing Gear	46.3/21.00	42.4/19.23	41.7/18.92
Gear Retraction System	97.5/44.23	85.1/38.60	82.7/37.51
Cowl & Engine Mount	61.3/27.81	56.0/25.40	56.0/25.40
Control System	50.0/22.68	50.0/22.68	50.0/22.68
Standard Equipment	55.0/24.95	55.0/24.95	55.0/24.95
Optional Equipment	270.0/122.47	270.0/122.47	270.0/122.47
Furnishings	200.0/40.72	200.0/90.72	200.0/90.72
Paint	13.5/6.12	13.5/6.12	13.5/6.12
Unusable Fuel	6.0/2.72	6.0/2.72	6.0.2.72
Total	389004.5	314628.6	306595.4
	2827.4/1282.51	2328.0/1055.98	2219.6/1006.81
Weight Calculated in Sizing Run	2821.8/1279.97	2324.3/1054.30	2215.1/1004.77

APPENDIX I (Cont'd)

Curtiss-Wright Subcontract

Twin-Engine Designs
Weight Breakdowns

Engine	TSIO-550	RC2-47	RC2-32
Gross Weight	6625/3005 lbs/kg	5650/2563 lbs/kg	5375/2438 lbs/kg
Wing Area	170.0/15.8 ft^2/m^2	162.5/73.7 ft^2/m^2	154.5/70.1 ft^2/m^2
Aspect Ratio	9.5	10.0	11.0
Wing Span	40.19/12.2 ft/m	40.31/12.3 ft/m	41.22/12.6 ft/m
Mean Aerodynamic Chord	51.29/1303 in./mm	48.88/1242 in./mm	45.44/1154 in./mm
Wing c.g. - L.E.	23.08/586 in./mm	22.00/559 in./mm	20.45/519 in./mm
Weight Item	lbs/kg	lbs/kg	lbs/kg
Wing	576.1/261	518.2/235	514.2/233
Fuselage	515.8/234	487.1/221	478.4/217
Vertical Tail	35.3/16	31.1/14.1	29.5/13.4
Horizontal Tail	64.4/29	56.9/25.8	54.5/24.7
Powerplants	1326.0/601	888.0/403	700.0/318
Nacelles	202.7/92	128.8/58.4	128.8/58.4
Landing Gear	225.4/102	188.6/85.5	178.3/80.9
Controls	71.3/32.2	66.8/30.3	60.9/27.6
Press. Heat & Vent	132.5/60	113.0/51.3	107.5/48.8
Fuel System	70.4/32	70.4/31.9	70.4/32
Hydraulics & Pneun.	165.6/75.1	141.3/64.1	134.4/61
Standard & Optional Equip.	550/75	550/249	550/249
Auxiliary Gear	3/1.4	3/1.4	3/1.4
Trapped Fluids	23.9/10.8	20.3/9.2	19.4/8.8
Unusable Fuel	6/2.7	6/2.7	6/2.7
Furnishings	209.1/95	209.1/95	209.1/95
Paint	25.3/11.5	24.8/11.2	24.3/11
Total	646273.3	542658	517692
	4202.8/1906	3503.4/1589	3268.7/1483
Weight Calculated by Trend Equation	4205.6/1908	3501.3/1588	3267.5/1482

APPENDIX II, COSTING INFORMATION

PRICING

The selling price (for purposes of estimating the value of new models) is considered to be the sum of 3 components:

1. The base price - that which is manufactured by Cessna (also accounts for minor purchased parts);
2. The powerplant contribution to the price - includes engine, propeller, and governor; and
3. The part of the price attributable to optional equipment (of which avionics account for about 50% of the value).

The base price is computed by:

$$\text{Base Price} = a(W_{EP})^{b}(V_{MAX})^{c}(S_W)^{d}(GW)^{e}$$

where $a = 7.268188*10^{-4}$
$b = 1.06942$
$c = 1.05600$
$d = .65289$
$e = .22723$

This is an empirical equation generated by applying a least squares regression analysis to the existing 1981 Cessna fleet. (The constant is valid only for pressurized aircraft.) The factors in the above equation are:

W_{EP} - Dry Empty Weight minus Weight of Powerplant (engine, governor, propeller)
V_{MAX} - Maximum Speed (knots)
S_W - Wing Area (ft^2)
GW - Takeoff Gross Weight (lbs)

Values of these factors for each plane and the resulting base price are shown in Table 3.7.1.

The price increment attributable to the powerplant is very difficult to estimate since it involves estimating the OEM cost not only of the engine but the propeller as well. Then the markup applied to the powerplant of that individual airplane must be considered. When the engine is not only new but is of a type not previously used in production aircraft the job becomes virtually impossible to do with any degree of certainty. Based on existing products and the fact that these are larger engines than now used in most Cessna products an increment of $35,000 per engine was chosen for all engines in the study.

The price increment attributable to optional equipment varies widely depending on the equipment chosen. Airplanes of this category can normally be expected to be equipped with radar, airconditioning, and a de-icing package in addition to the usual avionics and interiors. Based on present Cessna prices for equipped planes that include these features an increment of $48,000 was chosen for the single engine planes and $82,000 for the twin engine planes.

