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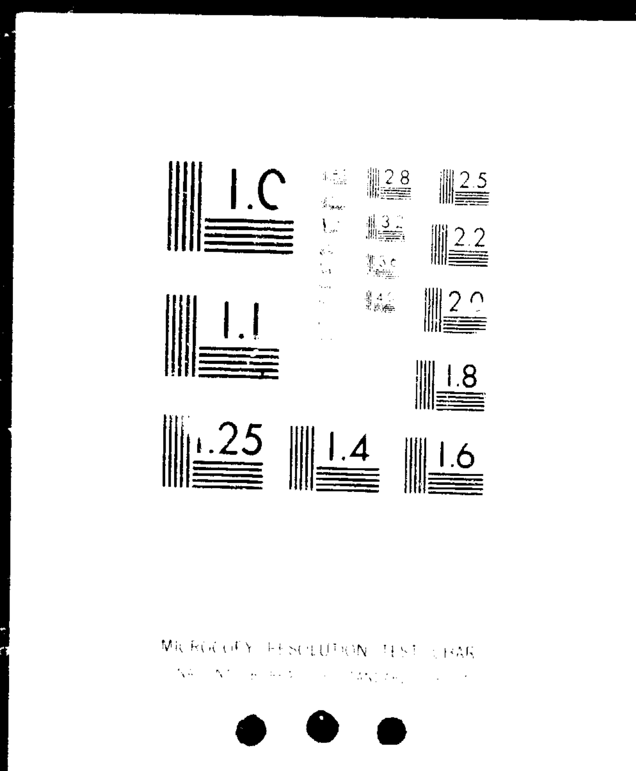

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Advanced General Aviation Comparative Engine / Airframe Integration Study

Leon A. Zmroczek

March, 1982

Prepared under
Contract NAS3-22220

by

BEECH AIRCRAFT CORPORATION
Wichita, Kansas

for

LEWIS RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA CONTRACTOR REPORT

ADVANCED GENERAL AVIATION

COMPARATIVE ENGINE/AIRFRAME INTEGRATION STUDY

Leon A. Zmroczek

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Prepared for:
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16. Abstract

NASA Contract NAS3-22220 provided for the comparison of four advanced general aviation engine concepts. Each concept was developed under a separate NASA contract. The results of the individual contracts served as a data base for the comparison.

The objective of the advanced general aviation comparative engine/airframe integration study was to establish a fair comparison of the in-airframe performance and efficiency of the advanced engine concepts.

The results of the study indicate that the proposed advanced engines can significantly improve the performance and economy of general aviation airplanes.

The engine found to be most promising was the highly advanced version of a rotary combustion (Wankel) engine. The low weight and fuel consumption of this engine, as well as its small size, make it ideally suited for aircraft use.

The data used for the turbine engine were found to be in error after the completion of the main study and a follow-up study was conducted with revised data to determine the effects of the errors. The improvements did not affect the ranking of the turbine engine although significant improvements in performance were obtained.

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1.0 SUMMARY

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2.0 INTRODUCTION

This study was performed under NASA contract NAS3-22220 - Advanced General Aviation Comparative Engine/Airframe Integration Study. The purpose of the study was to evaluate the performance of several advanced engine candidates proposed for use in general aviation aircraft. The study was to result in a relative ranking of the engine candidates in order of their suitability and desirability as aircraft engines.

Each of the engine concepts was developed under a separate NASA contract. The purpose of these contracts was to identify the technologies required to produce an advanced aircraft engine and to estimate the performance capabilities of the advanced engines.

The four types of engines considered in this study are:

1) Spark ignition engines
2) Diesel engines
3) Rotary engines
4) Turbine engines

A baseline spark ignition engine is also included to provide an estimate of the capability of current engines.

An installation concept was established for each engine candidate in a single and a twin airframe and the performance of the resulting configuration was analyzed. The performance of each engine was evaluated in a fixed airframe mode and in a fixed mission mode to determine the capabilities of each engine. The mission performance calculations were performed using the General Aviation Synthesis Program (GASP) developed by NASA (Reference 1).

The engines were ranked according to their relative performance in the study. Factors considered in ranking the engines included weight, fuel use, performance and installation.

3.0 ENGINE CANDIDATES

Four types of engines were considered in this study. Each engine concept was the subject of a previous NASA study contract. These earlier contracts defined the capabilities of the advanced engines and identified the technological developments necessary to achieve the design goals.

The engine candidates considered in the study were:

1) Spark ignition engines
   a) Advanced technology
   b) Highly advanced technology
2) Diesel engines
   a) Highly advanced technology
3) Rotary engines
   a) Advanced technology
   b) Highly advanced technology
4) General Aviation Turbine Engine - GATE

The cruise power rating of the engines considered in the study was 250 horsepower at 25000 feet. The cruise rating of the turbine engine was 250 equivalent shaft horsepower at 25000 feet at a true airspeed of 240 knots (M=0.4). The equivalent power of the turbine engine is based on a propeller efficiency of 0.8 as supplied by NASA.

The climb power ratings of the engines in the study were set by the engine manufacturers. Rate of climb at design cruise altitude was not a design requirement in the engine design studies. Differences in climb power ratings lead to significant differences in climb capability as will be seen later.

The characteristics of the study engines are shown in Table 1 and in Figures 1 and 2. Comparisons of the power output, cruise fuel flow and engine weight are shown in Figures 3, 4, and 5. These data were supplied by NASA.

The turbine engine data shown in Table 1 were found to be in error after completion of the main study. Revised data indicated a 10% reduction in specific fuel consumption and a 10% reduction in basic engine weight. Figures 4 and 5 show both the original data and the revised data.

3.1 Spark Ignition Engines

The two spark ignition engines evaluated in the study were studied by Teledyne Continental Motors Aircraft Products Division under contract NAS3-21272 (Reference 2). The two engines studied bracket a level of technology anticipated by 1990.

Advanced Technology Spark Ignition Engine

The advanced technology spark ignition engine, designated GTSIO-420, is a six cylinder, horizontally opposed, geared engine. The engine is aircooled and is equipped with fuel injection, turbocharging and turbocompounding. This engine burns avgas.

Advanced features of this engine are its electronic fuel control system and the turbocompounding machinery. Weight reduction has been accomplished by careful use of existing materials. Improvements in SFC are due to the turbocompounding and a lean fuel schedule.

Highly Advanced Technology Spark Ignition Engine

The highly advanced technology spark ignition engine, designated GTSIO-420/SC is physically very similar to the advanced technology spark ignition engine. The addition of a stratified charge combustion chamber and a direct injection fuel system allows this engine to burn a variety of fuels including avgas and jet fuel. The weight of this engine has been reduced by extensive use of advanced technology materials (e.g. titanium). Electronic fuel, air and ignition control systems also contribute to the fuel efficiency of this engine.

3.2 Diesel Engine

A single diesel engine was evaluated in this study although three versions were studied under contract NAS3-20830 (Reference 3). The technology levels envisioned for development were similar to those of the spark ignition engines. Only the highly advanced technology diesel engine was evaluated in the airframe integration study.

The highly advanced technology diesel engine is targeted for 1992 availability. The engine is a four cylinder, aircooled radial engine which uses a two stroke power cycle. The engine features fuel injection, turbocharging and after-cooling. Jet fuel is the fuel of choice although some multifuel capability could be provided.

A unique feature of this engine is a turbocharger-starter loop. A separate combustor in the turbocharger loop allows the turbocharger tc be run as an auxiliary power unit with the main engine shut down. Bleed air from the turbocharger loop is used to warm and start the primary engine.

Advanced materials and high pressure, high efficiency turbochargers are critical to the development of this engine. The limited cylinder cooling desired necessitates high temperature materials for cylinders, pistons and other engine components. Advanced materials will also be needed to meet engine weight and fuel consumption goals.

3.3 Rotary Engines

Little detailed information was available on the rotary engines at the time of contract completion. These engines were studied by Curtiss-Wright Corporation under contract with NASA. A summary of available information follows.

Advanced Technology Rotary Engine

The advanced technology rotary engine, designated RC2-47 is a two rotor Wankel-type engine. The engine is fuel injected, turbocharged and liquid-cooled. A stratified charge combustion chamber and timed fuel injection allow the engine to operate well using a variety of fuels. Mounting pads have been integrated into the aft end of the rotary engines which allow mounting of all engine accessories directly to the engine. These mounting pads simplify and streamline the installation of these engines.

The liquid cooling of the rotary engines is unique among the advanced engine candidates. It is felt that the liquid cooling will provide an unusual degree of installation flexibility. The weight of the cooling system is included in the basic weight of the engines as listed in Table 1.

Highly Advanced Technology Rotary Engine

The highly advanced technology rotary engine, designated RC2-32, is physically similar to the advanced technology rotary engine. Advanced features of this engine include retracting or unloading apex seals and higher operating speed (higher rotor speed). The engine utilizes advanced materials to reduce engine weight and reduce wear.

3.4 Turbine Engine

General Aviation Turbine Engine

The general aviation turbine engine (GATE) concept was studied by four contractors under four NASA contracts. NASA extracted the data used in this study from the results of the GATE study performed by Teledyne Continental Motors, General Products Division under contract NAS3-20757 (Reference 4). The data are typical of data generated in the four studies.

The engine proposed for the general aviation engine/airframe integration was a single shaft turbine engine. The primary fuel for this engine was jet fuel although some multifuel capability should be available. The low weight and low specific fuel consumption of this engine is made possible by the use of advanced high temperature materials which allow increased operating temperatures and pressures. The engine also features electronic fuel and speed controls. The selling price of this engine was predicted to be competitive with the other study engines, however, reliable and consistent selling price information was not available for any of the study engines.

3.5 Baseline Engine

The Teledyne Continental Motors TSIO-550 engine was chosen as the baseline engine for the study. The TSIO-550 is a six cylinder, horizontally opposed air cooled, direct drive spark ignition engine This engine features fuel injection and turbocharging and will burn only avgas.

4.0 ENGINE DATA

Table 1 includes all of the engine data used in the study, in particular, scaling rules for engine weight, external engine dimensions, center of gravity location, power output, fuel flow and heat rejection rates for each engine. This data was compiled and approved by NASA prior to commencement of the study effort and provided a solid data base on which to perform the study.

NASA discovered two errors in the turbine engine data after completion of the main study. A follow-on study was conducted to determine the influence of the errors on the results of the study. The revised turbine engine data indicated that the specific fuel consumption (fuel flow) and the basic engine weight shown in Table 1 should be reduced by 10%.

4.1 Engine Weight

Engine weight was divided into two parts - basic weight and additional weight. Both basic weight and additional weight are shown in Table 1 for each engine. The basic weight is the weight of the engine as supplied by the manufacturer. The additional weight is the weight of items required for the engine to operate in an airframe. Additional weight includes items such as the battery, propeller, and engine mount vibration isolators. A list of the additional weight items for each engine is shown in Table 2. The additional weight of each study engine includes items required by that engine. The standard equipment was different for each study engine, and the additional weight items were added to the basic engine weight to provide an equivalent equipment level for all of the study engines. Any items not mentioned in the additional weight list are included in the basic engine weight.

Scaling rules are shown in Table 1 for scaling the basic weight with changes in engine horsepower. These laws apply only to the basic weight. The additional weight was not scaled. Scaling for the diesel engine is shown in Figure 1.

4.2 Dimensions and Center of Gravity Location

The external dimensions of each engine, length, width and height, are shown in Table 1. Scaling rules are also shown where applicable. The center of gravity location of each engine is also shown.

The external dimensions were used in conjunction with sketches of the engines to establish nacelle size and shape. The center of gravity location was used to establish airframe changes and engine location required to balance each airframe.

4.3 Power Output and Fuel Flow

Engine power output and specific fuel consumption are shown in Table 1. The variation of power and SFC with altitude is shown for at least two power settings for each engine. Engine RPM is also noted.

Note that the turbine engine data shown include installed shaft horsepower and exhaust thrust. These values are listed separately. This engine is sized to 250 equivalent horsepower at 25000 feet and 240 knots true airspeed (M=0.4) as noted in Table 1. The data, as supplied by NASA, incorporates a propeller efficiency of 0.8 in the calculation of equivalent horsepower.

Scaling of power output, as required in several parts of the study, was done linearly for all operating conditions. Power for all operating conditions was scaled by a constant factor as required.

Specific fuel consumption was not changed with changes in engine size (power rating) except for the diesel and the turbine engines. The scaling trend for the diesel engine specific fuel consumption is shown in Figure 1. Relative scaling for the turbine engine specific fuel consumption is shown in Figure 2.

4.4 Heat Rejection Rates

The heat rejection rate for each engine at cruise is indicated as a percent of cruise horsepower produced. A cooling requirement of 75% for an engine producing 250 horsepower indicates a heat rejection rate of 187.5 horsepower or 7,950 btu/min.

The heat rejection at cruise was used to establish cooling drag estimates for each engine. This estimate of cooling drag was added to the total airplane drag for mission analysis. This method produces a small error in mission performance. However, the error is not significant for the normal missions envisioned for the study airplanes. Cooling drag estimates are shown in Table 3.

5.0 TECHNICAL APPROACH AND METHODS

5.1 Contract Requirements

The desired method for comparison of the engine designs was outlined in the contract statement. The contract required that an equitable comparison be made to determine which engine would be most useful to the general aviation industry. Since each engine had been evaluated in a previous study the purpose of this contract was to insure a comparison on an equitable basis.

Some specific requirements of the contract were:

1. Establish an installation concept for each engine in a pressurized single and a pressurized twin airframe.
2. Determine the performance of the resulting engine/airframe combinations. The performance was to be evaluated on both a fixed airframe basis and a fixed mission basis.
3. Perform several parametric analyses to determine the effects of design goals on the relative performance of the engines.
4. Establish the acquisition and operating costs of each airframe/engine combination.

Installation Concepts

An installation concept was established for each engine in a pressurized single and a pressurized twin airplane configuration. The goal of this part of the study was to determine any major installation problems or advantages with the advanced engines.

An engine mounting system was selected for each engine/airframe combination to take advantage of the features of each engine. A nacelle was designed to minimize the drag of each installation. Air inlets and cooling air flow paths were arranged as well as possible based on the information available for each engine.

Performance Analysis

The performance of each engine airframe combination was to be evaluated using two modes of analysis; fixed airframe and fixed mission. The fixed airframe concept was used to establish the installation details for each engine. The fixed mission concept produced an airframe/engine combination capable of performing a baseline mission (i.e. carry a given payload a certain range at a given speed and altitude).

Parametric Analysis

An investigation was made to determine the impact of design goals and design point specifications on the relative performance of the engines. The effects of changing design cruise speed, design cruise altitude design range and engine inlet efficiency were examined. Each study was conducted on a fixed mission basis with only the parametric variable changed to establish its effect on engine and airframe size.

Cost Analysis

Acquisition cost and operating costs were to be determined for each airframe/engine combination.

Technology Recommendations

The manufacturers contract reports were reviewed together with the results of the engine/airframe integration study to arrive at a recommendation for further work. Areas of concern governing the choice of one engine over another were also considered in this section of the study to provide additional insight into the desirability of each engine candidate.

5.2 INSTALLATION CONCEPT

Baseline Engine Installation

A single and a twin airframe utilizing the baseline spark ignition engine were established as the baseline airframes for the study. These airframes are shown in Figures 6 and 7. Details of the baseline engine installations are shown in Figures 8 and 9. The baseline engine uses a bed type mounting system and downdraft cooling.

Conventional configurations and conventional construction at a current level of technology were used throughout the study to provide a high degree of confidence in the weight analysis and the performance analysis. This permitted the differences in airplane performance to be credited directly to to engine characteristics. It is expected that the relative performance of the advanced engines would not be affected by an across the board airframe technology improvement.

Advanced Engine Installations

The first step in evaluating each of the advanced engines was to install each in a single and a twin airplane. The low weight of the advanced engines produced problems in balancing the airframes using these engines.

Balance problems in the single engine airplane were solved by extending the nose of the airplane. All of the advanced engine singles required a 14 inch stretch. Additional balance problems in the single engine airplanes were solved by moving the wing and/or providing a nose baggage area.

Balance problems with the twin engine airplanes were easily solved by adjusting nacelle length.

Spark Ignition Installations

The airplane three view drawings for the single and twin with the spark ignition engine are shown in Figures 10 and 11. Figures 12 and 13 are the engine installation drawings for the single and twin. The advanced technology and highly advanced technology spark ignition engines are externally similar, therefore one drawing is sufficient to describe the installation for both engines.

The advanced spark ignition engines are bed mounted and updraft cooled. Cooling air enters low at the front of the nacelle. The cooling air on the twin exits through an ejector at the top rear of the nacelle. A cowl flap is provided for additional cooling at low speed. The cooling air for the single exits through the bottom of the nacelle. Air is not ejected through the top of the cowl to prevent any debris from impinging on the windshield.

A separate oil cooler is not required for these engines. The oil sump is finned and acts as an oil cooler. Air is routed past the oil sump to insure proper cooling. This air exits through the same openings as the engine cooling air.

The nose on the single engine airplane has been extended to provide proper weight balance for the airplane and also to accommodate the longer engines. The additional structure required by the nose extension eliminates most of the weight reduction of the advanced technology spark ignition engine.

Diesel Installation

Figures 14 and 15 are the three view drawings for the diesel engine single and twin and Figures 16 and 17 are the corresponding installation detail drawings.

The radial design of this engine does not lend itself to bed mounting. The engine mount for the single is a combination mount which uses a lower bed-type mount and an upper truss mount. The radial design fits very well into a single engine airplane cowling however the turbocharger and accessories may need to be relocated slightly to facilitate installation.

All cooling air for the single engine installation enters through one inlet below the propeller spinner and exits through an opening in the bottom of the cowl. A cowl flap is also provided for additional cooling. Combustion air enters through a separate inlet on the right side of the cowling.

The nacelle required to completely surround the diesel engine in a twin installation is quite large due to the radial design of the engine. The frontal area of the nacelle can be significantly reduced by using a smaller nacelle with bumps or blisters to enclose the injector on each cylinder. This produces a nacelle with approximately the same frontal area as the spark ignition installation.

A truss type mount was used to install the diesel in the twin airframe. The turbocharger and other accessories have been relocated to fit inside the truss mounts.

All cooling air enters through a single opening and exits at the bottom of the nacelle similar to the single. Combustion air is drawn from the same plenum chamber as the cooling air.

Rotary Installations

Figures 18 and 19 are the airplane three-view drawings for single and twin airplanes using the rotary engines and Figures 20 and 21 are the respective installation detail drawings. The advanced rotary and the highly advanced rotary are externally similar and both installations are covered by a single drawing. The rotary engines can be bed mounted or truss mounted.

A bed mount was used to install the rotary engine in the single. Locating the coolant radiator was the most difficult problem encountered in installing the rotary engines in the single. The radiator was mounted in an upright position near the left side of the cowl. Cooling air enters through a single inlet below the propeller and exits through a single opening at the bottom of the cooling air plenum.

The rotary engines were truss mounted for the twin installation. Notice that the engine is very tightly cowled. This is possible since the engine is liquid cooled. The single scoop air inlet supplies both combustion and cooling air. A single outlet is provided for cooling air and exhaust.

The integral accessory mounts on the back of the engine provide a very convenient installation package. The liquid cooling provides a high degree of installation flexibility particularly in the twin. The small size and light weight of these engines provide room in the single for a nose baggage compartment behind the firewall.

GATE Installation

Figures 22 and 23 show the airframe three-views for the single and twin with the general aviation turbine engine. The corresponding installation details are shown in Figures 24 and 25.

The general aviation turbine is truss mounted for the single installation. Separate inlets have been provided for both combustion air and oil cooler air. Combustion air enters below the propeller. Oil cooler air enters the right side of the cowling through a NACA duct and is exhausted through the left side of the cowl. Engine exhaust is carried overboard by a rather large exhaust stack. The large stack required by this engine may produce a significant drag increase on the single. A nose baggage compartment is shown behind the firewall.

The turbine is also truss mounted in the twin installation. The combustion air inlet is located below the propeller and oil cooler air is supplied through a NACA duct in the bottom of the nacelle. An ejector is used to dump exhaust gas and cooling air out the back of the nacelle over the wing. The nacelle for this engine is very small and streamlined.

A problem exists in the propeller required for a single shaft turbine engine. The propeller for a single shaft turbine engine must be capable of being set to flight idle and to ground low pitch settings. Current propellers of this type have hubs large enough to cover the general aviation turbine's combustion air inlet. This problem can be eliminated by moving the combustion air inlet away from the propeller shaft.

5.3 PERFORMANCE ANALYSIS

Performance estimation and airframe sizing were performed using the NASA developed General Aviation Synthesis Program (GASP). The program is a whole airplane design and synthesis program capable of a wide range of performance and stability calculations.

Inputs required by the program include limited airframe geometry, engine data, weight trend data and drag data. This data, together with the synthesis equations, establishes the airplane definition.

The capabilities of the program include engine sizing, constrained airframe sizing, stability and control analysis and performance estimation. A simplified flow chart of the program is shown in Figure 26.

Program output is arranged in a mission profile format including taxi, takeoff, climb, cruise, descent and landing.

Propeller size for each engine/airframe combination was chosen to provide 87 to 89% installed efficiency at cruise and to provide climb efficiency of about 75%. Some variation in propeller efficiency was unavoidable since the nacelle contributes to blockage behind the propeller and because the engine speed was different for each engine.

The methods of analysis used to establish engine preference are shown below.

1. Fixed Airframe Analysis
2. Fixed Wing Area; Constant Range
3. Fixed Wing Loading; Constant Range
4. Fixed Mission Analysis

The fixed airframe analysis and the fixed mission analysis were rerun in a follow on study using revised turbine engine data. All ground rules were applied as in the main study.

Baseline Performance

The performance of the baseline engine/airframe combinations was evaluated to establish a baseline mission for the single and the twin airplanes.

The mission established for the single consisted of an 800 nautical mile cruise at 25000 feet, with a 1200 pound payload. Cruise speed was to be at least 200 knots.

The twin engine airplane was required to have 920 nautical mile cruise range at 25000 feet with a 1300 pound payload. Cruise speed for the twin was to be at least 235 knots.

The mission specified for both the single and the twin included a takeoff at standard sea level conditions and a climb to 25000 feet at maximum rate of climb. A 45 minute fuel reserve at cruise speed and altitude was also required.

Performance capabilities checked for each airplane included:

1. Takeoff distance to 50 feet (maximum gross weight, sea level, standard day)

2. Maximum rate of climb
   a. at sea level
   b. at 25000 feet (or cruise altitude)

3. Time to climb to 25000 feet (or cruise altitude)

4. Landing distance from 50 feet (maximum gross weight, sea level, standard day)

Fixed Airframe Analysis

The fixed airframe analysis consisted of determining the performance of the baseline airframes with the advanced engines. The airframes used for analysis were those established by the installation concept phase of the study. Figures 27 and 28 show the results of this analysis for the singles and twins respectively.

Airplane gross weight, wing area, and payload were held constant for this analysis. Airframe empty weight was lower than the baseline airplane empty weight for all of the advanced engines. The gross weight was held constant by adding fuel to the airplane. The additional fuel coupled with the low specific fuel consumption of the advanced engines produces airplanes with very long range capability. The engines producing the longest range are the highly advanced engines, the diesel and the rotary in particular.

All of the advanced engines improve the cruise speed performance of the study airplanes. The increase in cruise speed is due primarily to the reduced cooling drag of the advanced engines. The turbine engine produces the largest increase in speed since the cooling drag of the turbine engine is the lowest of all the advanced engines, however, the drag of the exhaust stack for the single engine airplane may result in a net drag increase and reduced cruise speeds for this airplane. This aspect was not considered in detail in this study.

Climb performance at sea level is adequate for all of the advanced engines. Climb performance at cruise altitude is an indicator of engine power reserve at altitude. There are significant differences in rate of climb at 25000 feet, due primarily to the differences in the methods used by the engine manufacturers to rate the power of their engines (see Figure 3). The engines which provide the highest climb rates are those which have excess power at 25000 feet. These engines (the spark ignition engines and the rotary engines) are throttled to produce the cruise power of 250 horsepower.

The spark ignition engines and the rotary engines produce airframes with more climb capability than either the diesel or the turbine engine. The diesel engine and the turbine engine lack any power reserve at altitude as seen in Figure 3. Both of these engines, as designed, use the same power setting for climb and cruise. The diesel produces 250 horsepower for climb or cruise at 25000 feet. The turbine produces 250 horsepower for cruise but only about 230 horsepower for climb at 25000 feet because of lower inlet total pressure due to reduced airspeed. These engines would need to be rerated, resized or redesigned for climb to alter this situation.

The changes in the turbine engine data resulted in a significant increase in the range capability of the turbine engine airplanes. No other performance capabilities were changed significantly from the original turbine airplanes.

Detailed numerical results of the fixed airframe analysis are contained in Tables A1 and A2 of Appendix A. Detailed results of the revised fixed airframe turbine engine analysis are shown in Table 5.

Fixed Wing Area Analysis

The fixed wing area analysis was performed to develop a minimum change airplane capable of performing the baseline range. The gross weight of the airplanes was allowed to change as required to meet the range requirement. The results of this study are shown in Figures 29 and 30. Detailed results are contained in Tables A3 and A4 of Appendix A.

All of the advanced engines reduced the gross weight and the empty weight of the study airplanes. The highly advanced rotary engine produced the lightest airframe followed by the diesel engine. The diesel engine produced the most fuel efficient airframe requiring less fuel than any other engine to fly the design range. The highly advanced technology spark ignition engine also produces a very fuel efficient airplane. The turbine engine produces an airplane which is lighter than the baseline but the fuel use is not significantly lower than the baseline.

The performance of the fixed wing area airplanes is similar to that of the fixed airframe airplanes. All of the advanced engines outperform the baseline engine at sea level. The turbine engine is the only engine not capable of meeting or exceeding the climb rate of the baseline engine at 25000 feet.

Fixed Wing Loading Analysis

The fixed wing loading analysis was performed in a manner similar to the fixed wing area analysis. The results are presented in Figures 31 and 32. The results of the fixed wing loading analysis are nearly identical to the results of the fixed wing area analysis. Detailed results are contained in Tables A5 and A6 of Appendix A.

Fixed Mission Analysis

The fixed mission analysis was performed to establish the efficiency possible by sizing the study engines and airframes to perform the baseline mission. This analysis resulted in a set of airplanes with the same cruise speed, range and altitude capability. Stall speed and landing distance were also held constant. Airplane gross weight and empty weight were allowed to change as required to perform the desired mission. The advanced engines were sized to perform the desired mission. Takeoff distance was allowed to vary within a reasonable range above or below the baseline distance. The results of this analysis are shown in Figures 33 and 34. Detailed results are contained in Tables A7 and A8 of Appendix A. Detailed results of the revised fixed mission turbine engine analysis are contained in Table 6.

The engines which produce the airplane with the lowest gross weight are the highly advanced rotary engine and the highly advanced technology diesel engine. However the highly advanced technology spark ignition engine, the advanced rotary engine and the turbine engine also produce light airframes. The highly advanced rotary engine produces the airplane with the lowest empty weight but the other advanced engines, particularly the turbine engine, produce airframes nearly as light.

The rate of climb of the airframes with the scaled engines, with the exception of the spark ignition engines, is not as good that of the baseline airplanes. The differences in rate of climb are caused by the design excess power previously mentioned as well as the reduction in engine size achieved by scaling the study engines. The engine size was driven primarily by cruise speed which was held constant in this analysis; rate of climb was variable.

The rotary engines provide acceptable rates of climb, although their climb performance is not as good as the baseline engine. The diesel and the turbine engine may need to be rerated, resized or redesigned to provide acceptable climb performance, particularly at cruise altitude. Resizing these engines for climb may reduce their efficiency and/or effect their weight and cost advantages.

The most efficient engine, that is, the engine requiring the least fuel for the design mission, is the diesel. The highly advanced rotary engine and the highly advanced technology spark ignition engine produce airframes which use only slightly more fuel than the diesel. The turbine engine uses more fuel than any other advanced engine in the study, even though it has been scaled down to less than eight-tenths of its original size. The turbine does, however, burn significantly less fuel than the baseline engine.

The results of the fixed mission analysis with the revised turbine engine data indicate a significant improvement in fuel economy and a reduction in airframe weight. The empty weights of the airframes with the improved turbine are equal to or lower than the empty weights of the highly advanced rotary engine airplanes. Mission fuel consumption of the improved turbine, while significantly lower than the original turbine, is still the highest of all the advanced engines. Other performance capabilities of the revised engine/airframe are very similar to those of the original turbine engine.

5.4 PARAMETRIC STUDIES

Several studies were performed to determine the effects of changing selected mission parameters on the relative performance of the advanced engines. These studies were performed in the same mar- r as the fixed mission analysis. Cruise altitude, cruise speed and cruise range were varied to check for changes in relative engine performance. Only the highly advanced engine of each type was used in this study. The single engine airplanes were analyzed in the parametric studies since it was found in the previous phase of the contract study that the relative performance was the same for singles and twins.

Altitude Parametric Study

Design cruise altitude was varied from 15000 feet to 35000 feet to determine the significance of cruise altitude on relative airframe sizing and relative engine performance. Cruise speed, range and payload were held constant. The resulting airplanes were capable of performing the baseline mission at a new design altitude. The results of the parametric altitude study are shown in Figures 35 and 36. Detailed numerical results are contained in Tables A9 through A12 in Appendix A.

The diesel engine is effected more by changes in altitude than the other study engines primarily because the power lapse rate of this engine above critical altitude is very high. At altitudes above 25000 feet the weight of an airplane using the diesel engine rises very rapidly. The reason for this is that the engine, as designed, must be quite large to maintain adequate power at these high altitudes. The diesel remains a very efficient engine in spite of this lapse rate. The fuel use increases very little even at 35000 feet.

The turbine engine on the other hand uses more fuel than the other advanced engines regardless of altitude.

The rotary engine maintains a slight edge in gross weight and empty weight on the other study engines for a large altitude range (17000 feet to above 35000 feet). Also the fuel requirement for the rotary is not significantly greater than the fuel required for the diesel or the spark ignition engine.

Design altitudes above 25000 feet are of dubious value for the class of airplane considered in this study. Only small improvements in fuel economy occur above 25000 feet and the airplanes designed for the higher altitudes are generally heavier than the 25000 foot cruise airplanes. The increase in empty weight would probably lead to increased costs for these airplanes.

Speed Parametric Study

Design cruise true air speed at 25000 feet was varied from 175 knots to 250 knots to determine the effects of cruise speed on relative engine performance. Range and payload were held constant. The results of this study are shown in Figures 37 and 38. The detailed results of this study are contained in Tables A13 through A16 of Appendix A.

The weight of the airplanes produced increases rapidly as the design cruise speed increases. The higher cruise speeds require larger, more powerful engines. These engines use more fuel. The net result is that a larger, heavier airplane is required to meet mission requirements.

The turbine engine at high cruise speeds produces lightweight airframes. The fuel economy of the turbine becomes more competitive with the other engines at high design cruise speeds. High ram pressure at high speed and lower specific fuel consumption of large engines (see Figure 2) required to obtain high cruise speeds contribute to the improved economy of the turbine under these conditions. The effect of airspeed, as noted here, may be more pronounced on the twin engine airplane since the twin is operating at a higher air speed.

The spark ignition engine produces heavy airplanes at high cruise speed due primarily to the lower power to weight ratio of this engine. The fuel economy remains competitive with the other advanced engines however.

The rotary engine produces the lightest airframe over a wide range of cruise speeds. Mission fuel requirements for the rotary are comparable to the other engines but the diesel maintains a slight edge in fuel economy throughout the speed range considered.

Range Parametric Study

The design range at 25000 feet was varied from 500 to 1200 nautical miles to examine the effect of range on relative engine performance. Payload and cruise speed were held constant for this study.

Aircraft empty weight and horsepower did not change significantly with design range. Mission fuel requirements changed quickly with range. The changes noted were generally linear with very little change in relative performance.

Results of this study are shown in Figures 39 and 40 and detailed results are contained in Tables A17 through A20 of Appendix A.

