NASA

FINAL REPORT

ADVANCED GENERAL AVIATION COMPARATIVE ENGINE/AIRFRAME INTEGRATION STUDY

by

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COMPARATIVE ENGINE/AIRFRAME INTEGRATION
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The following Cessna personnel were principal contributors to the project: J. Huggins, J. Ellis, A. Mueller, C. Olson, J. Dembrey, and L. Engelbrecht.
# TABLE OF CONTENTS

Summary 1

Introduction 2

Methods and Data Base 3
  Study Phases and Guidelines 3
  Mission Definition 3
  Engine Data 5
  Airframe Data Base
    Weight 6
    Drag 6
    Propellers 14
    Wing Technology 16
    Acquisition Cost 16
    Direct Operating Cost 18
    Noise 18
  Sizing Method 18
  Efficient Flight 21

Airframe Design and Installation Concept 26
  Baseline Airframe
    Single Engine 26
    Twin Engine 26
  Rotary Powered Airframe
    Single Engine 26
    Twin Engine 31
  Diesel Powered Airframe
    Single Engine 34
    Twin Engine 34
  Spark Ignition Powered Airframe
    Single Engine 34
    Twin Engine 43
  Gas Turbine Powered Airframe
    Single Engine 43
    Twin Engine 48

Results and Discussion 51
  Methods of Comparison 51
  Evaluations
    Weight 52
    Horsepower 52
    Payload/Range 52
    Mission Fuel 55
    Direct Operating Cost 56
    Effect of Assumed Fuel Cost on DOC 56
    Acquisition Cost 64
    Effect of Engine Cost on Price and DOC 64
    Cruise Coefficient 64
    Evaluation Criteria 70
<table>
<thead>
<tr>
<th>TABLE</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Mission Definition &amp; Minimum Performance Levels</td>
<td>4</td>
</tr>
<tr>
<td>II</td>
<td>Summary Engine Data Chart</td>
<td>7</td>
</tr>
<tr>
<td>III</td>
<td>Complete Engine Data Chart</td>
<td>8</td>
</tr>
<tr>
<td>IV</td>
<td>Miscellaneous Engine Data</td>
<td>9</td>
</tr>
<tr>
<td>V</td>
<td>Drag Summary</td>
<td>15</td>
</tr>
<tr>
<td>VI</td>
<td>Acquisition Costs</td>
<td>17</td>
</tr>
<tr>
<td>VII</td>
<td>Data Base - Direct Operating Cost</td>
<td>19</td>
</tr>
<tr>
<td>VIII</td>
<td>Effect Of Engine Cost On Aircraft Price &amp; DOC</td>
<td>69</td>
</tr>
<tr>
<td>IX</td>
<td>Evaluation Scheme</td>
<td>73</td>
</tr>
<tr>
<td>X</td>
<td>Effect Of High Efficiency Inlet</td>
<td>94</td>
</tr>
<tr>
<td>XI</td>
<td>Effect Of Sizing For Cruise At 35,000 Feet</td>
<td>98</td>
</tr>
<tr>
<td>XII</td>
<td>Effect Of Sizing For Cruise At 17,000 Feet</td>
<td>99</td>
</tr>
<tr>
<td>XIII</td>
<td>Effect Of Operating At Reduced Power</td>
<td>101</td>
</tr>
<tr>
<td>XIV</td>
<td>Effect Of Advanced Airframe</td>
<td>104</td>
</tr>
<tr>
<td>XV</td>
<td>Effect Of 10% Improvement In SAGE Engine</td>
<td>106</td>
</tr>
<tr>
<td>FIGURE</td>
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<td>--------</td>
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<td>1</td>
<td>Effect Of Engine Scaling On Specific Fuel Consumption - General Aviation Turbine Engine</td>
<td>10</td>
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<td>Advanced Diesel Engine Characteristics-Effect of Altitude On Engine Power and Brake Specific Fuel Consumption</td>
<td>11</td>
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<tr>
<td>3</td>
<td>Advanced Diesel Engine Characteristics-Effect Of Engine Scaling On Specific Weight and Brake Specific Fuel Consumption</td>
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<td>Program Structure</td>
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<td>Typical Sizing Output</td>
<td>22</td>
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<tr>
<td>7</td>
<td>Typical Sizing Output</td>
<td>23</td>
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<td>Baseline Single</td>
<td>27</td>
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<td>29</td>
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<td>RC2-32 Highly Advanced Rotary Engine Single Engine Installation Concept</td>
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<td>13</td>
<td>RC2-32 Highly Advanced Rotary Engine Twin Engine Installation Concept</td>
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<td>Diesel Single</td>
<td>35</td>
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<tr>
<td>15</td>
<td>GTDR-246 Highly Advanced Lightweight Diesel Engine Single Engine Installation Concept</td>
<td>36</td>
</tr>
<tr>
<td>16</td>
<td>Diesel Twin (Upright Mounting)</td>
<td>37</td>
</tr>
<tr>
<td>17</td>
<td>GTDR-246 Low Profile Engine</td>
<td>38</td>
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<tr>
<td>18</td>
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<td>39</td>
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<td>STDW-246 Highly Advanced Lightweight Diesel Engine - Twin Engine Installation Concept</td>
<td>40</td>
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<td>20</td>
<td>Advanced Spark Ignition Single</td>
<td>41</td>
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<tr>
<td>21</td>
<td>GTSIO-420SC Highly Advanced Spark Ignition Engine - Single Engine Installation Concept</td>
<td>42</td>
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<td>22</td>
<td>Advanced Spark Ignition Twin</td>
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<tr>
<td>24</td>
<td>GATE Single</td>
<td>46</td>
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<td>47</td>
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<td>48</td>
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<td>27</td>
<td>GATE Highly Advanced Turboprop Engine Twin Engine Installation Concept</td>
<td>49</td>
</tr>
<tr>
<td>28</td>
<td>Takeoff Gross Weight - Method II</td>
<td>50</td>
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<tr>
<td>29</td>
<td>Takeoff Gross Weight - Method III</td>
<td>53</td>
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<tr>
<td>30</td>
<td>Engine Power At Cruise - Method III</td>
<td>54</td>
</tr>
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<td>31</td>
<td>Range - Method I</td>
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</tr>
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</table>
32 Payload - Method I
33 Mission Fuel - Method II
34 Mission Fuel - Method III
35 Direct Operating Cost - Method I
36 Direct Operating Cost - Method II
37 Direct Operating Cost - Method III
38 Effect of Fuel Cost on Direct Operating Cost
39 Acquisition Cost - Method I
40 Acquisition Cost - Method II
41 Acquisition Cost - Method III
42 Increase in Cruise Coefficient - Method II
43 Increase in Cruise Coefficient - Method III
44 Evaluation Criteria - Method I
45 Evaluation Criteria - Method II
46 Evaluation Criteria - Method III
47 Effect of Varying Mission Payload on Aircraft Sizing
48 Effect of Varying Mission Range on Aircraft Sizing
49 Effect of Cooling Drag on Aircraft Sizing
SUMMARY

The NASA Advanced Aviation Comparative Engine/Airframe Integration Study was initiated to help determine which of four promising concepts for new general aviation engines for the 1990’s should be considered for further research funding. The engine concepts included one highly advanced version each of a rotary, diesel, spark ignition and turboprop powerplant; a conventional state-of-the-art piston engine was used as a baseline for comparison. In addition, advanced but lower risk alternatives were defined for the rotary and spark ignition engines. Late in the study, NASA revised the turboprop data to show significantly improved characteristics, defining a powerplant whose technological challenge is comparable to the other highly advanced engines. The original turboprop data is now viewed as representative of a lower risk and/or lower cost design.

Computer simulations were used to determine how the various characteristics of each engine interacted in the design process of pressurized singles and twins. Comparisons were made of how each engine performed relative to the others when integrated into an airframe and required to fly a transportation mission. The contemporary fleet of Cessna airplanes provided the data base for the study. However, design improvements expected to be available by 1990 were included to reflect the level of performance expected in that time frame.

Evaluation of the results placed heavy emphasis on low fuel consumption and direct operating cost and on high flight efficiency; acquisition cost, noise, multi-fuel capability and ease of installation were also considered but not weighted as heavily.

The results indicate that the highly advanced rotary engine offers the best all around performance and features for future general aviation aircraft. The diesel engine was the next most promising concept and was rated only slightly lower than the rotary. The other engines, though showing worthwhile advances relative to today's engines, did not appear as promising as these two powerplants. In particular the turboprop should be viewed primarily as a viable replacement for the baseline engine, offering market appeal rather than large improvements in efficiency or cost. A parametric analysis indicated that these results were essentially independent of the assumptions made in the study. It did show, however, the advisability of rematching the diesel turbocharger so that greater climb power is available.

The use of these rotary and diesel engines will lead to improved operating economics and freedom from our present dependence upon the availability of avgas. It is recommended that NASA fund research efforts which will provide enabling technology for both engines.
INTRODUCTION

General Aviation is a vital, integral part of the American transportation system (see Ref. 1) which reduces travel time relative to surface means, yet allows easy access to a vast number of destinations not served by scheduled air transportation. However, as uses and opportunities for small airplanes increase, rising fuel costs and spot unavailability of certain types of fuel are hampering their functional utilization. This is a trend which will almost certainly get worse. There is, therefore, an urgent need for more efficient engines capable of accepting the more readily available kerosene-based fuels, or better yet, having a wide tolerance for many fuel types. If the general aviation industry is to remain healthy and if the aircraft are to continue serving the public as they have, these engines must be developed in a timely way.

NASA, recognizing these needs, has funded seven recent studies examining four different powerplant concepts which fulfill the basic requirements for the new engine. These conceptual designs include advance spark ignition engines (Ref. 2), lightweight diesel engines (Ref. 3-4), stratified charge rotary engines (Ref. 5) and advanced small turboprop engines (Ref. 6-9).

Each of these engines exhibits, in varying degrees, the desirable characteristics of low specific fuel consumption, multi-fuel tolerance and reduced size and weight. However, the original studies do not permit a direct comparison of one engine against the others due to their having been conducted by different contractors using different guidelines. The present study was initiated to provide just such a comparison, starting with a common cruise design point and a consistent set of engine weight estimates.
METHJDS AND DATA BASE

STUDY PHASE AND GUIDELINES

The study was divided into the following four major phases: Phase 1 was devoted to organization, gathering appropriate data, and modification of Cessna computer programs where necessary; Phase 2 covered the comparative evaluation of seven different engines in typical missions; Phase 3 explored variations in data, missions and configurations to show the influence of the assumptions made in Phases 1 and 2; in Phase 4 the technology plan recommendations were developed.

From the outset it was decided to base the bulk of the study on fairly conventional airframes, both in terms of structure and aerodynamics. This would make available an extensive and reliable data base and would, it was felt, provide the clearest picture of possible improvements due to the new engines themselves. The impact of an aerodynamically and structurally advanced airframe on the basic results is considered, however.

MISSION DEFINITION

Separate missions for pressurized single and twin engine airplanes were defined. These two typical transportation missions were derived by considering the capabilities of successful general aviation aircraft using the same class of engine (that is, 300 takeoff horsepower and up, which is the high end of the present day engine power spectrum), and then extrapolating them to generally more desirable levels just within the capability of the baseline powerplant.

The mission requirements selected are shown in Table I. In addition to the payload the airplanes were assumed to be equipped with optional equipment totalling 122kg (270lb) for the single and 204kg (450lb) for the twin.

The operational height was set at 25000 ft because cruise altitude has consistently been increasing in recent designs (for better efficiency - see Ref. 10) and because the present FAA regulations tend to limit this growth to 25000 ft (see discussion below on altitude variation, under parametric studies).

The fuel volume and weight are based on 45 minutes reserve at normal cruise power. The minimum wing size must have sufficient volume to hold all of the fuel needed for the basic mission without requiring use of nacelle tanks.
<table>
<thead>
<tr>
<th>PAYLOAD—occupants and baggage</th>
<th>PRESSURIZED SINGLE-ENGINE</th>
<th>PRESSURIZED TWIN-ENGINE</th>
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</thead>
<tbody>
<tr>
<td>PAYLOAD—occupants and baggage</td>
<td>544 kg (1200 lbs)</td>
<td>635 kg (1400 lbs)</td>
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<tr>
<td>RANGE @ MCP</td>
<td>1296 km (700 NM)</td>
<td>1482 km (800 NM)</td>
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<tr>
<td>3 CRUISE SPEED</td>
<td>370 km/hr (200 KTS)</td>
<td>417 km/hr (225 KTS)</td>
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<tr>
<td>CRUISE ALTITUDE</td>
<td>7620 m (25000 ft)</td>
<td>7620 m (25000 ft)</td>
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<tr>
<td>RATE OF CLIMB AT CRUISE ALTITUDE</td>
<td>152 m/min (500 ft/min)</td>
<td>152 m/min (500 ft/min)</td>
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<tr>
<td>TIME TO CLIMB</td>
<td>30 min</td>
<td>30 min</td>
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<tr>
<td>SINGLE ENGINE RATE OF CLIMB AT 5000 FT</td>
<td>---</td>
<td>76 m/min (250 ft/min)</td>
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<td>TAKEOFF DISTANCE AT SEA LEVEL</td>
<td>762 m (2500 ft)</td>
<td>914 m (3000 ft)</td>
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<tr>
<td>STALL SPEED</td>
<td>113 km/hr (61 KTS)</td>
<td>139 km/hr (75 KTS)</td>
</tr>
<tr>
<td>NOISE*</td>
<td>per FAR part 36</td>
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</table>

*See discussion on page 18
The time-to-cruise-altitude requirement was set because experience indicates that cruise altitudes which take excessive time to reach are not often used. The rate of climb requirement was added to insure that reasonably quick increases in altitude could be made while operating in the 20000ft and above range.

ENGINE DATA

The characteristics of each engine were based almost entirely on data supplied by NASA, which in turn came from the feasibility studies defining the engines (Ref 2 through 9). Several of the engine feasibility studies considered both a near term or moderate technical risk engine and a longer term or high technical risk engine. In defining the engines NASA chose one high technology engine from each of the 4 engine types. In addition moderate risk advanced spark ignition and rotary engines were included. The latter are considered by NASA and the designers to be fall back designs should the more advanced engines prove to be unfeasible. A modern current technology spark ignition engine was also specified as a baseline for comparative purposes. These constituted the seven original powerplants analyzed. Late in the study, an eighth engine was added in the form of a revised version of the GATE with improvements of 10% in weight and specific fuel consumption. This was felt to better represent the philosophy of the GATE work, and provided a turboprop engine with a level of technology comparable to that of the highly advanced I.C. engines. The bulk of the GATE results shown in the report refer to the original turboprop engine; special reference is made to the revised engine where appropriate, and specific results are discussed on page 103.

All data were supplied for engines sized to 250 cruise horsepower at 25000 ft. For the turboprop this was taken to be 250 equivalent installed horsepower (i.e. SHP + TV/550\(\eta_{prop}\)) where \(T\) = residual jet thrust, \(V\) = velocity in feet per second and \(\eta_{prop}\) is an average propeller efficiency of 80%.

No systematic designation scheme was available to cover all the various engines. The baseline was given the mnemonic TSIO-550 which is standard for Teledyne Continental Motors. This stands for: turbosupercharged, injected, opposed with 550 cubic inch displacement. The advanced spark ignition engines (also by Teledyne Continental Motors) were designated GTSIO-420 for the advanced engine and GTSIO-420SC for the highly advanced engine. The code is the same as above with the added letters standing for gearing and stratified charge. The diesel goes by the mnemonic GTDR-246 or geared, turbocharged, diesel, radial, with 246 cubic inch displacement. The rotaries are designated RC2-47 (advanced) and RC2-32 (highly advanced). The designation stands for rotary combustion, two rotors, with a displacement (the definition of which
is peculiar to rotary engines) of 47 or 32 cubic inches per rotor. The turboprop goes by the acronym GATE, standing for General Aviation Turbine Engine which was the title of the set of studies defining this powerplant.

A summary chart showing the most pertinent data on engine characteristics is included as Table II. The complete NASA approved data package is shown on Table III. Other miscellaneous engine data are shown on Table IV and Figures 1 through 4.

As noted above and shown in Tables II and III, each engine excels in one or more characteristics. The rotaries and GATE have low RPM (good noise characteristics and propeller efficiency), the diesel and highly advanced spark ignition have the lowest SFC's, the rotaries and spark ignition have the highest climb power at altitude, while the GATE, rotaries and GTSIO-420SC are capable of using the widest spectrum of fuel types.

It should be noted, however, that the design philosophy of the turboprops stressed low initial cost rather than low fuel consumption.

AIRFRAME DATA BASE

The simulation requires data on drag, propeller characteristics, high lift devices, weight, pricing, operating expenses and noise. Each is dependent on airframe design and is discussed in detail below.

WEIGHT: Airframe weight is broken into some 15 to 20 components (depending on model type) and each is estimated by an appropriate equation - usually a parametric fit to the present Cessna fleet. The equations, therefore, represent riveted and bonded aluminum structure. For this study the estimated weight for the major structural assemblies was reduced by 5% based on anticipated use of lighter materials, more extensive use of bonding, and better design and manufacturing practices.

DRAG: The drag level of the single was based on the Cessna 210 which is one of the fastest aircraft in its class. The drag of the twin engine design was based on Cessna Models T303 and 421.