The total estimated selling price is shown in Table 3.7.1.

DIRECT OPERATING COST

The components considered in generating DOC and an outline of how they are generated are shown in Table 3.7.2. The following discussion covers how these values were calculated in this study.

For the engines considered herein no data was available to accurately estimate the cost of either the engine periodic maintenance nor the reserve for engine overhaul. Values of $9/engine and $8/engine were chosen which are in line with the current values for the larger TSIO-520's.

Propeller overhaul, airframe maintenance and systems maintenance are found as in Table 3.7.2. The factors used in the empirical curve fits for the last two components are shown in Table 3.7.3.

Hull and liability insurance rates are found in Table 3.7.4. The rate for the single engine aircraft is .0160 and for the twin is .0150. A utilization of 500 hours/year was assumed for both.

Fuel cost was calculated assuming a cost of $1.70 per gal, a density of 6 lb/gal, a BHP in cruise of 250, and the SFC's shown in Table 3.7.3.

The oil consumption was assumed to be .1 GPH per hour per engine at a cost of $6/gallon.

Depreciation is based on the total aircraft selling price. It is, therefore, not independent of the assumed price for the engine.

Reserves for avionics was based on assuming that avionics accounts for 50% of the optional equipment price.

Table 3.7.5 shows the values of each component of the DOC and the total for each plane.

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TABLE 3.7.1

FACTORS USED IN COMPUTING AIRCRAFT PRICE

	SINGLE ENGINE			TWIN ENGINE		
	TSIO-550	RC2-47	RC2-32	TSIO-550	RC2-47	RC2-32
W_{EP}	1910.4	1630.0	1615.6	2314.5	2084.1	2038.3
V_{MAX}	209.1	249.5	252.8	243.3	275.4	279.5
S_W	177	150	142.5	170	162.5	154.5
GW	4550	3900	3775	6625	5650	5375
Base Price	131677	116053	113171	203799	191644	182601
Powerplant Price	35000	35000	35000	70000	70000	70000
Optional Equip Price	48000	48000	48000	82000	82000	82000
Total	214677	199053	196171	355799	343644	334601

TABLE 3.7.3

FACTORS USED IN COMPUTING DIRECT OPERATING COST

	SINGLE ENGINE			TWIN ENGINE		
	TSIO-550	RC2-47	RC2-32	TSIO-550	RC2-47	RC2-32
TOGW	4550	3900	3775	6675	5650	5375
BHP (T.O.)	350	320	320	700	640	640
Price	214677	199053	196171	355799	343644	334601
Optional Equip Price	48000	48000	48000	82000	82000	82000
SFC	.446	.371	.355	.446	.371	.355

TABLE 3.7.2

DIRECT OPERATING COSTS FOR GENERAL AVIATION AIRCRAFT
1981 Estimate

1) ENGINE PERIODIC MAINTENANCE

Use past experience (i.e. similar engine/airframe combination) or engine manufacturer's estimate.

Otherwise use:

$$\frac{\text{Number of labor hours for 100 hour inspection} \times \text{labor rate}}{100}$$

Then double this answer to account for parts.

Labor rate right now runs	\$20/hour	S/E (Single Engine)
	\$25/hour	M/E (Multi-Engine)
	\$30/hour	Turboprops

Turboprops must be considered under a different formula. Instead of being inspected every hundred hours, they undergo a series of Hot Section Inspections during the overhaul period. These are usually of considerably greater time than 100 hours. For some engines the work scheduled for each HSI is different as the time from last overhaul increases.

$$\frac{\Sigma\ (\text{cost of labor} + \text{cost of parts})\ \text{for HSI's} + \text{misc.} \begin{pmatrix}\text{filters, igniters +} \\ \text{labor not included in HSI}\end{pmatrix}}{\text{TBO}}$$

2) RESERVES FOR ENGINE OVERHAUL

The assumption (conservative) is made that every other overhaul will require, instead of an overhaul, a remanufactured engine. Therefore:

$$\frac{(\text{overhaul cost} + \text{cost of remanufactured engine})/2}{\text{TBO}}$$

*For Turboprops:

$$\frac{\text{overhaul cost (labor + parts)} + \begin{matrix}\text{allowance for premature removal** of} \\ \text{engine and engine accessories*** and} \\ \text{engine components****}\end{matrix}}{\text{TBO}}$$

**Allowance for engine removal amounts to 1/5 to 1/2 of engine overhaul cost
***Starter generator, etc.
****Turbines, nozzles, etc.

3) PROPELLER OVERHAUL

Propeller		DOC ($/hr)
Fixed Pitch		.11
S/E controllable	LSE*	.43
	HPSE**	.60
	Centurion class	.82
M/E controllable (per propeller)		.90

4) AIRFRAME MAINTENANCE

This number is based on a parametric fit of the available data.