Inlet Efficiency Study

A study was devised, in response to a request from NASA, to examine the effect of combustion air inlet ram recovery on the study engines.

This study was targeted at the intermittent combustion engines. The turbine engine data already includes a reasonable ram recovery effect and no significant performance improvements would be expected from an increase in ram recovery.

First the characteristics of each intermittent combustion engine were examined to evaluate the potential benefit of a high recovery inlet system. Ram pressure recovery affects engines differently depending on the operating point of the engine and the restraints which establish that operating point.

An engine operating at its design continuous power at a given altitude will not benefit from a high recovery inlet. An increase in inlet pressure (or density), if utilized by the engine, would raise the brake mean effective pressure (BMEP) above the maximum allowable BMEP (design continuous BMEP). The engine would have to be redesigned (higher technology) to allow the increased BMEP. This is the case for an engine operating at or below critical altitude.

The spark ignition engines and the rotary engines are throttled at 25000 feet to produce 250 horsepower. These engines are operating at design continuous power under these conditions. An improvement in ram recovery would not increase the performance of these engines below 25000 feet, however improvements in ram recovery could increase the critical altitude by as much as 2000 feet at cruise speed.

An engine operating below its design continuous power can use ram pressure to boost the BMEP (up to a maximum of design continuous BMEP) and increase power output. This will occur for an engine operating above critical altitude, that is, an engine using all of its turbocharger capacity.

The diesel engine, operating at 25000 feet, is well above its critical altitude of 17000 feet, and it will benefit from a high recovery inlet. A power increase of 16 percent is possible at cruise condition (25000 feet, 235 knots) with 100 percent ram recovery. This increase assumes that engine power output is dependent on air density at the compressor inlet flange.

A fixed mission single and twin were analyzed with a diesel engine and a high recovery (100%) inlet to examine the effects of the inlet. Specific fuel consumption was assumed not to vary with speed. Specific fuel consumption was allowed to vary with altitude and power setting. The results of the study are shown in Table 4.

The horsepower required at cruise speed and altitude is virtually unaffected by the ram recovery. The high recovery inlet permits a smaller engine to produce the required cruise power. The required mission fuel was not significantly affected by the change in ram recovery, since cruise speed and cruise fuel flow did not change.

Although cruise performance was not significantly affected by the inlet efficiency improvement, a reduction in climb and takeoff performance was noted due to the smaller engine used. The takeoff distances required by the airplanes with the high recovery inlets were slightly longer than the airplanes using the low recovery system. Rate of climb was lower and time to climb to cruise altitude was longer for the high recovery engines. The performance changes noted occur at low airspeeds, where ram recovery is less effective and the performance of the airplane is established mostly by static engine power rating.

This study indicates that no change in relative performance occurs at high inlet recovery ratios. This is not to say that an advanced engine would not benefit at all from a high recovery inlet. An inlet such as this may be used to improve the high speed performance of an engine but gains in overall economy of operation cannot be expected.

5.5 COST ANALYSIS

An estimate of acquisition cost and operating cost for each engine/airframe combination was requested by the contract. These estimates were made, to the extent possible, for the fixed airframe airplanes and for the fixed mission airplanes.

Sufficient information was not available for many of the study engines to produce a complete estimate of operating cost or acquisition cost. Engine acquisition cost was not available on a comparable basis for all of the study engines, therefore, engine acquisition cost was treated as a parametric value in the costing analysis.

A complete operating cost estimate would include fuel cost and use, oil cost and use, inspection and maintenance costs, insurance cost, hangar or storage costs and engine exchange or overhaul costs. Insurance, storage or hangaring, and airframe inspection costs are functions of airframe size and type. These costs would be about the same for any of the airframes developed in this study. Oil use, engine overhaul or exchange costs, and engine maintenance cost are functions of engine size and type. No information was available on these costs and no method exists to adequately estimate these costs particularly for the advanced engines considered in this study.

Fuel cost is the only part of the operating cost which could be adequately estimated. Fuel cost per hour has been established for each study airplane.

Acquisition Cost

Airplane acquisition cost is based on aircraft empty weight, engine cost, standard equipment cost and standard avionics cost.

Airframe cost was based on historical data and learning curve theory. Airframe weight was estimated from aircraft empty weight, engine weight and weight of additional equipment. Airframe materials were priced on the basis of current materials costs. An eighty percent learning curve was used to estimate manhour expenditure per airplane and current labor rates were used to estimate labor costs. Amortized development cost, factory profit and dealer markup were added to the cost of materials and labor to produce a base selling price. An additional increment was added for typical optional equipment and avionics to arrive at total acquisition cost. An outline of the cost analysis method is given in Appendix B.

Engine cost for the above procedure was treated parametrically. The results are shown in Figure 41. The information in Figure 41 is presented as a percent change from baseline. The baseline costs for the single and twin were established at a cost for the baseline engine of $10,000.

In general, the fixed airframe airplanes with the advanced engines cost more than the baseline airplanes for the same engine cost. The fixed mission airplanes cost less than the baseline airplanes for the same engine cost.

These charts can also be used to determine the relative costs of airframes if the costs of the engines are known.

Fuel Cost

Fuel cost estimates were based on fuel cost per gallon and cruise fuel flow. The current costs for 100 LL avgas ($1.90 per gallon) and Jet A fuel ($1.70 per gallon) were used to establish fuel cost per hour.

Fuel cost per pound was found by dividing the cost per gallon by the appropriate fuel density. 100 LL avgas has a density of 5.87 pounds per gallon for a cost of 32.4 cents per pound. Jet A fuel has a density of 6.74 pounds per gallon and a cost of 25.2 cents per pound. Fuel costs per hour was found by multiplying fuel cost per pound by cruise fuel flow rate in pounds per hour. The results were normalized by dividing the fuel cost per hour by the fuel cost per hour for the baseline airplanes. The normalized results are shown in Figure 42.

All of the advanced engines except the advanced technology spark ignition engine are capable of burning jet fuel. The baseline engine and the advanced technology spark ignition engine require 100 LL avgas. The comparison of fuel cost for engines which burn a particular fuel is equivalent to a comparison of fuel flow. Fuel cost per gallon introduces differences only in the case of engines using different fuels. Figure 42 indicates that several of the advanced engines will cost less than half as much to operate as the baseline. This margin is dependent on the relative costs of avgas and jet fuel.

6.0 CONCLUSIONS AND ENGINE RANKING

The factors considered in establishing a ranking of the study engines were airplane empty weight, mission fuel requirements, airplane climb performance and engine installation characteristics. Acquisition cost and operating cost were not considered heavily in ranking since engine cost was not available.

6.1 Mission Fuel

The fuel required to perform a mission was considered heavily in establishing the engine ranking. The type and amount of fuel an engine requires is very important particularly when fuel supplies are limited.

The diesel engine consistently required less fuel for a particular mission than the other advanced engines. However, the highly advanced technology spark ignition engine and the highly advanced rotary engine were very close to the diesel in fuel economy requiring no more than 6 percent more fuel than the diesel in general. The turbine could not achieve comparable fuel economy except at very high cruise speeds.

The 6 percent spread in mission fuel requirements amounts to less than 40 pounds for the twins and less than 20 pounds for the singles. A slight change in engine characteristics during development or the failure of a critical technology item to meet design expectations could result in a change in relative efficiency of the engines. Additional uncertainty exists in the scaling rules employed to size the study engines.

The diesel engine, the highly advanced technology spark ignition engine and the highly advanced rotary are considered nearly equal in fuel efficiency ranking.

6.2 Airplane Weight

The highly advanced rotary engine and the turbine engine produced the airplanes with the lowest empty weights. The airplanes having the lowest gross weight were those using the highly advanced rotary engine and the diesel engine.

Although the rotary engine produces the lightest airframe, the other highly advanced engines produce airframes which are no more than 8 percent heavier than the airframe with the rotary engine. This eight percent change in airplane weight is considered significant since it is caused primarily by a change in engine weight. Engine weight accounts for less than 25 percent of the empty weight of the baseline airplane.

The highly advanced rotary engine is the most favorable engine since it produces an airframe with low empty weight and low gross weight. A light airframe should result in lower acquisition and operating costs. The turbine is competitive with the rotary on the basis of empty weight however the fuel required by the turbine elevates the gross weight significantly above that of the rotary engine airplane.

The highly advanced technology spark ignition engine, the diesel and the advanced rotary (RC2-47) also produce light weight airplanes.

6.3 Performance - Rate of Climb

Airplane performance is an important marketing consideration for an airframe manufacturer. Significant differences exist in the performance levels of the study engine/airframe combinations. The differences are caused primarily by differences in the engine climb power ratings set by the engine manufacturers and by differences in power lapse rate with altitude.

The spark ignition engines, as designed, provide better climb performance than the other advanced engines, followed by the rotary engines, the diesel engine and the turbine engine. The spark ignition engines provide rates of climb better than the baseline engine. The rotary engines' climb performance is below that of the baseline though not significantly.

The diesel and turbine engine powered airplanes do not climb as well as the airplanes powered by the other study engines. The climb power available from these engines was assumed to be maximum cruise power since no special climb power rating was specified.

Redesigning or rerating the engines for climb would improve the climb performance, however this would require changes in operating temperatures, operating pressures, fuel flows or other design features. These changes are outside of the airframe contractor's area of expertise and no investigations of the benefits of redesign or rerating were conducted.

6.4 Range-Payload Capability

The results of the fixed airframe analysis indicate the range-payload capability of each advanced engine at maximum cruise speed. Installation of an advanced engine in an existing airframe can provide increased range, increased payload or both. The fixed airframe study shows the extreme case of constant payload.

The highly advanced rotary engine, providing over twice the range of the baseline engine, would be an excellent candidate for improving exisitng airplanes. All of the advanced engines improve the range-payload capability of the airplanes in the study.

The range-payload improvement is important particularly for the entry position of a new engine as a replacement or retrofit into existing airframes.

6.5 Engine Installation

The turbine engine and the rotary engine provide the smallest most compact packaging of the advanced engines. The size and shape of the power plant are of particular concern in the twin configuration where increases in engine frontal area directly affect the airplane frontal area and drag.

The spark ignition engines and the diesel engine have no particular installation advantages or disadvantages compared to the baseline engine. The auxiliary power feature of the diesel engine turbocharger loop, while convenient for ground operations, provides no fuel efficiency advantage for the airplanes in this study, nor does this feature influence the sizing of the diesel engine.

The turbine engine requires a rather large exhaust stack. The stack introduces no major problem on the twin where exhaust can be dumped over the wing but the stack may make a significant contribution to the drag on the single engine airplane. The size and shape as well as the low weight of this engine allows a very clean and efficient installation on the twin.

The rotary engine, with its small frontal area and liquid cooling, provides a very clean and flexible installation. The integral accessory mounting pads improve the efficiency and simplicity of the installation.

6.6 RANKING

Final engine ranking was accomplished by means of a numerical system. The details of the ranking system and the results are outlined in Appendix C. The ranking system was based on mission fuel use, airplane empty weight, time to climb to 25000 feet, relative installation efficiency and multifuel capability.

The final ranking of the engines is based on the fixed mission analysis and is as follows:

1. Highly Advanced Rotary, RC2-32

2. Highly Advanced Technology Diesel

3. Highly Advanced Technology Spark Ignition, GTSIO-420/SC

4. Advanced Rotary, RC2-47

5. General Aviation Turbine Engine, GATE

   (Revised engine is significantly better than original but no change in rank occurs)

6. Advanced Technology Spark Ignition, GTSIO-420

The highly advanced rotary engine was the top ranking engine in the study. Low engine weight and flexible installation are the engine's strong points. The installation flexibility stems from the integral accessory pads on the engine and from the liquid cooling. The liquid coolant allows the cooler to be located in almost any position on the aircraft and should help reduce the frontal area and drag of the installation. The generally small size of the engine also helps reduce drag particularly in the twin. Multifuel capability makes this engine more attractive for operations in areas where fuel availability is limited. The performance of the engine is generally comparable to that of current engines and fuel economy is excellent.

The diesel engine was ranked second. The diesel was the most fuel efficient engine in the study and the engine was also quite lightweight. Unfortunately, the climb performance of this engine at cruise altitude was poor, in part because the engine was rated to cruise at full available altitude horsepower.

A larger engine which could be throttled for cruise would provide improved climb performance, albeit with some sacrifice in empty weight and cruise range or efficiency. Alternatively the engine could be rerated or redesigned for climb. Performance improves at design altitudes below 20000 feet. Installation is comparable to the baseline engine.

The highly advanced spark ignition engine was ranked third. The engine's strong points are efficiency comparable to the diesel engine and excellent performance at altitude. The installation requirements are nearly identical to that of the baseline engine. The spark ignition engine, however, is somewhat heavier than the rotary or the diesel.

The general aviation turbine engine is comparable in weight and size to the rotary engine. The specific fuel consumption is higher for the turbine than for any other engine in the study including the baseline. The turbine engine has a definite place as a jet fuel burning replacement for the baseline engine. As such, this turbine engine would improve the range-payload capability of current airframes. The prospect of jet fuel operations would be very attractive to overseas customers. The performance and efficiency of the turbine engine improve at high design cruise speeds (larger engines) so this engine might be an excellent candidate for very high performance airplanes.

6.7 OTHER CONSIDERATIONS

The objective of this study was to rank the subject engines according to their in-airframe performance. The final ranking based on the performance evaluation is shown above. There are other engine characteristics which require examination before a final decision is made to pursue a single engine.

Vibration

The vibration level of an engine may directly or indirectly impact the weight of an airframe. An engine which vibrates excessively may require a sturdier engine mount, heavier vibration isolators or additional soundproofing to provide an acceptable piloting environment. Certainly vibration will add to pilot and airframe fatigue. Vibration may also have an impact on engine reliability, however no data is available on the real reliability of any of the advanced engines.

The engines thought to have the lowest vibration level are the turbine and the rotary engines. The continuous combustion of a turbine produces very little vibration and rotary engines are generally very smooth running engines due to the rotary design.

The diesel engine and the spark ignition engines are anticipated to have vibration characteristics comparable to current spark ignition engines.

Unresolved Technologies

Certain critical technology items must be developed for each engine candidate to meet the design goals used as a basis for this study. The ability to develop the required technology must be considered in the decision to develop a particular engine candidate.

The spark ignition engines are, with the exception of the turbocompounding and the stratified charge, growth versions of existing engines. The success of both of the above technologies is critical to the capabilities of the highly advanced technology spark ignition engine. The stratified charge combustion chamber is responsible for the multifuel capabilities of the engine. The technology required should not present an overwhelming obstacle to the development of the engine. Turbocompounding machinery, the second critical development item, has presented maintenance and reliability problems in the past when applied to aircraft engines. Any such problems must be eliminated from an advanced engine if it is to be utilized successfully by the general aviation industry.

The diesel engine is dependent for its success, on the development of advanced, lightweight, high-temperature materials. These materials are imperative for the engine to tolerate the reduced or limited cylinder cooling proposed for this engine. This engine is also dependent on the development of a very high efficiency turbocharger to meet the specific fuel consumption goals set for it. The turbocharger/bleed air starter is a new concept which will require sufficient development to eliminate maintenance and reliability problems.

The rotary engine, like the spark ignition engine, will require considerable development for the stratified charge combustion chamber to meet SFC goals and to provide multifuel capability. Advanced materials will be required to achieve the desired engine weight levels, and a significant amount of development is required on apex seal technology for these engines to meet design goals.

The turbine engine, in addition to requiring advanced high strength, high temperature materials, must be produced at a price competitive with other engines. Turbine engines, due to supply/demand economics, have historically been much more expensive than other aircraft engines (spark ignition). This trend needs to be reversed if the turbine engine is to be a successful alternative for general aviation aircraft.

Public Acceptance

The view of the perspective customer cannot be neglected when marketing a general aviation product. Neither the diesel engine or the rotary engine have established a reputation in the general aviation community. These top ranked engines may encounter stiff resistance or indifference unless their safety and reliability are unquestionable.

The spark ignition engine and the turbine engine, on the other hand, have established a record of reliability among pilots and maintenance personnel. The turbine engine in particular, has a reputation for trouble free operation which makes it the most desirable engine from an acceptance standpoint.

7.0 RECOMMENDATIONS

The top ranked engine, as stated previously, is the highly advanced rotary, RC2-32. This engine can be strongly recommended for continued development. The decision to develop this engine, as with any engineering decision, is a compromise. The other engines in the study are also efficient and effective alternatives to the baseline engine. The diesel engine and the highly advanced technology spark ignition engine are, within the accuracy of the study, nearly as promising as the rotary engine.

The ability to develop an engine within the desired time frame is as important as that engines performance capability. The rotary engines achieve significant improvements over current technology engines with less reliance on very advanced technology procedures than the other advanced engines. The advanced rotary, RC2-47, is also a very promising engine which may be available earlier than RC2-32. The multifuel capability of even this early engine increases the desirability of its development.

A primary concern in the general aviation community, particularly overseas, is the availability of avgas. Jet fuel is often available or is much more abundant than avgas for overseas operators. The cost of current turbine engines prohibits their use in small aircraft of the type studied in this program. Any low cost, efficient engine capable of burning jet fuel would be very attractive to the general aviation manufacturer.

NASA may need to consider developing the technologies required by all the advanced engines in common and allow the individual manufacturers to apply the technologies to their designs rather than invest in the development of a single engine type. This type of development would foster competition among the engine manufacturers and may provide a wider range of engine options for the 1990's. This would allow the general aviation manufacturer to select an engine suited to his particular application.

ORIGINAL PAGE IS
OF POOR QUALITY

ENGINE TYPE	SPARK IGNITION			DIESEL	ROTARY		TURBINE
TECHNOLOGY	CURRENT TECHNOLOGY BASELINE TSIO 550	ADVANCED [illegible]	HIGHLY ADVANCED GTSIO 420 SC	HIGHLY ADVANCED 1992 TECHNOLOGY	ADVANCED RC2-47	HIGHLY ADVANCED RC2-32	GATE DESIGN [illegible]
ENGINE WEIGHT BASIC + ADDITIONAL	585 + 121 = 706	485 + 121 = 606	405 + 121 = 526	367 + 121 = 488	348 + 139 = 487	255 + 138 = 393	195 + 196 = 391
SCALING (BASIC WT)	$W_B = HP^{.88}$	$W_B = HP^{.88}$	$W_B = HP^{.88}$	SEE FIGURE 1	W_B = 92 + .8 (TOHP)	W_B = 85.4 + .53 (TOHP)	$W_B = HP^{.72}_{GROSS}$
DIMENSIONS (INCHES)	L = 50.62 W = 34.06 H = 20.02	L = 59.25 W = 33.375 H = 19.25	L = 59.25 W = 33.375 H = 19.25	L = 41.30 W = 24.20 H = 25.00	L = 52.0 W = 18.0 H = 17.0	L = 48.6 W = 16.0 H = 16.0	GEARBOX = 16.10 CASING 12.10 L = 37.60 H = 19.0
SCALING	NONE	NONE	NONE	NONE	L = 44.8 + .0225 (TOHP) W/H NONE	L = 42.3 + .0197 (TOHP) W/H NONE	DIAM. ∝ H ∝ $HP^{.36}_{GROSS}$ L ∝ $HP^{.27}_{GROSS}$
CG LOCATION	23.6 AFT 0.9 BELOW 0.65 RIGHT	32.6 AFT 0.56 BELOW 0.80 RIGHT	33.6 AFT 0.52 BELOW 0.90 RIGHT	15.7 AFT ON ℄ ON ℄	22.8 AFT ON ℄ ON ℄	22.7 AFT ON ℄ ON ℄	18.8 AFT 3.52 ABOVE ON ℄
POWER (HP) (AT ISA CONDITIONS)	ALT / MCP / CRUISE 0 / 350 / 247 5K / 359 / 256 10K / 358 / 262 15K / 348 / 263 20K / 327 / 259 25K / 298 / 250 30K / 265 / 240 35K / 231 / 228 RPM / 2800 / 2300	ALT / MCP / CRUISE 0 / 350 / 229 5K / 367 / 242 10K / 374 / 251 15K / 366 / 256 20K / 351 / 256 25K / 323 / 250 30K / 290 / 240 35K / 252 / 228 RPM / 2400 / 2150	ALT / MCP / CRUISE 0 / 350 / 228 5K / 364 / 243 10K / 368 / 252 15K / 360 / 257 20K / 343 / 255 25K / 316 / 250 30K / 280 / 240 35K / 245 / 228 RPM / 2400 / 2150	ALT / MCP & CRUISE / ECONOMY CRUISE 0 TO 17K / 360 / 297 20K / 320 / 264 25K / 250 / 206 30K / 184 / 153 35K / 120 / 99 RPM / 2300 / 2300	ALT / MCP / CRUISE 0 TO 21K / 320 / 250 25K / 275 / 250 30K / 227 / 208 35K / 190 / 176 RPM / 2400 / 2000	ALT / MCP / CRUISE 0 TO 21K / 320 / 250 25K / 275 / 250 30K / 227 / 208 35K / 190 / 176 RPM / 2400 / 2000	GATE DATA ... INSTALLED CRUISE ESHP ... [illegible]
SFC (LB/HP-HR)	0 TO 35K / 0.600 / 0.446	0 TO 35K / 0.486 / 0.358	0 TO 35K / 0.334 / 0.331	0 TO 17K / 0.313 / 0.290 20K / 0.317 / 0.293 25K / 0.323 / 0.299 30K / 0.330 / 0.305 35K / 0.336 / 0.311	0 TO 25K / 0.394 / 0.371 30K / 0.380 / 0.367 35K / 0.382 / 0.369	0 TO 25K / 0.372 / 0.355 30K / 0.370 / 0.354 35K / 0.378 / 0.357	REDUCED CRUISE POWER ... [illegible]
SCALING POWER	LINEAR	LINEAR	LINEAR	LINEAR	LINEAR	LINEAR	LINEAR
SCALING SFC	NONE	NONE	NONE	SEE FIGURE 1	NONE	NONE	SEE FIGURE 2
COOLING REQUIREMENT PERCENT SHP	10.0 %	7.76 %	7.93 %	7.03 %	5.85 %	6.11 %	3 % GROSS ESHP

EXTRAPOLATE LINEARLY TO 35K FT

1. BASIC WEIGHT TO BE SCALED WITH POWER ... ADDITIONAL WEIGHT IS CONSTANT ... ALL WEIGHTS ARE IN POUNDS
2. CG LOCATION REFERENCED TO PROP FLANGE ... VERTICAL POSITION REFERENCED TO PROPSHAFT ℄
3. GATE DATA SCALED AS INDICATED ... SHAFT HORSEPOWER ... THRUST LBS
4. [illegible]

FINAL REVISION

Beech Aircraft Corporation

NASA FOUR ENGINE STUDY MASTER DATA CHART TABLE 1

D 70898

TABLE 1

BREAKDOWN OF ADDITIONAL ENGINE WEIGHT

SPARK IGNITION AND DIESEL

Battery	23
Propeller	80
Spinner	4
Mounting Isolators	5
Overvoltage Relay	1
Prop Attaching Parts	4
Exhaust Dump	4
TOTAL	121 lbs.

GATE

Battery	65
Propeller	80
Spinner	4
Starter/Generator	17
Exhaust Pipe	5
Anti-Ice	2
Accessory Drives	3
Vacuum Pump	2
Oil	8
Additional	10
	196 lbs.

ROTARY	ADVANCED	HIGHLY ADVANCED
Battery	23	23
Propeller	80	80
Spinner	4	4
Governor	3	3
Starter Switch	1	1
Voltage Regulator	1	1
Overvoltage Relay	1	1
Alternator	17	17
Mounting Isolators	5	4
Prop Attaching Parts	4	4
TOTAL	139 lbs.	138 lbs.

TABLE 2

COOLING REQUIREMENTS
AND COOLING DRAG ESTIMATES

	BASELINE	SPARK IGNITION		DIESEL	ROTARY		GATE
	TSIO-550	GTS10-420	GTS10-420SC		RC2-47	RC2-32	TURBINE
Cruise Cooling Req't (BTU/MIN)	10600	8230	8400	7460	6200	6480	330
Cruise Cooling Drag ΔF Sq. Ft.	.528	.409	.419	.371	.309	.323	.0162

TABLE 3

DIESEL INLET EFFICIENCY STUDY

	SINGLE		TWIN	
RECOVERY	0%	100%	0%	100%
GROSS WEIGHT (LBS.)	3,762	3,728	5,517	5,440
EMPTY WEIGHT (LBS.)	2,225	2,192	3,530	3,504
PAYLOAD (LBS.)	1,200	1,200	1,300	1,300
FUEL WEIGHT (LBS.)	337	336	637	636
SEA LEVEL BHP	312	276	297	252
CRUISE BHP	217	215	206	204
TAKE-OFF DISTANCE	2,130	2,205	2,380	2,555
SEA LEVEL R/C	1,480	1,255	1,970	1,640
ALTITUDE	25,000	25,000	25,000	25,000
TIME TO CLIMB	21.6	24.8	16.5	20.0
CRUISE R/C	590	518	750	613
CRUISE SPEED (KTAS)	207	207	236	236
RANGE (NM)	799	801	921	921
LANDING DISTANCE	1,660	1,660	2,600	2,600
STALL SPEED (KEAS)	58	58	75	75
WING AREA ($FT.^2$)	166	164	155	153
WING SPAN (FT.)	35.5	35.3	34.3	34.1
ASPECT RATIO	7.6	7.6	7.6	7.6

TABLE 4

GENERAL AVIATION TURBINE ENGINE

REVISED DATA* - FIXED AIRFRAME ANALYSIS

	SINGLE		TWIN	
	ORIGINAL GATE	REVISED GATE*	ORIGINAL GATE	REVISED GATE*
Gross Weight (Lbs.)	4267	4267	6700	6700
Empty Weight (Lbs.)	2259	2236	3680	3637
Payload (Lbs.)	1200	1200	1300	1300
Fuel Weight (Lbs.)	808	831	1720	1763
Sea Level BHP	525	525	525	525
Cruise BHP	250	250	250	250
Take-Off Distance	2020	2020	2225	2225
Sea Level R/C	1345	1345	1795	1795
Altitude	25000	25000	25000	25000
Time to Climb	27.5	27.6	20.7	20.8
Cruise R/C	505	500	690	685
Cruise Speed (KTAS)	218	218	260	260
Range (NM)	1297	1516	1638	1905
Landing Distance	1660	1660	2600	2600
Stall Speed (KEAS)	58	58	75	75
Wing Area ($Ft.^2$)	188	188	188	188
Wing Span (Ft.)	37.8	37.8	37.8	37.8
Aspect Ratio	7.6	7.6	7.6	7.6

TABLE 5

*SFC Reduced 10%
Basic Engine Weight Reduced 10%

GENERAL AVIATION TURBINE ENGINE

REVISED DATA* - FIXED MISSION ANALYSIS

	SINGLE		TWIN	
	ORIGINAL GATE	REVISED GATE*	ORIGINAL GATE	REVISED GATE*
Gross Weight (Lbs.)	3835	3740	5579	5435
Empty Weight (Lbs.)	2144	2104	3389	3345
Payload (Lbs.)	1200	1200	1300	1300
Fuel Weight (Lbs.)	491	436	890	790
Sea Level BHP	440	434	389	388
Cruise BHP	199	196	182	181
Take-Off Distance	2015	2005	2210	2175
Sea Level R/C	1265	1285	1550	1595
Altitude	25000	25000	25000	25000
Time to Climb	30.8	30.2	25.6	24.8
Cruise R/C	415	422	490	510
Cruise Speed (KTAS)	206	207	233	234
Range (NM)	800	800	921	920
Landing Distance	1660	1660	2600	2600
Stall Speed (KEAS)	58	58	75	75
Wing Area ($Ft.^2$)	169	165	157	153
Wing Span (Ft.)	35.8	35.4	34.5	34.0
Aspect Ratio	7.6	7.6	7.6	7.6

TABLE 6

*SFC Reduced 10%
Basic Engine Weight Reduced 10%

LIST OF SYMBOLS

B	BASELINE ENGINE TSIO-550
S	ADVANCED TECHNOLOGY SPARK IGNITION ENGINE
S	HIGHLY ADVANCED TECHNOLOGY SPARK IGNITION ENGINE
D	HIGHLY ADVANCED TECHNOLOGY DIESEL ENGINE
R	ADVANCED TECHNOLOGY ROTARY ENGINE
R	HIGHLY ADVANCED TECHNOLOGY ROTARY ENGINE
G	GENERAL AVIATION TURBINE ENGINE - GATE