A parabolic polar representation for drag is used, with $C_d0$ calculated from the equivalent skin friction coefficient (i.e. an empirically determined weighted average that accounts for skin friction, miscellaneous protruberances, etc) and the total wetted area. The induced drag coefficient $C_{d1}$ is calculated from the equation:
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*Installed ESPH
# TABLE III

## COMPLETE ENGINE DATA CHART

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<td>SFC</td>
<td>0.600</td>
<td>0.600</td>
<td>0.600</td>
<td>0.600</td>
<td>0.600</td>
<td>0.600</td>
<td>0.600</td>
<td>0.600</td>
</tr>
<tr>
<td>SCALING POWER</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
</tr>
<tr>
<td>SCALING SFC</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
<td>LINEAR</td>
</tr>
<tr>
<td>CYCLING REVERSAL</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>PERCENT HP</td>
<td>77.6%</td>
<td>77.6%</td>
<td>77.6%</td>
<td>77.6%</td>
<td>77.6%</td>
<td>77.6%</td>
<td>77.6%</td>
<td>77.6%</td>
</tr>
</tbody>
</table>

*Notes: All data subject to change. The data is approximate at sea level and standard conditions.*
### TABLE IV
**MISCELLANEOUS ENGINE DATA**

a) Cooling drag data supplied by TCM for max cruise with cowl flaps closed

<table>
<thead>
<tr>
<th>INSTALLATION</th>
<th>TSIO-550</th>
<th>GTSO-420</th>
<th>GTSO-420SC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINGLE</td>
<td>0.0404 sqm (.435 sqft)</td>
<td>0.0229 sqm (.247 sqft)</td>
<td>0.0193 sqm (.208 sqft)</td>
</tr>
<tr>
<td>TWIN</td>
<td>0.0321 sqm (.345 sqft)</td>
<td>0.0182 sqm (.196 sqft)</td>
<td>0.0153 sqm (.165 sqft)</td>
</tr>
</tbody>
</table>

b) Fuel Compatibility

<table>
<thead>
<tr>
<th>ENGINE</th>
<th>AVGAS</th>
<th>DIESEL</th>
<th>JET FUELS</th>
<th>OTHERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSIO-550</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSIO-420</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GTSO-420SC</td>
<td>?</td>
<td>?</td>
<td>X</td>
<td>?</td>
</tr>
<tr>
<td>GTDR-246</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>RC2-47, &amp; -32</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>GATE</td>
<td>?</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C) INSTALLATION WEIGHTS

<table>
<thead>
<tr>
<th>DIESEL AND ALL SPARK IGNITION</th>
<th>GATE</th>
<th>ROTARY</th>
<th>RC2-47</th>
<th>RC2-32</th>
</tr>
</thead>
<tbody>
<tr>
<td>BATTERY</td>
<td>10.4</td>
<td>29.5</td>
<td>10.4</td>
<td>23</td>
</tr>
<tr>
<td>PROPELLER</td>
<td>36.3</td>
<td>36.3</td>
<td>36.3</td>
<td>80</td>
</tr>
<tr>
<td>SPINNER</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>4</td>
</tr>
<tr>
<td>MOUNTING ISOLATORS</td>
<td>2.3</td>
<td>7.7</td>
<td>2.3</td>
<td>5</td>
</tr>
<tr>
<td>OVER-VOLTAGE RELAY</td>
<td>5.1</td>
<td>1.4</td>
<td>.9</td>
<td>2</td>
</tr>
<tr>
<td>PROP ATTACH HDWR</td>
<td>1.8</td>
<td>2.3</td>
<td>1.8</td>
<td>4</td>
</tr>
<tr>
<td>EXHAUST PIPE</td>
<td>1.8</td>
<td>3.6</td>
<td>.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.5</td>
<td>1.4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.5</td>
<td>2.1</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>54.9</td>
<td>88.8</td>
<td>63.1</td>
<td>139</td>
</tr>
<tr>
<td></td>
<td>121</td>
<td>196</td>
<td>139</td>
<td>138</td>
</tr>
</tbody>
</table>
FIGURE 1
EFFECT OF ENGINE SCALING ON SPECIFIC FUEL CONSUMPTION
GENERAL AVIATION TURBINE ENGINE

RATIO OF EQUIVALENT SPECIFIC FUEL CONSUMPTION AT SCALED POWER TO EQUIVALENT SPECIFIC FUEL CONSUMPTION AT 474 KILOWATTS (635 HORSEPOWER) VERSUS EQUIVALENT TAKEOFF POWER

ESFC/ESFC @ 474kilowatts (635hp)

horsepower

0 100 200 300 400 500 600 700 800

0 100 200 300 400 500

kilowatts

EQUIVALENT TAKEOFF POWER OF SCALED ENGINE
FIGURE 2
ADVANCED DIESEL ENGINE CHARACTERISTICS
EFFECT OF ALTITUDE ON ENGINE POWER
AND BRAKE SPECIFIC FUEL CONSUMPTION

FOR ENGINES RATED AT 260kW (350HP) TAKEOFF POWER
100kW (135HP) CRUISE POWER
FIGURE 3
ADVANCED DIESEL ENGINE CHARACTERISTICS
EFFECT OF ENGINE SCALING ON
SPECIFIC WEIGHT AND BRAKE
SPECIFIC FUEL CONSUMPTION

BSFC @ 7620m
(g/kW-hr)

0.36
0.34
0.32
0.30

BSFC @ 25000ft
(#/hp-hr)

0.8
0.6
0.4
0.2

SPECIFIC WGT
(kg-wet/kW)

1.6
1.2
0.8
0.4

SPECIFIC WGT
(#-wet/takeoff shp)

0.0
0.2
0.4
0.6
0.8
1.0

SPECIFIC WGT
(kg-wet/kW)

(horsepower)

(kilowatt)

TAKEOFF POWER OF SCALED ENGINE
FIGURE 4
ADVANCED DIESEL ENGINE CHARACTERISTICS
EFFECT OF ENGINE SPEED ON POWER OUTPUT AND BRAKE SPECIFIC FUEL CONSUMPTION
ALL ALTITUDES

ENGINE SPEED (percent of maximum)

<table>
<thead>
<tr>
<th>Engine Speed</th>
<th>Full Power Cruise</th>
<th>Economy Cruise</th>
</tr>
</thead>
<tbody>
<tr>
<td>40%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SHAF POWER (% of maximum power)

BSFC (% of BSFC @ max power)

FULL POWER CRUISE
ECONOMY CRUISE
\[ C_{di} = \left( kC_{do} + 0.33/AR \right)C_L^2 \]

where \( k \) is empirically determined by evaluating airplanes of a configuration similar to the one being sized. The values of skin friction coefficient and \( k \) used in this study are shown in Table V. Also shown are the increments for gear drag, flap drag and the fuselage wetted area for the different configurations (including nacelles for the twins); the sizing program determines the wetted areas of the wings and empennage and calculates the total.

One of the most difficult problems is that of estimating engine cooling drag, which can be expected to vary widely over the range of engines considered. The heat rejection rate for each engine was known, but the associated pressure drop was not available for any of the powerplants. Without precise information on both values only rough estimates of drag are possible. Reference 11 gives some typical values which can be used to estimate cooling drag, but the range of possible values is so large that the data are all but useless for a comparison such as this. Reasonable estimates based on available data and experience were used in Phase 2 and a parametric drag variation was done in Phase 3 to determine the effects of different levels. The Phase 2 cooling drags used were:

<table>
<thead>
<tr>
<th>ENGINE</th>
<th>DRAG LEVEL</th>
<th>REASON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>12% of total drag</td>
<td>Contemporary state of the art</td>
</tr>
<tr>
<td>Diesel and Adv S.I.</td>
<td>8% of total drag</td>
<td>Reduced heat rejection; improved state of the art</td>
</tr>
<tr>
<td>Rotaries</td>
<td>0% of total drag</td>
<td>Well designed liquid cooling system</td>
</tr>
<tr>
<td>GATE</td>
<td>0% of total drag</td>
<td>Turboprop</td>
</tr>
</tbody>
</table>

PROPELLERS The 1941 Hamilton Standard Propeller performance method is used in deriving the Cessna data base and is, therefore, the method used for estimating thrust in the sizing program.

A propeller configuration was chosen to match the mission requirements and the characteristics of each engine. Only one propeller optimization, however, was run for each engine/mission combination; i.e., the propeller choice was not part of the synergistic design process and, therefore, the propeller configuration may not represent the absolute optimum design though it will be very close. This optimization was constrained to keep propeller diameter to low enough values that the airplane could be certified under existing noise regulations. Diameter was also not allowed to exceed 90 inches to keep gear length and weight reasonable. This optimization process considered six climb points equally weighted with one cruise point to give good overall mission performance.
### TABLE V

**COMPONENTS USED IN ESTIMATING DRAG**

<table>
<thead>
<tr>
<th>CONFIGURATION</th>
<th>SINGLE ENGINE</th>
<th>TWIN ENGINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQUIVALENT SKIN FRICITION COEF.</td>
<td>.0049</td>
<td>.0055</td>
</tr>
<tr>
<td>( k^* )</td>
<td>.30</td>
<td>.45</td>
</tr>
<tr>
<td>DRAG INCREMENT FOR TAKEOFF (FLAPS &amp; GEAR)</td>
<td>( \text{sqm} )</td>
<td>( \text{sqft} )</td>
</tr>
<tr>
<td>BASELINE</td>
<td>26.66</td>
<td>287.0</td>
</tr>
<tr>
<td>RC2-47</td>
<td>27.36</td>
<td>294.5</td>
</tr>
<tr>
<td>RC2-32</td>
<td>27.36</td>
<td>294.5</td>
</tr>
<tr>
<td>GTDR-246</td>
<td>27.56</td>
<td>296.7</td>
</tr>
<tr>
<td>GTSIO-420</td>
<td>27.30</td>
<td>293.9</td>
</tr>
<tr>
<td>GTSIO-420SC</td>
<td>23.41</td>
<td>305.8</td>
</tr>
<tr>
<td>GATE</td>
<td>27.14</td>
<td>292.1</td>
</tr>
</tbody>
</table>

\[ C_D = (kC_D^0 + \frac{.33}{\lambda})^2 \]
Use of constant speed, 3-bladed propellers with Clark-Y airfoils was assumed based on experience with this class of airplane.

The recently completed NASA study on General Aviation Propellers (GAP, see Ref. 15) indicates that significant gains are possible in propeller design. These gains are due to a combination of advances in aerodynamics and materials. In keeping with the general philosophy of conservatism only about one-half of the projected gains shown for these new propellers were incorporated into the study model. The gains used were:

- Change in weight: 20 lb decrease
- Change in efficiency: 3% increase
- Change in noise: 2 dB(A) decrease

WING TECHNOLOGY At the present time new laminar flow airfoils are being developed, but it is not certain that they will be in common use by 1990. The problems of maintaining the necessary manufacturing tolerances in conventional metal structures at a reasonable cost and of maintaining the necessary degree of cleanliness in day to day operations are obstacles to their adoption. Therefore, the use of turbulent boundary layer airfoils was assumed.

The flaps selected are conventional single slotted surfaces with moderate aft travel during deployment extending over 85% of the span. A trimmed maximum lift coefficient (with 30 degrees landing flaps) of 2.1 was assumed for the study and should be easily attainable. With the flaps occupying most of the wing span, slot lip spoilers and feeler ailerons are employed for lateral control.

ACQUISITION COST The total cost (in 1981 dollars) is estimated as the sum of airframe cost, powerplant cost, and the cost of optional equipment.

The airframe portion is estimated by a parametric fit to the 1981 Cessna fleet. This correlation relates price as an exponential function of dry empty weight (minus propulsion system and optional equipment weights), takeoff gross weight, maximum speed and wing area. The form of the equation and the exponents used are shown in Table VI.

The engine contribution to the selling price was estimated based on an arbitrary $100 per takeoff horsepower. This is slightly higher than today's average due to the necessary investment (using inflated dollars) in research and tooling to build a completely new powerplant. The $100/10 figure was also used for the turboprop but was applied to the gross (un-installed i.e. shaft plus accessory) equivalent horsepower for takeoff (sea level, standard day, zero airspeed).
TABLE VI

ACQUISITION COSTS

COST = Costs attributable to airframe + powerplant + optional equipment

AIRFRAME -- Parametric fit to Cessna's current fleet

\[ S = a W_E^b V_{max}^c S_W^d W^e \]

- \( a = 7.268188 \times 10^{-4} \)
- \( b = 1.06942 \)
- \( c = 1.056 \)
- \( d = 0.65289 \)
- \( e = 0.72723 \)

- \( W_E = \text{BEW - Optional Eq. - Powerplant} \)
- \( V_{max} = \text{Maximum Speed in Knots} \)
- \( S_W = \text{Wing Area (ft}^2\text{)} \)
- \( W = \text{TAKEOFF GROSS WEIGHT (lbs)} \)

POWERPLANT -- $100/\text{Takeoff Horsepower Rating (IC Engines)}$

- $100/\text{Equivalent Uninstalled Takeoff Horsepower (Turboprop, Sea Level Std day, Zero Airspeed)}$

OPTIONAL EQUIPMENT -- Typical Values for Well Equipped Planes

- $48,000 \text{ Single Engine}$
- $82,000 \text{ Twin Engine}$

17
The cost values chosen for optional equipment are typical of well-equipped IFR airplanes as they are ordered today. For the single engine model the value used was $48,000; for the twin it was $32,000.

**DIRECT OPERATING COST** The components considered in estimating DOC are: engine maintenance and overhaul, propeller overhaul, airframe and systems maintenance, cost of oil, fuel and insurance, depreciation, and reserves for avionics. A description of how these items are generated is included in Appendix I. For a study of hypothetical engines some of the terms such as engine maintenance and overhaul must be generalized even further; these are shown on Table VII.

The components of direct operating cost which relate to the engine were not available for the new powerplants (for example, overhaul cost). Fortunately, these are second order terms and even large errors have little effect on the total DOC. In lieu of better numbers the inputs to the DOC estimation routine, shown in Table VII, were based on an analysis of the current Cessna fleet. Turboprop values were generalized from data supplied by manufacturers of current generation turbine engines.

Note that depreciation (to zero residual in 7.5 years) is included in this estimate, making it an amortized direct operating cost. Five hundred hours annual utilization was assumed.

**NOISE** Noise is estimated by an equation based on a parametric fit to the present Cessna fleet. This relates noise primarily to propeller tip mach number, but also shows it to be a function of engine horsepower, number of blades, number of engines, rate of climb and a flag indicating whether the engine is normally aspirated or turbocharged. Again, in lieu of better information, this was used directly for all of the engines.

**SIZING METHODOLOGY**

If the engines are to be compared on an equitable basis, then each must be installed in the "best" airframe for that engine. "Best" in the context of this study meaning lowest mission fuel, lowest DOC and lowest acquisition cost, usually achieved by minimizing weight.

The computer logic that iterates on the design variables to determine the minimum (or best) aircraft configuration is called a sizing program. This one is designed to run on a Hewlett-Packard 9225A desk top computer system. The program structure is shown schematically on Figure 5. The input module prompts the user to supply all the numerical descriptions of the mission requirements, the engine, propeller and airframe characteristics, the economic
**TABLE VII**

**DATA BASE**

DIRECT OPERATING COST
BASED ON ANALYSIS OF CURRENT CESSNA FLEET

- **ENGINE MAINTENANCE**

  0.225 $/hr/eng - BHP/eng (IC)

  \[
  \frac{1}{2} \text{ PURCHASE PRICE IN} \quad 4000 \text{ HR TBO PERIOD} \quad \text{TURBOPROP}
  \]

- **ENGINE OVERHAUL**

  PARAMETRIC FIT (IC)

  \[
  \frac{1}{2} \text{ PURCHASE PRICE IN} \quad 4000 \text{ HR TBO PERIOD} \quad \text{TURBOPROP}
  \]

- **AIRFRAME/SYSTEM MAINTENANCE**

  PARAMETRIC FITS OF CURRENT FLEET

- **PROPELLER OVERHAUL**

  TYPICAL CURRENT VALUES

- **INSURANCE (HULL & LIABILITY)**

  1981 RATES

- **FUEL COSTS**

  $1.70/JAL (BOTH AVGAS AND JET FUEL)

- **OIL COSTS**

  $6.00/JAL

- **DEPRECIATION**

  ZERO RESIDUAL IN 7.5 YEARS ? 500 HR/yr

- **AVIONICS**

  10% OF AVIONICS COST EVERY 1000 HRS
  (AVIONICS ACCOUNT FOR HALF THE OPTIONAL EQUIPMENT COSTS)
Figure 5

Program Structure

Input Module

Select Design Variables

Varies T/OGW to meet Primary Design Constraint

Calculates Perf at Weight for Primary Constraint

Output Module (Carpet Plot)
factors and the design characteristics to be varied as well as the range of variation.

The actual calculations then proceed automatically with a main routine sequentially changing the designated design variables. (The program works with any two factors - for example, wing area and aspect ratio - at the discretion of the analyst.) The program then varies takeoff gross weight (TOGW) to meet any of the design requirements chosen by the user. On the chart on Figure 5, a solid line is drawn showing payload-range as the selected requirement; dotted lines indicate that rate of climb, cruise speed, etc. could just as easily have been used. Once the TOGW is determined which allows the airplane to meet this primary design requirement, then that weight is used to calculate the other performance characteristics of the design. After the calculations are finished a separate module prints and automatically plots the results.

A typical output is shown on Figure 6. This is a carnets plot in which each point represents an airplane capable of carrying a 1200 pound payload 700 nautical miles. The weight is actually the independent variable used to drive the range to the selected value. Every airplane represented on this graph has a different set of performance characteristics, some better than the specified constraints and some worse.

The program then plots overlays showing the boundaries where the remaining constraints are just met; an example is shown in Figure 7. The shaded region represents all airplanes that (1) are faster than the minimum cruise speed, (2) have a higher rate of climb than the minimum, and (3) have a stall speed lower than the maximum allowed. Note that although a maximum takeoff field length (TOFL) was specified it is not constraining in this example since all points in the shaded region exceed the requirement. The minimum weight point shown here occurs at a wing area of approximately 170 sq ft and an aspect ratio of around 8.5.

Actually, some 17 to 18 overlays are commonly used for each design to check such characteristics as fuel volume, acquisition cost, DOC, cruise efficiency, etc. The process makes all of the design choices visible and allows an easy tradeoff of one benefit against another.

**EFFICIENT FLIGHT**

The aircraft speed that minimizes fuel consumption is the speed for maximum lift to drag ratio (VL/D). For general aviation aircraft this usually corresponds to a power setting of around 45%; experience indicates that virtually no flights are made at this low speed. Reference 10 discusses this incompatibility between common usage and best fuel speed and why it is impractical to
FIGURE 7

PERFORMANCE CONSTRAINTS ON
CARPET PLOT OF CONSTANT PAYLOAD RANGE
design an airframe to cruise at maximum L/D. Briefly summarized:

\[ \frac{D}{L} = AV^2 + \frac{\beta}{V^2} \]

where:

- \( A = \frac{p}{2W} \) and \( B = \frac{2W}{\rho b^2} \)
- \( \rho \) = density
- \( f \) = equivalent flat plate area
- \( W \) = weight
- \( b \) = wing span
- \( e \) = span efficiency

High L/D is achieved by keeping the terms \( A \) and \( B \) small. Yet lowering the value of \( \rho \) (i.e., flying at higher altitudes) or raising the value of \( W \) to decrease \( A \) increases \( B \) and conversely. The same is true of the fictitious areas \( f \) and \( b^2 \) since they exist in some proportionality. Further:

\[ \frac{L}{D_{\text{max}}} = \sqrt{\left(\frac{\pi e b^2}{2f}\right)} \quad \text{and} \quad \frac{V_L}{D} = \frac{\sqrt{2W/\rho}}{\sqrt[4]{\pi e b^2}} \]

which illustrates that a high value of \( L/D \) requires a low ratio of \( f \) to \( b^2 \) whereas a high value of \( V_L/D \) requires a low product of \( f \) and \( b^2 \). Further, providing adequate power for climb means that there is an excess for cruise, making it all too easy to exceed \( V_L/D \). If he isn't using all, or most of the power available, the pilot feels that he is wasting time.