DOC = 1.472 + .000534 TOGW - .000373 BHP (Total
+2.774 (only for twins) + 1.878 (only if pressurized)

5) INSURANCE (HULL + LIABILITY)

See attached charts

6) FUEL COST

$$\text{DOC} = \frac{\text{price}}{\text{gal}} \times \frac{\text{gal per}}{\text{hour}}$$ (present price of AV gas is calculated at $1.70 gal)

7) OIL COST

$$\text{DOC} = \frac{\text{price}}{\text{gal}} \times \text{GPH used}$$ (present price of oil is $6/gal which also accounts for cost of oil filter)

or alternately use

$$\text{DOC} = \frac{\text{actual price}}{\text{gal}} \times \text{GPH used} + \frac{\text{cost of filter}}{\text{\# hrs between filter change}}$$

(including both consumed and lost during change)

8) DEPRECIATION

$$= \frac{\text{Total equipped airplane price}}{7.5 \times \text{utilization rate/year}}$$ i.e. discounted to zero residual in 7.5 years

9) RESERVES FOR AVIONICS

$$\frac{10\%\text{ of total avionic package (standard + optional)}}{1000}$$

10) RESERVES FOR SYSTEMS MAINTENANCE

DOC = -.513 + 000803 TOGW + 1.109 (if pressurized)

Again this is a parametric fit of available data.

* Light Single Engine ** High Performance Single Engine

TABLE 3.7.4
INSURANCE RATES APPLICABLE TO 1981 CESSNA MODELS

October, 1980

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Pleasure & Business Rates For Well-Qualified Pilots:

Hull Value	Single Engine Rate	Multi-Engine Rate
$15,000 - 24,999	3.00%	
25,000 - 39,999	2.75	
40,000 - 59,999	2.50	
60,000 - 99,999	2.00	
100,000 - 149,000	1.75	
150,000 - 200,000	1.60	
150,000 - 299,999		1.75%
300,000 - 499,999		1.50
500,000 - 750,000		1.35
750,000 - 1 Mil.		1.10
1 Mil - 1.5 Mil.		1.00

Legal Liability limit of $5,000,000 combined single limit.

Seats	Annual Premium
4	$ 575
5	675
6	725
7	825
8	975
9	1,075
10	1,175
11	1,250

TABLE 3.7.5

DIRECT OPERATING COST

	SINGLE ENGINE			TWIN ENGINE		
	TSIO-550	RC2-47	RC2-32	TSIO-550	RC2-47	RC2-32
Engine Maintenance	9.00	9.00	9.00	18.00	18.00	18.00
Engine Overhaul	8.00	8.00	8.00	16.00	16.00	16.00
Propeller	.82	.82	.82	.90	.90	.90
Airframe	5.65	5.31	5.25	9.92	8.90	8.76
Insurance Liab.	1.45	1.45	1.45	1.65	1.65	1.65
Insurance Hull	6.87	6.37	6.28	10.67	10.31	10.44
Fuel	31.59	26.28	25.15	63.18	52.56	50.29
Oil	.60	.60	.60	1.20	1.20	1.20
Dep	57.25	53.08	52.31	94.88	91.64	89.23
Res for Avionics	2.40	2.40	2.40	4.10	4.10	4.10
Systems	4.25	3.73	3.63	5.92	5.13	4.91
Total	127.88	117.04	114.89	226.42	210.39	205.08

Technology Enablement Development Plan (Task IV)

A development plan has been prepared for advancing new technology to a state where it can be used in a new, highly advanced engine design to be initiated in the 1985 time period.

The plan is made up of three overlapping sections representing three interrelated engine types chosen to provide a logical progression from hardware presently available to components of advance technology that will be developed in the course of the program. In all cases following, the planned program is written in the positive sense, although it should be understood that this is a recommended plan and is subject to change as a function of changing needs and resources. The RC1-60T phase, particularly, can be eliminated and selected content incorporated in the RC1-75T program. This would result in a delay in initiating hardware testing, but would increase technology testing effectiveness since the RC1-75T will be a test vehicle designed for this program.

The first section of the plan, shown in Figure 4.1.1, represents testing to be conducted on the RC1-60T. Since this is an existing engine, the hardware (including the turbocharger) is available for test immediately after initiation of the program. This will give an early-on base of data at higher speed and BMEP than previously obtained on a turbocharged SCRC engine. The RC1-60T is structurally limited and will run only short evaluations, whereas extensive testing will be performed with the RC1-75T incorporating new designs which provide increased structural capability.

The second section, shown in Figure 4.1.2, is for an RC1-75T. This is to be an engine test rig capable of the higher thermal and pressure loading planned for the "Clean Sheet" engine. It will require new designs and procurement of the long lead time items such as rotors and rotor housings. This rig will be used to advance technologies known to scale well to different sizes.

The third section of the plan, shown in Figure 4.1.3, is for the RC1-XT. This is intended to be the best guess at the time of the eventual engine size. This new size will require more new hardware and the usual development of a completely new engine, in order to serve as a rig. It will primarily be used to further technologies considered to be affected by absolute size. As the program progresses developed items from the larger rig will be fed into the smaller rig.

RC1-60T (Figure 4.1.1)

The initial testing will be a performance survey with configurations already tested, but the speed and power will be extended beyond previous scope. There will be some risk in using existing hardware in this realm; but loading will be run to maximum attainable performance levels. This will provide initial insight into seal wear and any other potentially limiting areas.