HIGHLY ADVANCED TECHNOLOGY DIESEL ENGINE
ENGINE WEIGHT AND BSFC SCALING

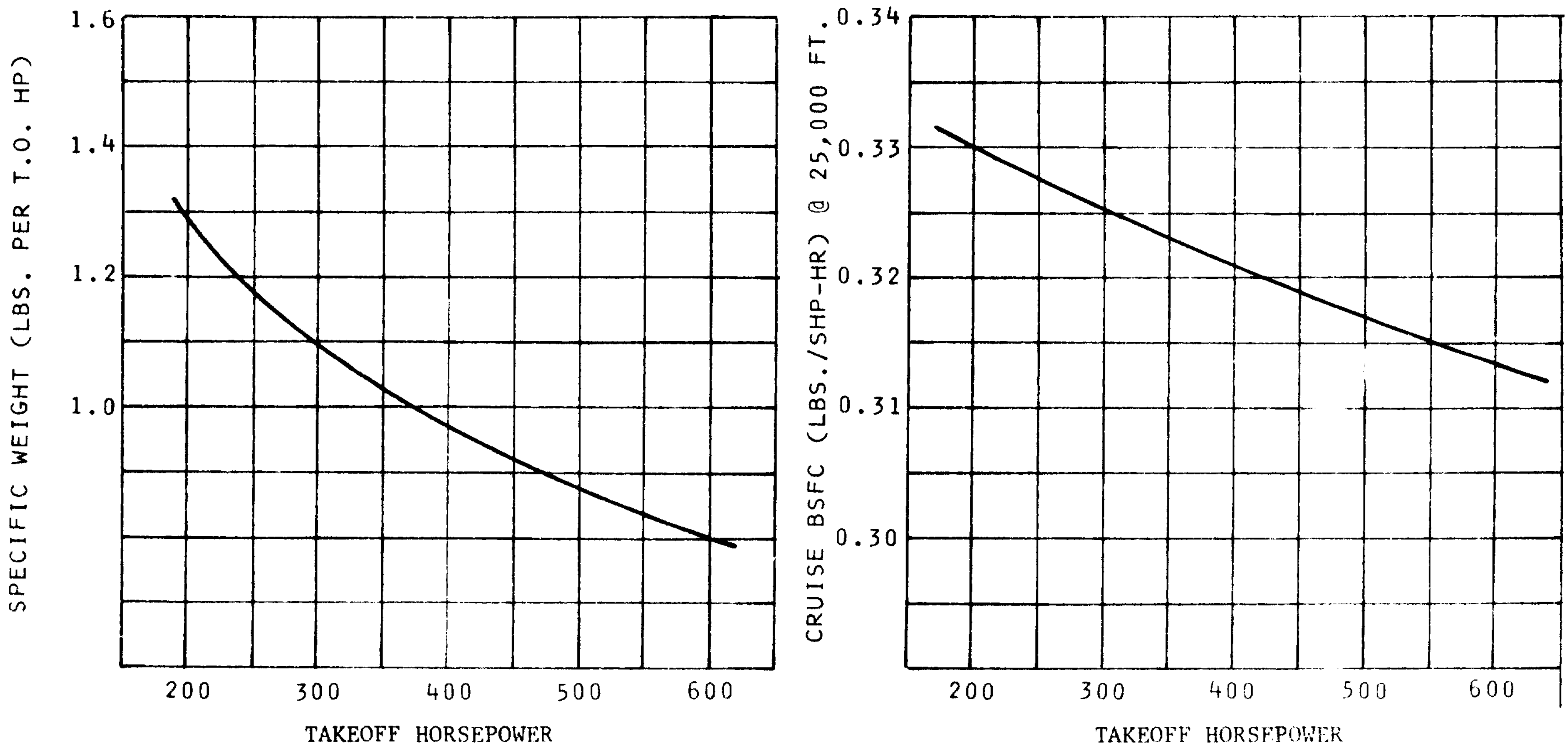

FIGURE 1

GATE DESIGN 3013-1

RELATIVE EBSFC VS. EQUIVALENT TAKEOFF HORSEPOWER

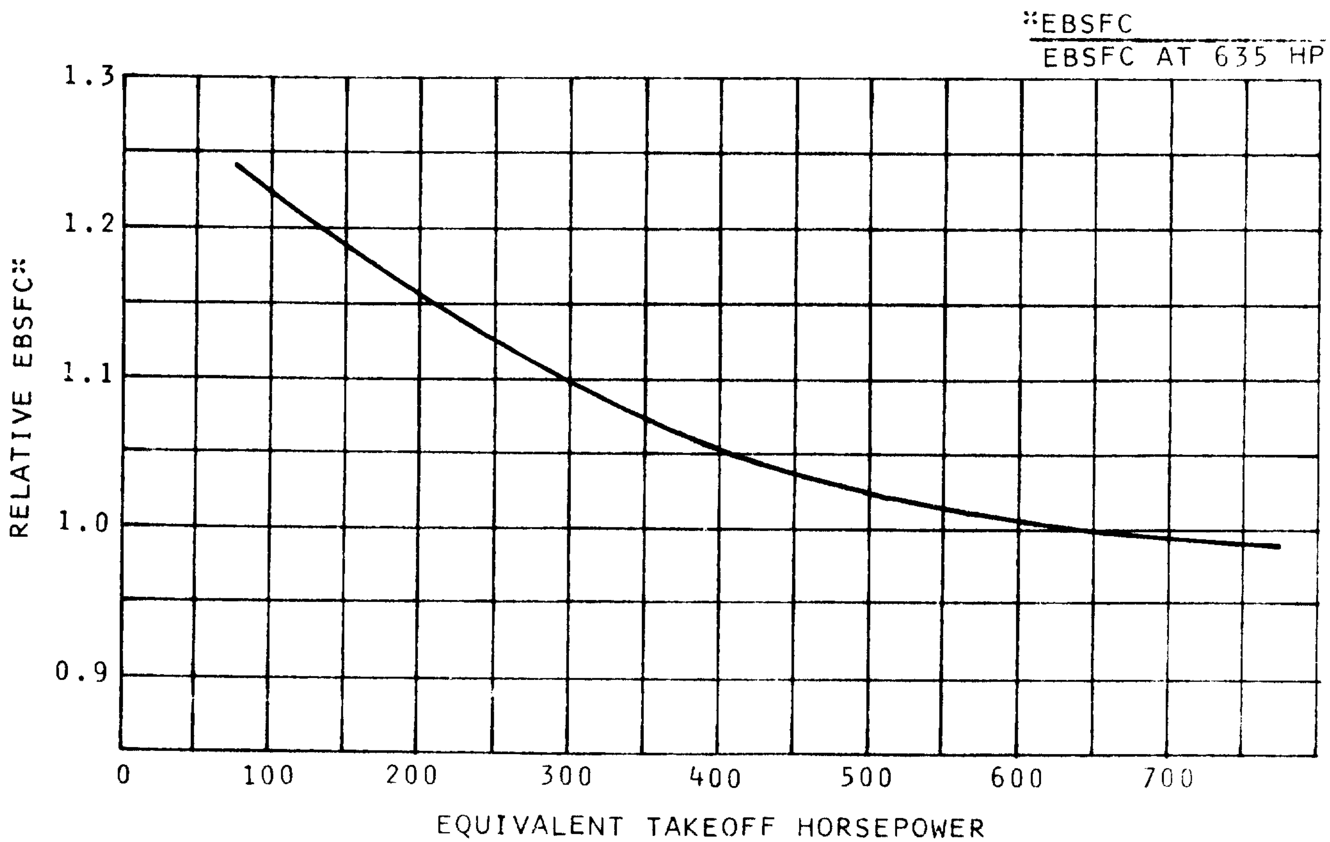

FIGURE 2

ENGINE CHARACTERISTICS

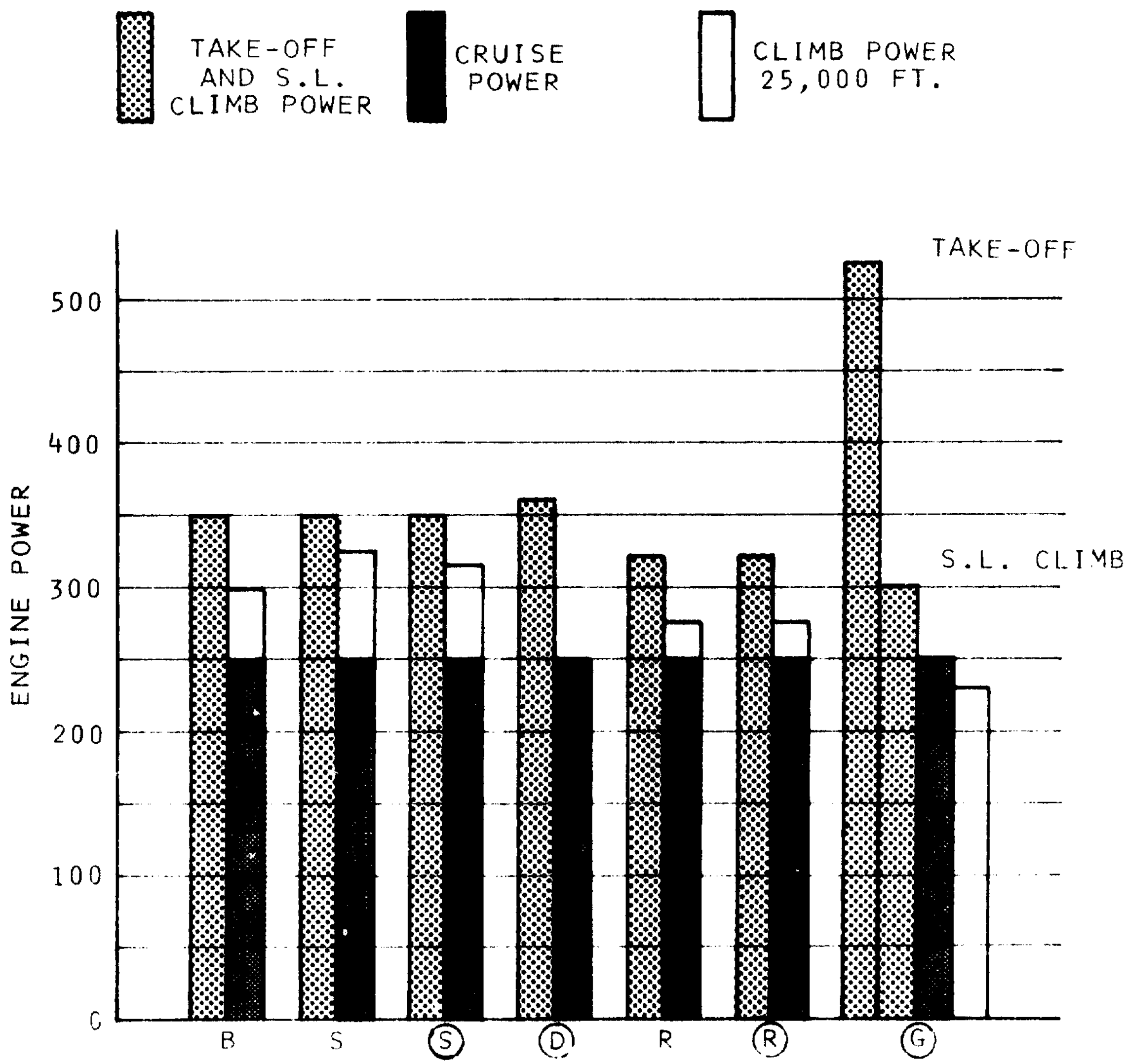

FIGURE 3

ENGINE CHARACTERISTICS

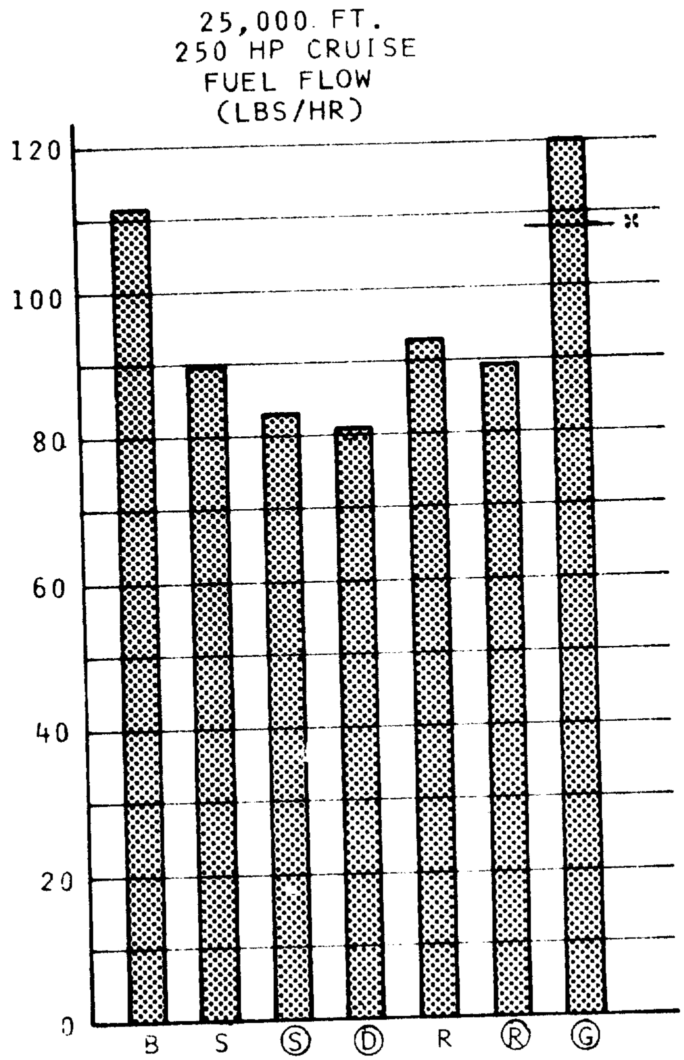

FIGURE 4

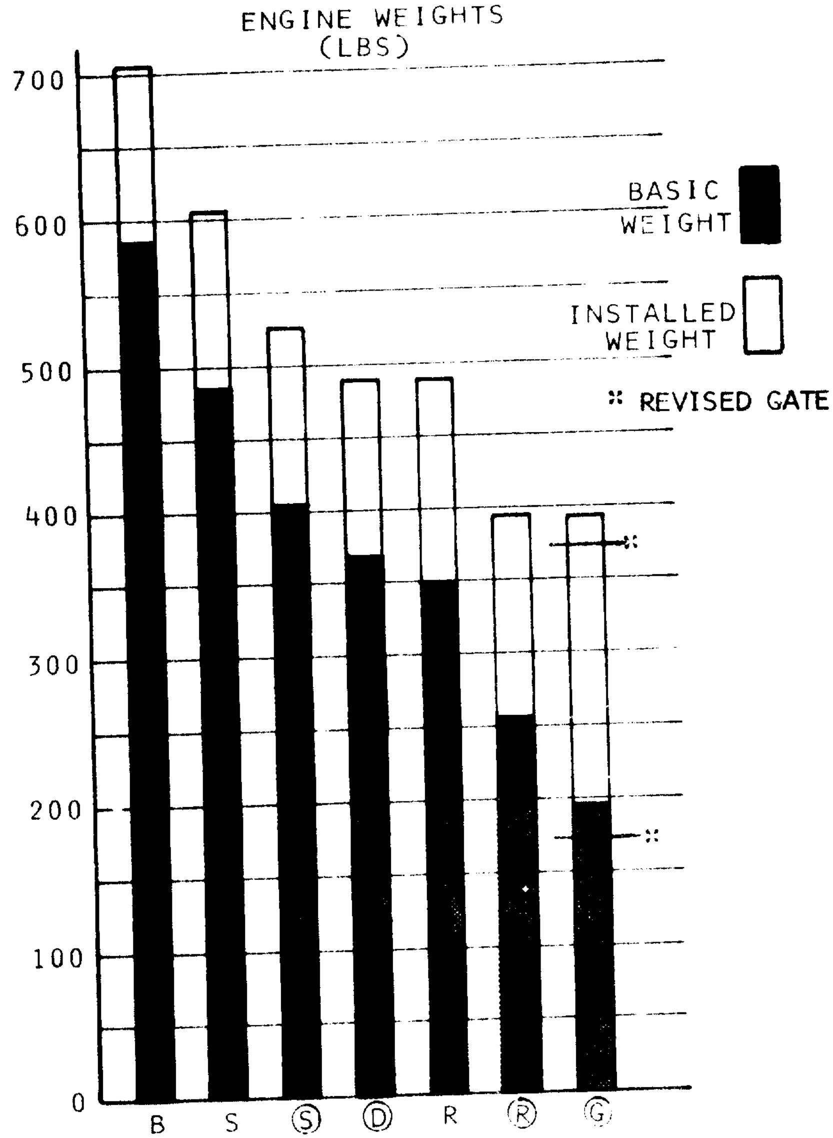

FIGURE 5

BASELINE SINGLE
TSIO-550

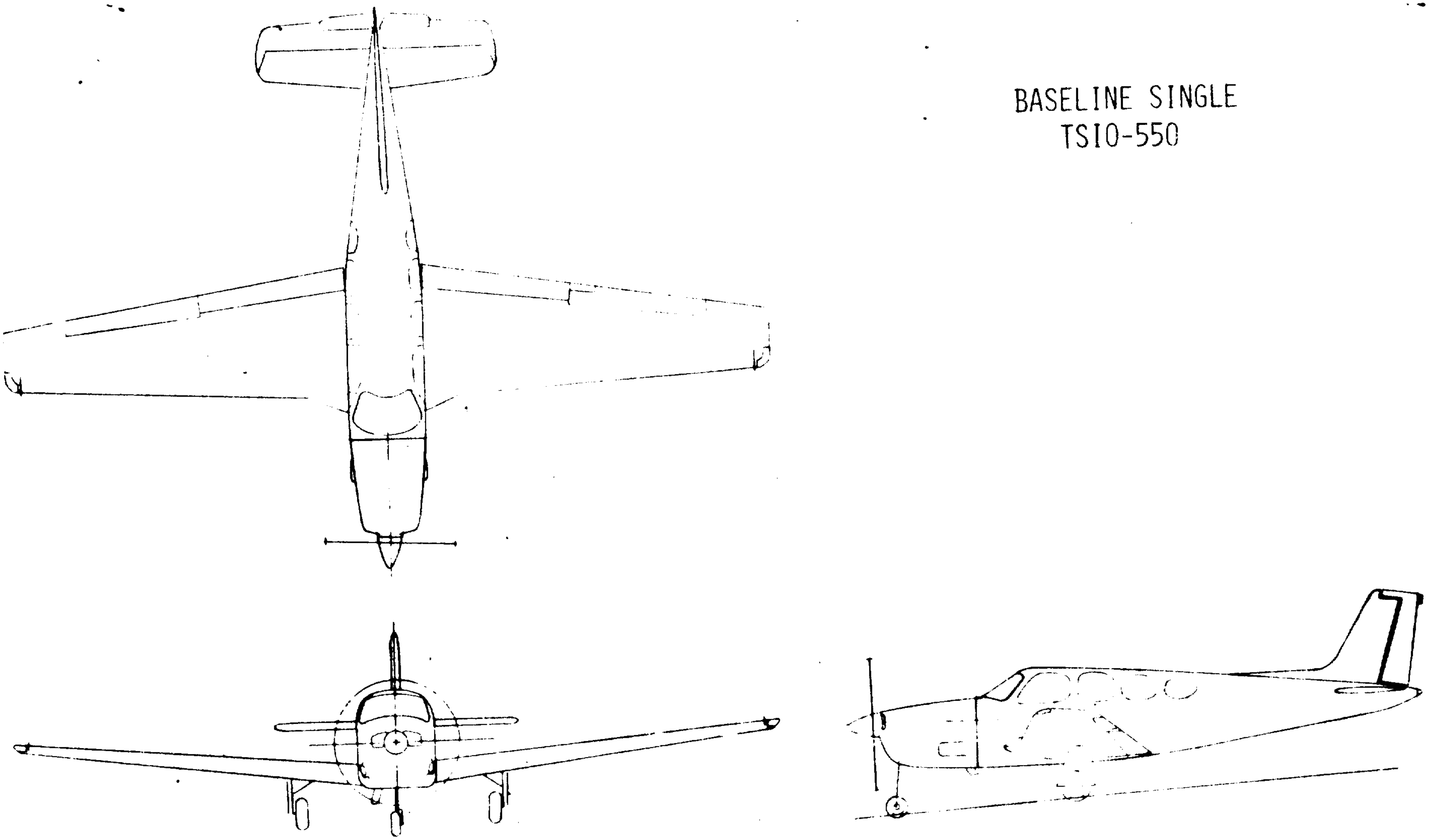

FIGURE 6

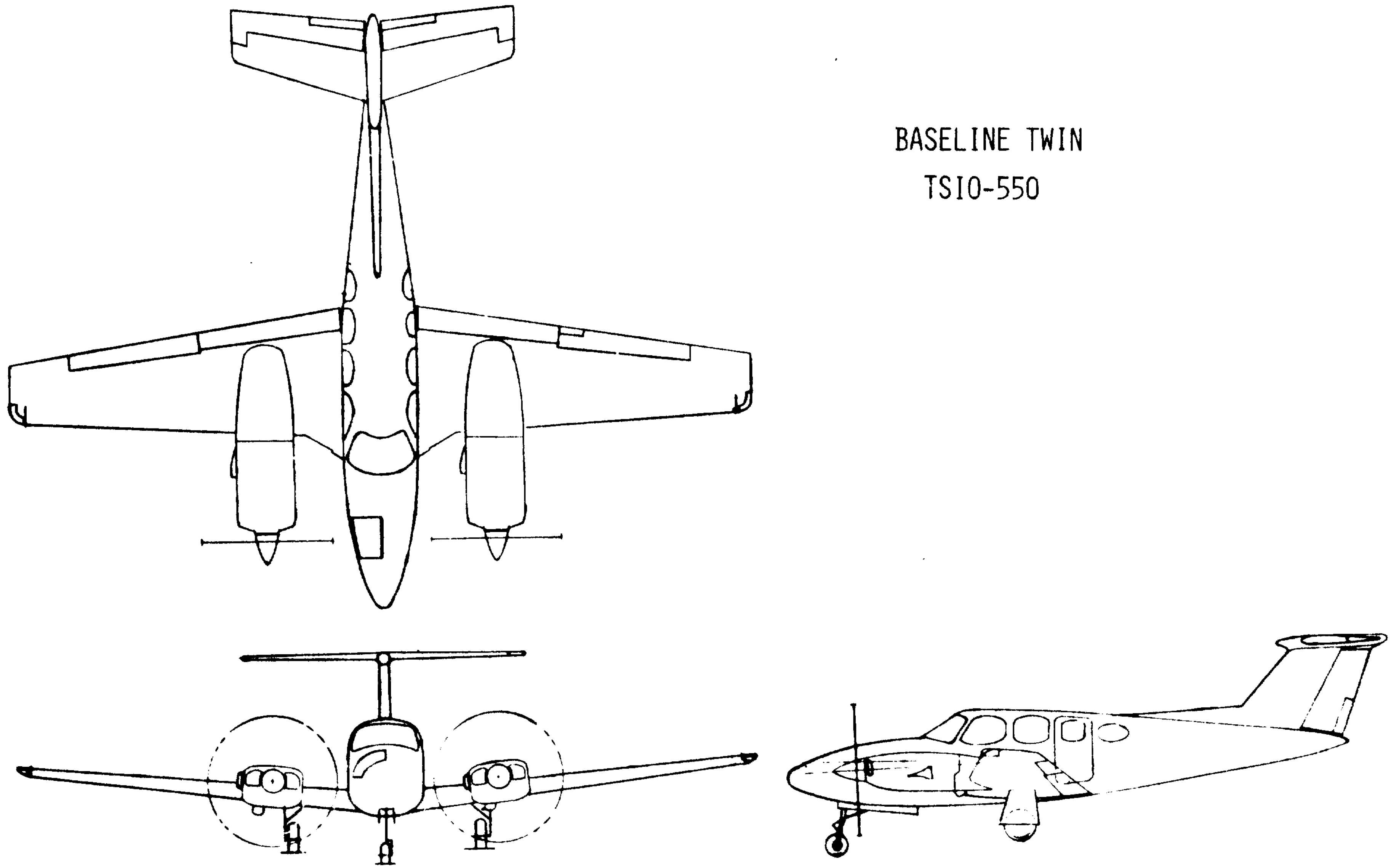

FIGURE 7

BASELINE SINGLE
INSTALLATION

TSIO-550

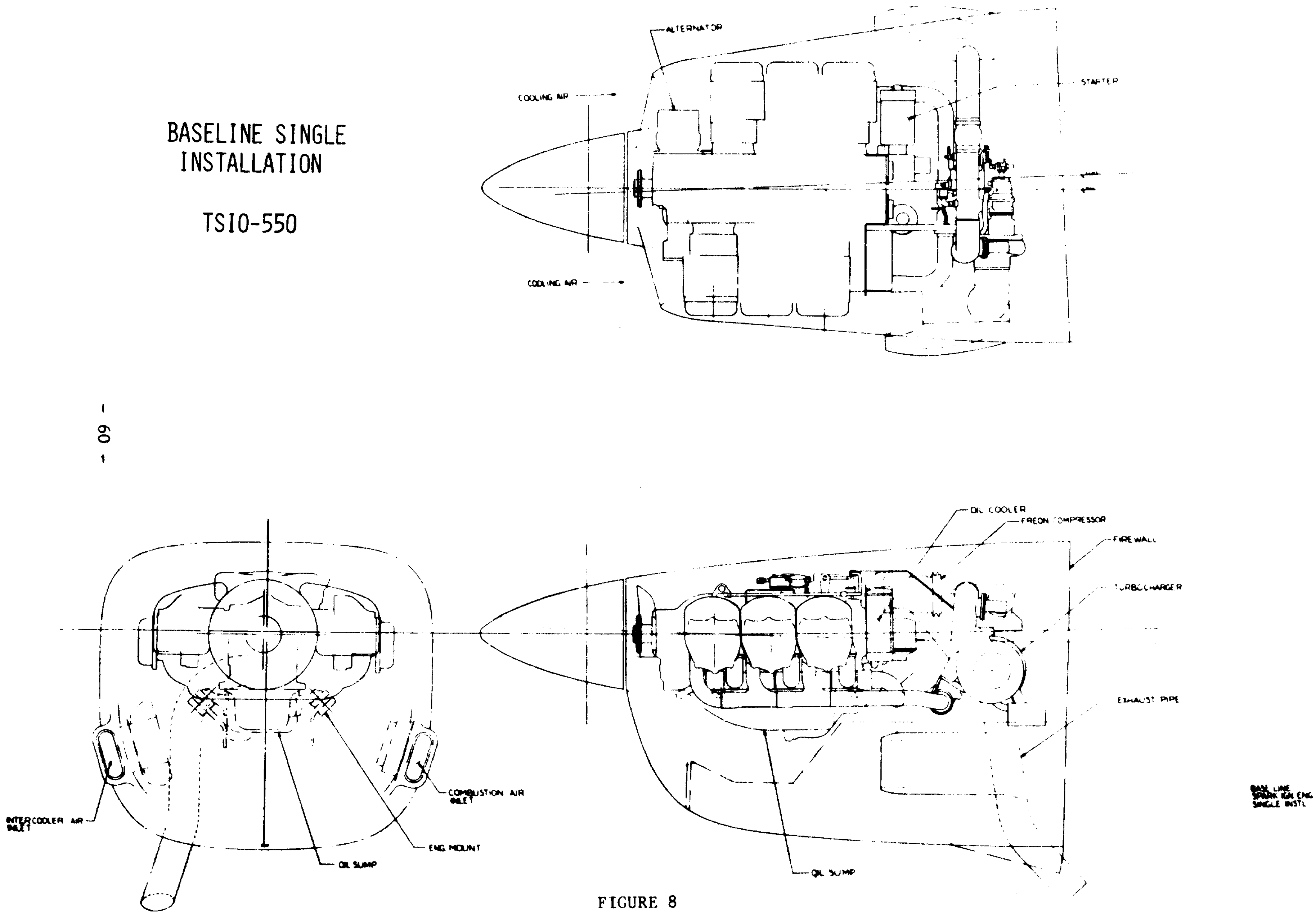

FIGURE 8