Having reviewed this "designer's dilemma" Reference 10 goes on to introduce the concept of the "least wasteful way to waste fuel" which is the least increase in fuel per unit increase in speed above \( V \) for maximum \( L/D \). This occurs at \( V^* \) which is defined as \( \sqrt{3(V_L/D)} \). On a typical trip, compared to flying at the speed for minimum fuel usage, flying at \( V^* \):

- is 32% faster
- reduces flight time by 24%
- uses only 16% more fuel

Flying at \( V^* \) minimizes the power required to maintain kinetic energy in the face of energy dissipation due to drag, and minimizes the energy required to move a given weight a given distance at a given velocity.

The new engines considered in this study produce a given horsepower at a much lower weight and with a greatly reduced fuel consumption compared to current powerplants. This affects the sizing process in many ways. Consider again Figure 7: reanalysis with one of the advanced engines would lower the entire carpet to smaller weights and would also, on the new carpet, cause the cruise speed line to move up and to the right while the stall speed, climb and takeoff lines would move down. The resultant minimum moves to low values of wing area and aspect ratio.

Instinctively this does not seem right, in particular the large...
reduction in aspect ratio. And indeed it is not a good way to size the airplane because advantage is being taken of the engine's good performance to make the wing inefficiently small. The problem is to match the airframe's efficiency to the engine's characteristics. As shown above, it is impractical to design an airplane to cruise at $V_L/D$; it is practical, however, to size one to cruise at $V^*$ (or slightly higher at maximum cruise power so that reduced power settings still maintain speeds around $V^*$). $V^*$ was, therefore, used as another constraint in this study to insure that efficient airframes were matched to each of the new engines. An alternative approach would be to constrain the cruising speed to that of the baseline, but this can also lead to choosing less efficient airframes. This is discussed in detail on page 97.
BASELINE AIRFRAMES

SINGLE ENGINE The Cessna P210 is the basis for the single engine configuration chosen for the study (shown in Figure 8 with the baseline engine). The cabin area pressure vessel is little different in configuration from the P210 except for being stressed to the higher pressurization level required for cruise at 25000 ft while maintaining a 10000 ft cabin altitude. The wing is redesigned for the new flap and roll control system and sized for the design mission of this study. The tail is resized as needed and uses higher aspect ratio surfaces than the P210. The engine compartment is changed, as necessary, to accommodate each engine.

TWIN ENGINE The twin engine baseline configuration for the study is shown on Figure 9. The design is seen to use a conventional, low wing layout with wing mounted engines. The wing configuration itself is the same as that of the single engine airplane except for the engine nacelles and is sized appropriately for each engine.

No installation drawings for the baseline engine were done since it is physically almost identical with the contemporary TSIO-520 which is in widespread use.

ROTARY-POWERED AIRFRAMES

SINGLE ENGINE The single engine design with the rotary engine is shown in Figure 10. For considerations of passenger comfort the size of the cabin compartment cannot be appreciably altered from the baseline. The wing cannot be moved very far fore or aft for both structural and aerodynamic reasons, so the lighter engine must be moved forward to keep the center of gravity in the correct position. This has the advantage of opening up a baggage compartment in front of the cabin which increases available baggage volume and provides an alternate loading area which makes center of gravity control easier. The wing area is smaller than for the baseline since the weight is considerably lower.

The engine installation drawing is shown in Figure 11 for the RC2-32 engine; the RC2-47 would be essentially the same. The small size of the engine allows it to fit easily into the cowl whose cross section is largely set by the cabin size. Accessibility should be very good relative to the baseline engine installation. The radiator, which should be large and thin for minimum cooling drag, fits comfortably within the cowl. There is also room to expand the cooling air to low speeds before entering the radiator, which is another requirement for low cooling drag. Induction
FIGURE 8  
BASELINE SINGLE  

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

GROSS WT, LB 4460  
SPAN, FT 40.2  
ASPECT RATIO 9.5
FIGURE 9
BASELINE TWIN

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

GROSS WT, LB  6850
SPAN, FT  44.5
ASPECT RATIO  11.0
FIGURE 10
ROTARY SINGLE

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

GROSS WT, LB  3881
SPAN, FT       34.9
ASPECT RATIO  8.3
Figure 11

RC 2-32 Highly-Advanced Rotary Engine Single-Engine Installation Concept

Coolant Radiator

Turbocharger

Charge Air Inlet

Inlet for Cabin Air Heat Exchangers

Cabin Pressurization Air Heat Exchangers

Charge Air Cooler

Cooling Air Outlet
and cooling air are brought in through NACA flush scoops on the sides of the cowling.

Air is bled from the compressor for cabin pressurization. Provision must be made both to cool and to heat it depending on the outside conditions. For air cooled engines the pressurized air is passed through a heat exchanger that is either cooled by outside ram air or heated by air from a shroud around the exhaust pipe. A similar system is envisioned for the liquid cooled engine except that the ram air passes through an auxiliary radiator before flowing over the pressurized air heat exchanger. Temperature is controlled by the amount of coolant flowing through this auxiliary radiator. For cooling the cabin air no fluid is used, while for heating, the auxiliary radiator is fully functional and the heat is transferred back to the exchanger.

**TWIN ENGINE** The twin engine configuration using the rotary engines is shown in Figure 12. The radiators are housed in leading edge extensions on the inboard wing panels (similar to the installation on the British de Havilland Mosquito of WWII). Although there might be slight weight penalties for this configuration, due to extra piping and coolant, it is felt that these would be offset by other advantages. Detailed examination of these factors was, however, beyond the scope of this study.

Again the radiators are kept large and thin with minimum flow velocities through them in order to reduce the cooling drag. They occupy the entire leading edge of the wing from the nacelle to the fuselage. Deice or antiice for the inboard wing sections will require careful development. Use of heat from the engine coolant to melt the ice will likely result in a runback of water which will refreeze on the wing and flaps. Pneumatic boots, however, will be difficult to locate without being affected by the heat and/or disturbing the flow into the radiator. It is possible that some combination of these two would work but more likely a completely new system will be required such as a glycol exuding leading edge.

The installation is shown on Figure 13. As can be seen the size of these engines allows the designer to produce extremely clean, thin nacelles with small cross sections and reduced wetted areas with a consequent reduction in drag. Further the destabilizing moment of the nacelle, which varies with the square of the width, is greatly reduced thus increasing stability or reducing the required tail size. Note that the spinners are the minimum size to accommodate the propeller hubs.

The exhaust is ducted overboard on the outside of the nacelle to minimize cabin noise. There is insufficient room in the small nacelles to bend the exhaust pipe down and duct the exhaust out the bottom, and a vertical turbocharger installation is not recommended because of problems routing the induction air to the compressor face.
FIGURE 12
ROTARY TWIN

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

RC2-41  RC2-32
GROSS WT, LB  5788  5454
SPAN, FT  38.1  35.0
ASPECT RATIO  9.8  8.45
FIGURE 13

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

CHARGE AIR INLET
AND FILTER

WING LEADING EDGE
RADIATOR

CHARGE AIR COOLER

TURBOCHARGER

CABIN PRESSURIZATION AIR
HEAT EXCHANGERS
DIESEL POWERED AIRFRAMES

SINGLE ENGINE The single engine airplane configured for the diesel is shown in Figure 14. Like the rotary, the light weight of this engine allows a baggage compartment to be added ahead of the cabin. The installation drawing is shown in Figure 15. The large frontal area of a radial presents no problem in the single since the cabin area dictates a large cross sectional area anyway. A propeller shaft extension was added for better cowling contours and an accompanying weight penalty of 3 pounds was added in the analysis.

The cabin air pressurization system employs a temperature regulation system identical to the rotary except that the auxiliary coolant radiator is replaced by an auxiliary oil radiator. (In either case should the system prove unworkable a system similar to that of an air cooled engine would probably be acceptable but would not have the simplicity of this design.)

TWIN ENGINE A similar engine installation was tried for the twin with the resultant 3-view shown in Figure 16. Compared to the baseline the nacelle shape is not bad. Compared to the rotary it is much less pleasing aesthetically, the wetted area is larger with a consequently greater drag and the large blockage area behind the propeller reduces its efficiency.

To offset these disadvantages the low profile engine configuration shown in Figure 17 was conceived. The power section is laid on its back so that the crankshaft rotates about a vertical axis with the output transferred 90 degrees through bevel gears to the propeller shaft. A 25 pound/engine weight penalty was added for this more complex gear box. This value is arbitrary and a careful design is expected to show that the new gear box is not much heavier than the one it replaces. The changes necessary to reverse the propeller rotation would be minimal.

The twin engine design utilizing this version of the diesel is shown on Figure 18. The nacelles are small and compact, shaped much like a cowling for a horizontally opposed engine. The installation itself is shown on Figure 19. This configuration will require careful attention to baffle design to provide cooling to all the cylinders. Again the spinner is the smallest that will enclose the propeller hub.

SPARK IGNITION POWERED AIRFRAMES

SINGLE ENGINE The single engine airframe adapted for the advance spark ignition engine is shown on Figure 20 and the engine installation is shown on Figure 21. These powerplants use a tuned
FIGURE 14
DIESEL SINGLE

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

GROSS WT, LB  3849
SPAN, FT      35.8
ASPECT RATIO  8.8
FIGURE 15

TD-246 HIGHLY-ADVANCED DIESEL ENGINE SINGLE ENGINE INSTALLATION CONCEPT

CHARGE AIR PLenum
AIR FILTER
OIL TANK
INTERCOOLER
AIR INLETS (LM & RM)
CABIN COOLING AIR EXIT
INTERCOOLER
APU INDUCTION AIR CIRCUIT
SONIC VENTURI
CABIN HEAT RADIATOR (ALTERNATE OIL COOLER)
TO CABIN
CABIN COOLING HEAT EXCHANGER
COWL FLAP
ENGINE COOLING AIR
FIGURE 16
DIESEL TWIN (UPRIGHT MOUNTING)
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME, FIXED PAYLOAD-RANGE
FIGURE 18
DIESEL TWIN
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

GROSS WT, LB  5753
SPAN, FT  39.1
ASPECT RATIO  10.6
FIGURE 19

TDI-246 HIGHLY-ADVANCED DIESEL ENGINE
TWIN-ENGINE INSTALLATION CONCEPT

INTERCOOLER INLET
(LH & RH)

INDUCTION AIR FILTER

STARTER-GENERATOR

ENGINE EXHAUST

SHOCK MOUNT

SUPERCHARGER TURBINE

INTERCOOLER AIR EXIT

INTERCOOLER

ENGINE COOLING AIR EXIT

CABIN COOLING AIR EXIT

OIL TANK

CABIN AIR COOLER/HEATER

APU AIR CIRCUIT

AIR STARTER
FIGURE 20
ADVANCED SPARK-IGNITION ENGINE
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME, FIXED PAYLOAD-RANGE

GROSS WT, LB  4117  3888
SPAN, FT  37.8  35.3
ASPECT RATIO  9.15  8.55
FIGURE 21

GTS10-420SC HIGHLY-ADVANCED SPARK-IGNITION ENGINE
SINGLE ENGINE INSTALLATION CONCEPT
exhaust system to improve turbocharger efficiency which makes the engines rather long. This limits the installation flexibility since the turbocharger cannot be relocated for the benefit of the airframe design. The length also precludes the installation of a nose baggage compartment.

Further the exhaust system, turbocompounding equipment and turbocharger are so located that it is unclear how accessories will be located at the back of the engine (as planned by TCM). Assuming that they are, maintenance may be difficult.

The overhead exhaust path requires an upflow cooling path. If the air is then ducted out through the top of the cowling, means must be provided to close the exit louvers in case of engine fire to prevent the blaze from coming through the cowling and destroying the windshield. If, on the other hand, the cooling air is ducted out the bottom through a cowl flap (as shown on Figure 21) then problems arise from heating of the accessories and turbocharger.

The engine designers envisioned cooling the oil by use of a finned sump. However the necessary ducting and baffling to get air to the sump and the required fin area on the sump are likely to be more complex and will weigh more than a conventional oil cooler. Therefore, Figure 21 shows a separate oil cooler.

Cabin air temperature can be controlled either by a conventional heat exchanger system or by a system similar to the diesel configuration.

TWIN ENGINE The twin engine spark ignition configuration and installation drawings are shown in Figures 22 and 23, respectively. Note here the relatively large nacelles. Also, whereas locating the accessories around the exhaust system was inconvenient on the single it is even more difficult in the compact nacelle of the twin.

GATE POWERED AIRFRAMES

SINGLE ENGINE The GATE powered single is shown on Figure 24 and the installation drawings are on Figure 25.

The turboprop is very light which makes it possible to include a nose baggage compartment. The exhaust, however, is difficult to dump overboard. As shown, the exhaust ducting is rather long and takes a number of bends to reach the bottom of the airplane and yet allow room for the nose gear; it also intrudes somewhat into the nose baggage area. Leading the exhaust out the side is impractical because of possible intrusion of the exhaust products into the cabin through the door.

For heating the cabin air a system similar to that used on
FIGURE 22
ADVANCED SPARK IGNITION TWIN

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

GROSS WT, LB 6314 5907
SPAN, FT 43.1 40.7
ASPECT RATIO 11 11
FIGURE 23

GTSIO-420 SC HIGHLY-ADVANCED SPARK-IGNITION ENGINE
TWIN-ENGINE INSTALLATION CONCEPT

[Diagram of engine installation concept]
FIGURE 24
GATE SINGLE

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

GROSS WT, LB  3907
SPAN, FT      35.5
ASPECT RATIO  8.45
conventional spark ignition engines is utilized, drawing hot ram air through a muff around the exhaust pipe.

Bleeding the compressor for cabin pressurization is impossible on this small turboprop because of unacceptable performance losses. Instead, a pump is mechanically driven through the accessory section to provide the required air.

**TWIN ENGINE** The twin engine configuration and installation are shown on Figures 26 and 27. Maintaining the c.g. location in a favorable position with the light weight of this engine precludes short nacelles where the exhaust can be ducted out the rear. Therefore, short overboard exhausts are provided. This has the advantage of allowing baggage or fuel storage in the rear of the nacelles.

Again, this installation is typical of that which would be used with either the original or the revised GATE definition.
FIGURE 26
GATE TWIN

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

GROSS WT, LB  5750
SPAN, FT  35.8
ASPECT RATIO  7.7
FIGURE 27

GATE HIGHLY-ADVANCED TURBOPROP ENGINE
TWIN-ENGINE INSTALLATION CONCEPT

[Diagram of aircraft engine installation]

- Cabin Pressurization Air Pump
- Sonic Venturi
- Heat Exchanger
- Engine Induction Air
- Heat Exchanger Air Inlet (Cold Source LH, Hot Source RH)
- Heater Muff
- Engine Exhaust
- To Cabin
RESULTS AND DISCUSSION

METHODS OF COMPARISON

The evaluation of the various engines is based on a comparison of the airframe/engine combination. Three methods are used to generate airframes for this comparison:

Method I. Fixed Airframe, Fixed Engine Size, Variable Mission

This method of comparison assumes that the airframe size and gross weight are fixed at the baseline values and the various engines are interchanged, and they are compared on their ability to produce the highest performance from that airframe. The advantage of this method is that it is representative of the first use to which any new engine is usually put, namely that of re-engining an existing airplane. The disadvantage is that it produces airplanes with considerable differences in range, payload, and speed and it is difficult to come to a consensus as to how these characteristics should be ranked in order to compare the results.

Method II. Fixed Engine Size, Fixed Mission, Variable Airframe

The second method of comparison allows the weight and wing geometry to change in order to most nearly match the entire vehicle performance to the requirements. This results in a more even handed comparison of the engines since each airframe is then the best configuration for that engine's characteristics. The disadvantage is that although the baseline engine is well sized, all of the new engines are somewhat oversized to do the given mission because of the smaller, lighter airframes which result. There is nothing to indicate that giving the engines the same cruise horsepower makes them "equal", whatever equal means in the context of this study. In any case, keeping a constant engine size does not show the true, maximum efficiency that the engines can deliver.

Method III. Fixed Mission, Variable Airframe and Engine

This analysis varies wing area and aspect ratio, gross weight and engine size concurrently to define the optimum design. This is probably the best means of comparing the engines because each engine is allowed to seek the lowest power level that will do the mission, considering its characteristics. The engines then are equal in terms of their ability to do a job rather than in terms of an arbitrary equality based on cruise horsepower. This precludes one engine having an advantage by any fortuitous matching of its rating and characteristics to the chosen mission. The only disadvantage of such a comparison is that it is much more time consuming than the first two methods.
EVALUATIONS

The results of the Phase 2 evaluation are discussed below and shown graphically on Figures 28 through 37 and 39 through 46. The results are also shown in tabular form in Appendix III.

Weight Method I, with the airframe fixed, has a constant gross weight and therefore no comparison is possible.

Using Method II, the variation in gross weight necessary to carry the required payload over the designated range is shown on Figure 28. All of the advanced engines show significant weight reductions relative to the baseline, with the exception of the GTSIO-420 (advanced spark ignition engine). Reductions of 12% to 17% are seen for the single engine designs (S.E.) and 14% to 20% for the twin engine designs (T.E.). This weight reduction is due to smaller engine weights, less fuel required, and structural weight savings resulting from lower gross weights and smaller, lower aspect ratio wings.

Allowing the engines to resize in the Method III type of analysis yields even larger reductions in total weight as shown in Figure 29. Once more excluding the GTSIO-420, the single engine weight reductions range from 15% to 19% and for the twins, from 18% to 23%. In each of these cases the highly advanced rotary (RC2-32) showed the largest potential for reducing the total aircraft weight. In general, here and throughout the comparisons, the twins show virtually the same trends as the singles.