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RC1-60T EXTENDED SPEED/EXTENDED BMEP
ADVANCE TESTING WITH AVAILABLE ENGINE/TURBOCHARGER

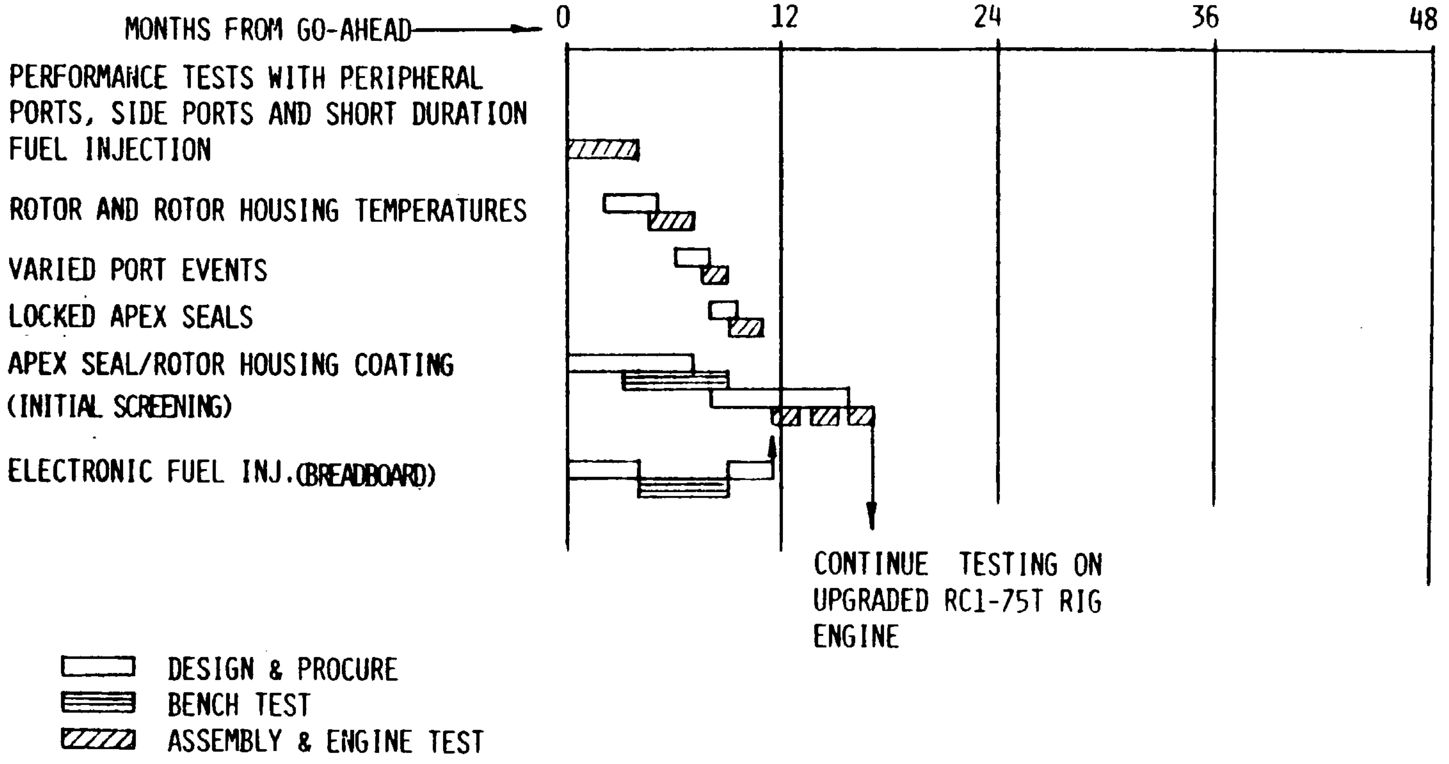

Figure 4.1.1

While the above testing is in progress, a second rotor housing will be instrumented with an array of thermocouples or flux plugs to measure heat input. The rotor will be instrumented with a variety of temperature sensitive paints. In a given location, this will indicate only the highest temperature experienced during the tests; but the distribution of temperature will provide useful information. Temperature sensitive paints have been used successfully for determining rotor temperature in other programs, and the use of slip rings or telemetering equipment would require a much more extensive effort.

The varied port events tests in this part of the program will be limited by what can be accomplished by inserts or routing out the ports within the limits of existing housing wall thickness.

Friction drag of the apex seals can be minimized at high speed by lifting them off the trochoid surface (See Volume II). This will be tested by locking the apex seals just off the trochoid surface with suitable pins or other means. Mechanically actuated configurations will be evaluated subsequently if advantage is demonstrated.

The Apex seal/rotor housing coating development will include new material combinations not previously tested. The mechanical wear rig available from prior programs will be used to evaluate compatibility and wear characteristics of various material combinations. After screening candidate materials, selected combinations will be procured and engine tested to further evaluate them under operating conditions prior to more extensive testing in the RC1-75T engine.

Early experience with electronic fuel injection on a turbocharged SCRC engine will be obtained by adapting a prototype (breadboard) system to the RC1-60T engine. This information will be available in time to input the final design of the RC1-XT electronic fuel injection system.