BASELINE SPARK IGNITION ENGINE TWIN INSTALLATION

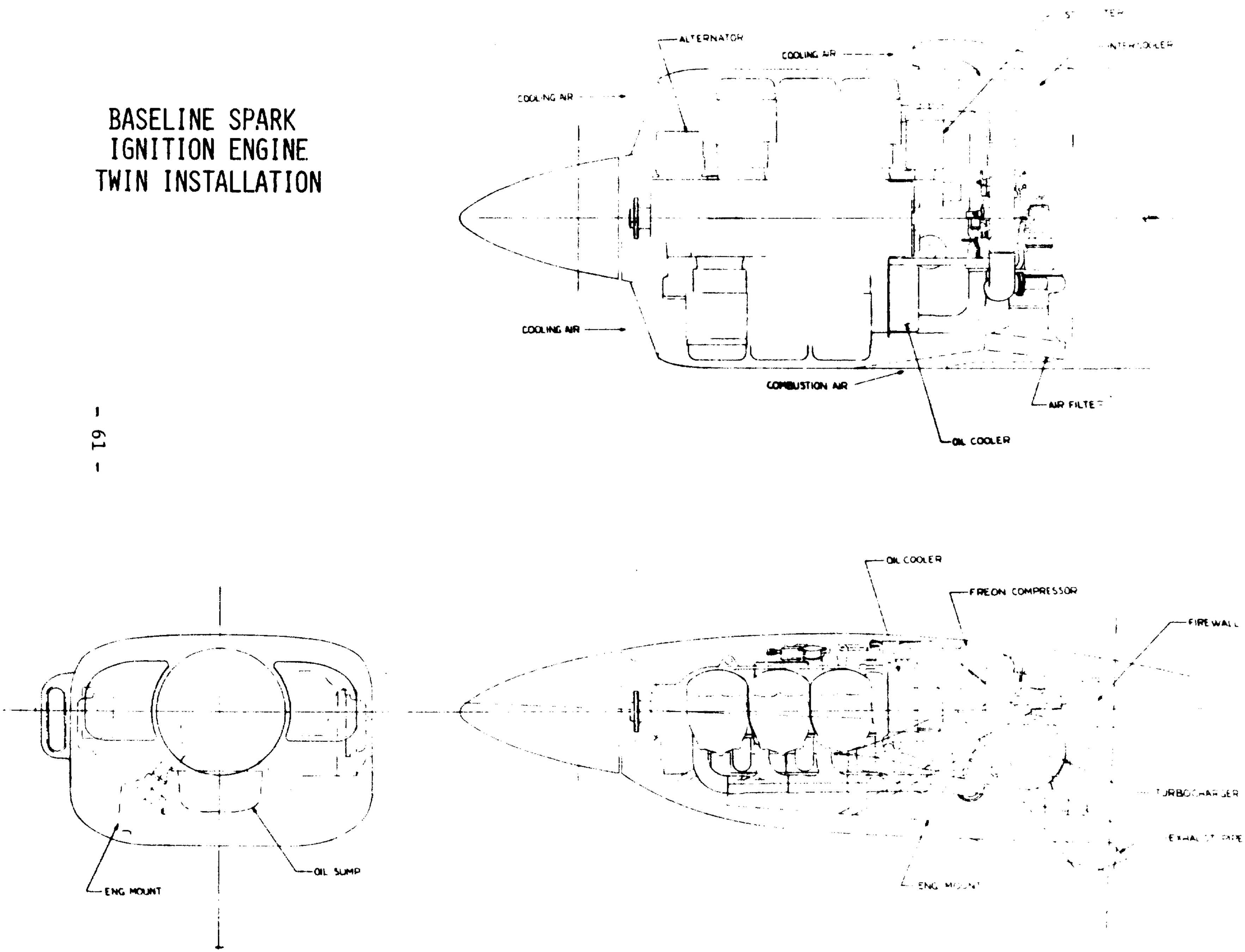

FIGURE 9

ADVANCED SPARK IGNITION SINGLE

GTSIO-420 & GTSIO-420/SC

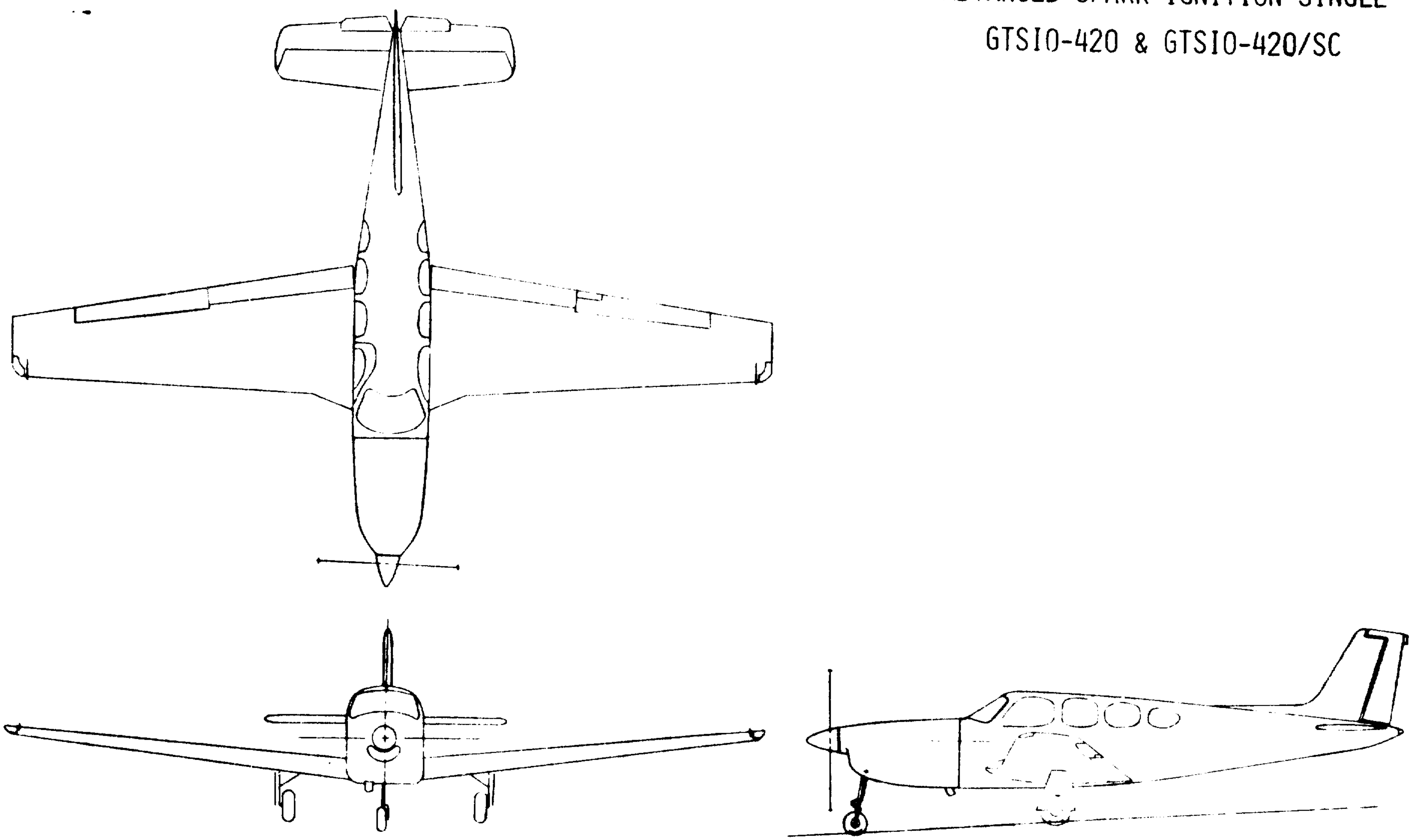

FIGURE 10

ADVANCED SPARK IGNITION TWIN

GTSIO-420 & GTSIO-420/SC

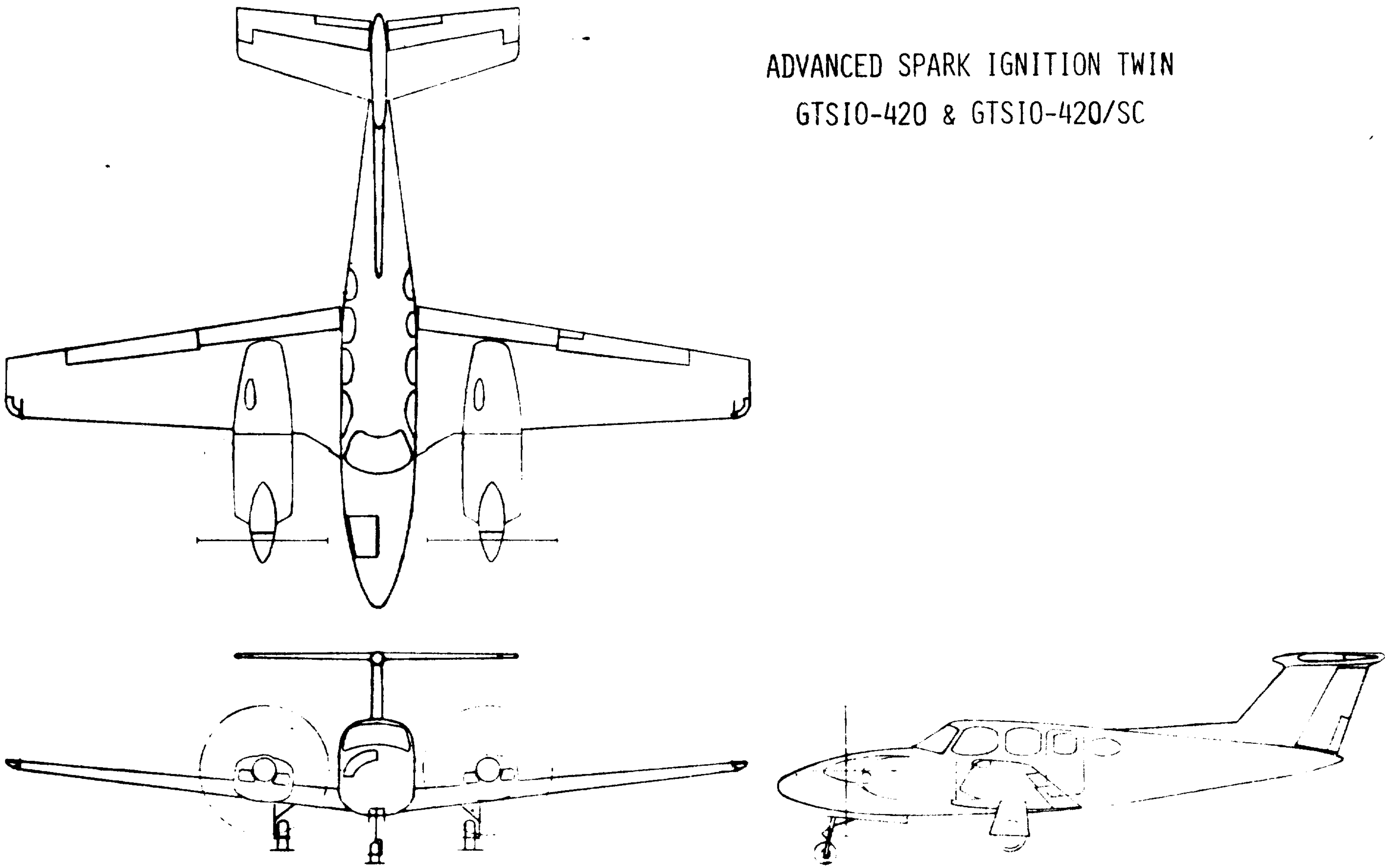

FIGURE 11

ORIGINAL PAGE IS
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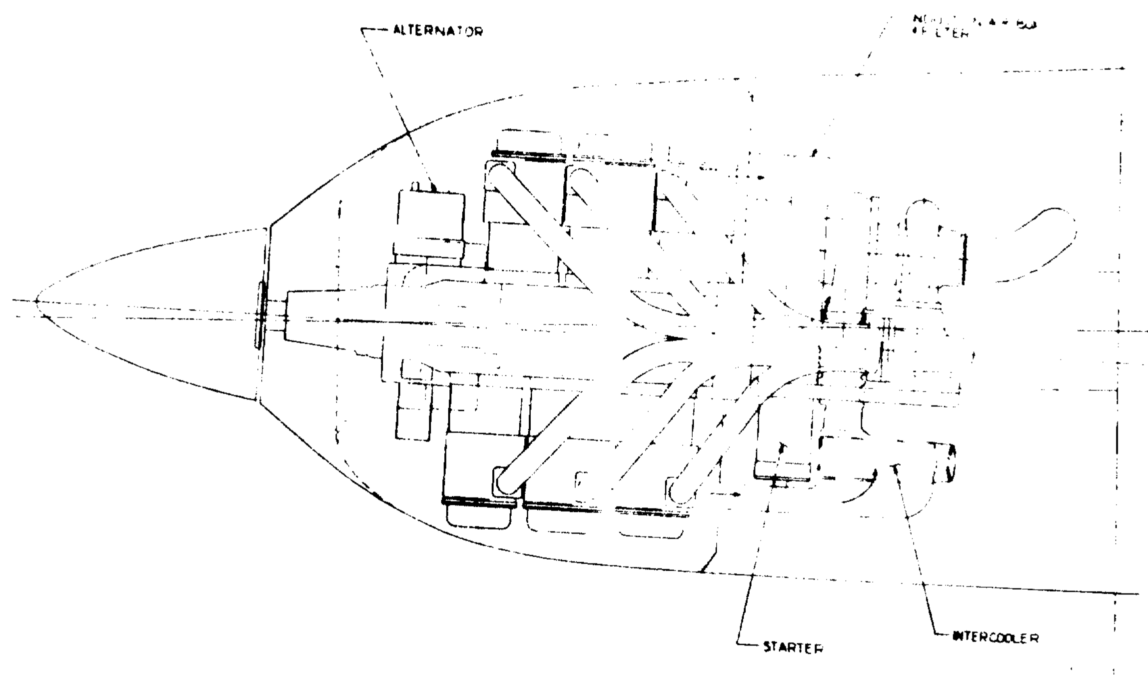
ADVANCED SPARK IGNITION ENGINE
SINGLE INSTALLATION



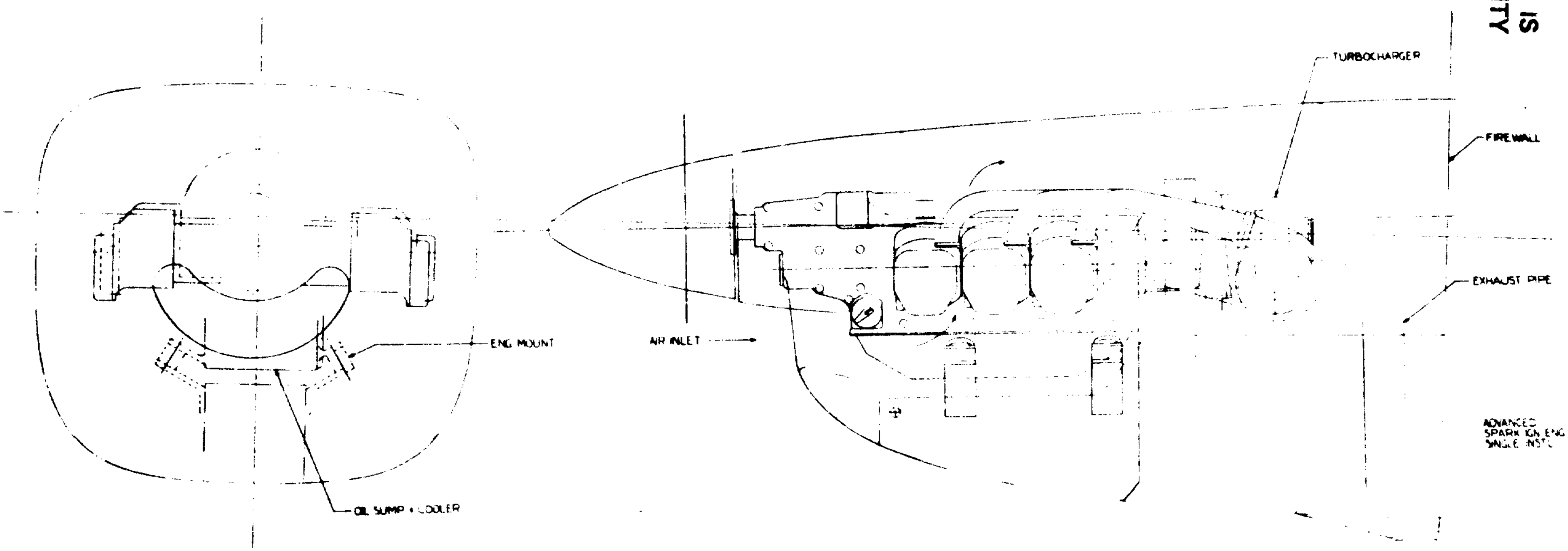


FIGURE 12

ADVANCED SPARK
IGNITION ENGINE
TWIN INSTALLATION

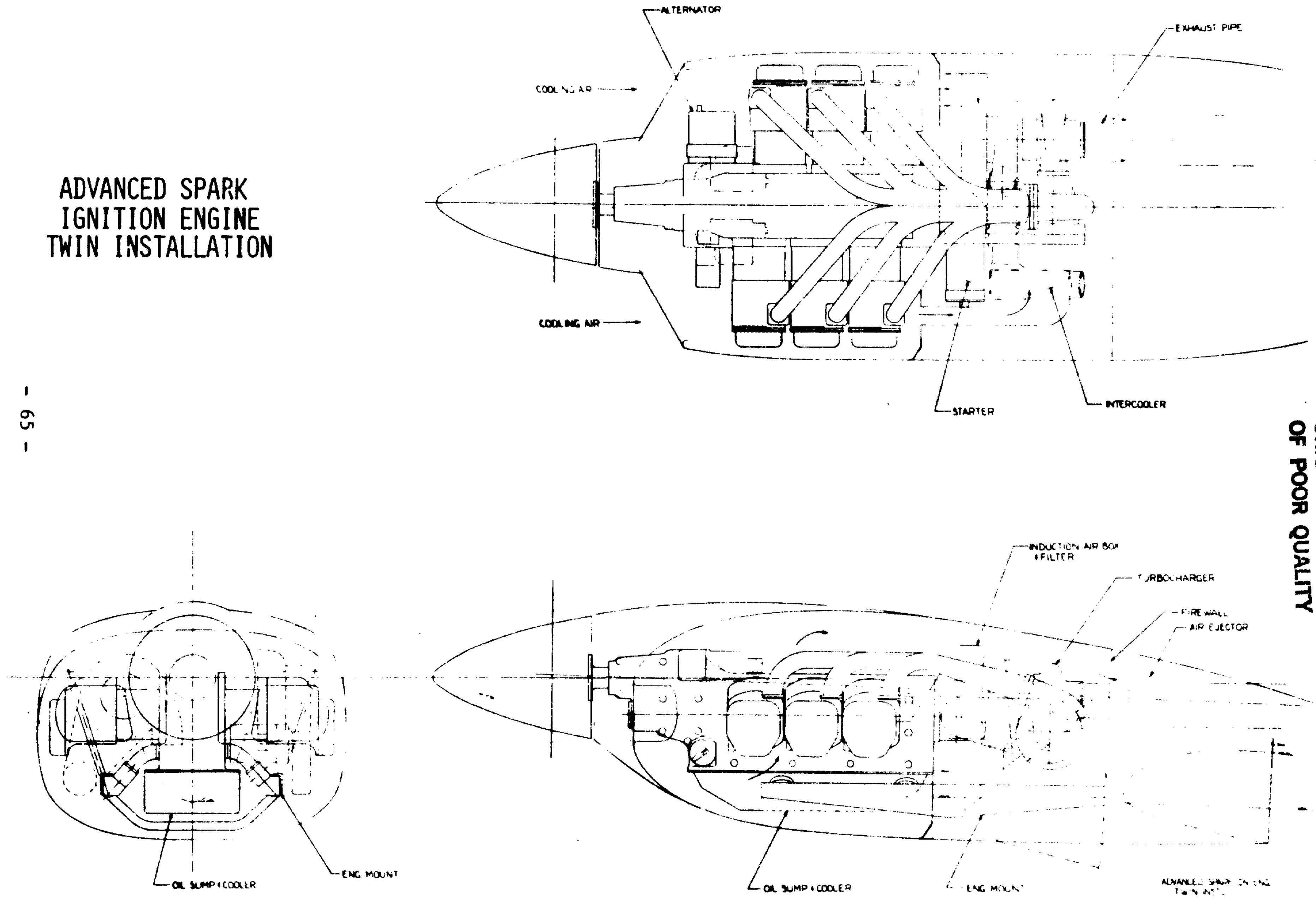
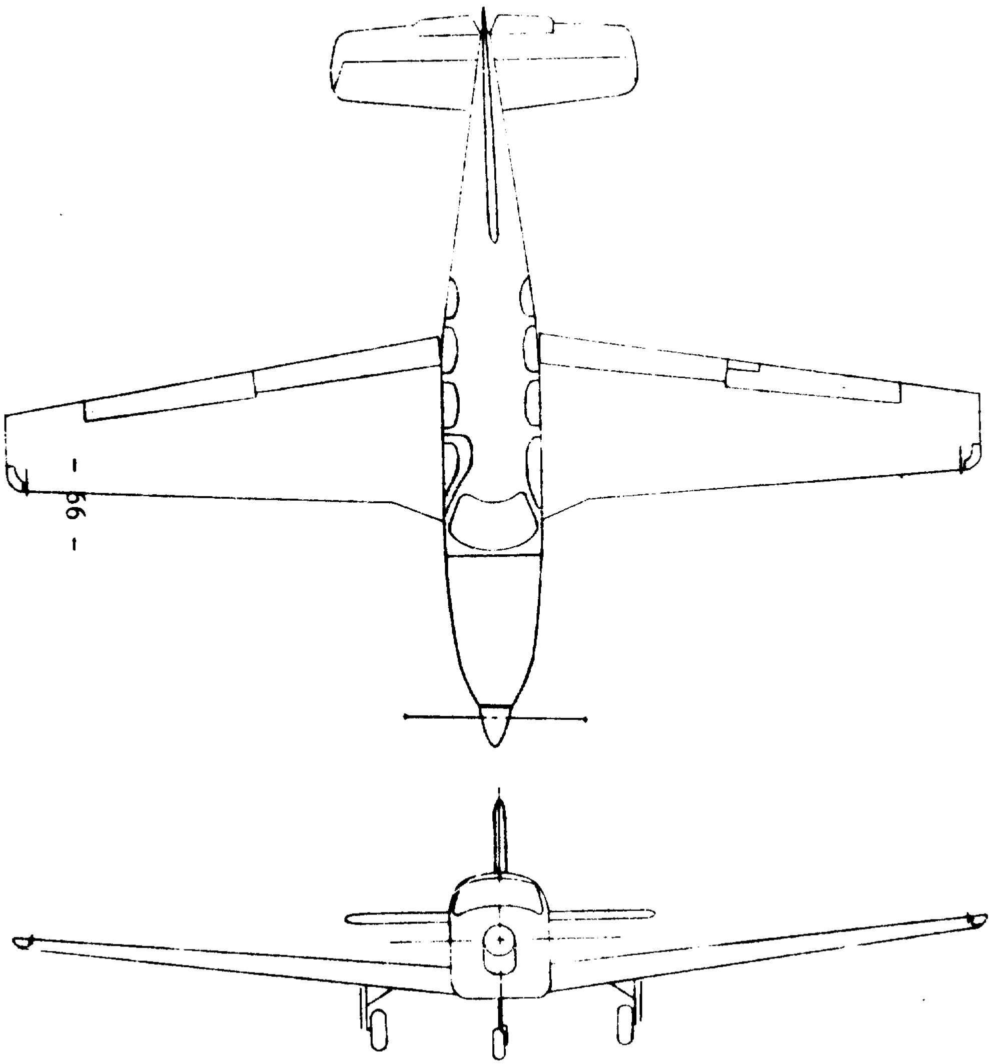