Horsepower The horsepower reductions possible when resizing the engine and airframe (Method III) are shown on Figure 30. With the exception of the diesel and GATE on the single engine designs, the lighter weights and lower engine SFC's allow the engines to be resized downward to about 200 horsepower with the new engines needing approximately 50 less horsepower to do the same job as the current technology baseline engine. The diesel and GATE engines in the single engine airplanes cannot be reduced by the same amount because of their high lapse rate with altitude which reduces the climb performance at 25000 ft. On the twins, the extra power required to provide adequate single engine performance also provides good climb rates at altitude and, therefore, the high lapse rates are not as limiting.

Payload-Range For Method I, where weight was held constant at the value required for the baseline engine, use of the new engines resulted in significant increases in performance. The lighter weight of the powerplants meant that additional useful load became available relative to the baseline configurations. This weight advantage was arbitrarily divided equally between fuel and payload.
FIGURE 28
TAKEOFF GROSS WEIGHT
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

BASELINE TSIO-550

ROTARY
- RC 2-47
- RC 2-32

DIESEL GTDR-246

SPARK
- GTSIO 420

IGNITION
- GTSIO 420SC

TURBOPROP GATE

(▼ indicates value for revised gate)
FIGURE 29
TAKEOFF GROSS WEIGHT
III. VARIABLE ENGINE AND AIRFRAME SIZE

BASELINE TS10-550
ROTARY { RC 2-47
         RC 2-32
DIESEL GTDR-246
SPARK { GTSIO 420
         IGNITION { GTSIO 420SC
TURBOPROP GATE

SINGLES
TWINS

0 1000 2000 3000 4000 5000 6000 7000 8000
0 1000 2000 3000 4000 5000 6000 7000 8000
KILограмMS
POUNDS
KILограмMS
POUNDS
FIGURE 30
ENGINE POWER AT CRUISE
III. VARIABLE ENGINE AND AIRFRAME SIZE

BASELINE TSIO-550

ROTARY
\{ RC 2-47
\{ RC 2-32

DIESEL GTDR-246

SPARK
\{ GTSIO 420
IGNITION
\{ GTSIO 420SC

TURBOPROP GATE
except for the twins where only as much fuel was added as could be accommodated in the outboard wing panels without adding the weight and complexity of tanks in the nacelles (the singles, with no nacelles, had adequate volume for the added fuel).

The increases in range are shown in Figure 31 and the increases in payload in Figure 32. The low weight of the rotary and GATE permit the largest increases in payload varying from 13% for the singles to almost 40% for the twins. The range increases for the rotary are also large at 105% (S.E.) and 69% (T.E.). The high fuel consumption of the GATE, however, limits range increases to 45% (S.E.) and 20% (T.E.). Since the diesel engine weighs more than the rotary the net useful load (payload and fuel) gained is less; however, due to the low fuel consumption of this engine the increases in range are large - 102% (S.E.) and 81% (T.E.).

Mission Fuel. The primary justification for undertaking the large investment in developing a new powerplant is to reduce fuel consumption. The mission fuel burned by each of the engines is shown in Figures 33 and 34 for Methods II and III, respectively. As can be seen, the original GATE shows very small reductions relative to the baseline engine. The moderate risk GTSIO-420 and the revised GATE show a somewhat greater reduction, but still have much less potential than the other four new I.C. engines. All four of these engines show similar savings of around 35% for Method II and 40% for Method III. The diesel powered twin burns the least fuel when compared on the basis of either Methods II or III. For Method II, the diesel powered single also shows the lowest fuel consumption. The GTSIO-420 shows the lowest consumption for the singles according to Method III.

Direct Operating Cost. The influence of the engines on direct operating cost (DOC) is shown on Figures 35 through 37. Method I type comparisons show only small changes in DOC between the various engines. This emphasizes the need to match the engine and airframe if the full benefits are to be realized. The GATE (both versions) and GTSIO-420 show only small decreases in DOC under Method II (Figure 36). The other four engines show substantial reductions of around $20/hour (S.E.) and around $40/hour (T.E.) or savings of over 15% for each configuration. Under Method III (Figure 37), these same four engines show reductions of $30/hour for singles and $60 to $70/hour for twins or savings of around 25%. This is a very substantial reduction—one which could have a major impact on the general aviation market.

Effect Of Assumed Fuel Cost On DOC. One item addressed in the parametric evaluations was the effect of fuel cost on the direct operating cost. For the Phase II analysis a nominal value of $1.70/gallon was used. This was typical of the price of avgas when the analysis was being run early in 1981. The same value was also used for jet fuel since recent data indicates that the difference
FIGURE 31

I. FIXED ENGINE AND AIRFRAME SIZE

RANGE

KILOMETERS

NAUTICAL MILES

SINGLES

TWINS

BASELINE TSIO-550

ROTARY

RC 2-47

RC 2-32

DIESEL GTDR-246

SPARK

GTSIO 420

IGNITION GTSIO 420SC

TURBOPROP GATE

1,000

2,000

3,000

4,000

5,000

6,000

7,000

8,000

9,000

10,000

11,000

12,000

13,000

14,000

15,000

16,000

17,000

18,000

19,000

20,000

KILOMETERS

57
FIGURE 32
PAYLOAD
I. FIXED ENGINE AND AIRFRAME SIZE

- BASELINE TSIO-550
- ROTARY
  - RC 2-47
  - RC 2-32
- DIESEL GTDR-246
- SPARK
  - GTSIO 420
- IGNITION
  - GTSIO 420SC
- TURBOPROP GATE

[Bar chart showing payload comparison between singles and twins for different engines.]
FIGURE 33
MISSION FUEL
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

BASELINE TSIO-550

ROTARY
\{ RC 2-47
  RC 2-32

DIESEL GTDR-246

SPARK
\{ GTSIO 420

IGNITION
\{ GTSIO 420SC

TURBOPROP GATE
(\(\triangledown\) INDICATES VALUE
FOR REVISED GATE

POUNDS
KILOGRAMS

POUNDS
KILOGRAMS
FIGURE 35
DIRECT OPERATING COST
I. FIXED ENGINE AND AIRFRAME SIZE

- BASELINE TSIO-550
- ROTARY { RC 2-47, RC 2-32 }
- DIESEL GTDR-246
- SPARK { GTSIO 420, GTSIO 420SC }
- TURBOPROP GATE

[Bar chart showing direct operating cost for different types of engines and configurations, with singles and twins categories.]
FIGURE 36
DIRECT OPERATING COST
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

- BASELINE TSIO-550
- ROTARY { RC 2-47, RC 2-32 }
- DIESEL GTDR-246
- SPARK { GTSIO 420, GTSIO 420SC }
- TURBOPROP GATE
  ( ▼ ▲ indicates value for revised gate )
Figure 37
DIRECT OPERATING COST
III. VARIABLE ENGINE AND AIRFRAME SIZE

- BASELINE TSIO-550
- ROTARY
  - RC 2-47
  - RC 2-32
- DIESEL GTDR-246
- SPARK
  - GTSIO 420
- IGNITION
  - GTSIO 420SC
- TURBOPROP GATE

Dollars per Hour
in price between these two fuels is narrowing and will eventually disappear, at least in this country. Variations in the price of fuel from $1/gallon to $4/gallon were analyzed for the highly advanced engines in the single engine configurations, with the results shown in Figure 38. The GATE (original definition) powered airplane has the highest DOC which grows larger with increasing fuel price. The revised GATE shows a lower level and slope but still remains consistently higher than the I.C. engines. The RC2-32 has the lowest DOC; as fuel prices increase this advantage decreases, but never completely disappears up to the maximum price studied. In effect, then, while fuel price has a major impact on DOC it does not significantly alter the relative rankings of the various engines.

**Acquisition Cost** The estimated purchase price of the various airplanes is shown in Figures 39 through 41 for Methods I through III, respectively. Comparisons based on Method I show slight increases for most of the advanced engines with only the GATE showing a significantly higher price. When the airframes are resized, however, as was done in Methods II and III, this picture changes. All except the GATE (both versions) and GTSIO-420 engines now show a large potential for reducing airplane price. The airplane using the RC2-32 has the largest estimated reduction in price at $30,000 for the single and $60,000 for the twin under Method II (or roughly a 15% decrease for both configurations). Corresponding numbers for Method III are $40,000 (S.E.) or a 20% decrease and $100,000 (T.E.) or a 25% decrease. As with DOC, decreases of this magnitude would have a major impact on the market.

**Effect of Engine Price On Acquisition Cost** The acquisition costs derived under Phase 2 are heavily dependant on the engine price used. That price, however, is probably the most difficult characteristic to predict accurately.

The effect of changing engine price is shown on Table VIII for Methods II and III. The information is presented as the increment that would have to be added to the assumed engine price to bring the cost of the aircraft up to the level of the baseline powered airplane. And since acquisition cost is reflected in DOC through depreciation, the change in engine price required to eliminate the advantages in DOC shown by the new powerplants is also indicated.

For the intermittent combustion engines, the change in engine price required to match acquisition costs is large and to match DOC levels it is larger still. From this analysis it appears unlikely that the assumed engine price could be sufficiently in error to significantly affect the Phase 2 results.

**Cruise Coefficient** To further compare the engines a cruise coefficient was defined as:

64
FIGURE 38
EFFECT OF FUEL COST ON DIRECT OPERATING COST
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME
SINGLE ENGINE CONFIGURATION

FUEL PRICE USED IN PHASE II STUDY

PRICE OF FUEL (1981 dollars/gal)

PRICE OF FUEL (1981 dollars/liter)
FIGURE 39

ACQUISITION COST
I. FIXED ENGINE AND AIRFRAME SIZE

- BASELINE TSIO-550
- ROTARY
  - RC 2-47
  - RC 2-32
- DIESEL GTDR-246
- SPARK
  - GTSIO 420
- IGNITION
  - GTSIO 420SC
- TURBOPROP GATE

Bar chart showing acquisition cost in thousands of dollars for different engine and airframe configurations.
FIGURE 40
ACQUISITION COST
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

THOUSANDS OF DOLLARS

BASELINE TSIO-550
ROTARY
RC 2-47
RC 2-32
DIESEL GTDR-246
SPARK
GTSIO 420
IGNITION
GTSIO 420SC
TURBOPROP GATE

(△ ▲ INDICATES VALUE
FOR REVISED GATE)
FIGURE 41
ACQUISITION COST

III. VARIABLE ENGINE AND AIRFRAME SIZE

BASELINE TSIO-550
ROTARY
{RC 2-47
RC 2-32
DIESEL GTDR-246
SPARK
{GTSIO 420
IGNITION
GTSIO 420SC
TURBOPROP GATE
# TABLE VIII

**PHASE III**

**EFFECT OF ENGINE COST ON AIRCRAFT PRICE AND DOC**

*shown: increment in engine cost required to make advanced and baseline single engine airplanes cost the same*

<table>
<thead>
<tr>
<th>BASIS OF COMPARISON</th>
<th>ENGINE</th>
<th>ACQUISITION COST</th>
<th>DIRECT OPERATION COST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ΔENGINE</td>
<td>% INCREASE</td>
</tr>
<tr>
<td>II</td>
<td>RC2-32</td>
<td>27,000</td>
<td>84</td>
</tr>
<tr>
<td>FIXED ENGINE</td>
<td>GTDR-246</td>
<td>14,000</td>
<td>39</td>
</tr>
<tr>
<td>VARIABLE AIRFRAME</td>
<td>GT610-420SC</td>
<td>16,000</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>GATE</td>
<td>-1,500</td>
<td>-3</td>
</tr>
<tr>
<td>III</td>
<td>RC2-32</td>
<td>41,000</td>
<td>160</td>
</tr>
<tr>
<td>VARIABLE ENGINE AND AIRFRAME</td>
<td>GTDR-246</td>
<td>25,900</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>GT610-420SC</td>
<td>35,000</td>
<td>131</td>
</tr>
<tr>
<td></td>
<td>GATE</td>
<td>-500</td>
<td>-1</td>
</tr>
</tbody>
</table>
\[ C = \frac{\text{payload} \times \text{VCRS} \times \text{Range}}{\text{Energy Consumed in cruise}} \]

and a relative cruise coefficient was defined as:

\[ R = \frac{C(\text{for a specific configuration})}{C(\text{for the baseline configuration})} \]

This latter value may be thought of as an increase in efficiency in moving a given payload at a given speed over a given range.

Relative cruise coefficient is shown in Figure 42 as a percentage increase over the baseline value. For Method II, the RC2-32, GTSIO-420SC, and GTDR-246 have the highest values, around 55% to 60% better than the baseline with the diesel being slightly better than the others.

The same comparison is shown in Figure 43 for Method III. Here, the same three engines have an advantage over the baseline of 60% to 70%. In this case, the rotary has the highest value for the twin and the GTSIO-420SC for the single.

**Evaluation Criteria**

A set of criteria was established early in the program to evaluate how each of the engines compared to the others. This evaluation scheme is outlined in Table IX. It reflects a point of view that a reduction in fuel consumption is the single most important characteristic for a new engine. The next most important characteristic is the potential to reduce direct operating cost, this factor being weighted only slightly lower than the first one. However, since fuel usage is also included in DOC the total weight given to reduced consumption is actually greater than the 10 point weighting factor would indicate. Acquisition cost, multifuel capability, flyover noise and installation factors are also included in the criteria.

The fuel compatibility of the engines is shown on Table IVb. Some of the engines (e.g. GTDR-246) are shown as capable of burning diesel fuel. The high viscosity of diesel at low temperatures, however, creates a problem in maintaining a reliable fuel flow to the engine unless fuel heaters and insulation are provided. Therefore, no points were awarded for this capability.

The installation factor is the most subjective. No points are awarded if the engine is judged equivalent to the baseline. The GTSIO-420 and GTSIO-420SC were considered in this category though in some ways this may have been generous since the turboshaft exhaust system will probably make accessory location and accessibility more difficult than on present day engines. The GATE in the single engine airframe was also awarded zero points because of the difficulty in ducting the hot exhaust overboard.
FIGURE 42
INCREASE IN CRUISE COEFFICIENT
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME
FIGURE 43
INCREASE IN CRUISE COEFFICIENT
III. VARIABLE ENGINE AND AIRFRAME SIZE

- BASELINE TSIO-550
  - RC 2-47
  - RC 2-32

- DIESEL GTDR-246

- SPARK
  - GTSIO 420
  - GTSIO 420SC

- TURBOPROP GATE
<table>
<thead>
<tr>
<th>TABLE IX</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EVALUATION SCHEME</strong></td>
</tr>
<tr>
<td>FUEL USAGE</td>
</tr>
<tr>
<td>DIRECT OPERATING COST</td>
</tr>
<tr>
<td>ACQUISITION COST</td>
</tr>
<tr>
<td>MULTI-FUEL CAPABILITY</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>FLYOVER NOISE</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>INSTALLATION FACTOR</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
The diesel engine was awarded 10 points since a baggage area can be put in the nose of the single, and slender, low drag nacelles can be used on the twin. The GATE in the twin was also given 10 points because of the slender nacelles and relatively uncomplicated installation.

The rotaries were judged to be much better than the baseline and were awarded 20 points. With the light weight and small size of this engine a baggage compartment can be added in the nose of the single. On the twin the nacelles are slender. The liquid cooling gives complete control over the engine temperature in all flight regimes for maximum operating flexibility.

These evaluation criteria were applied to all engines for all three comparison methods and the results are shown in Figures 44 through 46 and in Tables AIII-VII and AIII-VIII. The absolute magnitudes of the numbers are virtually meaningless and only the relative rankings are of any importance. In general the RC2-47, RC2-32, GTDR-246 and GTSIO-420SC all have similar values for each method. The GATE (both versions) and GTSIO-420 ranked considerably lower. The RC2-32 was consistently the best with the diesel usually a close second.

**PARAMETRIC EVALUATIONS**

As noted above, the data from Phase II exhibited the same trends for both the singles and twins. Therefore, only the single engine airframes were carried forward into the parametric evaluations of Phase III. In the interest of time and available budget the baseline engine and the backup engine concepts (RC2-47 and GTSIO-420) were dropped from the analysis.

The parametric evaluations involving fuel cost and engine price have already been discussed. Other variations in input data and mission definition were analyzed as follows:

**Mission Definition** The effects of selecting different missions (payload and range) are shown on Figures 47 and 48. The range was varied by plus or minus 200 NMi from the basic mission value of 700 NMi and the payload was varied by plus or minus 2 passengers (±400 pounds) from the basic mission value of 6 passengers. The comparison was by method II. In no case is there any crossover of the important parameters (evaluation criteria or fuel used) that would indicate that the original mission unfairly favored one engine over another.