RC1-75T (Figure 4.1.2)

State-of-the-art turbochargers (preferably off-the-shelf) will be selected and procured for most of the testing since it is expected that advance technology units will not be available until later in the program.

Shakedown testing is not expected to be very extensive since this rig engine will combine existing and strengthened components. Tests will be run with various compression ratios to evaluate the trade-off between reduction of combustion peak pressure and metal temperatures versus any degradation in fuel consumption resulting from lower expansion ratio when using lower compression ratios.

Various rotor pocket configurations including both shape and phasing will be evaluated together with various fuel injection nozzle types and locations. This will require extensive testing to develop configurations which will optimize the combustion process in the high speed, high power regime.

RC1-75T HIGH SPEED/HIGH BMEP
UPGRADED RIG ENGINE COMPONENTS FOR HIGH SPEED & LOAD
(SCALABLE TECHNOLOGIES)

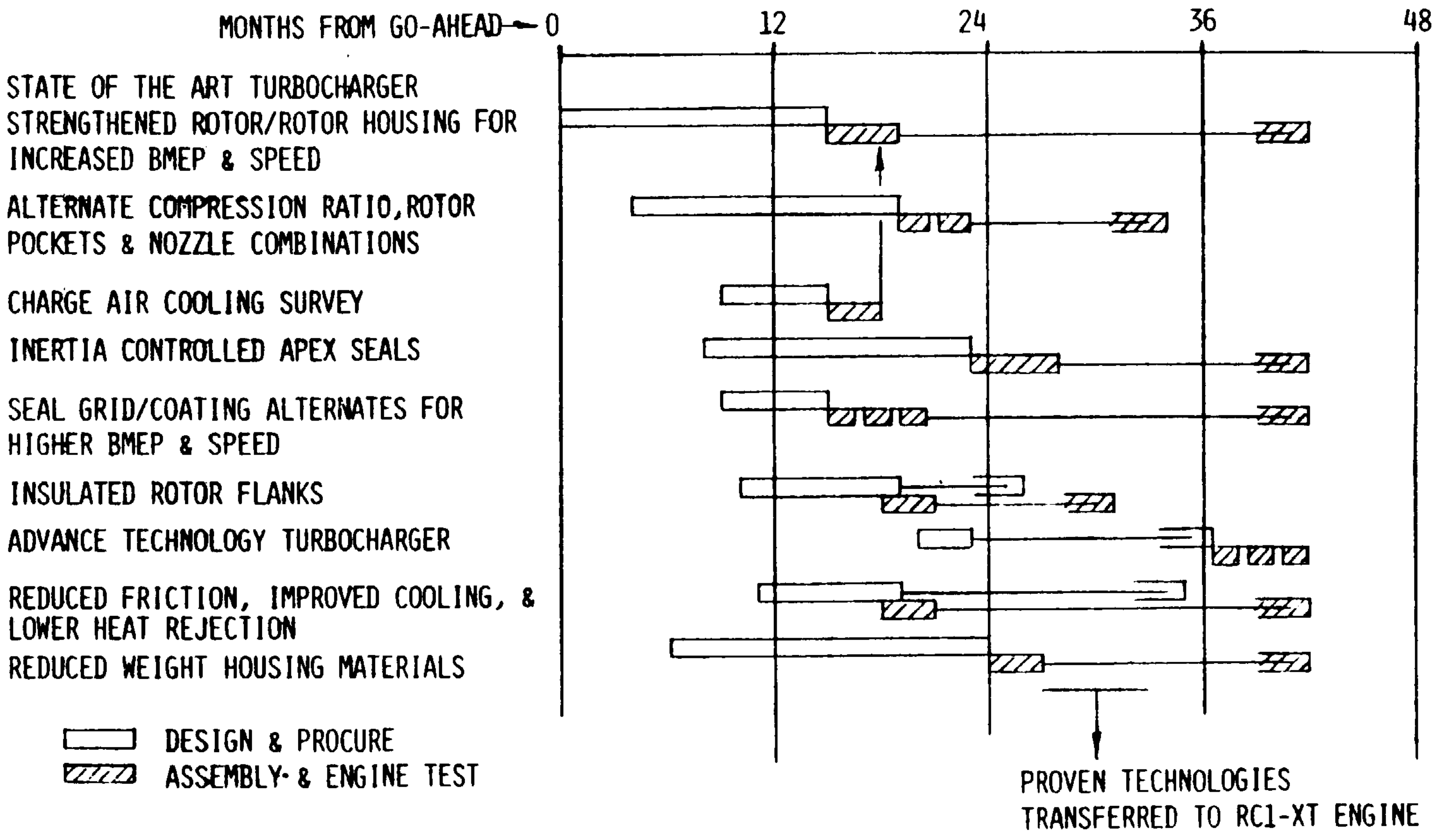

Figure 4.1.2

The charge air cooling survey will be performed to evaluate effect on engine parameters. Therefore, the heat exchanger will be a workhorse (test equipment) unit, probably air-to-water with controllable water flow rate.