FIGURE 13

ORIGINAL PAGE IS
OF POOR QUALITY

ADVANCED DIESEL SINGLE
HIGHLY ADVANCED TECHNOLOGY DIESEL



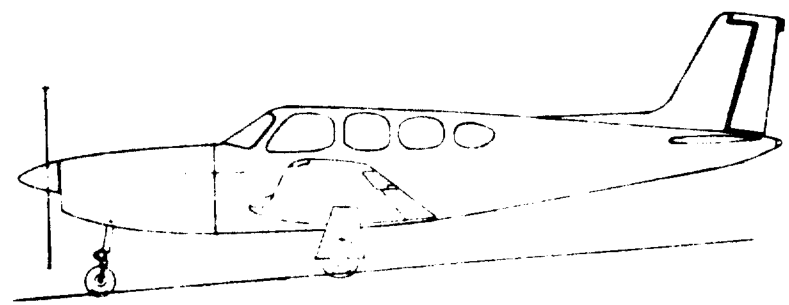


FIGURE 14

ADVANCED DIESEL TWIN
HIGHLY ADVANCED TECHNOLOGY DIESEL

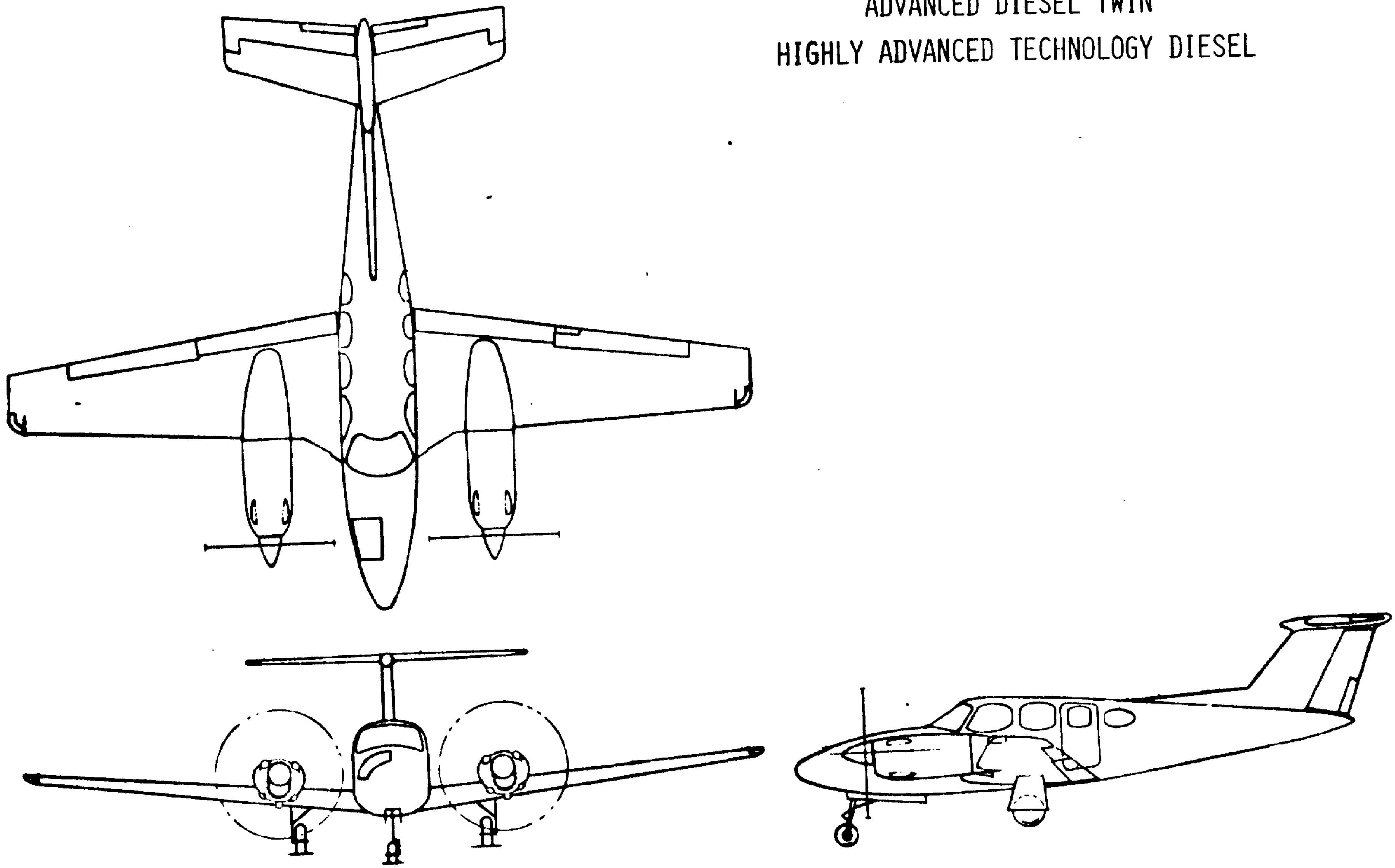


FIGURE 15

DIESEL ENGINE
SINGLE INSTALLATION

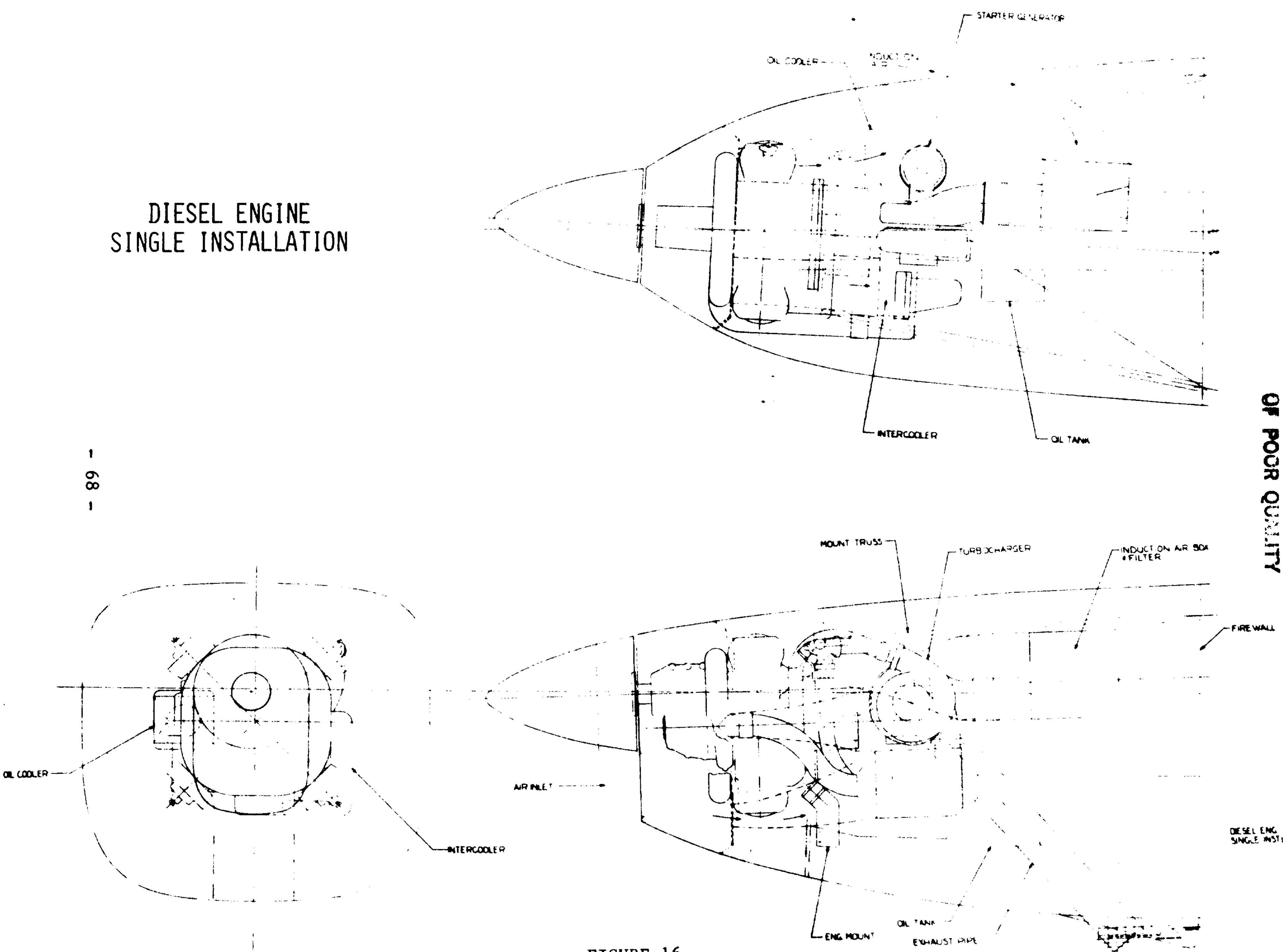


FIGURE 16

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS OF POOR QUALITY

DIESEL ENGINE TWIN INSTALLATION

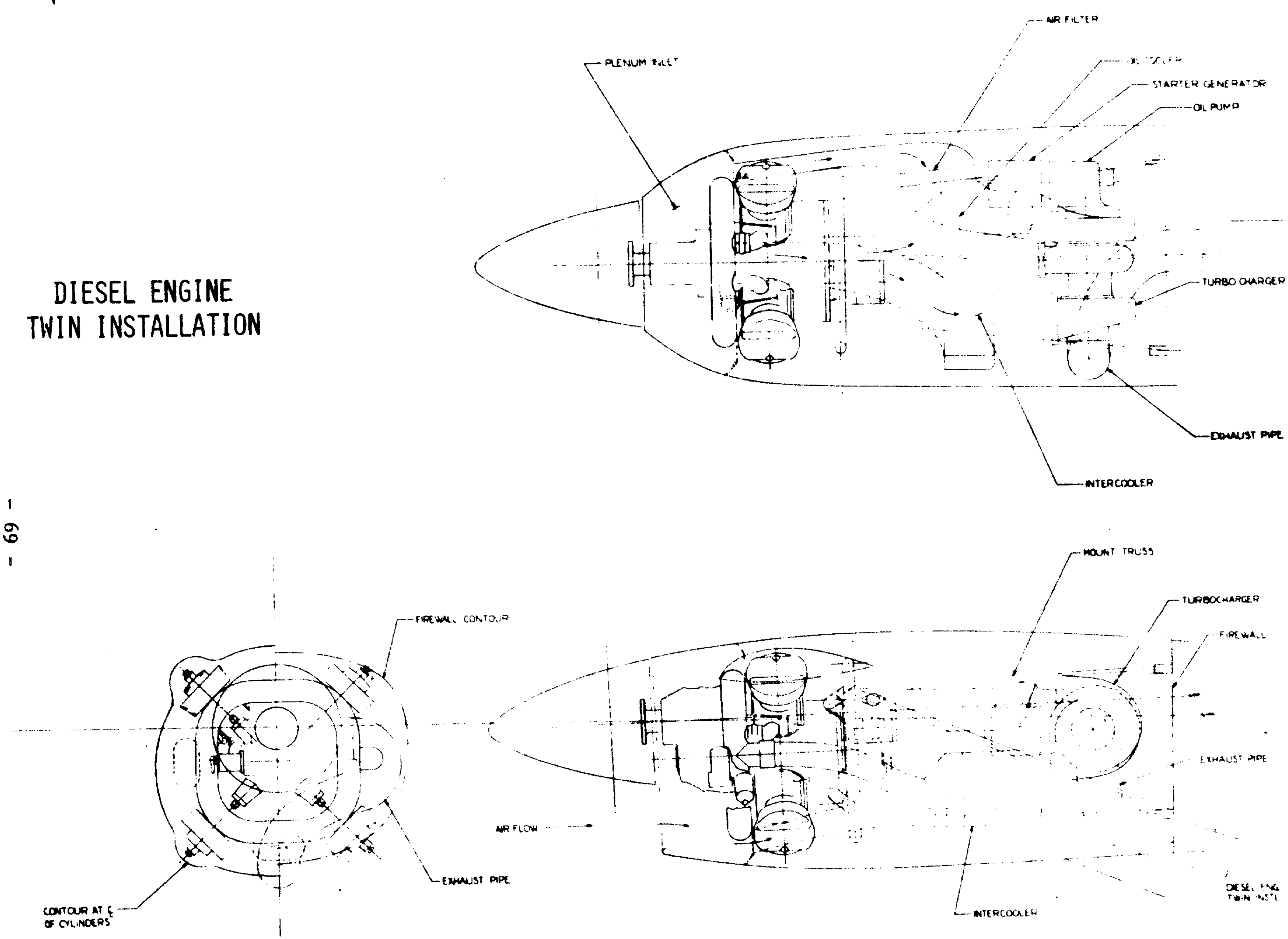


FIGURE 17

ROTARY SINGLE

RC2-47 & RC2-32

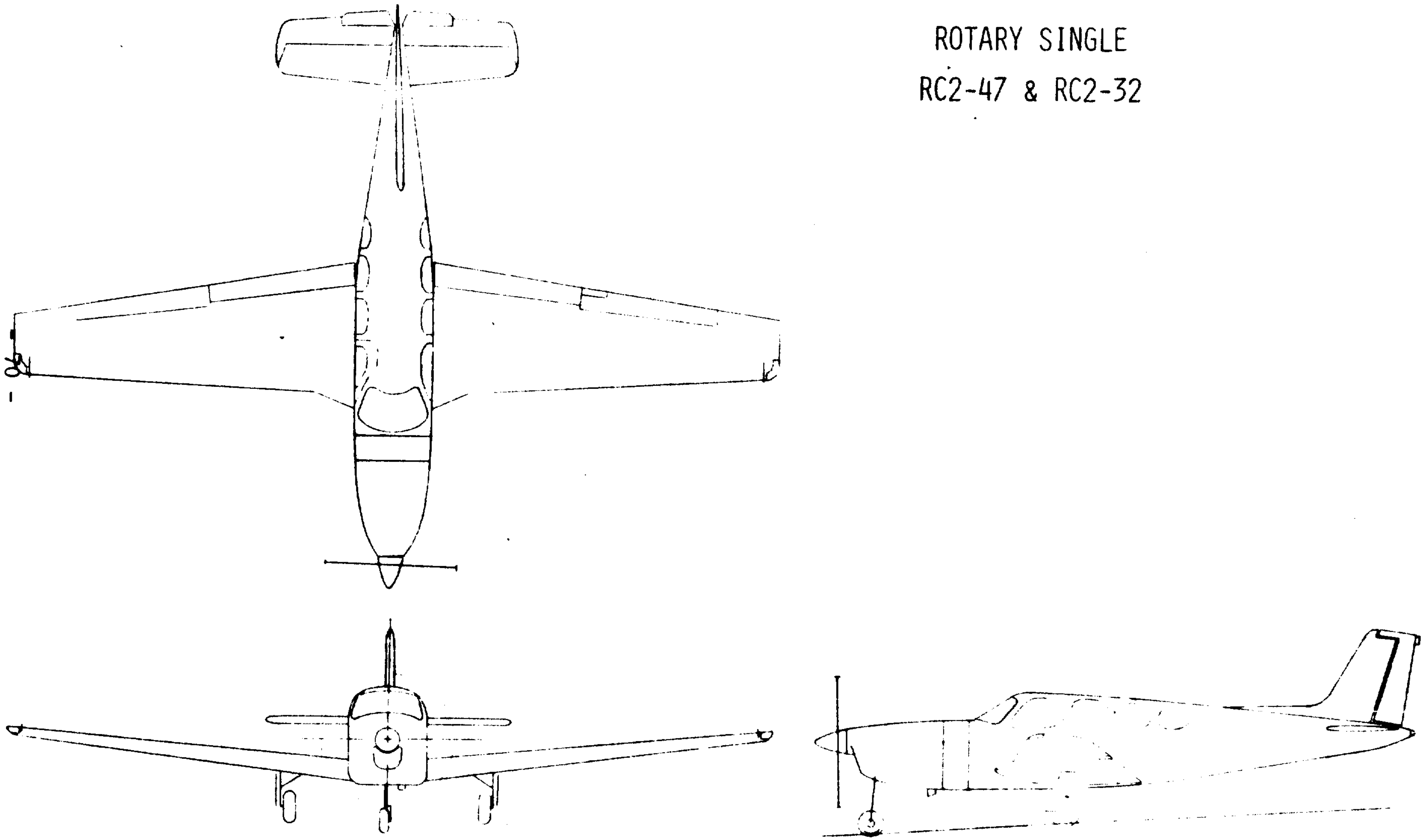


FIGURE 18

ROTARY TWIN

RC2-47 & RC2-32

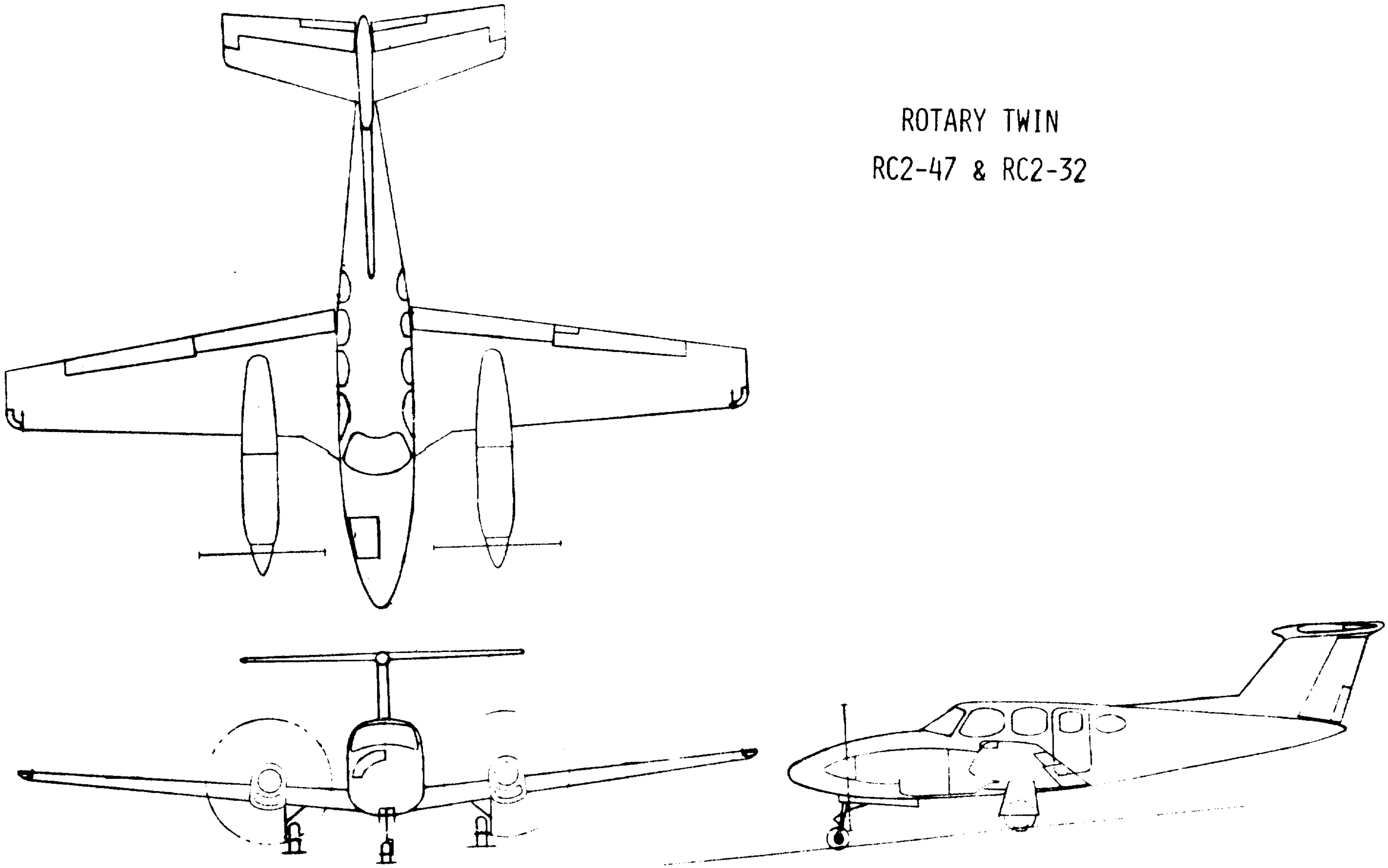


FIGURE 19

ROTARY ENGINE
SINGLE INSTALLATION

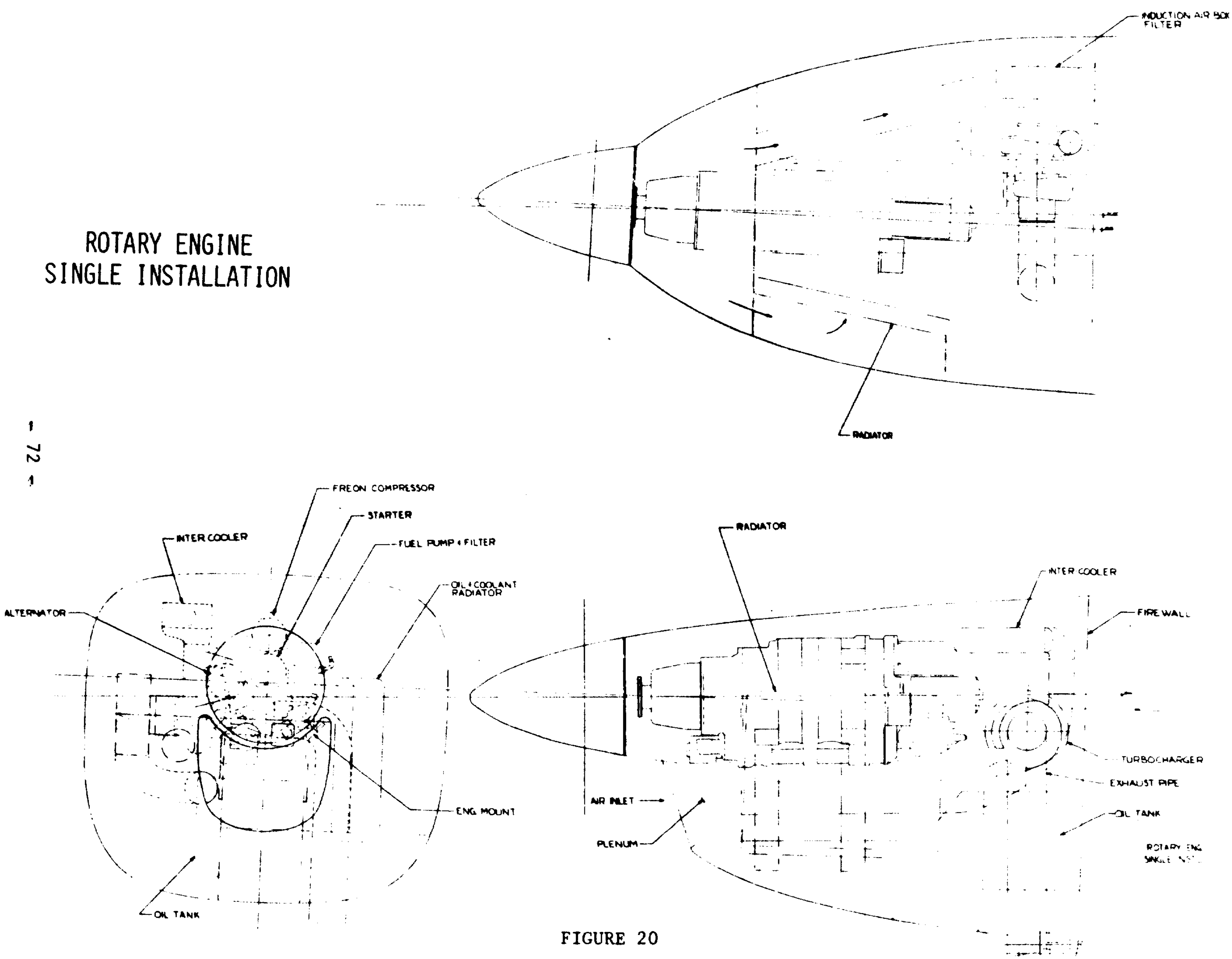


FIGURE 20

ORIGINAL PAGE IS
OF POOR QUALITY

ROTARY ENGINE TWIN INSTALLATION

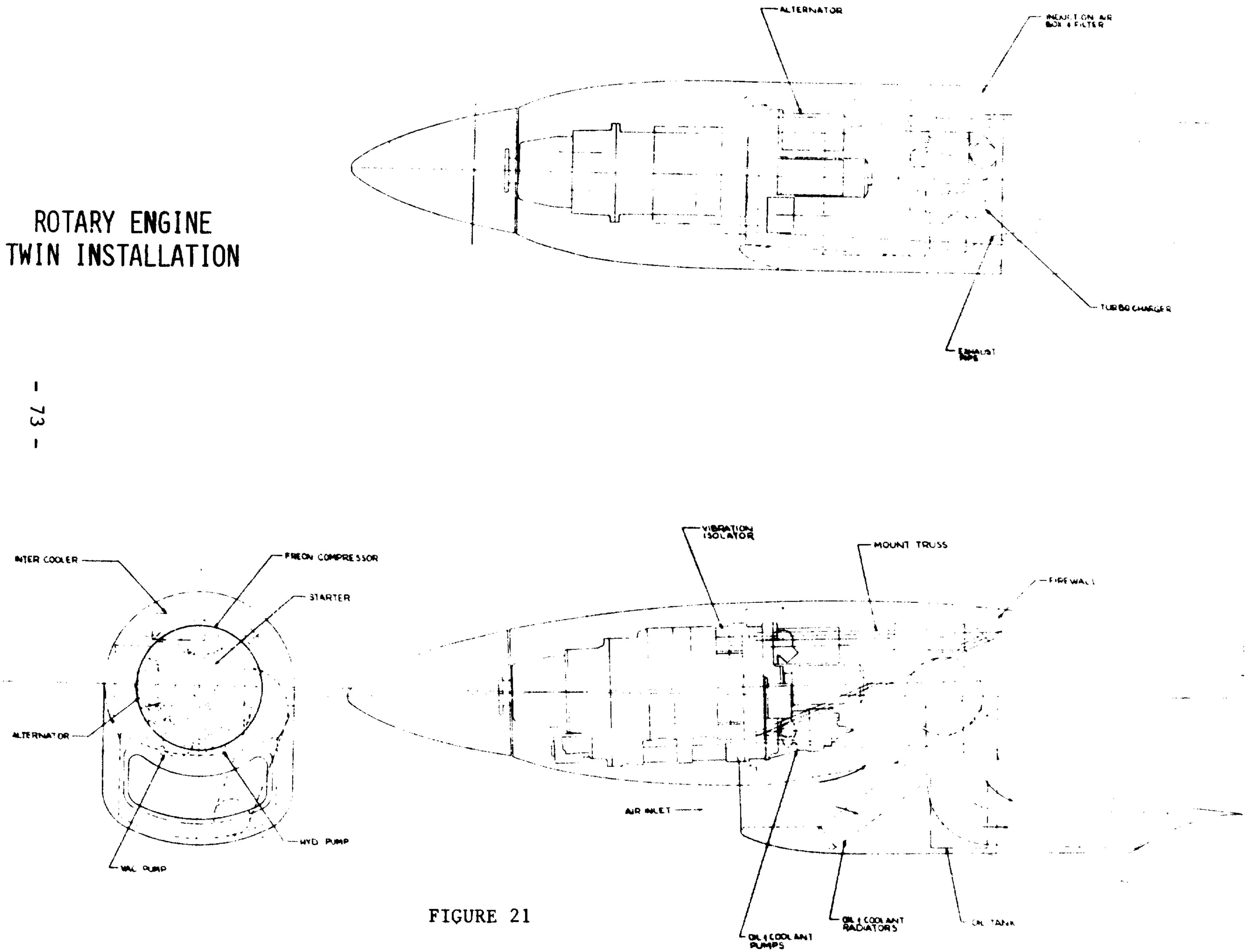


FIGURE 21

ORIGINAL PAGE IS OF POOR QUALITY

ROTARY ENG TWIN INST.

TURBINE SINGLE
GATE TURBINE

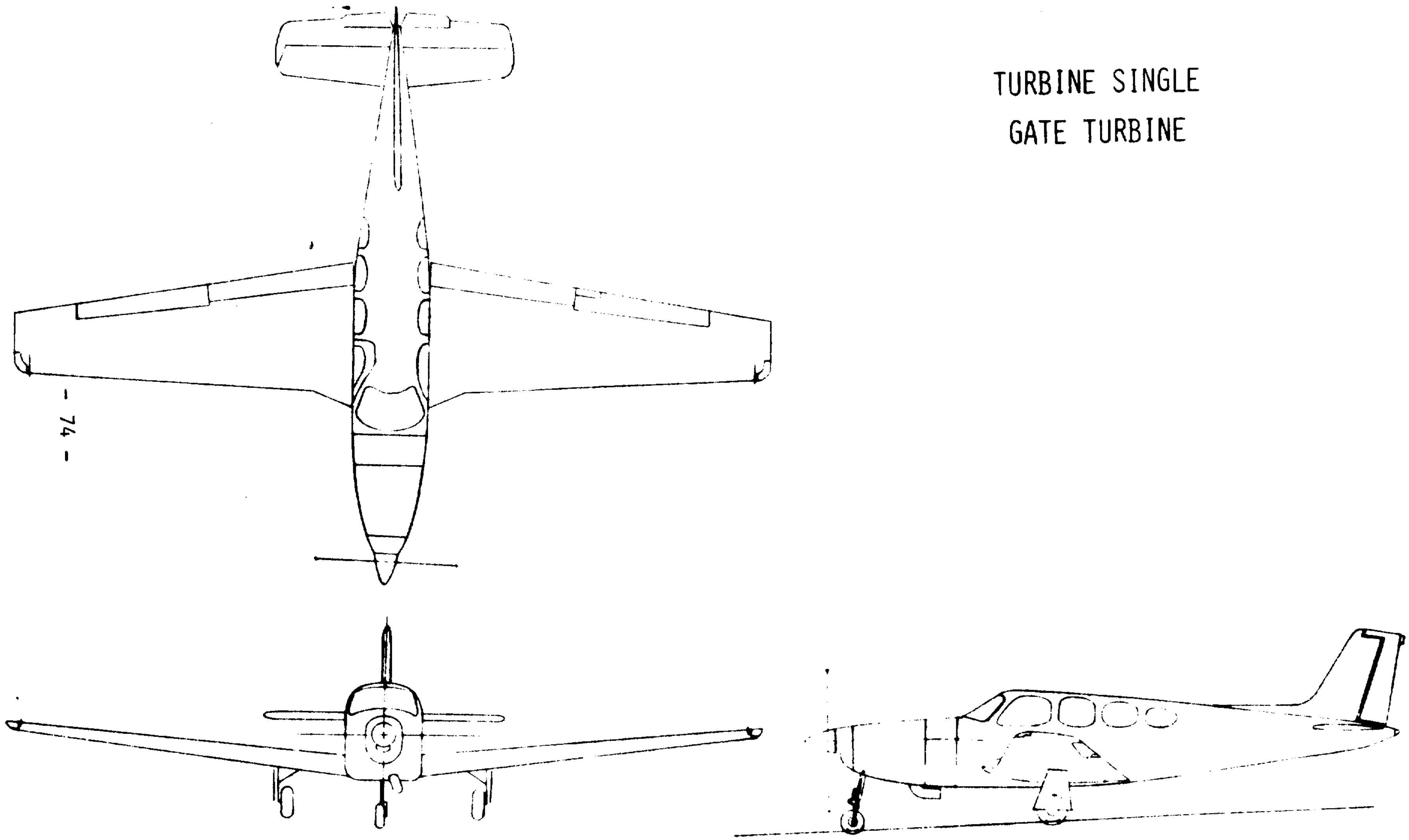


FIGURE 22

TURBINE TWIN

GATE TURBINE

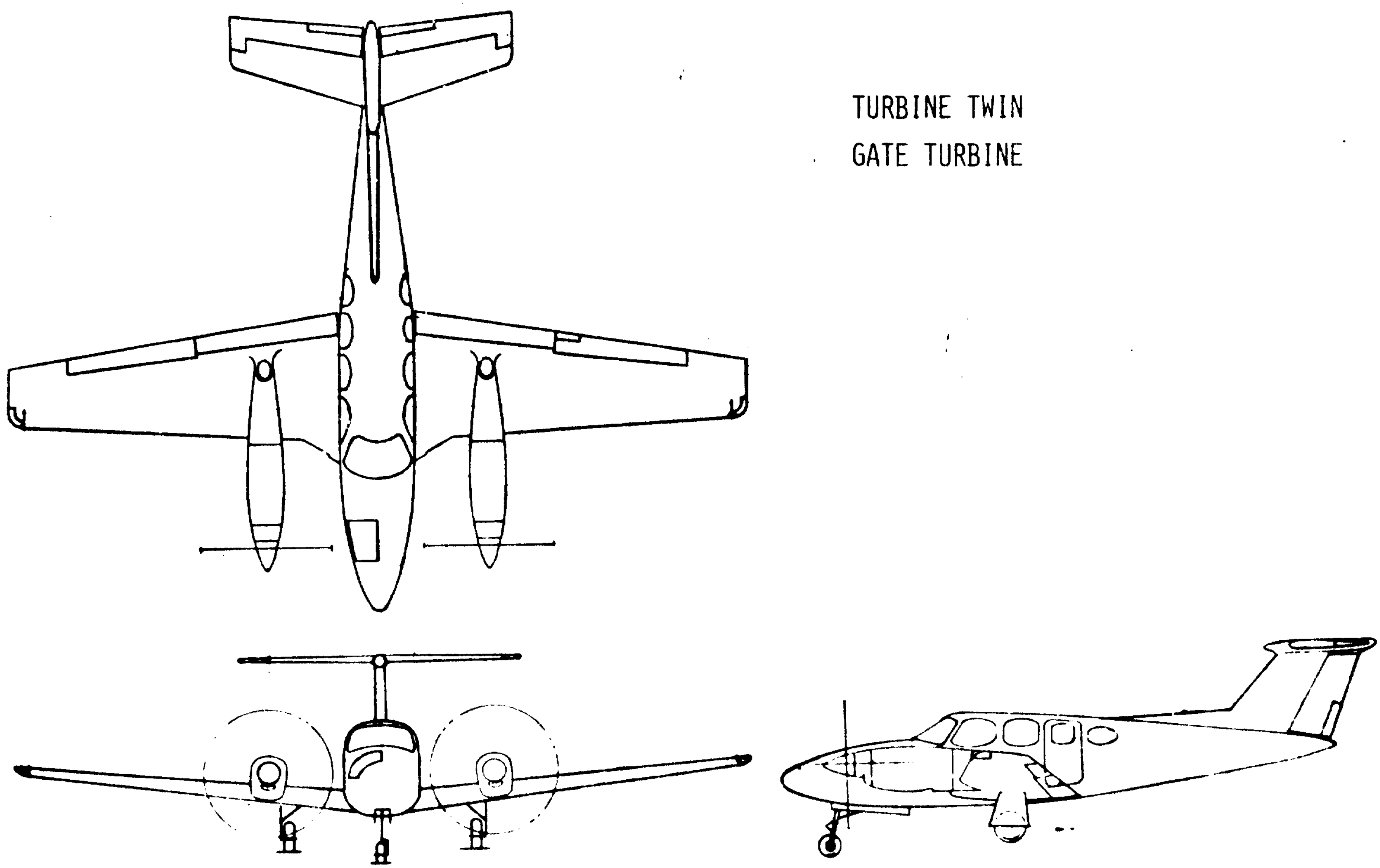
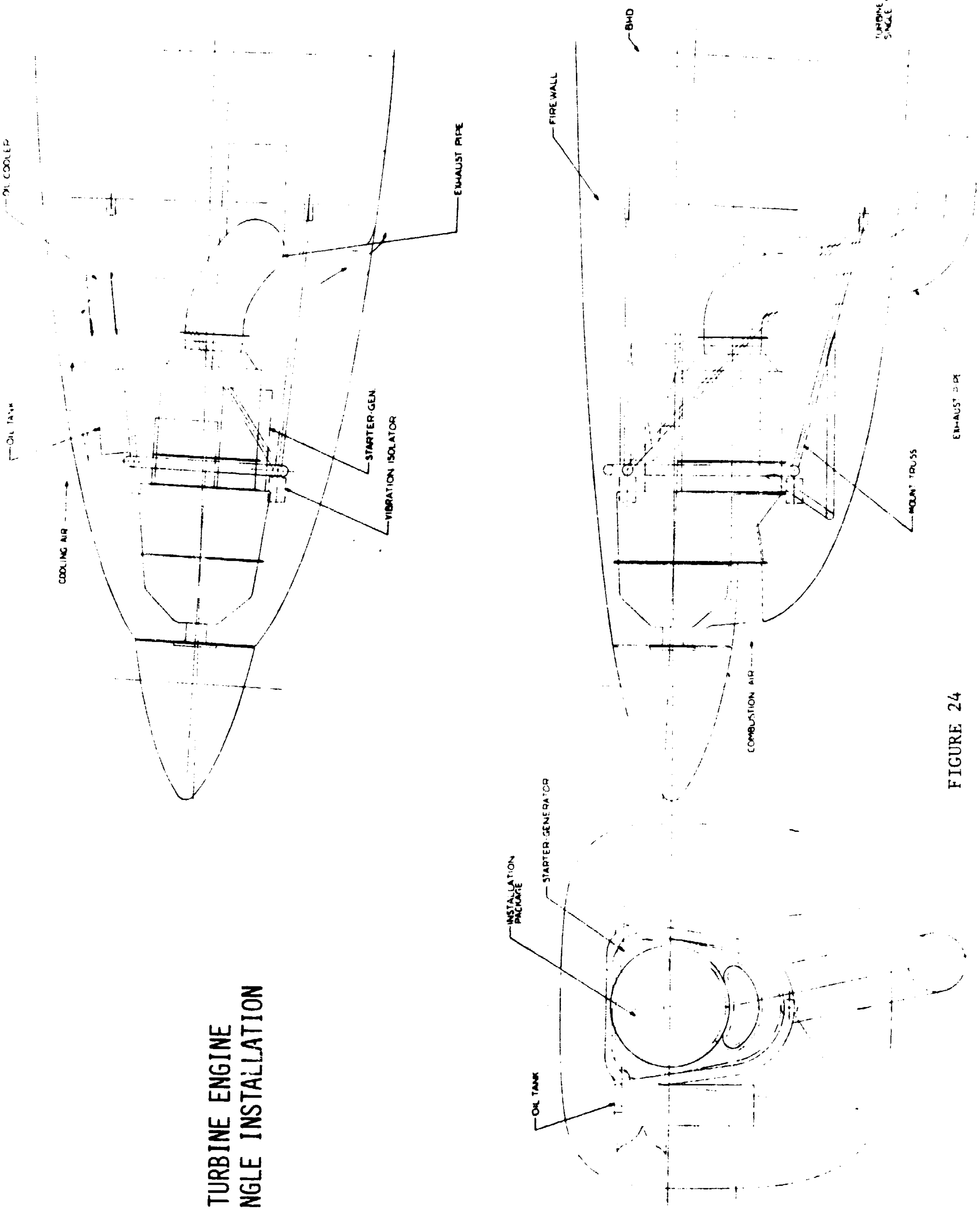


FIGURE 23

ORIGINAL PAGE IS
OF POOR QUALITY



TURBINE ENGINE
SINGLE INSTALLATION

FIGURE 24

ORIGINAL PAGE IS OF POOR QUALITY

TURBINE ENGINE TWIN INSTALLATION

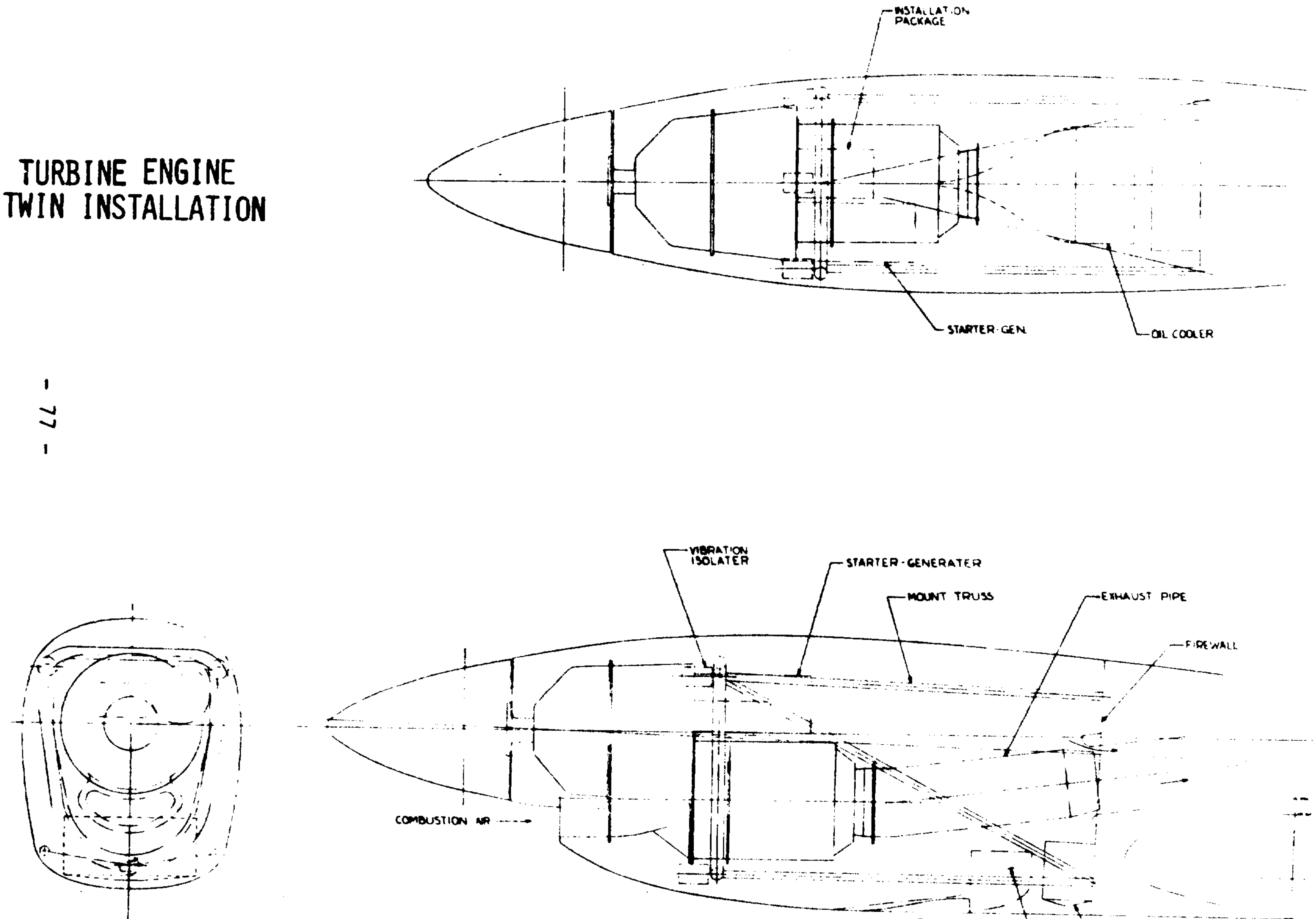


FIGURE 25

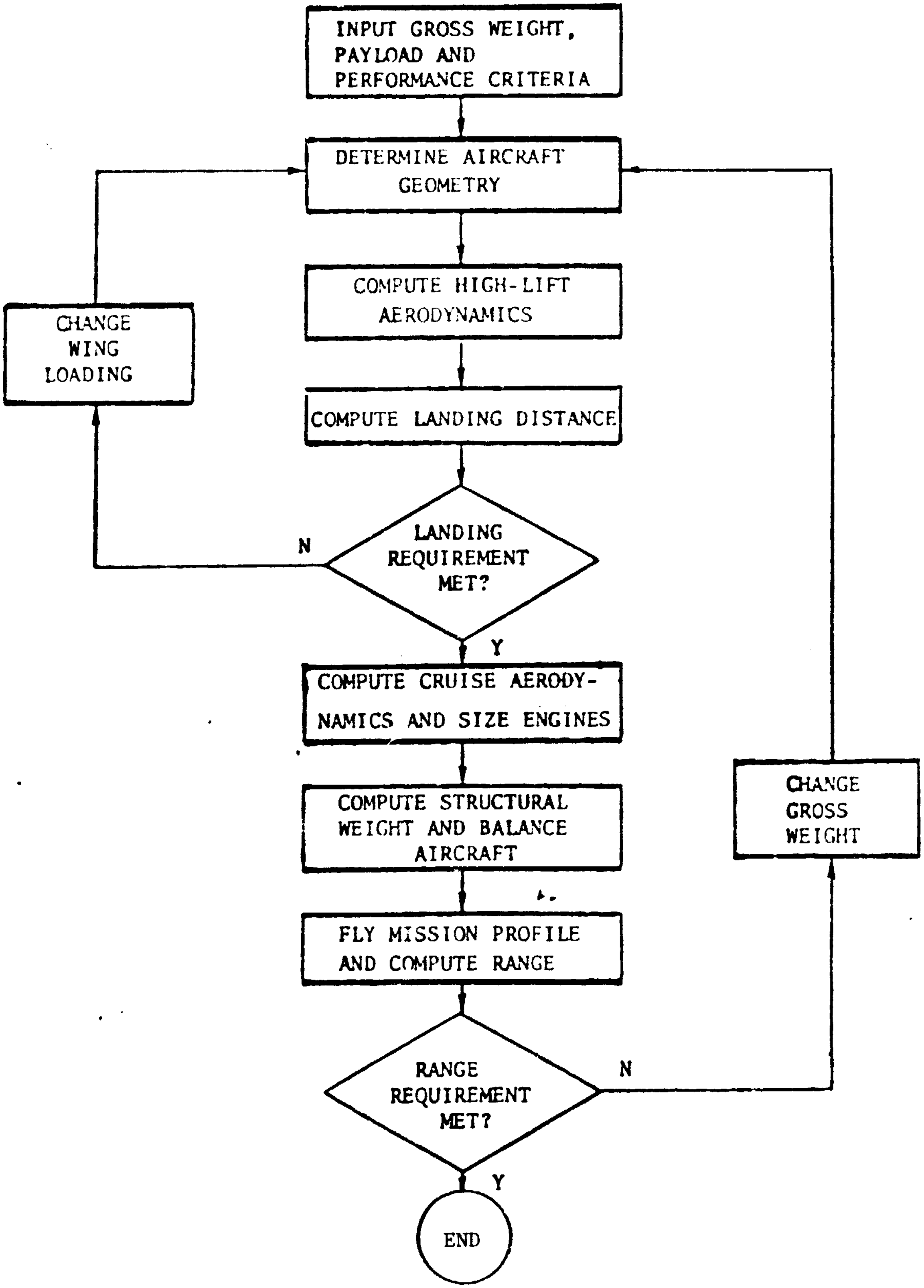

INPUT GROSS WEIGHT, PAYLOAD AND PERFORMANCE CRITERIA
DETERMINE AIRCRAFT GEOMETRY
COMPUTE HIGH-LIFT AERODYNAMICS
CHANGE WING LOADING
COMPUTE LANDING DISTANCE
LANDING REQUIREMENT MET?
N
Y
COMPUTE CRUISE AERODY-NAMICS AND SIZE ENGINES
COMPUTE STRUCTURAL WEIGHT AND BALANCE AIRCRAFT
CHANGE GROSS WEIGHT
FLY MISSION PROFILE AND COMPUTE RANGE
RANGE REQUIREMENT MET?
N
Y
END