**Cooling Drag** As discussed previously, cooling drag was impossible to estimate with any degree of precision. The actual values for any of these engines may, therefore, be different from those used in the Phase II analysis. Those values were chosen somewhat
FIGURE 44
EVALUATION CRITERIA
I. FIXED ENGINE AND AIRFRAME SIZE

BASLINE TSIO-550

ROTFARY
{ RC 2-47
{ RC 2-32

DIESEL GTDR-246

SPARK
{ GTSIO 420
IGNITION
{ GTSIO 420SC

TURBOPROP GATE

COMPARATIVE RATING
Figure 45
EVALUATION CRITERIA
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

Baseline TSIO-550
Rotary
- RC 2-47
- RC 2-32
Diesel GTDR-246
Spark
- GTSIO 420
Ignition
- GTSIO 420SC
TurboProp Gate
(△ ▲ indicates value for revised gate)
FIGURE 46
EVALUATION CRITERIA
III. VARIABLE ENGINE AND AIRFRAME SIZE

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>COMPARATIVE RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASELINE TSIO-550</td>
<td></td>
</tr>
<tr>
<td>ROTARY</td>
<td></td>
</tr>
<tr>
<td>RC 2-47</td>
<td></td>
</tr>
<tr>
<td>RC 2-32</td>
<td></td>
</tr>
<tr>
<td>DIESEL GTDR-246</td>
<td></td>
</tr>
<tr>
<td>SPARK</td>
<td></td>
</tr>
<tr>
<td>GTSIO 420</td>
<td></td>
</tr>
<tr>
<td>IGNITION</td>
<td></td>
</tr>
<tr>
<td>GTSIO 420SC</td>
<td></td>
</tr>
<tr>
<td>TURBOPROP GATE</td>
<td></td>
</tr>
</tbody>
</table>

- SINGLE
- TWINS
FIGURE 47
EFFECT OF VARYING MISSION PAYLOAD ON AIRCRAFT SIZING
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME
SINGLE ENGINE CONFIGURATION

---

RC 2-32  --  --  GTDR-245  -----  GTSIO 420SC  -----  GATE

a) EFFECT ON TOGW
PAYLOAD (pounds)
800  1200  1600

b) EFFECT ON WING AREA
PAYLOAD (pounds)
800  1200  1600

TOGW (kilograms)
2200  2000  1800  1600  1400

WING AREA (sq meters)
10  12  14

PAYLOAD (kilograms)
300  500  700

WING AREA (sq feet)
100  140  180

PAYLOAD (kilograms)
FIGURE 47 continued
EFFECT OF VARYING MISSION PAYLOAD ON AIRCRAFT SIZING
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME
SINGLE ENGINE CONFIGURATION

--- RC 2-32 --- GTDR-246 --- GTSIO 420SC --- GATE

(c) EFFECT ON ASPECT RATIO
PAYLOAD (pounds)
800 1200 1600

(d) EFFECT ON WING SPAN
PAYLOAD (pounds)
800 1200 1600

ASPECT RATIO

WING SPAN (meters)

WING SPAN (feet)

PAYLOAD (kilograms)

PAYLOAD (kilograms)
FIGURE 47 continued

EFFECT OF VARYING MISSION PAYLOAD ON AIRCRAFT SIZING
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME
SINGLE ENGINE CONFIGURATION

--- RC 2-32 --- GTDR-246 --- GTSIO 420SC --- GATE

e) EFFECT ON ACQUISITION COST

f) EFFECT ON DIRECT OPERATING COST

PAYLOAD (pounds)

800  1200  1600

PAYLOAD (kilograms)

300  500  700

PAYLOAD (pounds)

800  1200  1600

PAYLOAD (kilograms)

300  500  700

PRICE (1981 dollars/1000)

250

220

150

100

50

PRICE (1981 dollars/1000)

250

220

150

100

50

150 dollars/hr

100 dollars/hr

50 dollars/hr
FIGURE 47 concluded
EFFECT OF VARYING MISSION PAYLOAD ON AIRCRAFT SIZING
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME
SINGLE ENGINE CONFIGURATION

--- RC 2-32 --- GTDR-246 --- GTSIO 420SC --- GATE

\( g \) EFFECT ON MISSION FUEL
PAYLOAD (pounds)
800 1200 1600

\( h \) EFFECT ON EVALUATION CRITERIA
PAYLOAD (pounds)
800 1200 1600

MISSION FUEL (kilograms)
300 500 700

MISSION FUEL (pounds)
250 300 350 400 450

COMPARATIVE RATING
-100 0 100 200 300

PAYLOAD (kilograms)
300 500 700
FIGURE 48
EFFECT OF VARYING MISSION RANGE ON AIRCRAFT SIZING
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME
SINGLE ENGINE CONFIGURATION

--- RC 2-32 --- GTDR-246 --- GTSIO 420SC --- GATE

a) EFFECT ON TOGW
RANGE (nautical miles)
500 700 900

TOGW (kilograms)
1600 1700 1800 1900
900 1100 1300 1500 1700
RANGE (kilometers)

b) EFFECT ON WING AREA
RANGE (nautical miles)
500 700 900

WING AREA (sq meters)
12 14 16
900 1100 1300 1500 1700
RANGE (kilometers)

WING AREA (sq feet)
130 150 170
FIGURE 48 continued
EFFECT OF VARYING MISSION RANGE ON AIRCRAFT SIZING
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME
SINGLE ENGINE CONFIGURATION

--- RC 2-32 --- GTDR-246 --- GTSIO 420SC --- GATE

c) EFFECT ON ASPECT RATIO
RANGE (nautical miles)
500 700 900

a)

d) EFFECT ON WING SPAN
RANGE (nautical miles)
500 700 900

b)

WING SPAN (meters)
WING SPAN (feet)
900 1100 1300 1500 1700
900 1100 1300 1500 1700

---
FIGURE 48 continued
EFFECT OF VARYING MISSION RANGE ON AIRCRAFT SIZING
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME
SINGLE ENGINE CONFIGURATION

---
RC 2-32 — — GTDR-246 — — GTSIO 420SC — — GATE
---

**e) EFFECT ON ACQUISITION COST**

![Graph showing effect on acquisition cost with range in nautical miles.](image)

**f) EFFECT ON DIRECT OPERATING COST**

![Graph showing effect on direct operating cost with range in nautical miles.](image)
FIGURE 48 concluded
EFFECT OF VARYING MISSION RANGE ON AIRCRAFT SIZING
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME
SINGLE ENGINE CONFIGURATION

--- RC 2-32 --- GTDR-246 --- GTSIO 420SC --- GATE

**g) EFFECT ON MISSION FUEL**

<table>
<thead>
<tr>
<th>RANGE (nautical miles)</th>
<th>500</th>
<th>700</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>MISSION FUEL (kilograms)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>1100</td>
<td>1300</td>
<td></td>
</tr>
<tr>
<td>1100</td>
<td>1300</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>1300</td>
<td>1500</td>
<td>1700</td>
<td></td>
</tr>
</tbody>
</table>

**h) EFFECT ON EVALUATION CRITERIA**

<table>
<thead>
<tr>
<th>RANGE (nautical miles)</th>
<th>500</th>
<th>700</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPARATIVE RATING</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>1100</td>
<td>1300</td>
<td></td>
</tr>
<tr>
<td>1100</td>
<td>1300</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>1300</td>
<td>1500</td>
<td>1700</td>
<td></td>
</tr>
</tbody>
</table>
optimistically; that is, it is unlikely that the cooling drag is less than estimated. On the other hand there is no reason to believe that any of the new engines would exhibit worse cooling drag than the baseline. This gives then, a reasonable approximation to the maximum and minimum cooling drags expected for each engine. Work on the Curtiss-Wright study (ref. 5) indicated that the variation in all aircraft characteristics with changes in cooling drag was linear over small ranges. Therefore, only 2 points need to be analyzed to define the trends.

The effects of variations in cooling drag are shown on Figure 49. Within this range of values the cooling drag has little effect on any aircraft characteristic except cruise speed and, in particular, the effect on DOC, acquisition cost and the evaluation criteria are minimal. This variable does not significantly alter the relative rankings between the 4 engines. The RC2-32, when evaluated with the highest reasonable drag level, still compares favorably with the others even when compared to the results for their best drag value. The conclusion is that had other values been chosen for cooling drag the results of the study would have been essentially the same.

High Efficiency Inlet  NASA requested an investigation of the effects of using a high efficiency induction system inlet on the intermittent combustion engines. These are regularly used on the turbines but are seldom applied to conventional engines which often draw their induction air from the same plenum that supplies the cooling air flow.

The effect of inlet efficiency was already included in the GATE data. For the other engines the horsepower output varied only with altitude (that is, the pressure of the air entering the induction system was the static pressure).

A higher efficiency inlet on the rotary would not have helped at cruise since the engine was already capable of generating its maximum cruise rating with no pressure recovery. The small effect it might have had on climb where velocity is low was judged to be insignificant and not worth analyzing.

The diesel, however, has a high lapse rate above 17000 ft, losing 13.4 horsepower for every 1000 ft above the critical altitude. Assuming that an intake capable of 90 percent ram recovery would cause no changes in SFC, weight or drag (since the air must be supplied to the compressor anyway) the single engine diesel was reanalyzed. These assumptions probably represent the maximum benefits that could reasonably be realized even with careful development. The results are shown on Table X for both Method II and III. The benefits shown for this inlet are not negligible. For method II the evaluation criteria which had been 15 points less than the RC2-32's became 6 points better; for method III where
FIGURE 49
EFFECT OF COOLING DRAG ON AIRCRAFT SIZING
II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

a) EFFECT ON TOGW

COOLING DRAG (eq feet)

B 2 2 2

COOLING DRAG (eq meters)

b) EFFECT ON WING AREA

COOLING DRAG (eq feet)

15

14

13

12

11

WING AREA (eq meters)

WING AREA (eq feet)

160

140

120

COOLING DRAG (eq meters)
FIGURE 49 continued

EFFECT OF COOLING DRAG ON AIRCRAFT SIZING

II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

c) EFFECT ON BASIC EMPTY WGT

\[ \text{COOLING DRAG (sq meters)} \]

\[ \begin{array}{c}
\text{BASIC EMPTY WGT (kilograms)} \\
900 \\
1000 \\
1100 \\
\end{array} \]

\[ \begin{array}{c}
\text{COOLING DRAG (sq feet)} \\
0.0 \\
0.02 \\
0.04 \\
0.06 \\
\end{array} \]

\[ \begin{array}{c}
\text{BASIC EMPTY WGT (pounds)} \\
2000 \\
2200 \\
2400 \\
\end{array} \]

\[ \begin{array}{c}
\text{COOLING DRAG (eq meters)} \\
0.0 \\
0.02 \\
0.04 \\
0.06 \\
\end{array} \]

\[ \begin{array}{c}
\text{COOLING DRAG (eq feet)} \\
0.0 \\
0.02 \\
0.04 \\
0.06 \\
\end{array} \]

d) EFFECT ON ASPECT RATIO

\[ \text{COOLING DRAG (sq meters)} \]

\[ \begin{array}{c}
\text{ASPECT RATIO} \\
6 \\
8 \\
10 \\
\end{array} \]

\[ \begin{array}{c}
\text{ASPECT RATIO} \\
6 \\
8 \\
10 \\
\end{array} \]

\[ \begin{array}{c}
\text{COOLING DRAG (sq feet)} \\
0.0 \\
0.02 \\
0.04 \\
0.06 \\
\end{array} \]

\[ \begin{array}{c}
\text{COOLING DRAG (eq meters)} \\
0.0 \\
0.02 \\
0.04 \\
0.06 \\
\end{array} \]
FIGURE 49 continued

EFFECT OF COOLING DRAG ON AIRCRAFT SIZING

II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

e) EFFECT ON RATE OF CLIMB

COOLING DRAG (sq feet)

<table>
<thead>
<tr>
<th>COOLING DRAG (sq meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
</tr>
</tbody>
</table>

ROC (feet/minute)

ROC (meters/minute)

f) EFFECT ON TIME TO CLIMB

COOLING DRAG (sq feet)

<table>
<thead>
<tr>
<th>COOLING DRAG (sq meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
</tr>
</tbody>
</table>

TIME TO CRUISE ALT (minutes)

TIME TO CRUISE ALT (minutes)
FIGURE 49 continued

EFFECT OF COOLING DRAG ON AIRCRAFT SIZING

II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

g) EFFECT ON TAKEOFF DISTANCE

COOLING DRAG (sq feet)

COOLING DRAG (sq meters)

h) EFFECT ON CRUISE SPEED

COOLING DRAG (sq feet)

COOLING DRAG (sq meters)
FIGURE 49 continued

EFFECT OF COOLING DRAG ON AIRCRAFT SIZING

II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

i) EFFECT ON NOISE

COOLING DRAG (eq feet)

0.0  0.2  0.4  0.6

0.00  0.02  0.04  0.06

COOLING DRAG (eq meters)

j) EFFECT ON MISSION FUEL

COOLING DRAG (eq feet)

0.0  0.2  0.4  0.6

0.00  0.02  0.04  0.06

COOLING DRAG (eq meters)
FIGURE 49 continued

EFFECT OF COOLING DRAG ON AIRCRAFT SIZING

II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

k) EFFECT ON ACQUISITION COST

<table>
<thead>
<tr>
<th>Cooling Drag (eq feet)</th>
<th>0.0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price (1981 dollars/1000)</td>
<td>210</td>
<td>200</td>
<td>190</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>GATE</td>
<td>GTDR-246</td>
<td>GTSIO 420SC</td>
<td>ORC 2-32</td>
</tr>
</tbody>
</table>

1) EFFECT ON DIRECT OPERATING COST

<table>
<thead>
<tr>
<th>Cooling Drag (eq feet)</th>
<th>0.0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doc (1981 dollars)</td>
<td>120</td>
<td>110</td>
<td>100</td>
<td>00</td>
</tr>
<tr>
<td></td>
<td>GATE</td>
<td>GTDR-246</td>
<td>GTSIO 420SC</td>
<td>ORC 2-32</td>
</tr>
</tbody>
</table>
FIGURE 49 concluded

EFFECT OF COOLING DRAG ON AIRCRAFT SIZING

II. FIXED ENGINE SIZE, VARIABLE AIRFRAME

m) EFFECT ON CRUISE COEFFICIENT

COOLING DRAG (eq feet)

PERCENT IMPROVEMENT

0.0 0.2 0.4 0.6

COOLING DRAG (eq meters)

n) EFFECT ON EVALUATION CRITERIA

COOLING DRAG (eq feet)

COMPARATIVE RATING

0.0 0.2 0.4 0.6

COOLING DRAG (eq meters)
## TABLE X  
**part 1**  
**EFFECT OF HIGH EFFICIENCY INLET**  
**TCM GTDR-246 DIESEL**  
**SINGLE ENGINE**

**FIXED ENGINE, VARIABLE AIRFRAME**

<table>
<thead>
<tr>
<th>Static Pressure to Engine</th>
<th>High Efficiency Inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TAKEOFF POWER</strong></td>
<td><strong>Cruise Power</strong></td>
</tr>
<tr>
<td>268 kW</td>
<td>360 BHP</td>
</tr>
<tr>
<td>186 kW</td>
<td>250 BHP</td>
</tr>
<tr>
<td><strong>Basic Empty Weight</strong></td>
<td><strong>Gross Weight</strong></td>
</tr>
<tr>
<td>1048 kg</td>
<td>2310 lb</td>
</tr>
<tr>
<td>1746 kg</td>
<td>3849 lb</td>
</tr>
<tr>
<td><strong>Wing Area</strong></td>
<td><strong>Wing Span</strong></td>
</tr>
<tr>
<td>13.6 sqm</td>
<td>146 sqft</td>
</tr>
<tr>
<td>10.91 m</td>
<td>35.8 ft</td>
</tr>
<tr>
<td><strong>Aspect Ratio</strong></td>
<td>8.80</td>
</tr>
<tr>
<td><strong>ROC at Cruise Alt</strong></td>
<td><strong>Time to Climb</strong></td>
</tr>
<tr>
<td>192 m/min</td>
<td>630 fpm</td>
</tr>
<tr>
<td>552 m</td>
<td>1810 ft</td>
</tr>
<tr>
<td><strong>Takeoff Distance</strong></td>
<td><strong>Stall Speed</strong></td>
</tr>
<tr>
<td>113 km/hr</td>
<td>61 KTS</td>
</tr>
<tr>
<td><strong>Cruise Speed</strong> (Initial)</td>
<td></td>
</tr>
<tr>
<td>404 km/hr</td>
<td>218 KTS</td>
</tr>
<tr>
<td><strong>Payload</strong></td>
<td><strong>Range</strong></td>
</tr>
<tr>
<td>544 kg</td>
<td>1200 lb</td>
</tr>
<tr>
<td>1296 km</td>
<td>700 NM</td>
</tr>
<tr>
<td><strong>Mission Fuel</strong></td>
<td><strong>Required Fuel Cap</strong></td>
</tr>
<tr>
<td>126.3 kg</td>
<td>278.5 lb</td>
</tr>
<tr>
<td>200 L</td>
<td>52.9 gal</td>
</tr>
<tr>
<td><strong>Relative Cruise Eff V/V</strong></td>
<td></td>
</tr>
<tr>
<td>1.58</td>
<td>1.58</td>
</tr>
<tr>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>Avg Cruise Speed</strong></td>
<td><strong>Maximum Speed</strong></td>
</tr>
<tr>
<td>407 km/hr</td>
<td>220 KTS</td>
</tr>
<tr>
<td>436 km/hr</td>
<td>235.5 KTS</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td><strong>DOC</strong></td>
</tr>
<tr>
<td>$188,000</td>
<td>$106.6/hr</td>
</tr>
<tr>
<td><strong>Noise Change</strong></td>
<td><strong>Evaluation Total</strong></td>
</tr>
<tr>
<td>-4 dBa</td>
<td>229*</td>
</tr>
</tbody>
</table>

*For comparison, the evaluation total on the RC2-32 was 244.*

94
<table>
<thead>
<tr>
<th></th>
<th>Static Pressure to Engine</th>
<th>High Efficiency Inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Takeoff Power</strong></td>
<td>242 kW 325 BHP</td>
<td>238 kW 319 BHP</td>
</tr>
<tr>
<td><strong>Cruise Power</strong></td>
<td>168 kW 226 BHP</td>
<td>166 kW 222 BHP</td>
</tr>
<tr>
<td><strong>Basic Empty Weight</strong></td>
<td>1020 kg 2249 lb</td>
<td>993 kg 2190 lb</td>
</tr>
<tr>
<td><strong>Gross Weight</strong></td>
<td>1710 kg 3770 lb</td>
<td>1676 kg 3696 lb</td>
</tr>
<tr>
<td><strong>Wing Area</strong></td>
<td>13.2 sqm 142 sqft</td>
<td>13.0 sqm 140 sqft</td>
</tr>
<tr>
<td><strong>Wing Span</strong></td>
<td>10.55 m 34.6 ft</td>
<td>9.81 m 32.2 ft</td>
</tr>
<tr>
<td><strong>Aspect Ratio</strong></td>
<td>8.45</td>
<td>7.40</td>
</tr>
<tr>
<td><strong>ROC at Cruise Alt</strong></td>
<td>152 m/min 500 fpm</td>
<td>152 m/min 500 fpm</td>
</tr>
<tr>
<td><strong>Time To Climb</strong></td>
<td>24.6 min 24.6 min</td>
<td>25.4 min 25.4 min</td>
</tr>
<tr>
<td><strong>Takeoff Distance</strong></td>
<td>619 m 2030 ft</td>
<td>629 m 2065 ft</td>
</tr>
<tr>
<td><strong>Stall Speed</strong></td>
<td>113 km/hr 61 KTS</td>
<td>113 km/hr 61 KTS</td>
</tr>
<tr>
<td><strong>Cruise Speed</strong></td>
<td>386 km/hr 208.5 KTS</td>
<td>397 km/hr 214.5 KTS</td>
</tr>
<tr>
<td><strong>Payload</strong></td>
<td>544 kg 1200 lb</td>
<td>544 kg 1200 lb</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>1296 km 700 NM</td>
<td>1296 km 700 NM</td>
</tr>
<tr>
<td><strong>Mission Fuel</strong></td>
<td>120.2 kg 265 lb</td>
<td>115.4 kg 254.5 lb</td>
</tr>
<tr>
<td><strong>Required Fuel Cap</strong></td>
<td>189 L 49.9 gal</td>
<td>182 L 48.1 gal</td>
</tr>
<tr>
<td><strong>Relative Cruise Eff</strong></td>
<td>1.60 1.60</td>
<td>1.58 1.58</td>
</tr>
<tr>
<td><strong>V/V</strong></td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Avg Cruise Speed</strong></td>
<td>390 km/hr 210.5 KTS</td>
<td>402 km/hr 217 KTS</td>
</tr>
<tr>
<td><strong>Maximum Speed</strong></td>
<td>420 km/hr 227 KTS</td>
<td>418 km/hr 225.5 KTS</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>$176,100 $176,100</td>
<td>$169,400 $169,400</td>
</tr>
<tr>
<td><strong>Doc</strong></td>
<td>$99.5/hr $99.5/hr</td>
<td>$96.8/hr $96.8/hr</td>
</tr>
<tr>
<td><strong>Noise Change</strong></td>
<td>-4.5 dBA -4.5 dBA</td>
<td>-4.5 dBA -4.5 dBA</td>
</tr>
<tr>
<td><strong>Evaluation Total</strong></td>
<td>274* 274*</td>
<td>299 299</td>
</tr>
<tr>
<td><strong>Fuel Efficiency</strong></td>
<td>3.56 km/L 17.70 NMPG</td>
<td>9.02 km/L 18.43 NMPG</td>
</tr>
</tbody>
</table>

* For comparison, the evaluation total on the RC2-32 was 322.
it had been 48 points less it moved to only 23 points behind. The fuel savings were 8.5 pounds (3 percent) for Method II and 10.5 pounds (4 percent) for Method III. These numbers indicate that, within the framework of the assumptions, the inlet could pay its way.