The locked apex seal test of the RC1-60T engine will provide indications of the reduction in friction that could be gained by using the inertia controlled apex seals (description in Volume II) to be tested in this part of the program. This technology will probably require successive tests and redesigns with engine builds run at operating conditions for the particular application.

Seal grid and rotor housing coating alternates will be pursued to develop new material options for high speed/high power operation with improved durability and reduced friction. Testing in the RC1-75T will continue the development initiated in the RC1-60T by extending the speed, power and time on test. Candidate materials and configurations will be subjected to successively increasing endurance testing with one or two configurations given 1000 hour tests.

Insulated rotor flanks offer potential advantages in reduced thermal gradients in the rotor and reduced heat rejection to engine oil as well as emissions control. The most probable approach would be direct deposited, stabilized zirconium oxide; however, there remains a problem of retention where there is thermal cycling. This effort is scheduled late in the program to take advantage of other developments. This testing may also include a rotor with zirconia coating encapsulated in a thin layer of metal which would reduce erosion and retain local spalling.

The advance technology turbocharger is also scheduled late in the program to take advantage of developments by others. Such a turbocharger would probably include a variable area turbine inlet.

Reduced friction and improved cooling designs will include the results from the seal grid effort, and will also investigate possibilities such as reduced seal spring force, single side and single oil seals and treatments of coolant passages to enhance heat transfer.

<u>RC1-XT</u> (Figure 4.1.3)

The third section of the development plan, shown in Figure 4.1.3 represents testing to be conducted on the RC1-XT engine as well as some bench testing. This will be a rig engine sized to the estimated final requirements of the highly advanced flight engine (RC2-YT). Its primary function will be to further new technologies considered non-scalable by providing test data to compare to theoretically predicted performance.

Since this is a completely new engine, it is anticipated that shakedown testing will be required to obtain dependable operation. This will include engine testing of the electronic fuel injection and the advance technology ignition systems which will be introduced early in this stage. Modification of the basic combustion configuration, to optimize performance, will be evaluated here in the event that the system developed on the larger engines does not scale exactly.