FIGURE 26

FIXED AIRFRAME SINGLES

CONSTANT GROSS WEIGHT
WING AREA
PAYLOAD
ENGINE SIZE
25,000 FT

VARIABLE PERFORMANCE
RANGE

* REVISED GATE

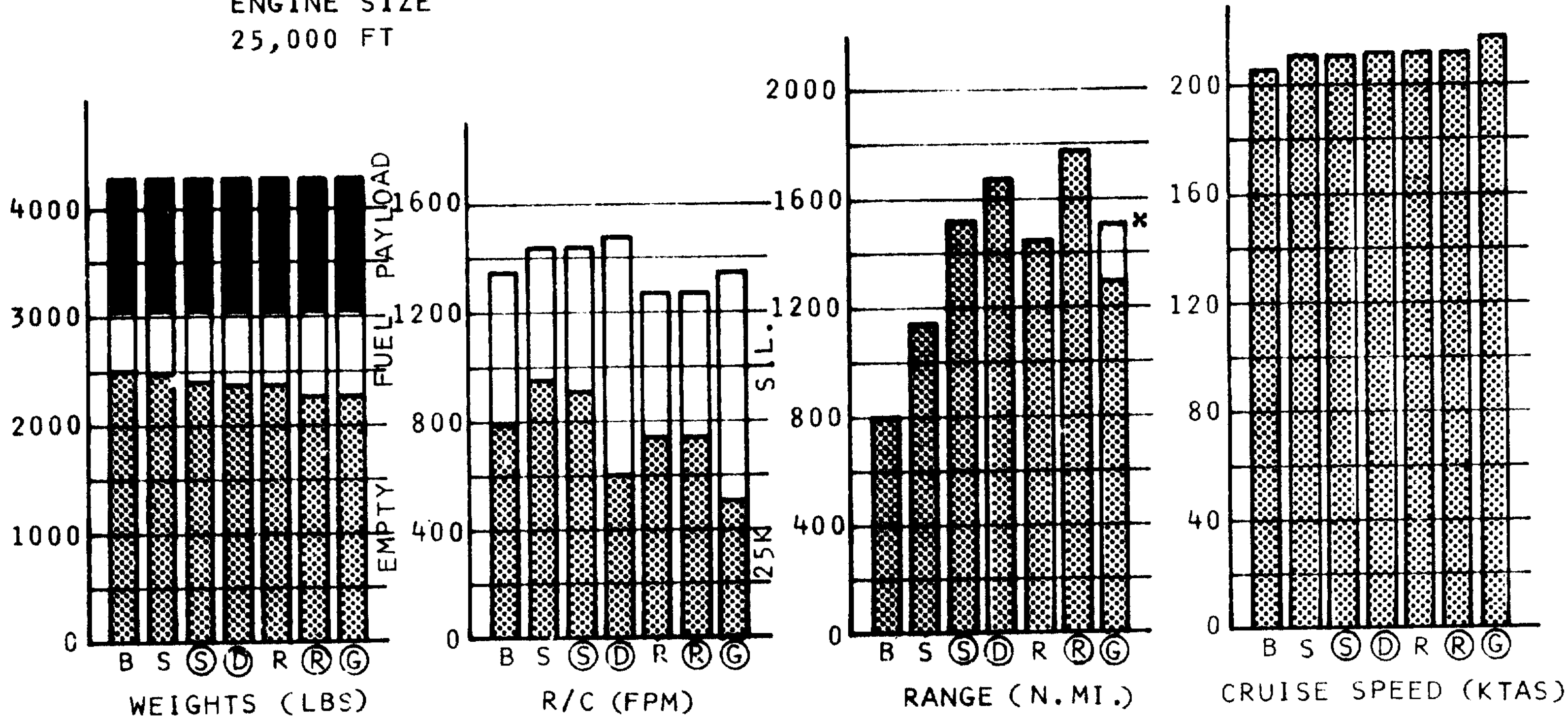


FIGURE 27

FIXED AIRFRAME TWINS

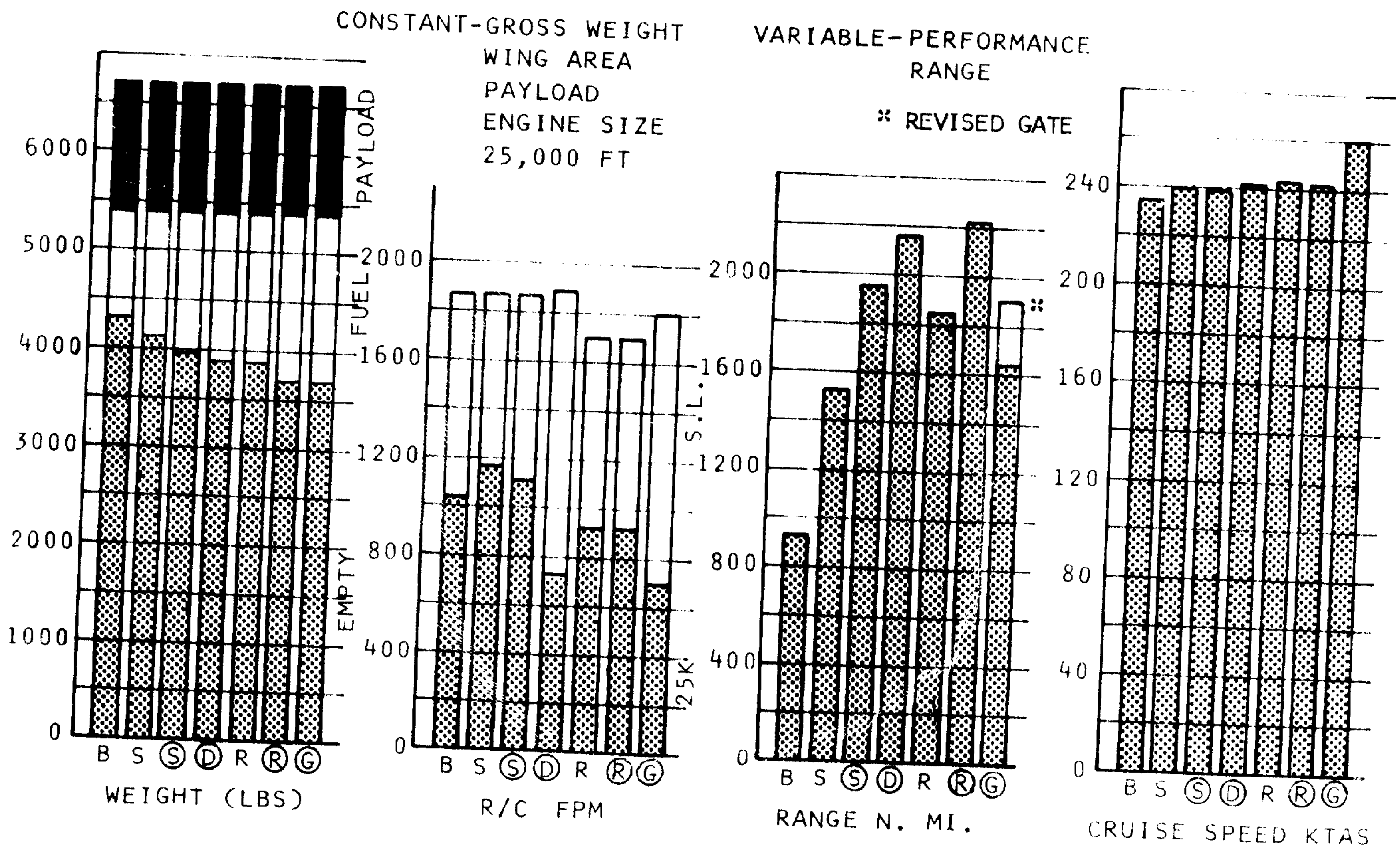


FIGURE 28

FIXED WING AREA SINGLES

CONSTANT—WING AREA
PAYLOAD
RANGE
ENGINE SIZE
25,000 FT

VARIABLE—GROSS WEIGHT
PERFORMANCE

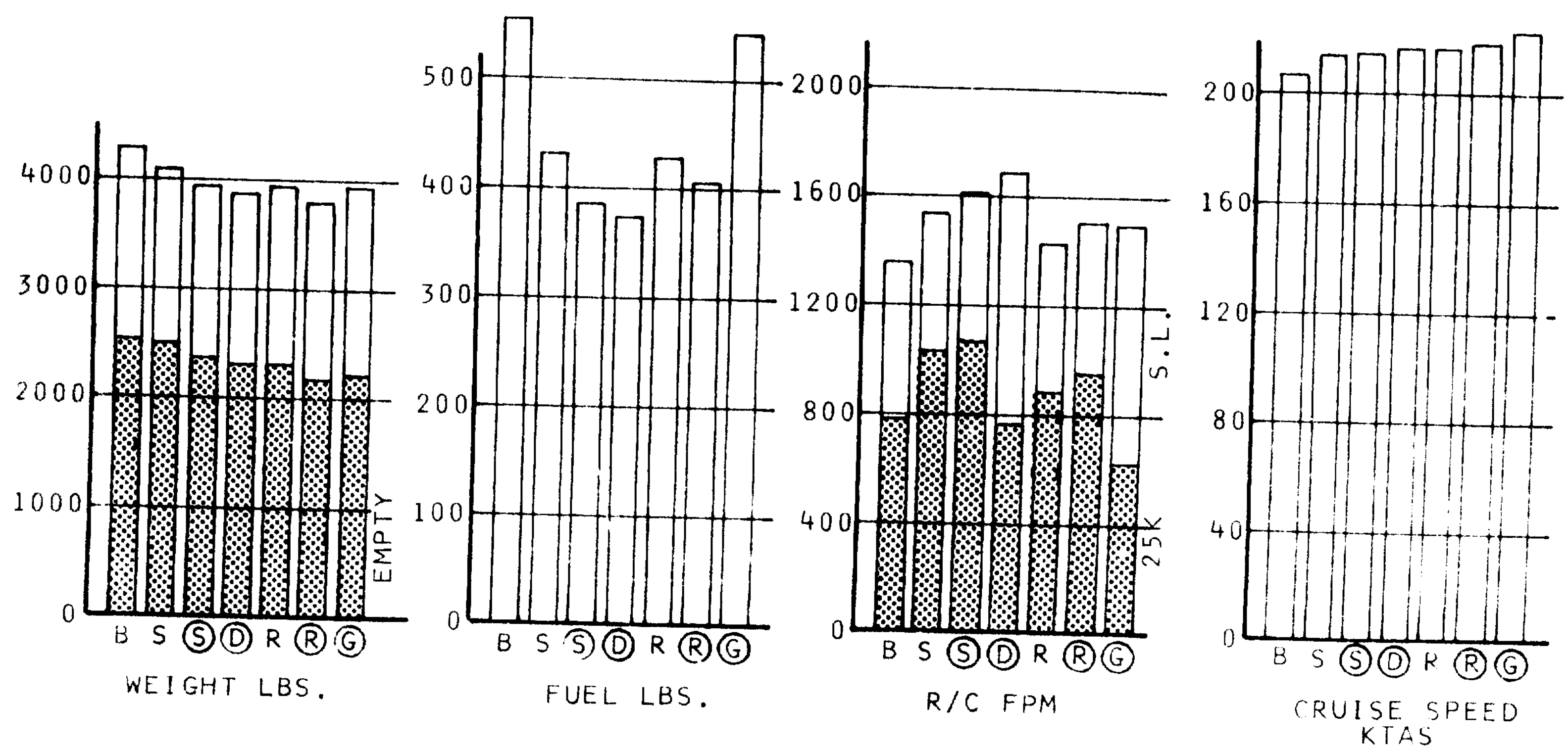


FIGURE 29

FIXED WING AREA TWINS

CONSTANT— WING AREA
PAYLOAD
RANGE
ENGINE SIZE
25,000 FT

VARIABLE—GROSS WEIGHT
PERFORMANCE

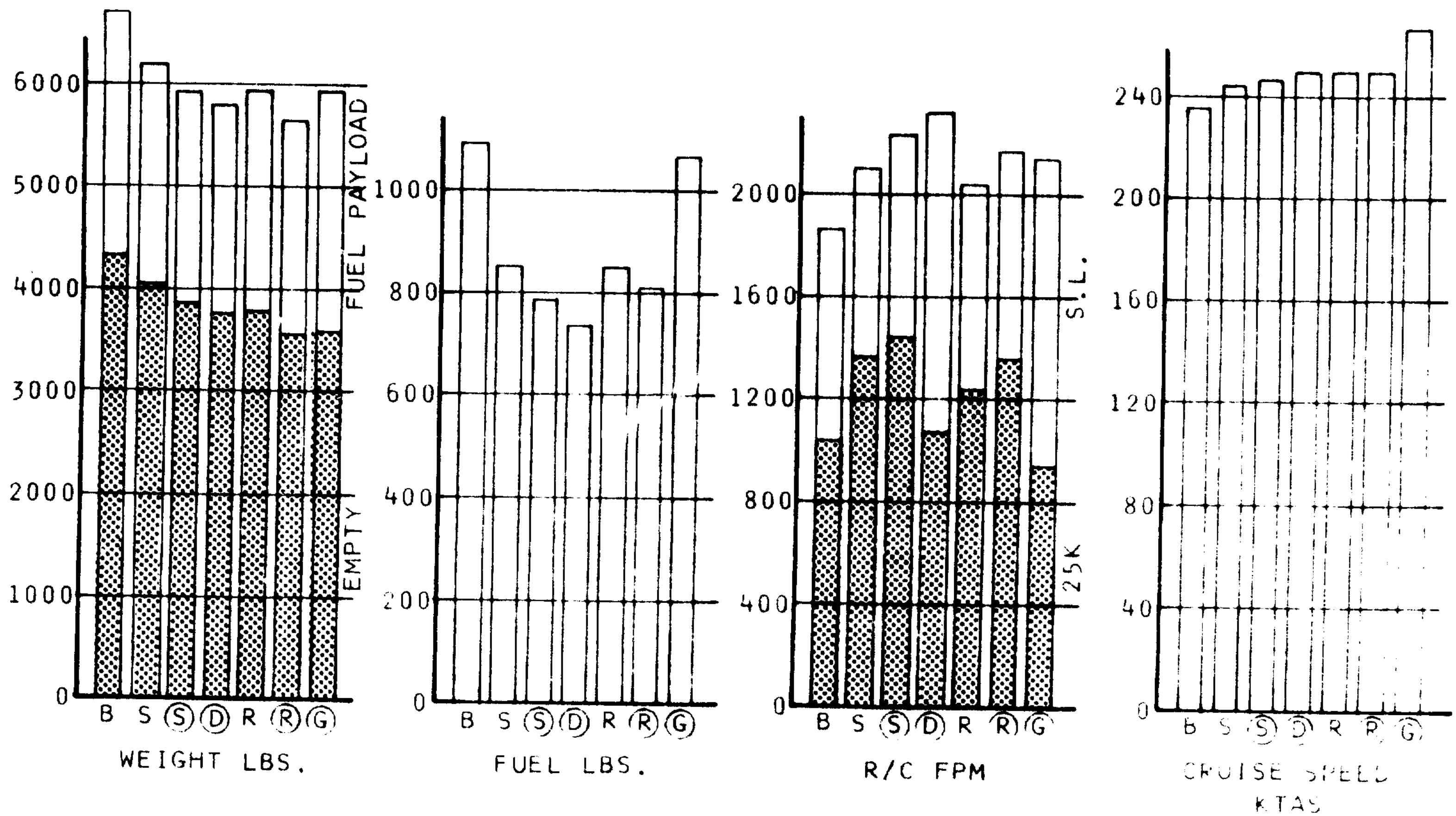


FIGURE 30

FIXED WING LOADING SINGLES

CONSTANT — WING LOADING
PAYLOAD
RANGE
ENGINE SIZE
25,000 FT

VARIABLE — GROSS WEIGHT
PERFORMANCE

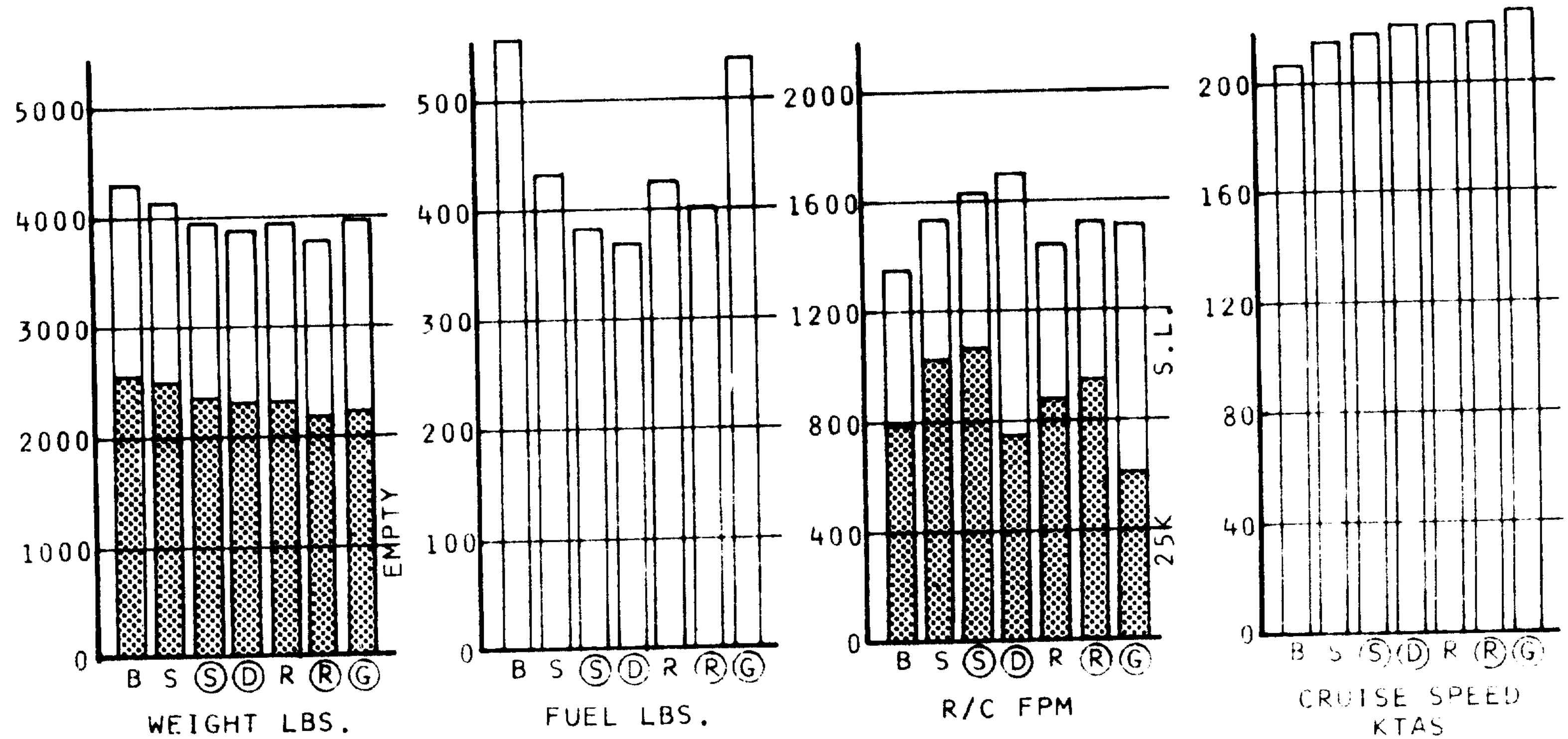


FIGURE 31

FIXED WING LOADING TWINS

CONSTANT — WING LOADING
PAYLOAD
RANGE
ENGINE SIZE
25,000 FT

VARIABLE — GROSS WEIGHT
PERFORMANCE

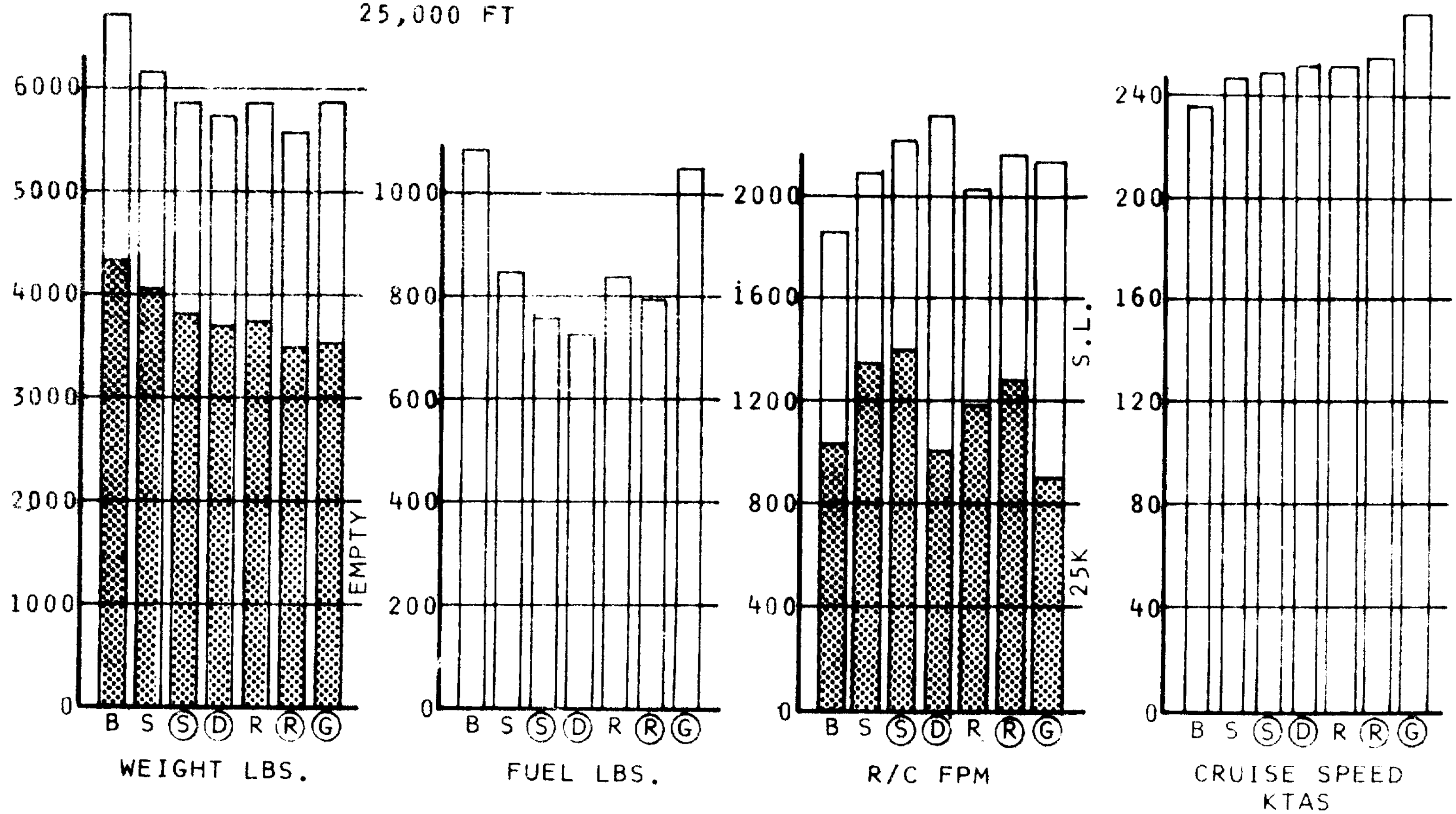


FIGURE 32

FIXED MISSION SINGLES

CONSTANT — RANGE
CRUISE SPEED
PAYLOAD
WING LOADING
25,000 FT

VARIABLE — GROSS WEIGHT
ENGINE SIZE

* REVISED GATE

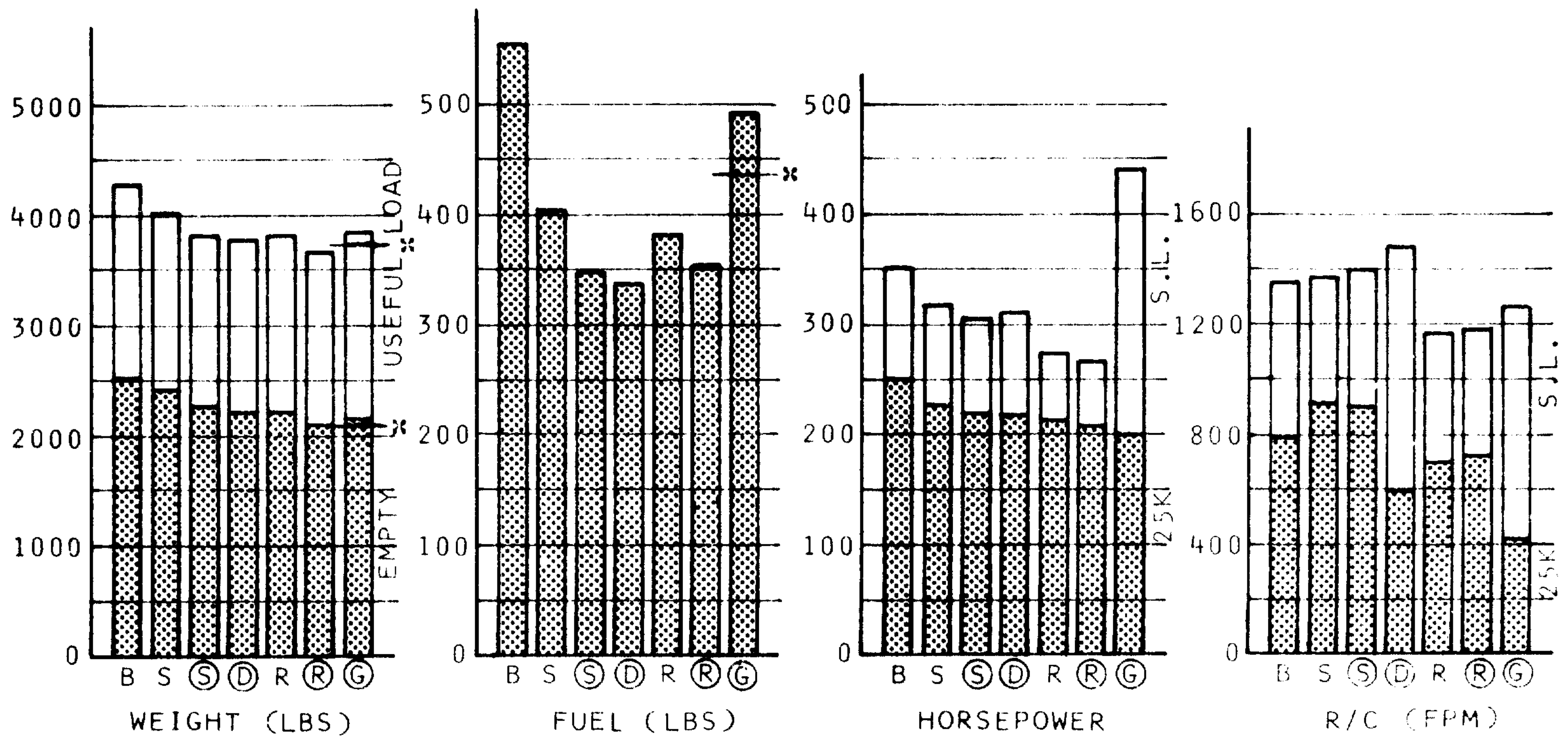


FIGURE 33

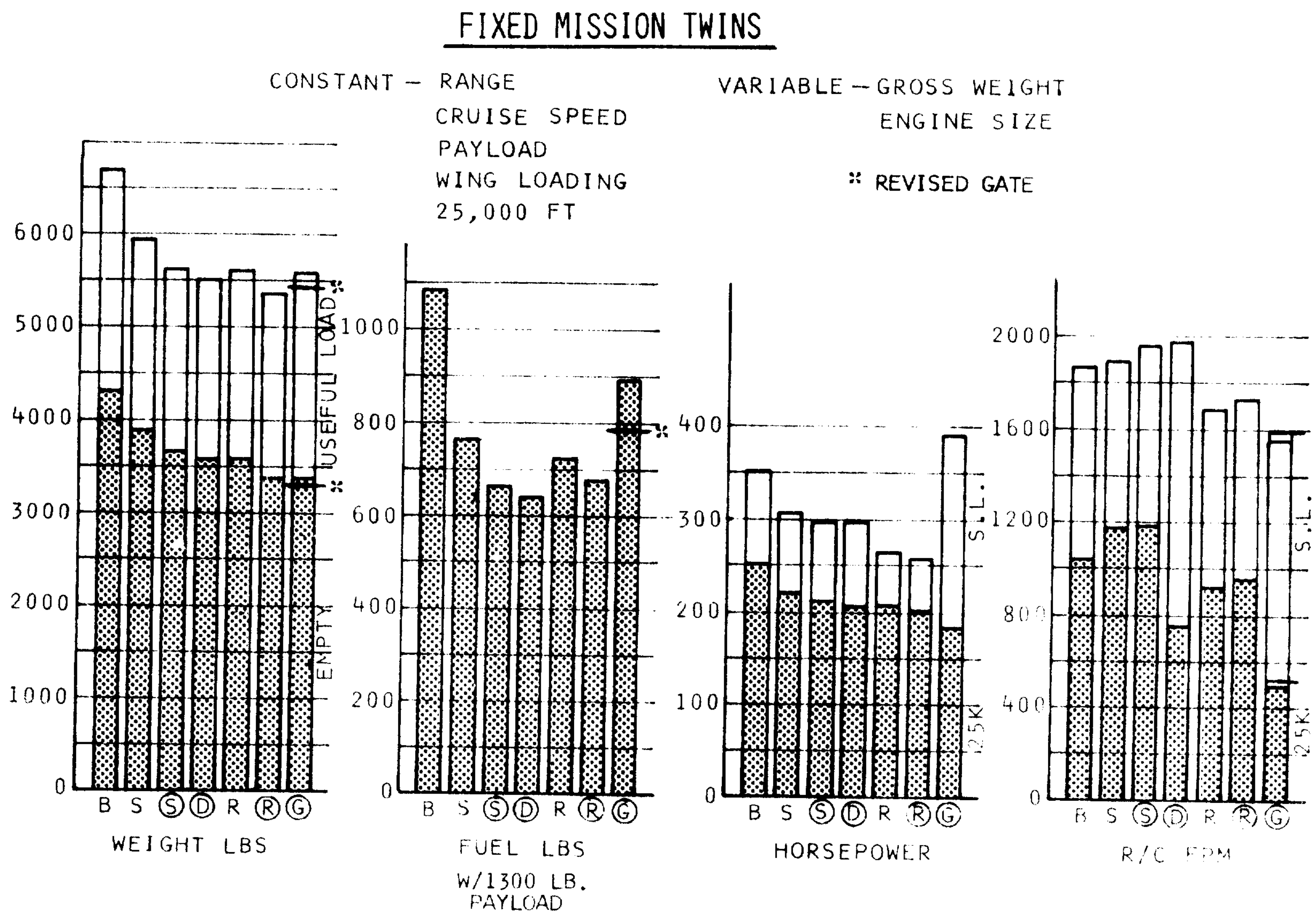

FIXED MISSION TWINS
CONSTANT — RANGE
CRUISE SPEED
PAYLOAD
WING LOADING
25,000 FT
VARIABLE — GROSS WEIGHT
ENGINE SIZE
* REVISED GATE
6000
5000
4000
3000
2000
1000
0
USEFUL LOAD
EMPTY
B S S D R R G
WEIGHT LBS
1000
800
600
400
200
0
FUEL LBS
W/1300 LB.
PAYLOAD
400
300
200
100
0
S.L.
25K
HORSEPOWER
2000
1600
1200
800
400
0
R/C FPM