The major effect of the advanced inlet was an apparent increase in the engine's critical altitude. It could, therefore, just as easily be argued that the turbocharger design for the diesel should be changed. (For example, using the APU burner to increase turbine output above 17000 ft.) Its low critical altitude puts the diesel at somewhat of a disadvantage relative to the other I.C. engines mostly due to the airplane's comparatively poor climb performance at high altitude. Reasonable increases in climb rate could, in the synergistic design process, offset significant increases in fuel burned during the climb. A change such as this might produce results equal to or better than the advanced inlet. However, since no engine data were available on this configuration, no tradeoff analysis could be run.

The lapse rate of the advanced spark ignition engine is virtually zero until above 25000 ft where it is still only 1/6 that of the diesel. Therefore, a high efficiency inlet could not produce nearly as large a change for this engine as for the diesel and was consequently not analyzed.

Cruise Altitude  Within the constraints of the engine's capabilities, increases in altitude usually bring increases in cruise efficiency. Because of this, turbocharged engines have been taking an increasingly larger share of the general aviation market. This trend has been accelerating in recent years as fuel costs continue to escalate.

For this reason the selected cruise altitude for the missions used in this study was 25000 ft, which is the next logical step above the 18000-23000 ft altitudes in common use today.

Lower altitudes than 25000 ft were not analyzed for all of the engines since future competitive aircraft will be capable of operating at this altitude and the aircraft of this study must also if they are to represent marketable products. The diesel's characteristics in particular seemed better matched perhaps to a lower altitude, but in Phase II it was analyzed at 25000 ft for the reason just stated.

The operation of small aircraft is effectively limited to 25000 ft primarily because of Federal Aviation Regulations (FAR's). Above that altitude the FAR's require fail-safe windshields and window panels (FAR-23.775e) and a supplemental oxygen dispensing unit (FAR-23.1447b). This, plus the higher pressurization differential (assuming that a 10000 ft cabin is maintained) adds
an estimated 50 pounds to the basic empty weight of the airplane. Small increases in altitude above 25000 ft are not justified because of this weight penalty. The four advanced engines were, therefore, analyzed assuming a substantial increase in cruise altitude to 35000 ft. The diesel and GATE, however, had such high thrust lapse rates that no solution could be found without extrapolating the engine size to unreasonably large values far beyond the range of data supplied.

The rotary and advance spark ignition engines could be sized to this altitude and the results are shown on Table XI. Even at this altitude, however, the increased efficiency cannot compensate for the heavier empty weight and higher horsepower required. The evaluation criteria, in particular, are noticeably worse than for the 25000 ft case.

It would be easy to conclude from these results that 25000 ft represents a reasonable maximum cruise altitude for general aviation. This would not, however, be correct. The correct conclusion is that the engine and turbocharger system must be matched to the cruise altitude intended for the aircraft. Simply scaling an engine to a larger size will not enable it to perform well at altitudes higher than where it was designed to operate.

With this in mind the baseline, RC2-32 and GTDR-246 were reanalyzed at a 17000 ft cruise altitude which corresponds to the diesel's critical altitude. This was done to see if the altitude choice had unfairly penalized the diesel. The results are shown on Table XII. Here the rotary and diesel are very evenly matched whereas at 25000 ft the rotary was clearly the superior powerplant. As pointed out above, marketing considerations make 17000 ft an impractical design altitude. The data in Figure XII merely demonstrate again the importance of a fair comparison of having all the engines designed for the same altitude. The diesel, which ran a close second to the rotary, would possibly have done better had its turbocharger been optimized for a higher altitude (see previous discussion under High Efficiency Inlet).

Cruise at Constant Airspeed There is an often quoted rule of thumb that says the horsepower required varies by the cube of the velocity. This indeed is a good approximation when considering the maximum speed where induced drag is low and parasite drag predominates. For general aviation aircraft flying at $V^*$, however, induced drag is high enough that the horsepower required varies by the square, not the cube, of the velocity.

Even so, since the Cessna method of sizing usually defines airplanes with varying cruise speeds, it may still be asked why the airplanes shouldn't be compared when sized to the same cruise speed and, therefore, presumably are using the same cruise horsepower. This usually is not a good procedure, however. First, from the
### TABLE XI
EFFECT OF SIZING FOR CRUISE AT 35000 FT
SINGLE ENGINE

<table>
<thead>
<tr>
<th>Engine</th>
<th>RC2-32</th>
<th>GTSIO-420SC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Takeoff Power</strong></td>
<td>347 kW 465 BHP</td>
<td>313 kW 420 BHP</td>
</tr>
<tr>
<td><strong>Cruise Power @32500'</strong></td>
<td>233 kW 380 BHP</td>
<td>224 kW 300 BHP</td>
</tr>
<tr>
<td><strong>Cruise Power @35000'</strong></td>
<td>200 kW 268 BHP</td>
<td>204 kW 274 BHP</td>
</tr>
<tr>
<td><strong>Basic Empty Weight</strong></td>
<td>1146 kg 2527 lb</td>
<td>1217 kg 2683 lb</td>
</tr>
<tr>
<td><strong>Gross Weight</strong></td>
<td>1856 kg 4092 lb</td>
<td>1929 kg 4252 lb</td>
</tr>
<tr>
<td><strong>Wing Area</strong></td>
<td>14.3 sqm 154 sqft</td>
<td>15.0 sqm 161 sqft</td>
</tr>
<tr>
<td><strong>Wing Span</strong></td>
<td>12.56 m 41.2 ft</td>
<td>12.83 m 42.1 ft</td>
</tr>
<tr>
<td><strong>Aspect Ratio</strong></td>
<td>11.0</td>
<td>11.0</td>
</tr>
<tr>
<td><strong>ROC at 35000 FT</strong></td>
<td>210 m/min 690 fpm</td>
<td>226 m/min 740 fpm</td>
</tr>
<tr>
<td><strong>Time to Climb</strong></td>
<td>23.2 min 23.2 min</td>
<td>26.5 min 26.5 min</td>
</tr>
<tr>
<td><strong>Takeoff Distance</strong></td>
<td>415 m 1360 ft</td>
<td>479 m 1570 ft</td>
</tr>
<tr>
<td><strong>Stall Speed</strong></td>
<td>113 km/hr 61 KTS</td>
<td>113 km/hr 61 KTS</td>
</tr>
<tr>
<td><strong>Cruise Speed</strong></td>
<td>453 km/hr 244.5 KTS</td>
<td>446 km/hr 241 KTS</td>
</tr>
<tr>
<td><strong>Payload</strong></td>
<td>544 kg 1200 lb</td>
<td>544 kg 1200 lb</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>1296 km 700 NM</td>
<td>1296 km 700 NM</td>
</tr>
<tr>
<td><strong>Mission Fuel Required Fuel Cap</strong></td>
<td>134.9 kg 297.5 lb</td>
<td>134.3 kg 296 lb</td>
</tr>
<tr>
<td><strong>V/V</strong></td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Avg Cruise Speed</strong></td>
<td>457 km/hr 247 KTS</td>
<td>450 km/hr 243 KTS</td>
</tr>
<tr>
<td><strong>Maximum Speed</strong></td>
<td>493 km/hr 266 KTS</td>
<td>452 km/hr 244 KTS</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>$239,500 $239,500</td>
<td>$229,000 $229,000</td>
</tr>
<tr>
<td><strong>Doc</strong></td>
<td>$130.2/hr $130.2/hr</td>
<td>$125.0/hr $125.0/hr</td>
</tr>
<tr>
<td><strong>Noise Change</strong></td>
<td>-3.5 dBA -3.5 dBA</td>
<td>-2.6 dBA -2.6 dBA</td>
</tr>
<tr>
<td><strong>Evaluation Total</strong></td>
<td>103</td>
<td>111</td>
</tr>
<tr>
<td><strong>Fuel Efficiency</strong></td>
<td>7.71 km/L 15.76 NMPG</td>
<td>7.75 km/L 15.84 NMPG</td>
</tr>
</tbody>
</table>

There was no solution for the GTDR-246 or the GATE within reasonable extrapolation of the engine size.
<table>
<thead>
<tr>
<th>TABLE XII</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFFECT OF SIZING FOR CRUISE AT 17,000 FT</td>
</tr>
<tr>
<td>SINGLE ENGINE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ENGINE</th>
<th>BASELINE</th>
<th>RC2-32</th>
<th>GTDR-246</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAKEOFF POWER</td>
<td>254 kW</td>
<td>205 kW</td>
<td>183 kW</td>
</tr>
<tr>
<td>CRUISE POWER @ 17000'</td>
<td>195 kW</td>
<td>160 kW</td>
<td>183 kW</td>
</tr>
<tr>
<td>BASIC EMPTY WEIGHT</td>
<td>1270 kg</td>
<td>916 kg</td>
<td>968 kg</td>
</tr>
<tr>
<td>GROSS WEIGHT</td>
<td>2060 kg</td>
<td>1616 kg</td>
<td>1670 kg</td>
</tr>
<tr>
<td>WING AREA</td>
<td>16.0 sqm</td>
<td>12.4 sqm</td>
<td>14.5 sqm</td>
</tr>
<tr>
<td>WING SPAN</td>
<td>12.95 m</td>
<td>8.90 m</td>
<td>9.94 m</td>
</tr>
<tr>
<td>ASPECT RATIO</td>
<td>10.5</td>
<td>5.35</td>
<td>6.80</td>
</tr>
<tr>
<td>ROC AT 17000 FT</td>
<td>271 m/min 890 fpm</td>
<td>253 m/min 830 fpm</td>
<td>199 m/min 653 fpm</td>
</tr>
<tr>
<td>TIME TO CLIMB</td>
<td>20.0 min 20.0 min</td>
<td>19.3 min 19.3 min</td>
<td>24.8 min 24.8 min</td>
</tr>
<tr>
<td>TAKEOFF DISTANCE</td>
<td>747 m 2450 ft</td>
<td>713 m 2340 ft</td>
<td>762 m 2500 ft</td>
</tr>
<tr>
<td>STALL SPEED</td>
<td>113 km/hr 61 KTS</td>
<td>113 km/hr 61 KTS</td>
<td>106 km/hr 57.5 KTS</td>
</tr>
<tr>
<td>CRUISE SPEED (INITIAL)</td>
<td>369 km/hr 199 KTS</td>
<td>369 km/hr 199 KTS</td>
<td>369 km/hr 199 KTS</td>
</tr>
<tr>
<td>PAYLOAD</td>
<td>544 kg 1200 lb</td>
<td>544 kg 1200 lb</td>
<td>544 kg 1200 lb</td>
</tr>
<tr>
<td>RANGE</td>
<td>1296 km 700 NM</td>
<td>1296 km 700 NM</td>
<td>1296 km 700 NM</td>
</tr>
<tr>
<td>MISSION FUEL</td>
<td>206 kg 455 lb</td>
<td>130 kg 286 lb</td>
<td>130 kg 287 lb</td>
</tr>
<tr>
<td>REQUIRED FUEL CAP</td>
<td>358 L 94.5 gal</td>
<td>202 L 53.4 gal</td>
<td>202 L 53.4 gal</td>
</tr>
<tr>
<td>V/V*</td>
<td>1.13</td>
<td>1.00</td>
<td>1.10</td>
</tr>
<tr>
<td>AVG CRUISE SPEED</td>
<td>372 km/hr 201 KTS</td>
<td>372 km/hr 201 KTS</td>
<td>372 km/hr 201 KTS</td>
</tr>
<tr>
<td>PRICE</td>
<td>$209,000</td>
<td>$158,000</td>
<td>$157,000</td>
</tr>
<tr>
<td>DOC</td>
<td>$125.5/hr</td>
<td>$92.2/hr</td>
<td>$91.3/hr</td>
</tr>
<tr>
<td>EVALUATION TOTAL</td>
<td>323*</td>
<td>323*</td>
<td>320*</td>
</tr>
<tr>
<td>FUEL EFFICIENCY</td>
<td>4.5 km/L 9.2 NMPG</td>
<td>8.0 km/L 16.4 NMPG</td>
<td>8.0 km/L 16.3 NMPG</td>
</tr>
</tbody>
</table>

*RELATIVE TO BASELINE SIZED FOR 17000 FT CRUISE
Method II comparison it can be seen that equal cruise horsepower does not produce equal cruise speeds for the various engine/airframe combinations. Second, there are on the order of 8 specific constraints that each design must meet but only 4 major variables (gross weight, wing area, aspect ratio and engine size) which can be changed in order to match the airplane's performance to these constraints. That means that only 4, at most, can be satisfied and these are chosen so that the other constraints are exceeded. Trying to pick one constraint, cruise speed, and saying that it will be met whatever the cost to the others usually means choosing design parameters that increase the drag to artificially hold the speed of one configuration down to the value of another.

There is another option, however, which is to compare the airplanes when cruising at the same speed at reduced throttle settings. There was sufficient part throttle data to do the analysis for the diesel and RC2-32 engines which were also the most interesting. These were analyzed while operating at so called "economy cruise" ratings, or throttle settings that allowed an efficient matching of the cruise airspeeds to that of the baseline single. The results are shown on Table XIII. Note that the takeoff gross weight, acquisition cost and DO= are virtually unchanged, while the evaluation criteria, relative cruise coefficient and mission fuel are nominally better. The effect is to make already dramatic improvements slightly better. It does not change the relative rankings of the engines nor does it make the large performance improvements of these engines, relative to today's powerplants, significantly more obvious.

Advanced Airframe As outlined in the section on assumptions, the study was modeled using aerodynamics, materials and missions for the 1990 airplanes which were logical progressions from the aircraft of today. There are, however, many active research and development programs which could radically alter that picture in the next decade. These possibilities are discussed below along with estimates of how much each would change the characteristics of a new airplane if the technology matured sufficiently to allow their use.

Composites Materials: Here the problem is not in material characteristics, which are in many ways already demonstrably better than aluminum, but in the costs associated with using them. Reference 14 suggests potential weight savings of at least 25 percent in major components (wings, fuselage, etc.) and 12 percent in the landing gear. These values are somewhat conservative compared to other estimates.