RC1-XT SIZE EFFECT TECHNOLOGY RIG

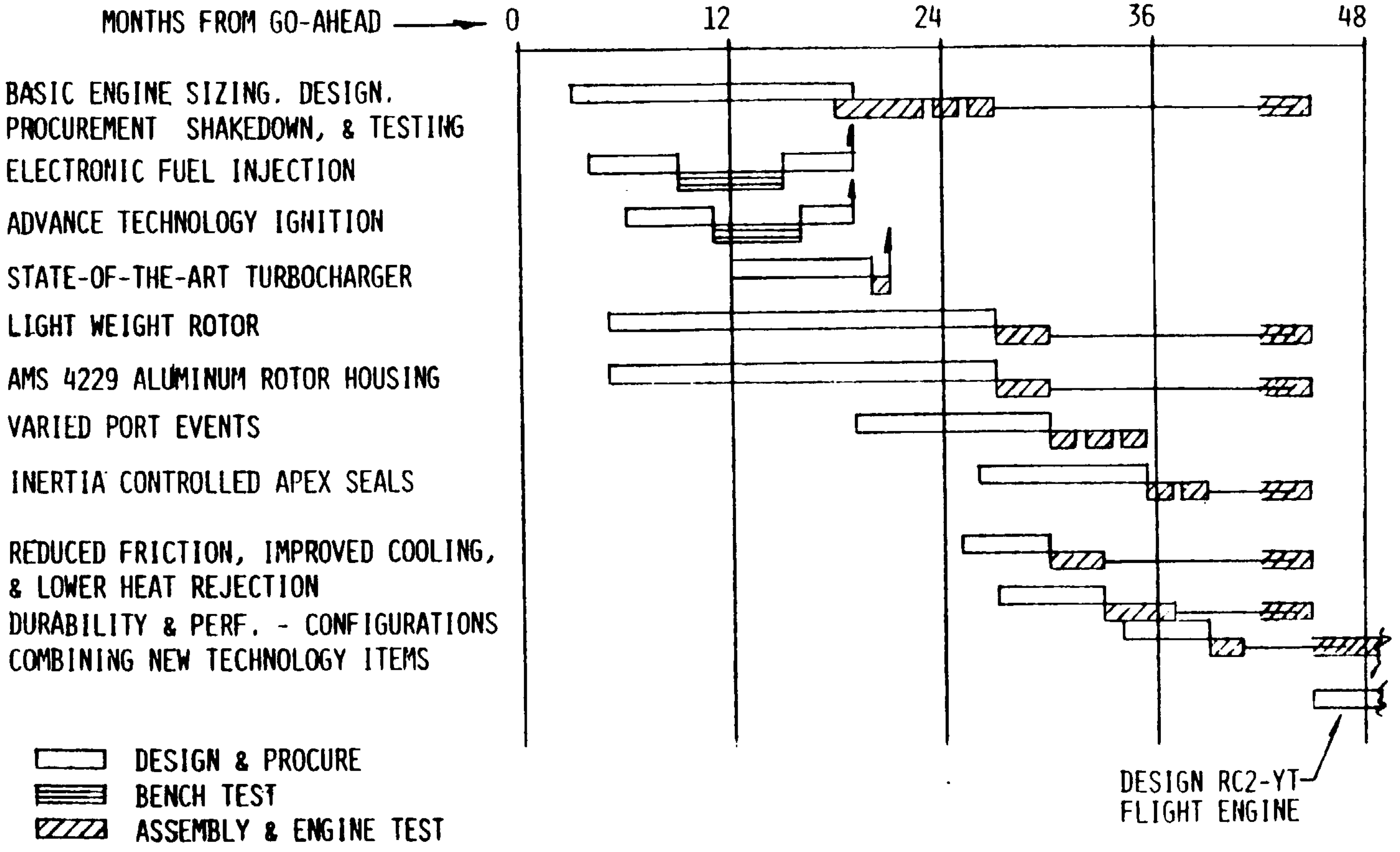

Figure 4.1.3

The turbocharger will be state-of-the-art test equipment to facilitate early testing. It is expected that alternate, interchangeable turbine inlets (Variable Area Ratio) and compressors will be used to establish best engine matching general relationships. A possible approach to optimize the recovery of exhaust energy would be to model the conditions from the exhaust port to the turbine inlet (pressure, temperatures, pipe dimensions, nozzle sizes) and test to verify the model. This would permit defining the requirements for a variable area turbine.

Inertia controlled apex seals for this engine will reflect the developments in the RC1-75T engine, thus providing sizing data as well as the opportunity to test alternate concepts.

A lightweight rotor will be given considerable emphasis because of the pyramid of benefits to bearings, mainshaft and counterweights. Whether this item is a thin wall cast iron rotor or any other approach (aluminum, titanium, composite) it will require a long procurement cycle since the process is the new technology. It may be possible to include the casting provisions necessary to add inertia controlled apex seals, but this could be done in a later stage if it appeared to compromise the initial objective of a lightweight rotor.

The aluminum rotor housings with increased material strength also require time for the casting process development. The material (AMS 4229) tends to be hot short, as is the present housing material (AMS 4220) for which successful casting procedures have been evolved.

Reduced friction and improved cooling designs will be fed in from the RC1-75T testing and applied to the RC1-XT engine.

The varied port events testing will be an extension of the preliminary effort on the RC1-60T engine. However, in the design and procurement of the rotor housings (or end housings if side intake ports are still considered), sufficient extra casting stock will be provided to allow significant variations.

Durability tests will be performed throughout the programs; however, specific durability tests will be conducted late in the program to gain data not brought out in performance tests. The configurations to be tested and the test format will depend upon results obtained. The durability tests will include cyclic as well as high power steady state conditions.

The final sizing of an RC2Y-T will occur in a design effort initiated toward the end of the technology enablement program. The engine size will be a function of (1) normal marketing projections regarding the needs in the General Aviation market and (2) the results obtained in advancing the new technology approaches in the completed programs.

Related Non-Aviation Technology Enablement Activity

During the forthcoming decade, considerable inputs from parallel and independent developments are expected to favorably impact upon the General Aviation engine enabling technology efforts. The key areas where related developments are anticipated are discussed below; however, based on past experience, there will be additional areas which are not recognized today.

1. Fuel Injection

With the increased acceptance of the diesel automotive and light truck small high speed engines, there has been a virtual explosion of activity, particularly in relation to electronically controlled and activated systems, on the part of all current and potential manufacturers.

United Technology's expansion of American Bosch's new plant and formation of an Automotive Group, Bendix's development of new electronic low and high pressure systems, CAV/Lucas' new U.S. plant and work in the U.K., Robert Bosch's, Stanadynes' and others' new systems are just a few of the manifestions of increased activity. In addition, engine advances, such as the possible introduction of direct injected diesels into the automotive market, as well as new military application requirements, are also contributing to this profusion of new technology. As an example of the latter category, the Garrett two stroke diesel section of the Cruise Missile power plant is in the early stages of running a new Bendix electronic high pressure injection system at 8000 RPM.

Curtiss-Wright contacted Bendix, United Technology and CAV/Lucas regarding their pertinent product planning during the contract study effort. All responded with interest and indications that participation in on-going programs outlined in this study was consistent with their current planning.

2. Controls/Diagnostics

Hand-in-hand with basic systems development, spurred on by the emission control requirements and the market demand for better fuel economy, electronic controls and diagnostic aids are similarly revolutionizing the automotive market place. While these controls and analysis systems cannot be considered a basic technology need, since it is likely that a high speed, high turn-down ratio injection system is required, they will add to power system reliability and safety.

3. Materials

Work on the automotive gas turbine over the past ten years has been the impetus which produced dramatic gains in ceramic technology. Ceramic turbocharger turbines are running today, ceramic regenerators/recuperators are being used, and ceramic gas turbine wheels and blades are approaching commercial practicability. In fact, if the gas turbine survives as a viable automotive power plant, it will only be because ceramic research will have succeeded in allowing (1) higher operating temperatures where needed for attractive fuel economy, (2) lower turbine inertias for good response levels, and (3) lower costs by manufacturing wheels without subsequent machining.

These advances in ceramic engineering are expected to benefit the rotary in many respects. Early tests have shown hot pressed silicon nitride to be an attractive apex seal material. Further improvements in shock loading strength are expected to make this and similar materials promising candidates for apex seals in engines with higher BMEP's and speeds.