FIGURE 34

PARAMETRIC ALTITUDE STUDY

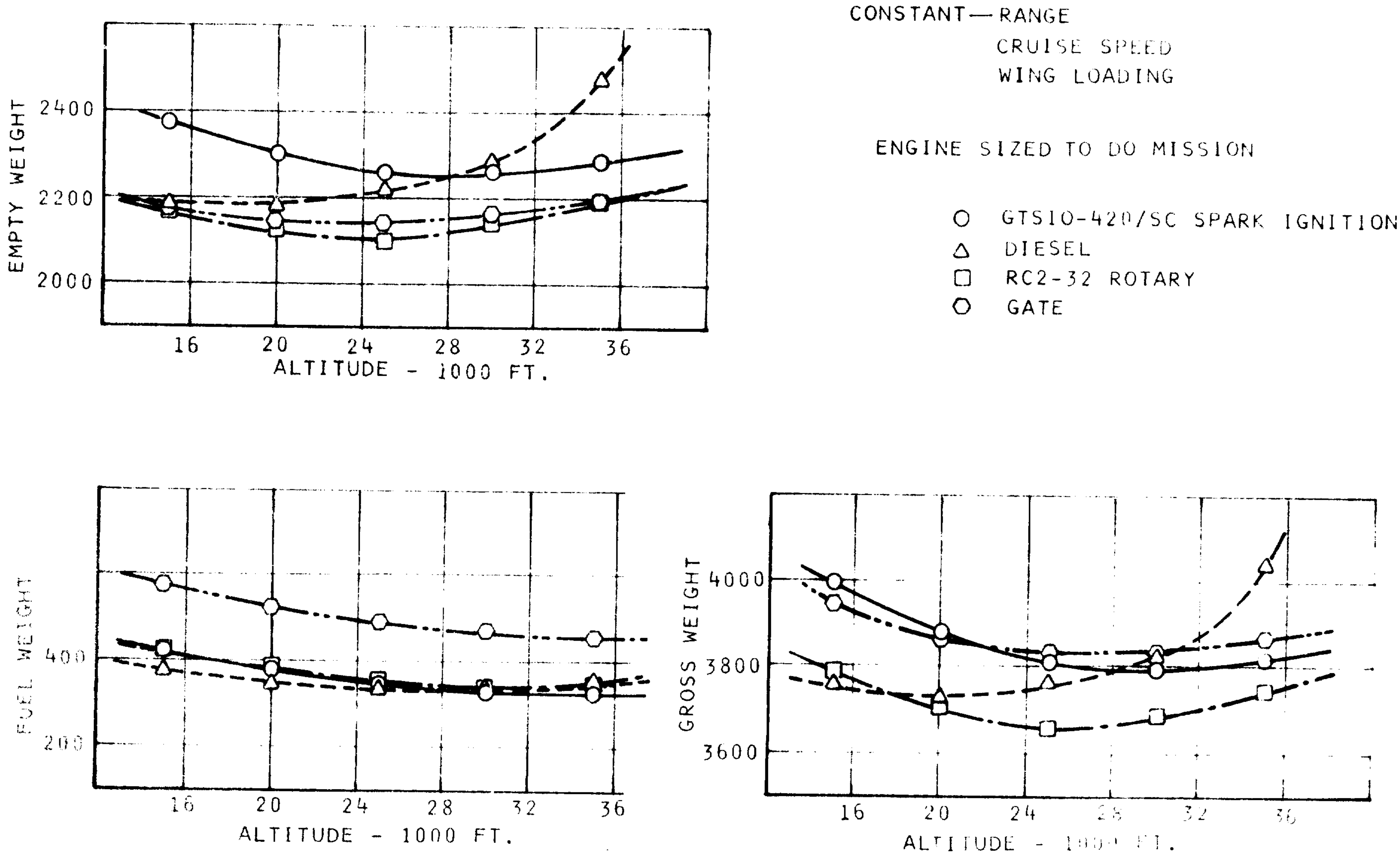


FIGURE 35

PARAMETRIC ALTITUDE STUDY

CONSTANT — RANGE
CRUISE SPEED
WING LOADING

O GTSIO-420/SC SPARK IGNITION
△ DIESEL
□ RC2-32 ROTARY
⬡ GATE

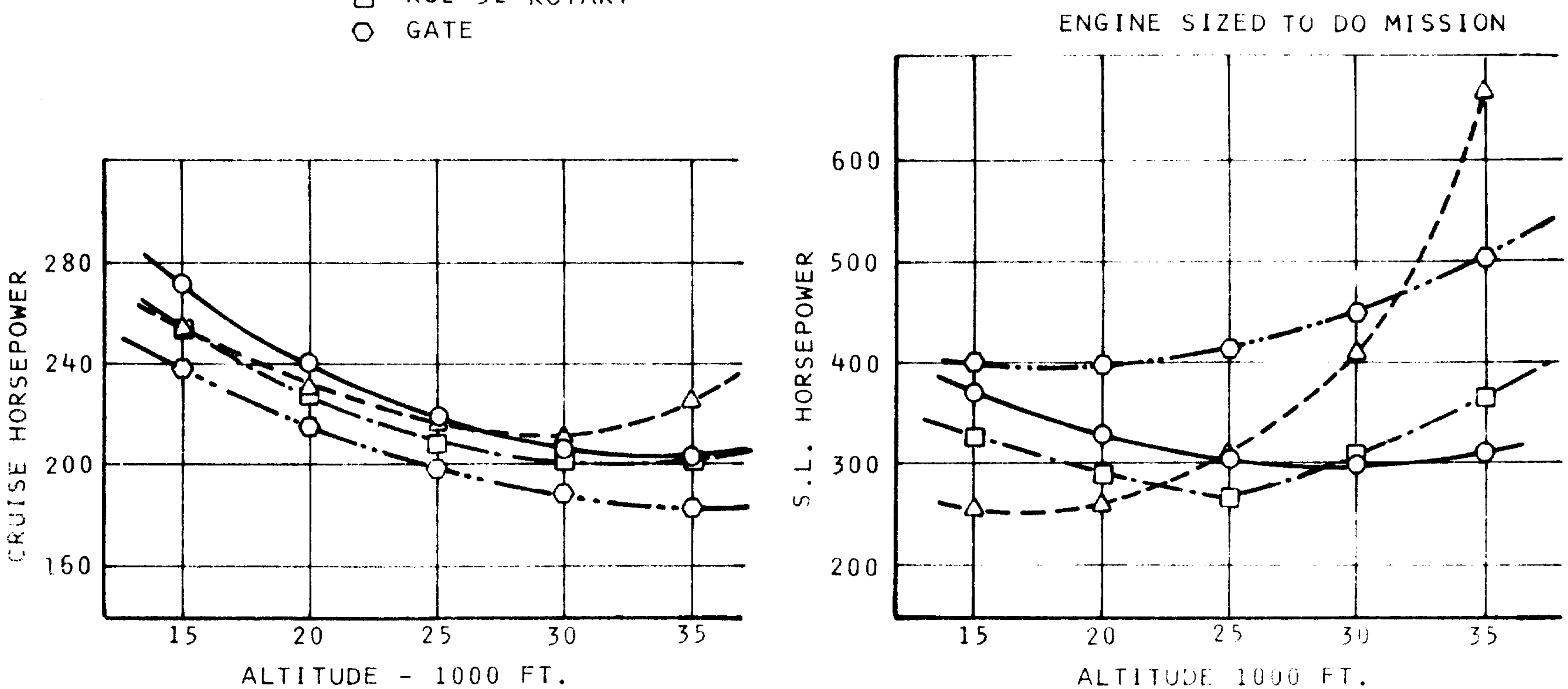


FIGURE 36

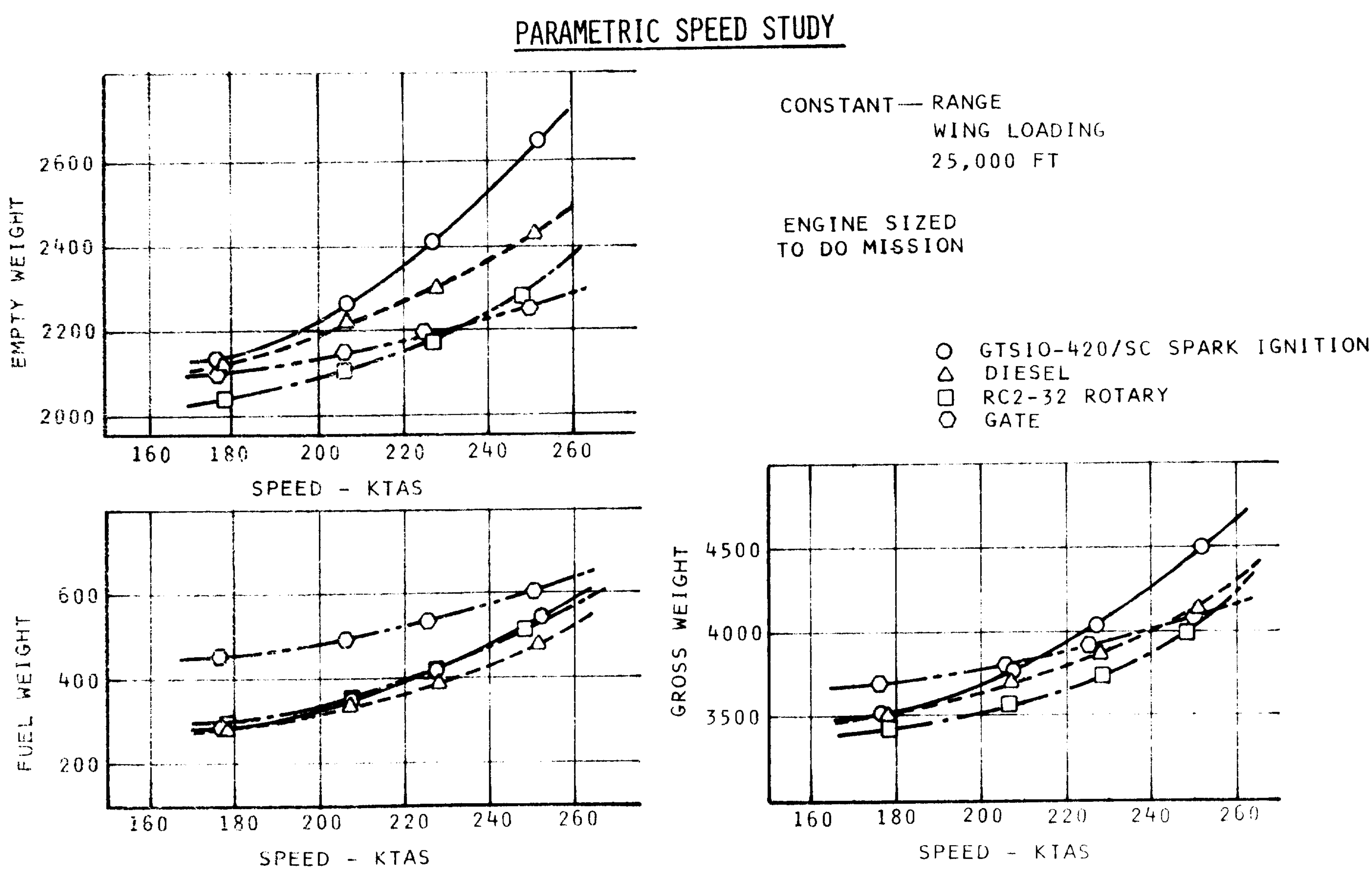

PARAMETRIC SPEED STUDY
CONSTANT — RANGE
WING LOADING
25,000 FT
ENGINE SIZED
TO DO MISSION
GTSIO-420/SC SPARK IGNITION
DIESEL
RC2-32 ROTARY
GATE
EMPTY WEIGHT
2000
2200
2400
2600
FUEL WEIGHT
200
400
600
GROSS WEIGHT
3500
4000
4500
160
180
200
220
240
260
SPEED - KTAS

FIGURE 37

PARAMETRIC SPEED STUDY

CONSTANT — RANGE
WING LOADING
25,000 FT

○ GTSIO-420/SC SPARK IGNITION
△ DIESEL
□ RC2-32 ROTARY
⬡ GATE

ENGINE SIZED
TO DO MISSION

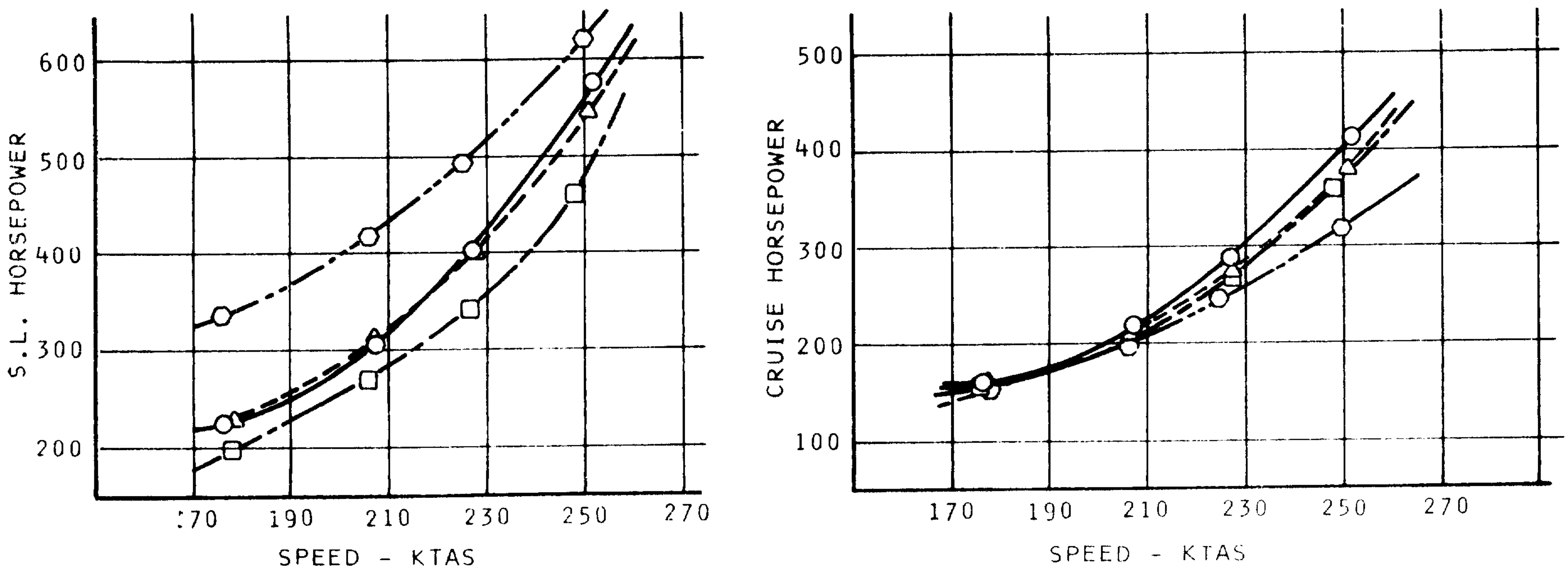


FIGURE 38

PARAMETRIC RANGE STUDY

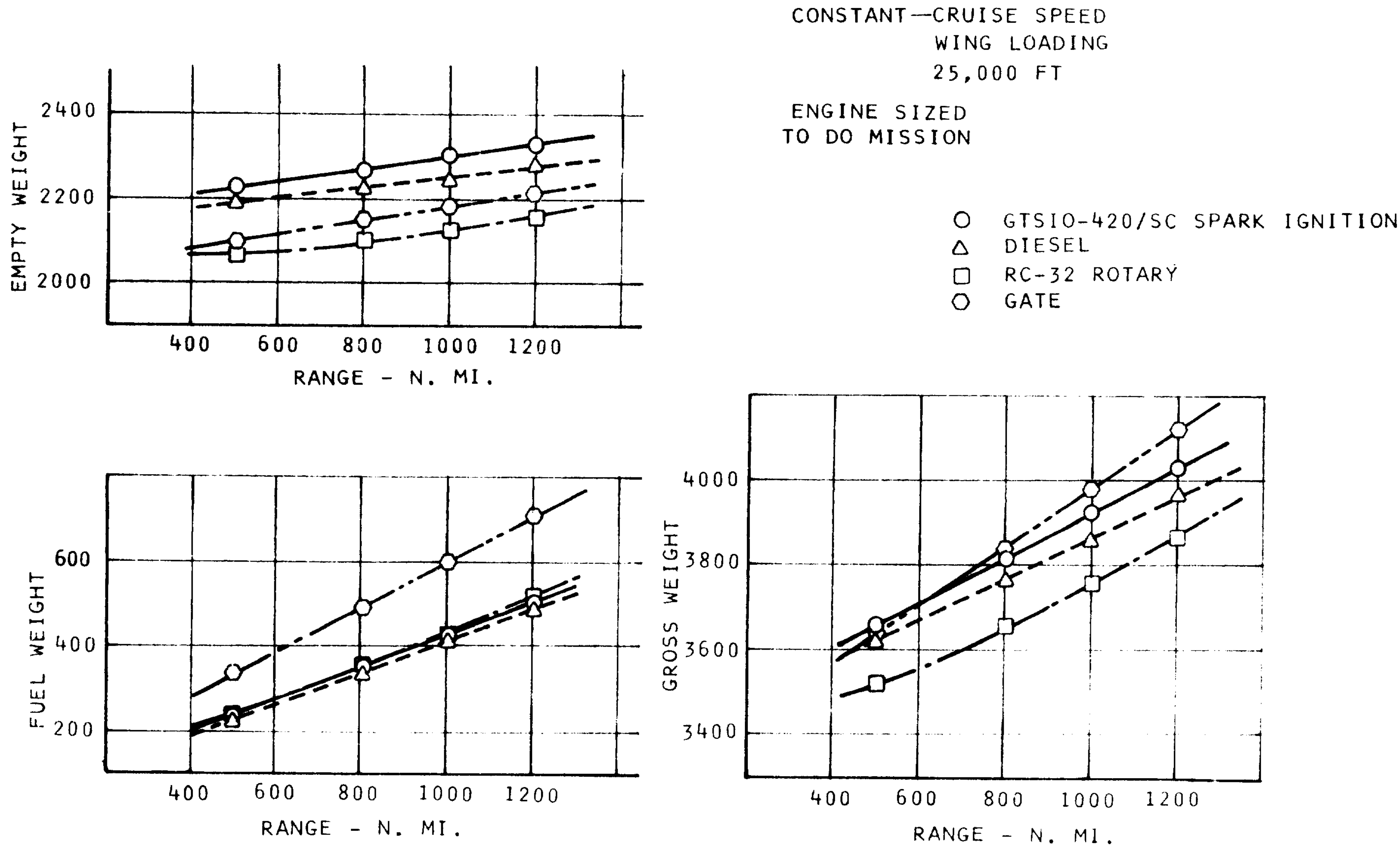
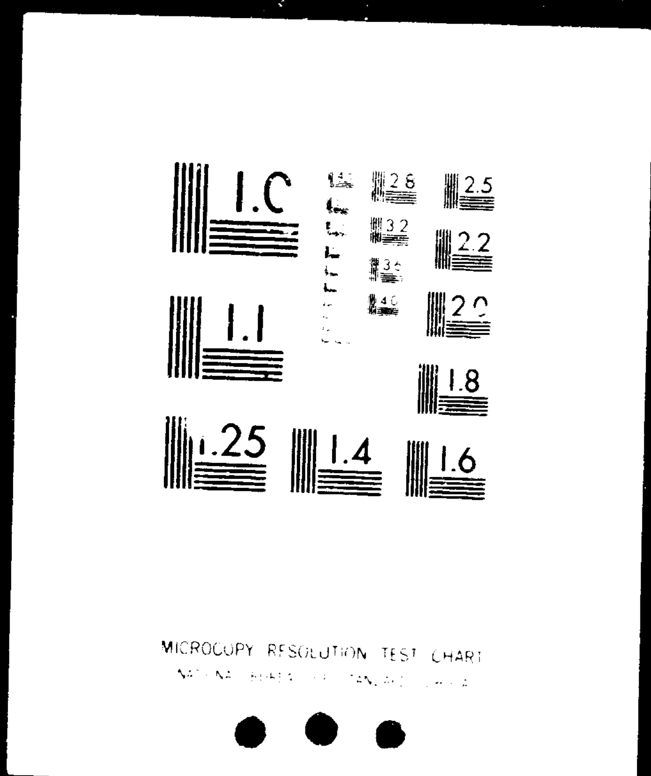


FIGURE 39

2 OF 2

N82-22268 UNCLAS



PARAMETRIC RANGE STUDY

CONSTANT—CRUISE SPEED
WING LOADING
25,000 FT

○ GTSIO-420/SC SPARK IGNITION
△ DIESEL
□ RC-32 ROTARY
⬡ GATE

ENGINE SIZED
TO DO MISSION

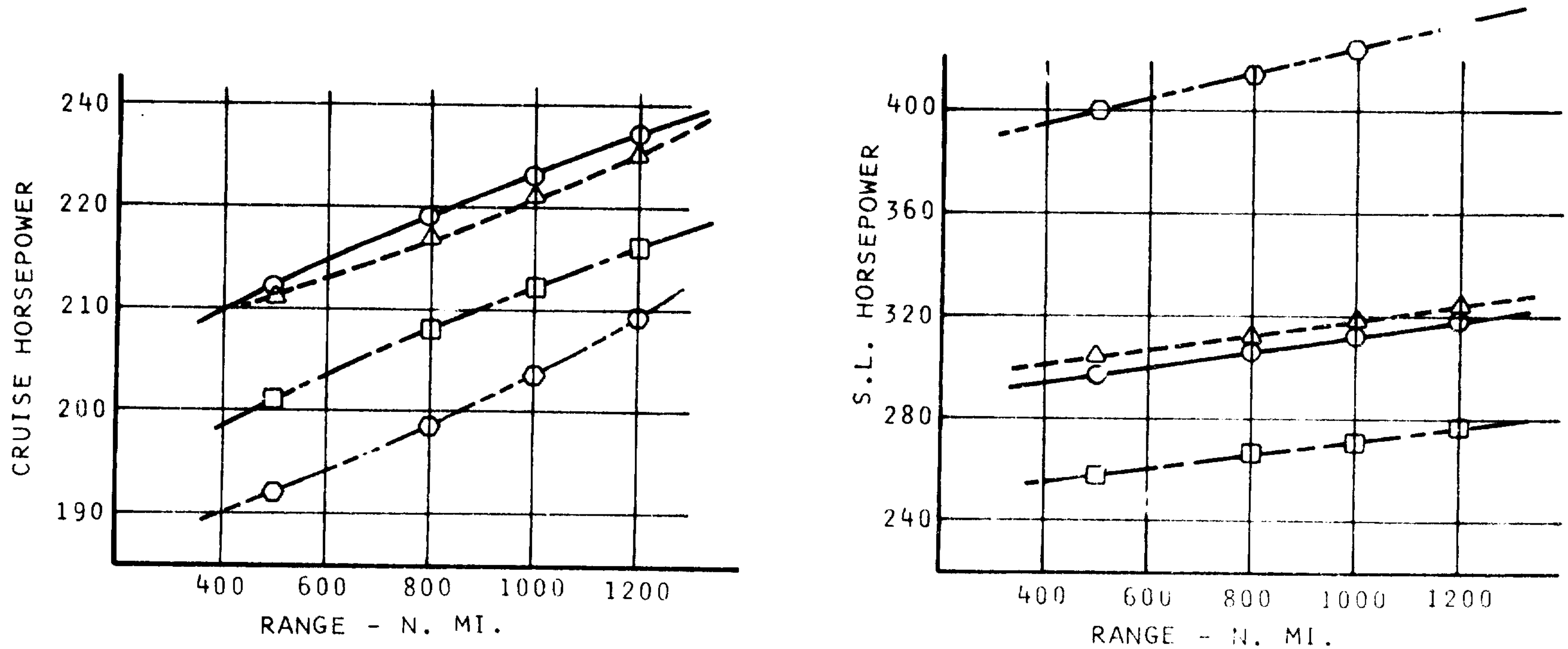


FIGURE 40

C-2

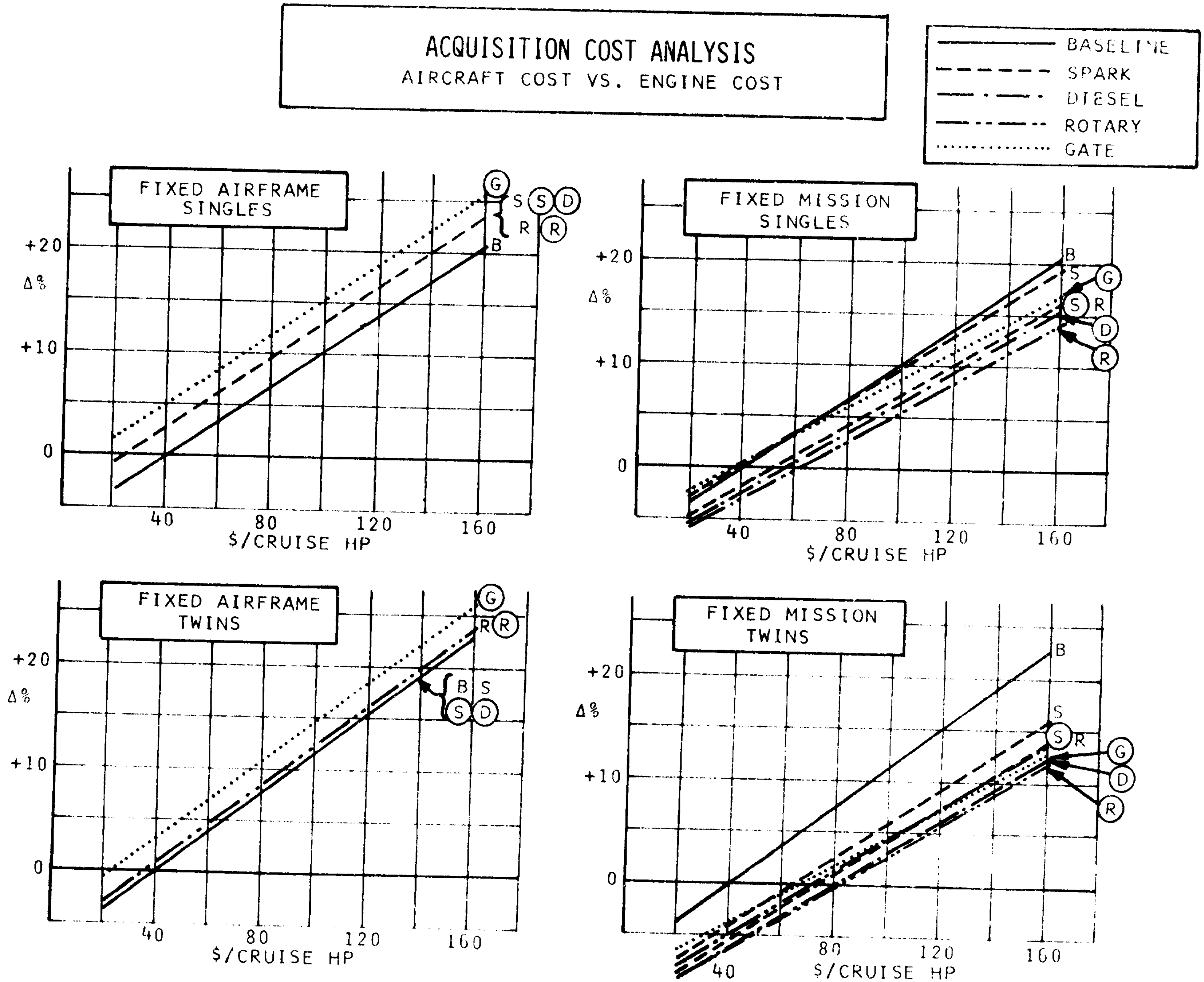

ACQUISITION COST ANALYSIS
AIRCRAFT COST VS. ENGINE COST
BASELINE
SPARK
DIESEL
ROTARY
GATE
FIXED AIRFRAME SINGLES
FIXED MISSION SINGLES
FIXED AIRFRAME TWINS
FIXED MISSION TWINS
+20
Δ%
+10
0
40
80
120
160
$/CRUISE HP

FIGURE 41

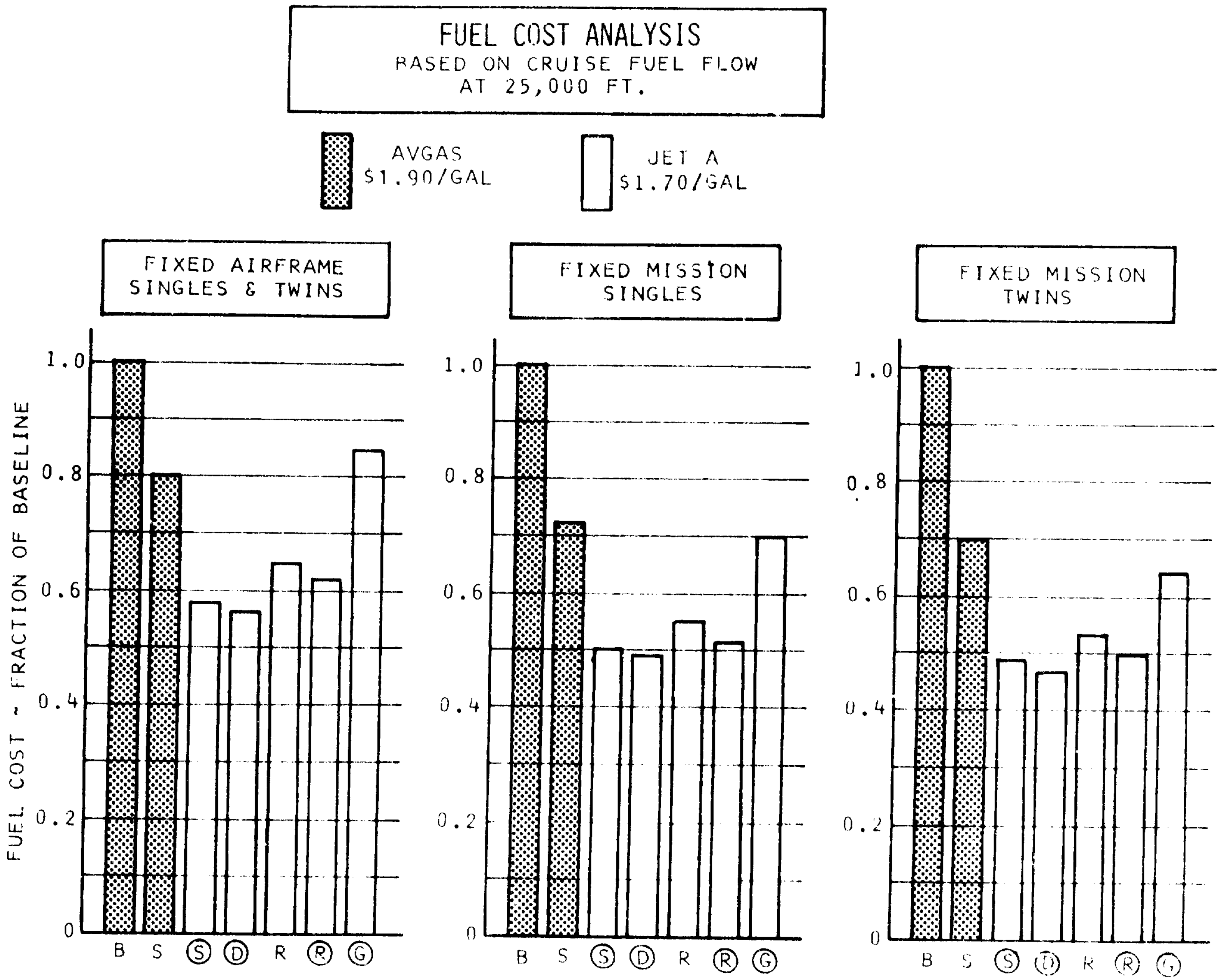

FUEL COST ANALYSIS
BASED ON CRUISE FUEL FLOW
AT 25,000 FT.
AVGAS
$1.90/GAL
JET A
$1.70/GAL
FIXED AIRFRAME
SINGLES & TWINS
FIXED MISSION
SINGLES
FIXED MISSION
TWINS
FUEL COST ~ FRACTION OF BASELINE
1.0
0.8
0.6
0.4
0.2
0
B
S
S
D
R
R
G