Propeller: The propeller characteristics used up to this point in the analysis took advantage of only about one half of the potential gains indicated by the NASA GAP study (Ref.15). The full gains used here are a 6 percent improvement in propeller efficiency (i.e., \( \eta_{\text{prop,new}} - \eta_{\text{prop,old}} = .06 \)), a 40 pound decrease in weight and a
TABLE XIII
part 1
EFFECT OF OPERATING AT REDUCED POWER
SINGLE ENGINE RC2-32

METHOD II FIXED ENGINE, VARIABLE AIRFRAME, FIXED PAYLOAD-RANGE AND CRUISE SPEED

<table>
<thead>
<tr>
<th>THROTTLE SETTING</th>
<th>MAXIMUM CRUISE</th>
<th>ECONOMY CRUISE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAKEOFF POWER</td>
<td>239 kW 320 BHP</td>
<td>239 kW 320 BHP</td>
</tr>
<tr>
<td>CRUISE POWER @25000'</td>
<td>186 kW 250 BHP</td>
<td>154 kW 206 BHP</td>
</tr>
<tr>
<td>BASIC EMPTY WEIGHT</td>
<td>965 kg 2127 lb</td>
<td>995 kg 2194 lb</td>
</tr>
<tr>
<td>GROSS WEIGHT</td>
<td>1674 kg 3691 lb</td>
<td>1676 kg 3696 lb</td>
</tr>
<tr>
<td>WING AREA</td>
<td>13.0 sqm 139.5 sqft</td>
<td>13.0 sqm 140 sqft</td>
</tr>
<tr>
<td>WING SPAN</td>
<td>10.00 m 32.8 ft</td>
<td>11.28 m 37.0 ft</td>
</tr>
<tr>
<td>ASPECT RATIO</td>
<td>7.73</td>
<td>9.80</td>
</tr>
<tr>
<td>ROC AT 25000 FT</td>
<td>249 m/min 816 fpm</td>
<td>290 m/min 950 fpm</td>
</tr>
<tr>
<td>TIME TO CLimb</td>
<td>22.1 min 22.1 min</td>
<td>20.2 min 20.2 min</td>
</tr>
<tr>
<td>TAKEOFF DISTANCE</td>
<td>585 m 1920 ft</td>
<td>563 m 1847 ft</td>
</tr>
<tr>
<td>STALL SPEED</td>
<td>113 km/hr 61 KTS</td>
<td>113 km/hr 61 KTS</td>
</tr>
<tr>
<td>CRUISE SPEED (INITIAL)</td>
<td>424 km/hr 229 KTS</td>
<td>382 km/hr 206 KTS</td>
</tr>
<tr>
<td>PAYLOAD RANGE</td>
<td>544 kg 1200 lb</td>
<td>544 kg 1200 lb</td>
</tr>
<tr>
<td>MISSION FUEL</td>
<td>134 kg 296 lb</td>
<td>114.5 kg 252.5 lb</td>
</tr>
<tr>
<td>REQUIRED FUEL CAP</td>
<td>214 L 56.5 gal</td>
<td>199 L 52.7 gal</td>
</tr>
<tr>
<td>V/V*</td>
<td>1.05</td>
<td>1.00</td>
</tr>
<tr>
<td>AVG CRUISE SPEED</td>
<td>423 km/hr 231 KTS</td>
<td>384 km/hr 207.5 KTS</td>
</tr>
<tr>
<td>MAXIMUM SPEED</td>
<td>439 km/hr 237 KTS</td>
<td>443 km/hr 239 KTS</td>
</tr>
<tr>
<td>PRICE</td>
<td>$175,000 $175,000</td>
<td>$180,000 $180,000</td>
</tr>
<tr>
<td>DDC</td>
<td>$102.7/hr $102.7/hr</td>
<td>$104.5/hr $104.5/hr</td>
</tr>
<tr>
<td>NOISE CHANGE</td>
<td>-1.0 dBA -1.0 dBA</td>
<td>-2.0 dBA -2.0 dBA</td>
</tr>
<tr>
<td>EVALUATION TOTAL</td>
<td>244</td>
<td>272</td>
</tr>
<tr>
<td>FUEL EFFICIENCY</td>
<td>7.73 km/L 15.30 NMPG</td>
<td>9.10 km/L 18.60 NMPG</td>
</tr>
</tbody>
</table>
## TABLE XIII
part 2
EFFECT OF OPERATING AT REDUCED POWER
SINGLE ENGINE GTDR-246

METHOD II FIXED ENGINE, VARIABLE AIRFRAME, FIXED PAYLOAD-RANGE AND CRUISE SPEED

<table>
<thead>
<tr>
<th>THROTTLE SETTING</th>
<th>MAXIMUM CRUISE</th>
<th>ECONOMY CRUISE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAKEOFF POWER</td>
<td>268 kw 360 BHP</td>
<td>268 kw 360 BHP</td>
</tr>
<tr>
<td>CRUISE POWER @25000'</td>
<td>166 kw 250 BHP</td>
<td>154 kw 206 BHP</td>
</tr>
<tr>
<td>BASIC EMPTY WEIGHT</td>
<td>1043 kg 2310 lb</td>
<td>1048 kg 2311 lb</td>
</tr>
<tr>
<td>GROSS WEIGHT</td>
<td>1746 kg 3849 lb</td>
<td>1726 kg 3807 lb</td>
</tr>
<tr>
<td>WING AREA</td>
<td>13.6 sqm 146 sqft</td>
<td>13.4 sqm 144.5 sqft</td>
</tr>
<tr>
<td>WING SPAN</td>
<td>10.91 m 35.8 ft</td>
<td>11.06 m 36.3 ft</td>
</tr>
<tr>
<td>ASPECT RATIO</td>
<td>3.80 3.90</td>
<td>9.10 9.10</td>
</tr>
<tr>
<td>ROC AT 25000 FT</td>
<td>192 m/min 630 fpm</td>
<td>200 m/min 656 fpm</td>
</tr>
<tr>
<td>TIME TO CLimb</td>
<td>21.4 min 21.4 min</td>
<td>20.9 min 20.9 min</td>
</tr>
<tr>
<td>TAKEOFF DISTANCE</td>
<td>552 m 1810 ft</td>
<td>547 m 1793 ft</td>
</tr>
<tr>
<td>STALL SPEED</td>
<td>113 km/hr 61 KTS</td>
<td>113 km/hr 61 KTS</td>
</tr>
<tr>
<td>CRUISE SPEED</td>
<td>404 km/hr 218 KTS</td>
<td>382 km/hr 206 KTS</td>
</tr>
<tr>
<td>(INITIAL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAYLOAD</td>
<td>544 kg 1200 lb</td>
<td>544 kg 1200 lb</td>
</tr>
<tr>
<td>RANGE</td>
<td>1296 km 700 NM</td>
<td>1296 km 700 NM</td>
</tr>
<tr>
<td>MISSION FUEL</td>
<td>126.3 kg 278.5 lb</td>
<td>111.6 kg 246 lb</td>
</tr>
<tr>
<td>REQUIRED FUEL CAP</td>
<td>200 L 52.9 gal</td>
<td>176 L 46.6 gal</td>
</tr>
<tr>
<td>V/V*</td>
<td>1.05 1.05</td>
<td>1.00 1.00</td>
</tr>
<tr>
<td>AVG CRUISE SPEED</td>
<td>407 km/hr 220 KTS</td>
<td>385 km/hr 208 KTS</td>
</tr>
<tr>
<td>MAXIMUM SPEED</td>
<td>436 km/hr 235.5 KTS</td>
<td>447 km/hr 236 KTS</td>
</tr>
<tr>
<td>PRICE</td>
<td>$188,000 $188,000</td>
<td>$187,000 $187,000</td>
</tr>
<tr>
<td>DOC</td>
<td>$106.6/hr $106.6/hr</td>
<td>$106.4/hr $106.4/hr</td>
</tr>
<tr>
<td>NOISE CHANGE</td>
<td>-4.0 dBA -4.0 dBA</td>
<td>-4.0 dBA -4.0 dBA</td>
</tr>
<tr>
<td>EVALUATION TOTAL</td>
<td>229 229</td>
<td>260 260</td>
</tr>
<tr>
<td>FUEL EFFICIENCY</td>
<td>3.22 km/L 16.80 NMPG</td>
<td>9.35 km/L 19.10 NMPG</td>
</tr>
</tbody>
</table>

102
4 dB(A) improvement in noise.

Accessories: An arbitrary weight reduction of 20 percent, due mostly to improved electronics and materials, has been assumed for the advanced airframes.

Laminar Flow Airfoils: Reference 16 indicates that a potential reduction in wing profile drag of 40 percent is reasonable if laminar flow is achieved over large areas of the surface. Assuming that the wing profile drag is approximately 1/3 of the total airframe value, then a savings of approximately 13 percent is possible.

Lift Coefficient: A trimmed maximum lift coefficient of 2.5 is assumed for this advanced airframe analysis and should be reasonably easy to obtain with the large span flaps.

Analysis: The improvements discussed above are in no way conservative but neither are any unreasonably optimistic. With adequate research funding they probably can be realized. The results of reanalyzing the single engine airframe powered by the baseline and RC2-32 engines and with these more optimistic assumptions are shown on Table XIV. Note that the price per pound of airframe was not changed despite the use of advanced materials, thus assuming a major reduction in the cost of manufacturing composite structures.

For the baseline single these improvements due to aerodynamics and materials show greater potential (as judged by the evaluation criteria) than the GTSIO-420 moderate risk, advanced spark ignition engine does. The improvements coupled with the RC2-32 show a potential savings in fuel (compared to the baseline) of 39 percent versus 33 percent for that engine without them.

REVISED GATE After work on Phase 2 had been virtually completed, NASA, in conjunction with Teledyne-CAE, discovered that an inadvertent error had been made when the Teledyne GATE engine was scaled to the higher design point altitude required for the present study. The result was an SFC and an engine weight which were almost exactly 10 percent too high. Therefore, the analysis was redone using Method II with the two indicated factors reduced by 10 percent.

The results, shown in Table XV and overplotted on Figures 28, 33, 36, 38, 40, 42, 45, indicate a very significant improvement but still do not compare favorably with the rotary and diesel powered machines. Note, however, that even these revised data are still based on a low-initial-cost design philosophy which was prevalent at the time that NASA initiated the GATE studies. An approach that strives specifically for low fuel consumption might well be more competitive with the other engine types.
### TABLE XIV
#### part 1
EFFECT OF ADVANCED AIRFRAME
SINGLE ENGINE TSIO -550

**METHOD II**  FIXED ENGINE, VARIABLE AIRFRAME, FIXED PAYLOAD-RANGE

<table>
<thead>
<tr>
<th>AIRFRAME DESIGN</th>
<th>CONSERVATIVE</th>
<th>OPTIMISTIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAKEOFF POWER</td>
<td>254 kW</td>
<td>254 kW</td>
</tr>
<tr>
<td></td>
<td>340 BHP</td>
<td>340 BHP</td>
</tr>
<tr>
<td>CRUISE POWER 325000'</td>
<td>186 kW</td>
<td>186 kW</td>
</tr>
<tr>
<td></td>
<td>250 BHP</td>
<td>250 BHP</td>
</tr>
<tr>
<td>BASIC EMPTY WEIGHT</td>
<td>1241 kg</td>
<td>1021 kg</td>
</tr>
<tr>
<td>GROSS WEIGHT</td>
<td>2023 kg</td>
<td>1780 kg</td>
</tr>
<tr>
<td>WING AREA</td>
<td>15.9 sqm</td>
<td>11.6 sqm</td>
</tr>
<tr>
<td>WING SPAN</td>
<td>12.25 m</td>
<td>11.16 m</td>
</tr>
<tr>
<td>ASPECT RATIO</td>
<td>9.50</td>
<td>10.70</td>
</tr>
<tr>
<td>ROC AT 25000 FT</td>
<td>198 m/min</td>
<td>259 m/min</td>
</tr>
<tr>
<td>TIME TO CLIMB</td>
<td>23.4 min</td>
<td>22.4 min</td>
</tr>
<tr>
<td>TAKEOFF DISTANCE</td>
<td>583 m</td>
<td>686 m</td>
</tr>
<tr>
<td></td>
<td>2240 ft</td>
<td>2250 ft</td>
</tr>
<tr>
<td>STALL SPEED</td>
<td>113 km/hr</td>
<td>113 km/hr</td>
</tr>
<tr>
<td>CRUISE SPEED (INITIAL)</td>
<td>382 km/hr</td>
<td>426 km/hr</td>
</tr>
<tr>
<td>PAYLOAD</td>
<td>544 kg</td>
<td>544 kg</td>
</tr>
<tr>
<td>RANGE</td>
<td>1296 km</td>
<td>1296 km</td>
</tr>
<tr>
<td>MISSION FUEL</td>
<td>200 kg</td>
<td>177 kg</td>
</tr>
<tr>
<td>REQUIRED FUEL CAP</td>
<td>344 L</td>
<td>314 L</td>
</tr>
<tr>
<td></td>
<td>91.0 gal</td>
<td>83.0 gal</td>
</tr>
<tr>
<td>V/V*</td>
<td>1.00</td>
<td>1.05</td>
</tr>
<tr>
<td>AVG CRUISE SPEED</td>
<td>387 km/hr</td>
<td>431 km/hr</td>
</tr>
<tr>
<td></td>
<td>209 KTS</td>
<td>232.5 KTS</td>
</tr>
<tr>
<td>PRICE</td>
<td>$202,000</td>
<td>$158,500</td>
</tr>
<tr>
<td>DOC</td>
<td>$122.0/hr</td>
<td>$108.0/hr</td>
</tr>
<tr>
<td>NOISE CHANGE</td>
<td>0.0 dBA</td>
<td>-1.0 dBA</td>
</tr>
<tr>
<td>EVALUATION TOTAL</td>
<td>0</td>
<td>134</td>
</tr>
<tr>
<td>FUEL EFFICIENCY</td>
<td>1.70 km/L</td>
<td>5.28 km/L</td>
</tr>
<tr>
<td></td>
<td>9.60 NMPG</td>
<td>10.80 NMPG</td>
</tr>
<tr>
<td>AIRFRAME DESIGN</td>
<td>CONSERVATIVE</td>
<td>OPTIMISTIC</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>TAKEOFF POWER</td>
<td>239 kW</td>
<td>239 kW</td>
</tr>
<tr>
<td>CRUISE POWER 325000'</td>
<td>186 kW</td>
<td>186 kW</td>
</tr>
<tr>
<td>BASIC EMPTY WEIGHT</td>
<td>965 kg</td>
<td>782 kg</td>
</tr>
<tr>
<td>GROSS WEIGHT</td>
<td>1674 kg</td>
<td>1479 kg</td>
</tr>
<tr>
<td>WING AREA</td>
<td>13.0 sqm</td>
<td>9.60 sqm</td>
</tr>
<tr>
<td>WING SPAN</td>
<td>10.00 m</td>
<td>8.50 m</td>
</tr>
<tr>
<td>ASPECT RATIO</td>
<td>7.73</td>
<td>7.55</td>
</tr>
<tr>
<td>ROC AT 25000 FT</td>
<td>249 m/min</td>
<td>293 m/min</td>
</tr>
<tr>
<td>TIME TO CLIMB</td>
<td>22.1 min</td>
<td>18.6 min</td>
</tr>
<tr>
<td>TAKEOFF DISTANCE</td>
<td>535 m</td>
<td>585 m</td>
</tr>
<tr>
<td>STALL SPEED</td>
<td>113 km/hr</td>
<td>113 km/hr</td>
</tr>
<tr>
<td>CRUISE SPEED (INITIAL)</td>
<td>424 km/hr</td>
<td>465 km/hr</td>
</tr>
<tr>
<td>PAYLOAD RANGE</td>
<td>544 kg</td>
<td>544 kg</td>
</tr>
<tr>
<td>MISSION FUEL REQUIRED FUEL CAP</td>
<td>134 kg</td>
<td>122 kg</td>
</tr>
<tr>
<td>V/V*</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>AVG CRUISE SPEED</td>
<td>428 km/hr</td>
<td>419 km/hr</td>
</tr>
<tr>
<td>PRICE</td>
<td>$175,000</td>
<td>$141,000</td>
</tr>
<tr>
<td>DOC</td>
<td>$102.7/hr</td>
<td>$92.0/hr</td>
</tr>
<tr>
<td>NOISE CHANGE</td>
<td>-1.0 dBA</td>
<td>-3.5 dBA</td>
</tr>
<tr>
<td>EVALUATION TOTAL</td>
<td>244</td>
<td>354</td>
</tr>
<tr>
<td>FUEL EFFICIENCY</td>
<td>7.73 km/L</td>
<td>8.51 km/L</td>
</tr>
</tbody>
</table>

**METHOD II FIXED ENGINE, VARIABLE AIRFRAME, FIXED PAYLOAD-RANGE**
### TABLE XV
#### EFFECT OF 10% IMPROVEMENT IN GATE ENGINE

**SINGLE ENGINE**

**METHOD II FIXED ENGINE, VARIABLE AIRFRAME, FIXED PAYLOAD-RANGE**

<table>
<thead>
<tr>
<th>ENGINE</th>
<th><strong>BASIC ENGINE</strong></th>
<th><strong>-10% WEIGHT &amp; SFC</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>TAKEOFF POWER</td>
<td>391 kw</td>
<td>391 kw</td>
</tr>
<tr>
<td>CRUISE POWER @25000'</td>
<td>186 kw</td>
<td>186 kw</td>
</tr>
<tr>
<td>BASIC EMPTY WEIGHT</td>
<td>1006 kg</td>
<td>975 kg</td>
</tr>
<tr>
<td>GROSS WEIGHT</td>
<td>1772 kg</td>
<td>1719 kg</td>
</tr>
<tr>
<td>WING AREA</td>
<td>13.8 sqm</td>
<td>13.4 sqm</td>
</tr>
<tr>
<td>WING SPAN</td>
<td>10.82 m</td>
<td>10.42 m</td>
</tr>
<tr>
<td>ASPECT RATIO</td>
<td>3.45</td>
<td>3.10</td>
</tr>
<tr>
<td>ROC AT 25000 FT</td>
<td>160 m/min</td>
<td>267 m/min</td>
</tr>
<tr>
<td>TIME TO CLimb</td>
<td>28.1 min</td>
<td>27.0 min</td>
</tr>
<tr>
<td>TAKEOFF DISTANCE</td>
<td>416 m</td>
<td>405 m</td>
</tr>
<tr>
<td>STALL SPEED</td>
<td>113 km/hr</td>
<td>113 km/hr</td>
</tr>
<tr>
<td>CRUISE SPEED (INITIAL)</td>
<td>418 km/hr</td>
<td>420 km/hr</td>
</tr>
<tr>
<td>PAYLOAD RANGE</td>
<td>544 kg</td>
<td>544 kg</td>
</tr>
<tr>
<td>MISSION FUEL REQUIRED FUEL CAP</td>
<td>1296 km</td>
<td>1296 km</td>
</tr>
<tr>
<td>V/V*</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>AVG CRUISE SPEED</td>
<td>423 km/hr</td>
<td>424 km/hr</td>
</tr>
<tr>
<td>RELATIVE CRUISE EFF</td>
<td>1.16</td>
<td>1.31</td>
</tr>
<tr>
<td>PRICE</td>
<td>$203,000</td>
<td>$198,000</td>
</tr>
<tr>
<td>DOC</td>
<td>$118.5/ hr</td>
<td>$114.0/ hr</td>
</tr>
<tr>
<td>NOISE CHANGE</td>
<td>-5.0 dBA</td>
<td>-5.0 dBA</td>
</tr>
<tr>
<td>EVALUATION TOTAL</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>FUEL EFFICIENCY</td>
<td>5.72 km/L 11.70 NMPG</td>
<td>6.41 km/L 13.10 NMPG</td>
</tr>
</tbody>
</table>
### TABLE XV