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 supports a racing version of the RX-7 engine which develops close to 300 horsepower (naturally aspirated) at speeds in the 10,000 RPM range. They have developed a relatively strong reinforced graphite seal compatible with the chromium plated trochoid bore for racing and, with increased involvement and the pressure for higher outputs, will probably move forward from that point.

United Technology Metal Products Division has been providing a hardfacing service using their Gator-Gard process. Their data shows lower wear than D-gun coating and at "considerably less cost", according to company sources.

The use of ceramic exhaust liners to minimize heat transfer to the housing and coolant has been used on the rotary engine and will become more important as efforts to reduce heat rejection and better utilize exhaust heat increase. Similarly, ceramic coatings or "caps" on the rotor combustion faces can reduce heat transferred to the lubricating oil.

For less rigorous sealing requirements, such as the side seals and possibly oil seals, polyimides and other new plastics show promise.

High speed engines demand light strong rotors. Advances in powder metal and sintering technology, as well as electron and laser beam welding, open up whole ranges of new possibilities. Improvements here too have been spurred on by the increasing use of aluminum, both higher strength and eutectic, for passenger car engines both here and in Europe.

Polimotor Research Incorporated has been conducting an engine test program using major engine parts (housings, connecting rods) made out of graphite reinforced resins. This work, in addition to the automobile industries' emphasis on plastics to reduce weight, may lead to significantly lighter rotary engine major parts. .

4. Turbocharging

The fuel economy values predicted in the engine conceptual designs were limited by the turbocharger pressure ratios expected to become commercially available over the next several years based on current development activity. For 25,000 feet cruise performance, the maximum practical (i.e., good efficiency and wide range) pressure ratio was assumed to be between five and six, which limits sea level ratios to around 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, improved turbochargers will permit higher rates of airflow and thus further improve BSFC predictions over the currently estimated values, even without any allowance for combustion efficiency improvements with continued rotary stratified charge development.

Automotive turbocharger developments, as well as associated controls, particularly for diesel engines, are expected to yield improvements which will be applicable to the rotary. Similarly, heavy duty diesel R&D will generate applicable technology.

Summary and Conclusions

General aviation rotary power plants which could be introduced commercially in 1990 were conceptually defined on the basis of technology advances to be attained by mid-decade. A comparative summary of the baseline and rotary engine size, weight, and fuel economy is shown in Tables 5.1.0 and 5.2.0. Engines incorporating this technology level have been defined and analyzed as part of an aircraft system. The results show substantial improvements for the rotary-engined airplanes over the baseline in all performance areas, and the airplanes accomplish demanding design missions with 30-35% less fuel. Other factors, including noise, cost, and installation features also favor the rotary combustion powerplants.

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. These increases will require technological advances in seal/coating wear, structural/cooling design, and mechanical and thermal efficiency. A program outline to achieve the required technology levels in these and related areas by mid-decade has been presented.

The commensurate technology advances are believed to be attainable with a practical technology enablement activity level. However, a more modest fall-back position engine, with relatively moderate advances in key operating parameters, has been defined and also shows significant gains over current reciprocating engines.

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 general aviation aircraft.

TABLE 5.1.0

BASIC ENGINE DATA

250 CRUISE HP @ 25000 FT

	TS10-550	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 @ CRUISE (LB/HP-HR)	.446	.371	.355

TABLE 5.2.0

BASIC ENGINE DATA

186 CRUISE KW @ 7620 M

	TS10-550	ADVANCED RC2-47	HIGHLY ADVANCED RC2-32
LENGTH (cm)	150.5	132	123
WIDTH	84.8	41.9	40.6
HEIGHT	48.9	41.9	40.6
WEIGHT - FLYABLE (kg)	265	158	116
SPECIFIC FUEL CONSUMPTION @ CRUISE (g/kw-Hr)	271	226	216

ADVANTAGES OF THE ROTARY STRATIFIED CHARGE AIRCRAFT ENGINE

MULTI-FUEL CAPABILITY

SMALL FRONTAL AREA

LOW ENGINE WEIGHT

REDUCED ENGINE COOLING AIR DRAG

IMPROVED RELIABILITY DUE TO FEWER PARTS

LOWER EXHAUST GAS TEMPERATURES

NO VALVES OR CAMS

SAFER CABIN HEAT

COOLANT COOLERS CAN BE WING DE-ICING

MORE RAPID FLIGHT DESCENTS PERMISSIBLE

LOW COST TURBOCHARGER FROM OTHER PRODUCTION RETAINED

SMALL EXHAUST AND INTAKE MANIFOLD VOLUMES BENEFIT TURBOCHARGING

LOW EXHAUST EMISSIONS

LOW FUEL CONSUMPTION

SMOOTH - BALANCED OPERATION

GOOD LOW TEMPERATURE STARTING CAPABILITY

LOW NOISE LEVEL

PROVEN PRODUCIBILITY OF ROTARY ENGINE

LOWER AIRFLOW THAN TURBINE ENGINES

BASE TECHNOLOGY DEMONSTRATED

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146

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