FIGURE 42

APPENDIX A

NUMERICAL RESULTS

ORIGINAL PAGE IS OF POOR QUALITY

FIXED AIRFRAME SINGLES

CONSTANT: Gross Weight
Wing Area
Payload
Engine Size
25,000 Feet

VARIABLE: Performance
Range

	BASELINE	SPARK IGNITION			ROTARY		GATE
	TSIO-550	GTSIO-420	GTSIO-420SC	DIESEL	RC2-47	RC2-32	TURBINE
Gross Weight (Lbs.)	4267	4267	4267	4267	4267	4267	4267
Empty Weight (Lbs.)	2514	2490	2405	2364	2362	2261	2259
Payload (Lbs.)	1200	1200	1200	1200	1200	1200	1200
Fuel Weight (Lbs.)	553	577	662	703	705	806	808
Sea Level BHP	350	350	350	360	320	320	525
Cruise BHP	250	250	250	250	250	250	250
Take-Off Distance	2200	2160	2155	2150	2235	2230	2020
Sea Level R/C	1350	1440	1440	1475	1270	1270	1345
Altitude	25000	25000	25000	25000	25000	25000	25000
Time-to-Climb	22.0	19.8	20.3	21.8	23.1	23.2	27.5
Cruise R/C	785	950	905	595	740	735	505
Cruise Speed (KTAS)	206	211	211	212	212	212	218
Range (NM)	803	1141	1517	1677	1446	1777	1297
Landing Distance	1660	1660	1660	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58	58	58	58
Wing Area ($Ft.^2$)	188	188	188	188	188	188	188
Wing Span (Ft.)	37.8	37.8	37.8	37.8	37.8	37.8	37.8
Aspect Ratio	7.6	7.6	7.6	7.6	7.6	7.6	7.6

TABLE A1

ORIGINAL PAGE IS OF POOR QUALITY

FIXED AIRFRAME TWINS

CONSTANT: Gross Weight
Wing Area
Payload
Engine Size
25,000 Feet

VARIABLE: Performance
Range

	BASELINE	SPARK IGNITION		DIESEL	ROTARY		GATE
	TS10-550	GTS10-420	GTS10-420SC		RC2-47	RC2-32	TURBINE
Gross Weight (Lbs.)	6700	6700	6700	6700	6700	6700	6700
Empty Weight (Lbs.)	4316	4117	3957	3881	3878	3690	3680
Payload (Lbs.)	1300	1300	1300	1300	1300	1300	1300
Fuel Weight (Lbs.)	1084	1283	1443	1519	1522	1710	1720
Sea Level BHP	350	350	350	360	320	320	525
Cruise BHP	250	250	250	250	250	250	250
Take-Off Distance	2470	2460	2460	2475	2565	2565	2225
Sea Level R/C	1865	1865	1860	1885	1695	1690	1795
Altitude	25000	25000	25000	25000	25000	25000	25000
Time-to-Climb	16.5	15.7	16.1	17.3	18.2	18.2	20.7
Cruise R/C	1035	1165	1110	725	920	915	690
Cruise Speed (KTAS)	235	240	239	242	243	242	260
Range (NM)	921	1522	1953	2153	1845	2218	1638
Landing Distance	2600	2600	2600	2600	2600	2600	2600
Stall Speed (KEAS)	75	75	75	75	75	75	75
Wing Area ($Ft.^2$)	188	188	188	188	188	188	188
Wing Span (Ft.)	37.8	37.8	37.8	37.8	37.8	37.8	37.8
Aspect Ratio	7.6	7.6	7.6	7.6	7.6	7.6	7.6

TABLE A2

FIXED WING AREA SINGLES

CONSTANT: Wing Area
Payload
Range
Engine Size
25,000 Feet

VARIABLE: Gross Weight
Performance

	BASELINE	SPARK IGNITION		DIESEL	ROTARY		GATE
	TSI0-550	GTSIO-420	GTSIO-420SC		RC2-47	RC2-32	TURBINE
Gross Weight (Lbs.)	4267	4096	3940	3876	3940	3794	3952
Empty Weight (Lbs.)	2514	2464	2355	2304	2312	2188	2211
Payload (Lbs.)	1200	1200	1200	1200	1200	1200	1200
Fuel Weight (Lbs.)	553	432	385	372	428	406	541
Sea Level BHP	350	350	350	360	320	320	525
Cruise BHP	250	250	250	250	250	250	250
Take-Off Distance	2200	2065	1985	1945	2030	1955	1895
Sea Level R/C	1350	1530	1610	1685	1430	1505	1500
Altitude	25000	25000	25000	25000	25000	25000	25000
Time-to-Climb	22.0	18.5	17.8	18.5	20.2	19.0	23.8
Cruise R/C	785	1030	1065	765	885	955	620
Cruise Speed (KTAS)	206	213	214	216	216	217	222
Range (NM)	803	798	802	799	801	800	800
Landing Distance	1660	1610	1570	1560	1570	1530	1580
Stall Speed (KEAS)	58	57	56	55	56	55	56
Wing Area (Ft.^{2})	188	188	188	188	188	188	188
Wing Span (Ft.)	37.8	37.8	37.8	37.8	37.8	37.8	37.8
Aspect Ratio	7.6	7.6	7.6	7.6	7.6	7.6	7.6

TABLE A3

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FIXED WING AREA TWINS

CONSTANT: Wing Area
Payload
Range
Engine Size
25,000 Feet

VARIABLE: Gross Weight
Performance

	BASELINE	SPARK IGNITION		DIESEL	ROTARY		GATE TURBINE
	IS10-550	GTS10-420	GTS10-420SC		RC2-47	RC2-32	
Gross Weight (Lbs.)	6700	6200	5916	5791	5923	5653	5944
Empty Weight (Lbs.)	4316	4052	3852	3757	3777	3549	3579
Payload (Lbs.)	1300	1300	1300	1300	1300	1300	1300
Fuel Weight (Lbs.)	1084	848	784	734	846	804	1065
Sea Level BHP	350	350	350	360	320	320	525
Cruise BHP	250	250	250	250	250	250	250
Take-Off Distance	2470	2210	2090	2045	2155	2025	1935
Sea Level R/C	1865	2095	2230	2320	2035	2170	2130
Altitude	25000	25000	25000	25000	25000	25000	25000
Time-to-Climb	16.5	13.8	13.1	13.4	14.6	13.6	16.6
Cruise R/C	1035	1360	1435	1065	1230	1350	940
Cruise Speed (KTAS)	235	244	246	249	249	250	266
Range (NM)	921	921	923	920	921	920	921
Landing Distance	2600	2455	2370	2335	2375	2295	2390
Stall Speed (KEAS)	75	72	71	70	71	69	71
Wing Area ($Ft.^2$)	188	188	188	188	188	188	188
Wing Span (Ft.)	37.8	37.8	37.8	37.8	37.8	37.8	37.8
Aspect Ratio	7.6	7.6	7.6	7.6	7.6	7.6	7.6

TABLE A4

FIXED WING LOADING SINGLES

CONSTANT: Wing Loading
Payload
Range
Engine Size
25,000 Feet

VARIABLE: Gross Weight
Performance

	BASELINE	SPARK IGNITION		DIESEL	ROTARY		GATE
	TSIO-550	GTSIO-520	GTSIO-520SC		RC2-47	RC2-32	[illegible]
Gross Weight (Lbs.)	4267	4088	3908	3840	3907	3750	3930
Empty Weight (Lbs.)	2514	2457	2328	2273	2285	2151	2195
Payload (Lbs.)	1200	1200	1200	1200	1200	1200	1200
Fuel Weight (Lbs.)	553	431	380	367	422	399	535
Sea Level BHP	350	350	350	360	320	320	525
Cruise BHP	250	250	250	250	250	250	250
Take-Off Distance	2200	2140	2090	2080	2140	2105	1975
Sea Level R/C	1350	1530	1625	1700	1440	1520	1505
Altitude	25000	25000	25000	25000	25000	25000	25000
Time-to-Climb	22.0	18.6	17.8	18.5	20.2	19.0	23.9
Cruise R/C	785	1020	1060	745	875	940	606
Cruise Speed (KTAS)	206	214	217	220	219	221	225
Range (NM)	803	801	800	799	800	800	800
Landing Distance	1660	1660	1660	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58	58	58	58
Wing Area ($Ft.^2$)	188	180	172	169	172	165	173
Wing Span (Ft.)	37.8	37.0	36.2	35.9	36.2	35.4	36.3
Aspect Ratio	7.6	7.6	7.6	7.6	7.6	7.6	7.6

TABLE A5

FIXED WING LOADING TWINS

CONSTANT: Wing Loading
Payload
Range
Engine Size
25,000 Feet

VARIABLE: Gross Weight
Performance

	BASELINE	SPARK IGNITION		DIESEL	ROTARY		GAS
	TSIO-550	GTSIO-420	GTSIO-420SC		RC2-47	RC2-32	TURBINE
Gross Weight (Lbs.)	6700	6161	5857	5726	5858	5580	5883
Empty Weight (Lbs.)	4316	4018	3804	3701	3723	3487	3534
Payload (Lbs.)	1300	1300	1300	1300	1300	1300	1300
Fuel Weight (Lbs.)	1084	843	753	725	835	793	1049
Sea Level BHP	350	350	350	360	320	320	525
Cruise BHP	250	250	250	250	250	250	250
Take-Off Distance	2470	2350	2295	2275	2375	2325	2095
Sea Level R/C	1865	2090	2225	2320	2030	2165	2140
Altitude	25000	25000	25000	25000	25000	25000	25000
Time-to-Climb	16.5	13.9	13.2	13.6	14.8	13.9	16.8
Cruise R/C	1035	1350	1405	1010	1185	1285	910
Cruise Speed (KTAS)	235	246	249	252	252	255	272
Range (NM)	921	920	920	920	920	921	919
Landing Distance	2600	2600	2600	2600	2600	2600	2600
Stall Speed (KEAS)	75	75	75	75	75	75	75
Wing Area ($Ft.^2$)	188	173	164	161	164	157	165
Wing Span (Ft.)	37.8	36.2	35.3	34.9	35.3	34.5	35.4
Aspect Ratio	7.6	7.6	7.6	7.6	7.6	7.6	7.6

TABLE A6

FIXED MISSION SINGLES

CONSTANT: Wing Loading
Payload
Range
Cruise Speed
25,000 Feet

VARIABLE: Gross Weight
Engine Size

	BASELINE	SPARK IGNITION		DIESEL	ROTARY		GATE
	TSIO-550	GTSIO-420	GTSIO-420SC		RC2-47	RC2-32	TURBINE
Gross Weight (Lbs.)	4267	4002	3811	3762	3804	3656	3835
Empty Weight (Lbs.)	2514	2399	2264	2225	2224	2103	2144
Payload (Lbs.)	1200	1200	1200	1200	1200	1200	1200
Fuel Weight (Lbs.)	553	403	347	337	380	353	491
Sea Level BHP	350	316	306	312	273	266	440
Cruise BHP	250	226	219	217	213	208	199
Take-Off Distance	2200	2170	2155	2130	2245	2230	2015
Sea Level R/C	1350	1370	1395	1480	1165	1175	1265
Altitude	25000	25000	25000	25000	25000	25000	25000
Time-to-Climb	22.0	20.5	20.3	21.6	24.1	23.6	30.8
Cruise R/C	785	910	905	590	695	715	415
Cruise Speed (KTAS)	206	207	207	207	206	206	206
Range (NM)	803	801	800	799	800	799	800
Landing Distance	1660	1660	1660	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58	58	58	58
Wing Area ($Ft.^2$)	188	176	168	166	168	161	169
Wing Span (Ft.)	37.8	36.6	35.7	35.5	35.7	35.0	35.8
Aspect Ratio	7.6	7.6	7.6	7.6	7.6	7.6	7.6

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TABLE A7

FIXED MISSION TWINS

CONSTANT: Wing Loading
Payload
Range
Cruise Speed
25,000 Feet

VARIABLE: Gross Weight
Engine Size

	BASELINE	SPARK IGNITION		DIESEL	ROTARY		GATE
	TS10-550	GTS10-420	GTS10-420SC		RC2-47	RC2-32	TURBINE
Gross Weight (Lbs.)	6700	5942	5620	5517	5612	5350	5579
Empty Weight (Lbs.)	4316	3880	3658	3580	3589	3377	3389
Payload (Lbs.)	1300	1300	1300	1300	1300	1300	1300
Fuel Weight (Lbs.)	1084	762	662	637	723	673	890
Sea Level BHP	350	306	296	297	263	256	389
Cruise BHP	250	219	211	206	206	200	182
Take-Off Distance	2470	2430	2405	2380	2545	2505	2210
Sea Level R/C	1865	1890	1955	1970	1685	1730	1550
Altitude	25000	25000	25000	25000	25000	25000	25000
Time-to-Climb	16.5	15.5	15.3	16.5	18.1	17.5	25.6
Cruise R/C	1035	1175	1180	750	915	950	490
Cruise Speed (KTAS)	235	235	234	236	235	235	233
Range (NM)	921	920	919	921	919	919	921
Landing Distance	2600	2600	2600	2600	2600	2600	2600
Stall Speed (KEAS)	75	75	75	75	75	75	75
Wing Area (Ft.^{2})	188	167	158	155	158	150	157
Wing Span (Ft.)	37.8	35.6	34.6	34.3	34.6	33.8	34.5
Aspect Ratio	7.6	7.6	7.6	7.6	7.6	7.6	7.6

TABLE A8

PARAMETRIC ALTITUDE STUDY - GTS10-420/SC SPARK IGNITION ENGINE - SINGLE

CONSTANT: Range
Cruise Speed
Wing Loading

(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3995	3880	3811	3793	3815
Empty Weight (Lbs.)	2374	2302	2264	2264	2289
Payload (Lbs.)	1200	1200	1200	1200	1200
Fuel Weight (Lbs.)	421	378	347	329	326
Sea Level BHP	370	330	306	300	312
Cruise BHP	272	240	219	206	203
Take-Off Distance	2075	2120	2155	2160	2135
Sea Level R/C	1685	1515	1395	1360	1435
Altitude	15000	20000	25000	30000	35000
Time-to-Climb	9.7	14.5	20.3	27.2	35.2
Cruise R/C	1495	1200	905	620	385
Cruise Speed (KTAS)	206	206	207	208	209
Range (NM)	799	802	800	799	800
Landing Distance	1660	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58	58
Wing Area ($Ft.^2$)	176	171	168	167	168
Wing Span (Ft.)	36.6	36.0	35.7	35.6	35.7
Aspect Ratio	7.6	7.6	7.6	7.6	7.6

TABLE A9

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PARAMETRIC ALTITUDE STUDY - DIESEL ENGINE - SINGLE

CONSTANT: Range
Cruise Speed
Wing Loading

(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3757	3729	3762	3825	4037
Empty Weight (Lbs.)	2183	2182	2225	2291	2482
Payload (Lbs.)	1200	1200	1200	1200	1200
Fuel Weight (Lbs.)	374	347	337	334	355
Sea Level BHP	254	260	312	412	676
Cruise BHP	254	231	217	212	225
Take-Off Distance	2295	2255	2130	2005	1920
Sea Level R/C	1090	1145	1480	1970	3010
Altitude	15000	20000	25000	30000	35000
Time-to-Climb	14.8	19.5	21.6	22.7	21.9
Cruise R/C	960	770	590	445	315
Cruise Speed (KTAS)	206	206	207	208	208
Range (NM)	799	798	799	799	801
Landing Distance	1660	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58	58
Wing Area ($Ft.^2$)	166	164	166	169	178
Wing Span (Ft.)	35.5	35.3	35.5	35.8	36.8
Aspect Ratio	7.6	7.6	7.6	7.6	7.6

TABLE A10

PARAMETRIC ALTITUDE STUDY - RC2-32 ROTARY ENGINE - SINGLE

CONSTANT: Range
Cruise Speed
Wing Loading

(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3783	3710	3656	3688	3743
Empty Weight (Lbs.)	2162	2128	2103	2143	2194
Payload (Lbs.)	1200	1200	1200	1200	1200
Fuel Weight (Lbs.)	421	382	353	345	349
Sea Level BHP	325	291	266	309	365
Cruise BHP	254	227	208	201	201
Take-Off Distance	2110	2160	2230	2120	2035
Sea Level R/C	1535	1340	1175	1480	1810
Altitude	15000	20000	25000	30000	35000
Time-to-Climb	10.7	16.3	23.6	26.0	29.6
Cruise R/C	1340	1115	715	550	405
Cruise Speed (KTAS)	205	206	206	207	207
Range (NM)	798	802	799	802	801
Landing Distance	1660	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58	58
Wing Area ($Ft.^2$)	167	164	161	163	165
Wing Span (Ft.)	35.6	35.2	35.0	35.1	35.4
Aspect Ratio	7.6	7.6	7.6	7.6	7.6

TABLE A11

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PARAMETRIC ALTITUDE STUDY - GATE TURBINE ENGINE - SINGLE

CONSTANT: Range
Cruise Speed
Wing Loading

(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3943	3867	3835	3833	3846
Empty Weight (Lbs.)	2169	2145	2144	2164	2191
Payload (Lbs.)	1200	1200	1200	1200	1200
Fuel Weight (Lbs.)	574	522	491	469	455
Sea Level BHP	426	423	440	478	538
Cruise BHP	239	215	199	189	183
Take-Off Distance	2040	2030	2015	1980	1950
Sea Level R/C	1165	1185	1265	1400	1600
Altitude	15000	20000	25000	30000	35000
Time-to-Climb	16.0	23.1	30.8	38.6	47.3
Cruise R/C	725	565	415	280	180
Cruise Speed (KTAS)	204	206	206	208	207
Range (NM)	799	799	800	800	801
Landing Distance	1660	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58	58
Wing Area ($Ft.^2$)	174	170	169	169	170
Wing Span (Ft.)	36.3	36.0	35.8	35.8	35.9
Aspect Ratio	7.6	7.6	7.6	7.6	7.6

TABLE A12

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PARAMETRIC SPEED STUDY - GTS10-420/SC SPARK IGNITION ENGINE - SINGLE

CONSTANT: Range
Wing Loading
25,000 Feet

(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3618	3811	4030	4397
Empty Weight (Lbs.)	2136	2264	2412	2649
Payload (Lbs.)	1200	1200	1200	1200
Fuel Weight (Lbs.)	282	347	418	548
Sea Level BHP	223	306	402	578
Cruise BHP	159	219	287	413
Take-Off Distance	2450	2155	2045	1975
Sea Level R/C	845	1395	1830	2365
Altitude	25000	25000	25000	25000
Time-to-Climb	30.2	20.3	15.8	12.4
Cruise R/C	565	905	1205	1555
Cruise Speed (KTAS)	176	207	227	251
Range (NM)	798	800	799	802
Landing Distance	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58
Wing Area (Ft.^{2})	160	168	178	194
Wing Span (Ft.)	34.8	35.7	36.7	38.4
Aspect Ratio	7.6	7.6	7.6	7.6

TABLE A13

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PARAMETRIC SPEED STUDY - DIESEL ENGINE - SINGLE

CONSTANT: Range
Wing Loading
25,000 Feet

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(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3615	3762	3895	4112
Empty Weight (Lbs.)	2132	2225	2305	2433
Payload (Lbs.)	1200	1200	1200	1200
Fuel Weight (Lbs.)	283	337	390	479
Sea Level BHP	231	312	399	546
Cruise BHP	160	217	277	379
Take-Off Distance	2370	2130	2035	1960
Sea Level R/C	975	1480	1860	2400
Altitude	25000	25000	25000	25000
Time-to-Climb	31.9	21.6	16.7	13.0
Cruise R/C	315	590	860	1200
Cruise Speed (KTAS)	178	207	228	251
Range (NM)	801	799	799	801
Landing Distance	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58
Wing Area ($Ft.^2$)	159	166	172	181
Wing Span (Ft.)	34.8	35.5	36.1	37.1
Aspect Ratio	7.6	7.6	7.6	7.6

TABLE A14

PARAMETRIC SPEED STUDY - RC2-32 ROTARY ENGINE - SINGLE

CONSTANT: Range
Wing Loading
25,000 Feet

(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3535	3656	3790	3995
Empty Weight (Lbs.)	2039	2103	2173	2282
Payload (Lbs.)	1200	1200	1200	1200
Fuel Weight (Lbs.)	296	353	417	513
Sea Level BHP	197	266	343	461
Cruise BHP	154	208	268	360
Take-Off Distance	2745	2230	2075	1990
Sea Level R/C	635	1175	1650	2135
Altitude	25000	25000	25000	25000
Time-to-Climb	38.5	23.6	17.7	13.7
Cruise R/C	410	715	1030	1380
Cruise Speed (KTAS)	178	206	227	248
Range (NM)	800	799	798	801
Landing Distance	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58
Wing Area ($Ft.^2$)	156	161	167	176
Wing Span (Ft.)	34.4	35.0	35.6	36.6
Aspect Ratio	7.6	7.6	7.6	7.6

TABLE A15

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PARAMETRIC SPEED STUDY - GATE TURBINE ENGINE - SINGLE

CONSTANT: Range
Wing Loading
25,000 Feet

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(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3752	3835	3928	4061
Empty Weight (Lbs.)	2102	2144	2194	2256
Payload (Lbs.)	1200	1200	1200	1200
Fuel Weight (Lbs.)	450	491	534	605
Sea Level BHP	356	440	523	657
Cruise BHP	154	199	244	318
Take-Off Distance	2085	2015	1975	1935
Sea Level R/C	955	1265	1500	1890
Altitude	25000	25000	25000	25000
Time-to-Climb	45.0	30.8	24.1	18.4
Cruise R/C	205	415	605	865
Cruise Speed (KTAS)	176	206	225	250
Range (NM)	799	800	800	800
Landing Distance	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58
Wing Area ($Ft.^2$)	165	169	173	179
Wing Span (Ft.)	35.4	35.8	36.3	36.9
Aspect Ratio	7.6	7.6	7.6	7.6

TABLE A16

PARAMETRIC RANGE STUDY - GTS10-420/SC SPARK IGNITION ENGINE - SINGLE

CONSTANT: Cruise Speed
Wing Loading
25,000 Feet

(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3660	3811	3925	4030
Empty Weight (Lbs.)	2223	2264	2301	2327
Payload (Lbs.)	1200	1200	1200	1200
Fuel Weight (Lbs.)	237	347	424	503
Sea Level BHP	297	306	312	318
Cruise BHP	212	219	223	227
Take-Off Distance	2150	2155	2170	2175
Sea Level R/C	1410	1395	1375	1365
Altitude	25000	25000	25000	25000
Time-to-Climb	19.9	20.3	20.8	21.1
Cruise R/C	925	905	880	865
Cruise Speed (KTAS)	207	207	206	206
Range (NM)	502	800	999	1198
Landing Distance	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58
Wing Area ($Ft.^2$)	161	168	173	178
Wing Span (Ft.)	35.0	35.7	36.2	36.7
Aspect Ratio	7.6	7.6	7.6	7.6

TABLE A17

PARAMETRIC RANGE STUDY - DIESEL ENGINE - SINGLE

CONSTANT: Cruise Speed
Wing Loading
25,000 Feet

(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3619	3762	3854	3965
Empty Weight (Lbs.)	2190	2225	2245	2278
Payload (Lbs.)	1200	1200	1200	1200
Fuel Weight (Lbs.)	229	337	409	487
Sea Level BHP	304	312	318	324
Cruise BHP	211	217	221	225
Take-Off Distance	2120	2130	2145	2150
Sea Level R/C	1505	1480	1465	1440
Altitude	25000	25000	25000	25000
Time-to-Climb	21.1	21.6	21.9	22.3
Cruise R/C	610	590	580	565
Cruise Speed (KTAS)	207	207	207	207
Range (NM)	500	799	999	1201
Landing Distance	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58
Wing Area ($Ft.^2$)	160	166	170	175
Wing Span (Ft.)	34.8	35.5	35.9	36.4
Aspect Ratio	7.6	7.6	7.6	7.6

TABLE A18

PARAMETRIC RANGE STUDY - RC2-32 ROTARY ENGINE - SINGLE

CONSTANT: Cruise Speed
Wing Loading
25,000 Feet

(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3509	3656	3758	3864
Empty Weight (Lbs.)	2068	2103	2126	2152
Payload (Lbs.)	1200	1200	1200	1200
Fuel Weight (Lbs.)	241	353	432	512
Sea Level BHP	258	266	271	277
Cruise BHP	202	208	212	216
Take-Off Distance	2215	2230	2235	2240
Sea Level R/C	1185	1175	1170	1165
Altitude	25000	25000	25000	25000
Time-to-Climb	23.2	23.6	24.0	24.3
Cruise R/C	735	715	700	690
Cruise Speed (KTAS)	206	206	206	206
Range (NM)	501	799	1001	1200
Landing Distance	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58
Wing Area ($Ft.^2$)	155	161	166	170
Wing Span (Ft.)	34.3	35.0	35.5	36.0
Aspect Ratio	7.6	7.6	7.6	7.6

TABLE A19

PARAMETRIC RANGE STUDY - GATE TURBINE ENGINE - SINGLE

CONSTANT: Cruise Speed
Wing Loading
25,000 Feet

(ENGINE SIZED TO DO MISSION.)

Gross Weight (Lbs.)	3635	3835	3980	4121
Empty Weight (Lbs.)	2098	2144	2183	2210
Payload (Lbs.)	1200	1200	1200	1200
Fuel Weight (Lbs.)	337	491	3980	711
Sea Level BHP	425	440	451	462
Cruise BHP	192	199	204	209
Take-Off Distance	1985	2015	2030	2030
Sea Level R/C	1305	1265	1235	1210
Altitude	25000	25000	25000	25000
Time-to-Climb	29.6	30.8	31.6	32.2
Cruise R/C	435	415	400	390
Cruise Speed (KTAS)	207	206	206	206
Range (NM)	499	800	998	1201
Landing Distance	1660	1660	1660	1660
Stall Speed (KEAS)	58	58	58	58
Wing Area ($Ft.^2$)	160	169	176	182
Wing Span (Ft.)	34.9	35.8	36.5	37.1
Aspect Ratio	7.6	7.6	7.6	7.6

TABLE A20

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APPENDIX B

Acquisition Cost Analysis Method

Total airplane acquisition cost is the total of materials cost, labor cost, development cost, factory profit, dealer markup and optional equipment costs.

Materials cost is the sum of engine cost, airframe cost, standard avionics cost and additional equipment costs.

Engine Cost

Airframe weight X airframe cost per pound

Standard avionics cost

Additional equipment cost

Total materials costs

Engine cost was treated parametrically because reliable cost data were not available for the advanced engines. Airframe weight was estimated by subtracting the weights of the engine, standard avionics and additional equipment from the empty weight of the airplane. The current cost per pound of airframe materials was used in the estimate. Additional equipment includes items which are not produced by the airframe manufacturer (tires, fasteners, upholstery, etc.)

Manhour expenditure per airplane was estimated from learning curve theory. Learning curve theory states that

$$y = A\ (1/X)^c$$

where

y = manhours required per airframe

x = number of airframes built

A = number of manhours currently required to produce the first airframe

c = "slope" of learning curve.

An eighty percent learning curve ($c = .3219$) was used to determine manhour expenditure, and current labor cost rates were used to determine labor costs per airplane. An eighty percent learning curve implies that the second (or 1000th) airframe requires 80% of the manhours required to produce the first (or 500th) airframe.

The development cost per airplane was estimated based on the airframe weight, the anticipated production run, and the current cost of developing a pound of airframe.

Total cost per airplane to the factory is the sum of materials cost, labor cost and development costs. Factory profit, dealer markup and optional equipment costs are added to the factory cost to arrive at total selling price (acquisition cost).

Material Cost	
Labor	
Development	
Factory Cost	Factory Cost
	Factory Profit
	Dealer Markup
	Optional Equipment
	TOTAL SELLING PRICE

APPENDIX C

Engine Ranking System

The items considered in ranking the advanced engines were:

1. Mission fuel weight
2. Airplane empty weight
3. Time to climb to 25000 feet.
4. Installation efficiency
5. Multi-fuel capability

The first three factors, fuel weight, empty weight, and time to climb, were computed as ratios of the baseline engine/airframe capabilities to the advanced engine/airframe capabilities. The ratios were established for the fixed mission singles and the fixed mission twins.

Weighting factors were applied to the ratios to indicate the relative importance of each item in the ranking procedure. A factor of forty was applied to the mission fuel and the empty weight ratios. A factor of twenty was applied to the time to climb ratio.

Installation efficiency was quantified as follows:

1. One (1) point was awarded for an engine which provided a nose baggage compartment (single) or a reduction of frontal area from the baseline (twin).

2. One or two points were awarded for a reduction in cooling drag. The decision to award one or two points depended on the magnitude of the cooling drag reduction.
3. One point was awarded on the basis of overall installation ease (real or perceived). This factor was to account for items such as mounting difficulties, accessory locations and overall engine layout.

Points for multi-fuel capability were awarded as follows:

0 if an engine burned only avgas

1 if an engine burned only jet fuel

2 if an engine was multi-fuel

A weighting factor of three (3) was applied to the installation efficiency and the multi fuel capability.

The above quantities and ratios were used to produce a ranking number as

$$RN = 40\ R_{MF} + 40\ R_{MTWT} + 20\ R_{TCC} + 3\ I_{IE} + 3\ I_{MC}$$

where,

RN = ranking number

$$R_{MF} = \frac{\text{baseline airplane mission fuel}}{\text{advanced engine airplane mission fuel}}$$

$$R_{MTWT} = \frac{\text{baseline airplane empty weight}}{\text{advanced engine airplane empty weight}}$$

$$R_{TTC} = \frac{\text{baseline airplane time to climb}}{\text{advanced engine airplane time to climb}}$$

I_{IE} = total of installation efficiency points

I_{MC} = total of multifuel capability points.

The ranking numbers of the singles and twins were then added together to provide a final ranking number for each engine.

ENGINE RANKING - FIXED MISSTON SINGLES

ENGINE	R_{MF}	R_{MTWT}	R_{TTC}	I_{IE}	I_{MC}	RN
BASELINE	1.0	1.0	1.0	0	0	100
ADVANCED TECHNOLOGY SPARK IGNITION	1.372	1.048	1.073	0+1+0	0	121
HIGHLY ADVANCED TECHNOLOGY SPARK IGNITION	1.594	1.110	1.084	0+1+0	2	139
HIGHLY ADVANCED TECHNOLOGY DIESEL	1.641	1.130	1.019	0+1+1	1	140
ADVANCED ROTARY	1.455	1.130	0.913	1+1+1	2	137
HIGHLY ADVANCED ROTARY	1.567	1.195	0.932	1+1+1	2	144
GATE TURBINE	1.126	1.173	0.714	1+2+1	2	124
(REVISED)	(1.268)	(1.195)	(0.729)	(1+2+1)	(2)	(131)

TABLE C1

ENGINE RANKING - FIXED MISSION TWINS

ENGINE	R_{MF}	R_{MTWT}	R_{TTC}	I_{IE}	I_{MC}	RN
BASELINE	1.0	1.0	1.0	0	0	100
ADVANCED TECHNOLOGY SPARK IGNITION	1.423	1.112	1.065	0+1+0	0	126
HIGHLY ADVANCED TECHNOLOGY SPARK IGNITION	1.638	1.180	1.078	0+1+0	2	143
HIGHLY ADVANCED TECHNOLOGY DIESEL	1.702	1.206	1.000	0+1+1	1	145
ADVANCED ROTARY	1.499	1.203	0.912	1+1+1	2	141
HIGHLY ADVANCED ROTARY	1.611	1.278	0.943	1+1+1	2	149
GATE TURBINE (REVISED)	1.218 (1.372)	1.274 (1.290)	0.645 (0.665)	1+2+1 (1+2+1)	2 (2)	131 (138)

TABLE C2

FINAL ENGINE RANKING

ENGINE	RN_{SINGLE}	RN_{TWIN}	RN_{TOTAL}
BASELINE	100	100	200
ADVANCED TECHNOLOGY SPARK IGNITION	121	126	247
HIGHLY ADVANCED TECHNOLOGY SPARK IGNITION	139	143	282
HIGHLY ADVANCED TECHNOLOGY DIESEL	140	145	285
ADVANCED ROTARY	137	141	278
HIGHLY ADVANCED ROTARY	144	149	293
GATE TURBINE (REVISED)	124 (131)	131 (138)	255 (269)

TABLE C3

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