**part 2**

EFFECT OF 10% IMPROVEMENT IN GATE ENGINE

TWIN ENGINE

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

<table>
<thead>
<tr>
<th>Engine</th>
<th><strong>Basic Engine</strong></th>
<th><strong>-10% Weight &amp; SFC</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Takeoff Power</strong></td>
<td>391 kW 525 BHP</td>
<td>391 kW 525 BHP</td>
</tr>
<tr>
<td><strong>Cruise Power @ 25000 ft</strong></td>
<td>136 kW 250 BHP</td>
<td>186 kW 250 BHP</td>
</tr>
<tr>
<td><strong>Basic Empty Weight</strong></td>
<td>1524 kg 3360 lb</td>
<td>1477 kg 3257 lb</td>
</tr>
<tr>
<td><strong>Gross Weight</strong></td>
<td>2508 kg 5750 lb</td>
<td>2514 kg 5542 lb</td>
</tr>
<tr>
<td><strong>Wing Area</strong></td>
<td>15.4 sqm 166 sqft</td>
<td>14.6 sqm 157 sqft</td>
</tr>
<tr>
<td><strong>Wing Span</strong></td>
<td>10.91 m 35.8 ft</td>
<td>10.64 m 34.9 ft</td>
</tr>
<tr>
<td><strong>Aspect Ratio</strong></td>
<td>7.70</td>
<td>7.70</td>
</tr>
<tr>
<td><strong>Roc At 25000 ft</strong></td>
<td>238 m/min 780 fpm</td>
<td>247 m/min 810 fpm</td>
</tr>
<tr>
<td><strong>Seroc @ 5000 ft</strong></td>
<td>119 m/min 390 fpm</td>
<td>123 m/min 405 fpm</td>
</tr>
<tr>
<td><strong>Time To Climb</strong></td>
<td>13.6 min 18.6 min</td>
<td>17.9 min 17.9 min</td>
</tr>
<tr>
<td><strong>Takeoff Distance</strong></td>
<td>383 m 1255 ft</td>
<td>375 m 1230 ft</td>
</tr>
<tr>
<td><strong>Stall Speed</strong></td>
<td>130 km/hr 70 KTS</td>
<td>131 km/hr 70.5 KTS</td>
</tr>
<tr>
<td><strong>Cruise Speed (Initial)</strong></td>
<td>464 km/hr 250.7 KTS</td>
<td>469 km/hr 253 KTS</td>
</tr>
<tr>
<td><strong>Payload Range</strong></td>
<td>635 kg 1400 lb</td>
<td>635 kg 1400 lb</td>
</tr>
<tr>
<td><strong>Mission Fuel Required Fuel Cap</strong></td>
<td>1492 km 800 NM</td>
<td>1482 km 800 NM</td>
</tr>
<tr>
<td><strong>V/V</strong></td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>Avg Cruise Speed</strong></td>
<td>471 km/hr 254.5 KTS</td>
<td>474 km/hr 256 KTS</td>
</tr>
<tr>
<td><strong>Relative Cruise Eff</strong></td>
<td>1.07</td>
<td>1.07</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>$377,000</td>
<td>$365,000</td>
</tr>
<tr>
<td><strong>Doc</strong></td>
<td>222.0/hr</td>
<td>212.0/hr</td>
</tr>
<tr>
<td><strong>Noise Change</strong></td>
<td>3.0 dBA</td>
<td>-4.0 dBA</td>
</tr>
<tr>
<td><strong>Evaluation Total</strong></td>
<td>61</td>
<td>122</td>
</tr>
<tr>
<td><strong>Fuel Efficiency</strong></td>
<td>3.23 km/L 6.60 NMPG</td>
<td>3.62 km/L 7.40 NMPG</td>
</tr>
</tbody>
</table>
CONCLUSIONS

* The advanced and highly-advanced internal combustion engines all offer the potential for substantially improved airplanes in all respects - performance, fuel burn, and cost - compared to the baseline, particularly if the airframe is resized to take advantage of the powerplant characteristics.

* The turboprop (either version) might be viewed as a viable replacement for the baseline engine, offering market appeal, but no major improvement in efficiency or cost.

* Results for singles and twins show the same trends, regardless of the method of comparison.

* Parametric studies show that the results are relatively insensitive to the assumptions (drag level, weights, costs, etc.) made and the missions chosen.

* Advanced materials and aerodynamic features can provide very worthwhile improvements in performance, fuel burn, and cost. Used in combination with the advanced engines, the gains become very large.

* On the basis of the evaluation criteria the engines in the study rank as follows:

<table>
<thead>
<tr>
<th>ENGINE</th>
<th>STRONG POINTS</th>
<th>WEAK POINTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) RC2-32 Rotary</td>
<td>Low fuel burn, low DOC, small size, low weight, multi-fuel capability</td>
<td>Cooling system maintenance</td>
</tr>
<tr>
<td>2) GTDR-246</td>
<td>Low fuel burn, low wt</td>
<td>Less multifuel capability</td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
<td>Lower overall performance than 1) or 2)</td>
</tr>
<tr>
<td>RC2-47 Rot</td>
<td>Same factors as RC2-32</td>
<td>Mechanical complexity</td>
</tr>
<tr>
<td>3) Tie</td>
<td>Low fuel burn, low wt</td>
<td></td>
</tr>
<tr>
<td>GTSIO 420SC</td>
<td></td>
<td>Relatively heavy, poor economics</td>
</tr>
<tr>
<td>Spark Ign</td>
<td>None, compared to other engines</td>
<td>High fuel consumption, high power lapse rate, high cost</td>
</tr>
<tr>
<td>4) GTSIO 420</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spark Ign</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5) GATE</td>
<td>Low weight &quot;turbine image&quot;</td>
<td></td>
</tr>
<tr>
<td>Turboprop</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TECHNICAL PROGRAM RECOMMENDATIONS

PREFERRED ENGINE CANDIDATE

Although all of the I.C. engines studied show substantial improvements over the baseline, the highly advanced rotary and diesel engines are clearly the preferred candidates for development by virtue of their very high ranking according to the evaluation criteria. If added importance is assigned to the ability to operate on the widest possible range of fuels, the rotary will have a definite edge.

TECHNOLOGY PROGRAM

It is recommended that a program be established by NASA which will focus on enabling technologies for both the rotary and diesel engines, paced to allow building of the "highly advanced" versions by 1990. Midway in this period, it would be highly desirable to have flightworthy experimental engines available for testing by an airframe manufacturer in order to assess installation factors, systems integration, vibration, performance, and certification potential. These interim "moderately advanced" engines might themselves be candidates for production, depending on their performance and market conditions; at any rate, the experience gained should be valuable in assessing and directing the overall program.
REFERENCES


11) Hoerner, Sighard F.: "Fluid-Dynamic Drag," published by the Author


APPENDIX I

DIRECT OPERATION 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:

\[
\text{Number of labor hours for 100 hour inspection} \times \text{labor rate} \quad \frac{100}{100}
\]

then double this answer to account for parts.

labor rate early 1981 ran

- $20/hour 3/E
- $25/hour 4/E
- $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.

\[
\frac{(\text{cost of labor} + \text{cost of parts}) \text{ for HSIs} + \text{misc.}}{\text{TBO}}
\]

(filters, igniters + labor not included in HSI)

2) RESERVES FOR ENGINE OVERHAUL

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

\[
\frac{(\text{overhaul cost} + \text{cost of remanufactured engine})}{2} \quad \text{TBO}
\]

For Turboprops:

\[
\frac{\text{overhaul cost} \ (\text{labor} + \text{parts}) + \text{additional allowances}}{\text{TBO}}
\]

Additional allowances includes an allowance for premature removal of the engine (1/5 to 1/2 of overhaul cost) and engine accessories (starter generator etc.) and engine components (Turbines, nozzles, etc.).
3) PROPELLER OVERHAUL

<table>
<thead>
<tr>
<th>Propeller Type</th>
<th>DOC ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Pitch</td>
<td>.11</td>
</tr>
<tr>
<td>S/E Controllable</td>
<td>.43</td>
</tr>
<tr>
<td>HPSE</td>
<td>.60</td>
</tr>
<tr>
<td>Centurion class</td>
<td>.82</td>
</tr>
<tr>
<td>M/E Controllable (per propeller)</td>
<td>.30</td>
</tr>
</tbody>
</table>

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 (Twins only) + 1.878 (if pressurized)

5) INSURANCE (HULL + LIABILITY)

See tables A IV-1 and A IV-2

6) Fuel cost

\[ \text{DOC} = \text{price per gal} \times \frac{\text{gal}}{\text{hour}} \times 2 \times \frac{\text{hour}}{\text{gal}} \times 100 \text{ gal used for all fuels} \]

7) OIL COST

\[ \text{DOC} = \text{price per gal} \times \frac{\text{gallons}}{\text{used}} \times \text{(approximates oil + filter)} \]

or alternately use

\[ \text{DOC} = \text{actual price per gal} \times \frac{\text{gallons}}{\text{used}} \times \frac{\text{cost of filter}}{\text{gallons}} + \frac{\text{hrs between filter change}}{\text{gallons}} \]

*Include oil consumed and oil lost during oil changes.

8) DEPRECIATION

\[ \text{Depreciation} = \frac{\text{Total equipped airplane price}}{7.5 \times \text{utilization rate / year}} \]

Depreciated to zero residual in 7.5 years

9) RESERVES FOR AVIONICS

\[ \text{Reserves for avionics} = \frac{10\% \times \text{total avionic package (standard + optional)}}{1000 \text{ hrs}} \]
10) RESERVES FOR SYSTEMS MAINTENANCE

\[
\text{DOC} = -0.513 + 0.000303 \times \text{TOW} + 1.109 \quad \text{(if pressurized)}
\]

Again this is a parametric fit of available data.

**TABLE A IV-1**

<table>
<thead>
<tr>
<th>Full Value</th>
<th>Single Engine Rate</th>
<th>Multi-Engine Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$15,000 - 24,999</td>
<td>3.00%</td>
<td></td>
</tr>
<tr>
<td>25,000 - 39,999</td>
<td>2.75</td>
<td></td>
</tr>
<tr>
<td>40,000 - 59,999</td>
<td>2.50</td>
<td></td>
</tr>
<tr>
<td>60,000 - 99,999</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>100,000 - 149,000</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>150,000 - 200,000</td>
<td>1.60</td>
<td></td>
</tr>
<tr>
<td>150,000 - 299,999</td>
<td></td>
<td>1.75%</td>
</tr>
<tr>
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**TABLE A IV-2**

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Legal Liability Limit of $5,000,000 combined single limit
## APPENDIX II

### MISCELLANEOUS DATA USED IN STUDY

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<td>Cabin Pressurization</td>
<td>Adequate for 10,000 ft cabin at cruise altitude</td>
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<td>Reserve Fuel</td>
<td>The gross weight was calculated assuming adequate fuel for the mission plus 45 minutes reserve at cruise power</td>
</tr>
<tr>
<td>Maximum Landing Weight For Twins</td>
<td>95% of Gross Weight</td>
</tr>
<tr>
<td>Shaft Horsepower</td>
<td>All engine power ratings supplied by NASA were assumed to be installed values; i.e., the power available to the propeller after all accessory drive requirements were met</td>
</tr>
<tr>
<td>Fuel for Starting Runup, Taxi, and Takeoff</td>
<td>The total fuel for these functions was estimated to be equivalent to .085 hours at takeoff power</td>
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<tr>
<td>Drag Due to Engine Out</td>
<td>A value of $C_d = 0.0035$ was used based on T303 data. This assumes inoperative engine propeller feathered and a bank angle of 5 degrees into the good engine</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>Values greater than 11 were not used. Primarily this was felt to be the maximum value to which the data base could be accurately extrapolated.</td>
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<tr>
<td>Takeoff Characteristics</td>
<td>Climb velocity at 50 feet/Vs = 1.2 Rolling Friction Coefficient = 0.02 Maximum Lift Coefficient = 1.6</td>
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<tr>
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APPENDIX III

TABULATED DATA

The results of the Phase 2 study, shown graphically in Figures 28 through 37 and 39 through 46, are tabulated herein. Included also is a table showing the values of each component of the evaluation criteria analysis for all engines for the three methods of comparison both for single and twin engine configurations.
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**TABLE AIII-I**

**AIRCRAFT COMPARISONS**

**SINGLE ENGINE**

**FIXED ENGINE & AIRFRAME SIZE**

**VARIABLE MISSION & PERFORMANCE**
### TABLE AIII-II

**AIRPLANE COMPARISONS**

**TWIN ENGINE**

**FIXED ENGINE & AIRFRAME SIZE**

**VARIABLE MISSION & PERFORMANCE**

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# TABLE AIII-III

## AIRPLANE COMPARISONS

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<th>GTSIO -420SC</th>
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**TABLE AIII-IV**

**AIRPLANE COMPARISONS**

**TWIN ENGINE**

**FIXED ENGINE & PAYLOAD RANGE**

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| ASPECT RATIO | 9.5 | 9.4 | 9.0 | 8.5 | 10.3 | 10.5 | 6.8 |

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<td>722</td>
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<td>391</td>
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<th>3.3</th>
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<td>V/V*</td>
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<td>1.00</td>
<td>1.30</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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| NOISE dBA | 0.0 | -1.0 | -1.0 | -4.5 | 0.0 | -0.5 | -5.0 |

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<th>180</th>
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<td>96</td>
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<td>100</td>
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<td>EVAL TOTAL</td>
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<td>274</td>
<td>221</td>
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121
## AIRPLANE COMPARISONS

### TWIN ENGINE

**FIXED PAYLOAD RANGE**

**VARIABLE ENGINE & AIRFRAME**

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<tr>
<th>ENGINE</th>
<th>TSIO-550</th>
<th>RC2-47</th>
<th>RC2-32</th>
<th>GTSIO</th>
<th>GTSIO-420</th>
<th>GTSIO-420SC</th>
<th>GATE</th>
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<td>BHP</td>
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<td>205</td>
<td>195</td>
<td>213</td>
<td>216</td>
<td>209</td>
</tr>
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</table>

| EMPTY WEIGHT | kg | 2009 | 1591 | 1470 | 1606 | 1765 | 1632 | 1517 |
|              | lb  | 4428 | 3485 | 3240 | 3540 | 3892 | 3597 | 3344 |

| GROSS WEIGHT | kg | 3107 | 2519 | 2381 | 2517 | 2727 | 2549 | 2547 |
|             | lb  | 6850 | 5553 | 5250 | 5550 | 6013 | 5620 | 5615 |

| WING AREA | sqm | 16.7 | 13.3 | 12.8 | 12.9 | 14.8 | 13.7 | 14.6 |
|           | sqft | 180  | 143  | 138  | 139  | 159  | 147  | 157  |

| WING SPAN | m  | 13.6 | 12.1 | 11.9 | 11.9 | 12.7 | 12.3 | 12.7 |
|           | ft  | 44.5 | 39.6 | 39.0 | 39.1 | 41.8 | 40.2 | 41.6 |

| ASPECT RATIO | | | | | | | |

| ROC | m/min | 312 | 285 | 291 | 239 | 367 | 364 | 162 |
| AT 25000' | fpm | 1025 | 935 | 955 | 785 | 1205 | 1195 | 530 |

| CLIMB TIME | min | 18.7 | 19.1 | 18.8 | 17.8 | 18.3 | 18.2 | 25.5 |
| SEROC | m/min | 105 | 76 | 76 | 130 | 112 | 112 | 76 |
| at 5000 ft | fpm | 343 | 250 | 250 | 425 | 367 | 367 | 250 |

| TAKEOFF DISTANCE | ft | 713 | 768 | 739 | 658 | 698 | 681 | 479 |

| STALL SPEED | km/hr | 135 | 135 | 135 | 139 | 135 | 135 | 131 |
| KTS | 73 | 73 | 73 | 75 | 73 | 73 | 71 |

| CRUISE SPEED | km/hr | 424 | 432 | 429 | 424 | 419 | 417 | 420 |
| KTS | 229 | 233 | 231 | 229 | 226 | 225 | 227 |

| PAYLOAD | kg | 635 | 635 | 635 | 635 | 635 | 635 | 635 |
|        | lb | 1400 | 1400 | 1400 | 1400 | 1400 | 1400 | 1400 |

| RANGE | km | 1482 | 1492 | 1482 | 1492 | 1432 | 1482 | 1482 |
|       | NM | 800 | 800 | 800 | 800 | 800 | 800 | 800 |

| MISSION FUEL | kg | 388 | 252 | 231 | 230 | 275 | 237 | 328 |
|              | lb | 855 | 555 | 509 | 506 | 606 | 523 | 723 |

| CRUISE MILEAGE | km/L | 2.7 | 4.7 | 5.1 | 5.2 | 3.9 | 5.0 | 3.6 |
|                | MPG | 5.6 | 9.7 | 10.5 | 10.6 | 7.9 | 10.3 | 7.4 |

| RELATIVE EFF | 1.00 | 1.55 | 1.66 | 1.65 | 1.40 | 1.59 | 1.08 |
| V/V* | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

| NOISE | dBA | 0.0 | -1.0 | -2.5 | -5.0 | -1.0 | -1.0 | -3.0 |

| PRICE | $/1000 | 381.5 | 301.5 | 286 | 307 | 341 | 312 | 333 |
| DOC | $/hr | 230 | 173 | 163 | 175 | 194 | 175 | 193 |

| EVAL TOTAL | --- | 300 | 355 | 312 | 191 | 286 | 170 |
### TABLE AIII-VII
RESULTS OF EVALUATION CRITERIA

#### SINGLE ENGINE

<table>
<thead>
<tr>
<th>ENGINE</th>
<th>FUEL BURNED</th>
<th>DOC</th>
<th>PRICE</th>
<th>MULTI-FUEL</th>
<th>NOISE</th>
<th>INSTL</th>
<th>TOTAL</th>
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## Table AIII-VIII
### Results of Evaluation Criteria

#### Twin Engine

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<th>ENGINES</th>
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<th>NOISE</th>
<th>INSTL</th>
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| II - FIXED ENGINE SIZE AND MISSION, VARIABLE AIRFRAME |
| RC2-47 | 108         | 47      | 30    | 10   | 10    | 20    | 225   |
| RC2-32 | 123         | 56      | 38    | 10   | 10    | 20    | 257   |
| GTDR-246| 140        | 49      | 27    | 5    | 10    | 10    | 241   |
| GTSIO-420| 91         | 18      | 0     | 0    | 0     | 0     | 109   |
| GTSIO-420SC | 128       | 45      | 22    | 10   | 0     | 0     | 205   |
| GATE   | 22          | 11      | 3     | 5    | 10    | 10    | 61    |

| III - FIXED MISSION, VARIABLE ENGINE AND AIRFRAME SIZE |
| RC2-47 | 140         | 30      | 50    | 10   | 0     | 20    | 300   |
| RC2-32 | 162         | 93      | 60    | 10   | 10    | 20    | 355   |
| GTDR-246| 163        | 77      | 47    | 5    | 10    | 10    | 312   |
| GTSIO-420| 116        | 50      | 25    | 0    | 0     | 0     | 191   |
| GTSIO-420SC | 155       | 77      | 44    | 10   | 0     | 0     | 286   |
| GATE   | 62          | 52      | 31    | 5    | 10    | 10    | 170   |