NASA-CR-159482

NASA-CR-159482
19810010591

N81-19117

5QT

NASA CR-159482
AIRESEARCH 21-2997

GENERAL AVIATION TURBINE ENGINE (GATE) STUDY FINAL REPORT

by C.F. BAERST and D.G. FURST

(NASA-CR-159482) GENERAL AVIATION TURBINE ENGINE (GATE) STUDY Final Report (AiResearch Mfg. Co., Phoenix, Ariz.) 274 p HC A12/MF A01 CSCL 21E G3/07 N81-19117 Unclas 16960

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
P.O. BOX 5217
PHOENIX, ARIZONA 85010

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135
CONTRACT NAS 3-20755

1. Report No. NASA CR-159482	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle General Aviation Turbine Engine (GATE) Study Final Report		5. Report Date 5 February 1979
		6. Performing Organization Code
7. Author(s) C. F. Baerst and D. G. Furst		8. Performing Organization Report No. 21-2997
		10. Work Unit No.
9. Performing Organization Name and Address AiResearch Manufacturing Company of Arizona A Division of the Garrett Corporation P.O. Box 5217 Phoenix, Arizona 85010		11. Contract or Grant No. NAS 3-20755
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address NASA-LEWIS Research Center 21000 Brookpark Road Cleveland, Ohio 44135		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Small general aviation airplanes and helicopters powered by reciprocating engines in the 75 to 298 kw (100 to 400 hp) class are the only segments of aviation where a transition to turbine power has not occurred. This has been due to the sizable cost difference between turbine and reciprocating engines.
This report presents the results of a study to investigate the feasibility of turbine engines for the smaller general aviation aircraft and identifies a technology program for developing the necessary technology. The study consisted of four tasks: (1) Market survey, (2) Broad scope trade-off studies, (3) Common-core concept evaluation and (4) Advanced technology plans. Major results included the definition of the 1988 general aviation market, the identification of turboprop and turboshaft engines that meet the requirements of the aircraft studies, a benefit analysis showing the superiority of gas turbine engines for portions of the market studied, and detailed plans for the development of the necessary technology.

17. Key Words (Suggested by Author(s))	18. Distribution Statement		
General Aviation Study Program			
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 277	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22151

NASA-C-168 Rev. 6-71

TABLE OF CONTENTS

PRECEDING PAGE BLANK NOT FILMED

TABLE OF CONTENTS (Contd)

TABLE OF CONTENTS (Contd)

LIST OF FIGURES

LIST OF FIGURES (Contd)

LIST OF FIGURES (Contd)

LIST OF FIGURES (Contd)

LIST OF FIGURES (Contd)

LIST OF TABLES

LIST OF TABLES (Contd)

LIST OF TABLES (Contd)

LIST OF TABLES (Contd)

SECTION I

1.0 Summary

The overall objective of this study was to provide data on the applicability of gas turbines in the 112 to 746 kilowatt (150 to 1000 shaft horsepower) class to general aviation aircraft. This information will aid The National Aeronautics and Space Administration in formulating the most effective technology program for small turbine engines. Airframe portions of this study were supported by the Cessna Aircraft Company, Pawnee Division, and the Bell Helicopter Company.

1.1 Task I - Market Survey

The objective of this task was to define the 1988 general aviation market including aircraft characteristics, mission requirements, major turbine engine sizes, and engine types.

A detailed market forecast was conducted that characterized the current and 1988 markets and projected the growth of the market utilizing trend and econometric forecasting methods. The present fixed-wing market was separated into 10 categories covering the power range up to 447 kw (600 hp) and ranging from the two-place, single-engine category to the pressurized, twin-engine category. The rotary-wing market was divided into three categories:

- o Single-engine piston
- o Single-engine turbine
- o Twin-engine turbine

An additional fixed-wing category, the current business turboprop market which utilizes engines in the 447 to 746 kw (600 to 1000 shp) class, was also evaluated.

The market projection for fixed-wing aircraft resulted in the following annual compounded growth rates:

- Single Engine - 4.3 percent
- Twin Engine - 4.4 percent
- Current Turboprop - 9.2 percent

This fixed-wing market will grow from slightly over 15,000 units in 1977 to almost 25,000 units in 1988. Factory billings in current-year dollars will increase from approximately 1 billion in 1977 to over 3 billion in 1988.

The forecast for the rotary-wing market shows a two-fold increase in shipments from 1000 unit shipments in 1977 to approximately 2000 units in 1988. U.S. rotary-wing factory billings are forecasted to grow from 200 million in 1977 to over 450 million in 1988.

A preliminary analysis, conducted during Task I, of the suitability of turbine engines to the various general aviation categories indicated that turbine engines could be superior to reciprocating engines on over 9000 of the 1988 total units of 25,000. The majority of the units where turbines would not be superior to reciprocating engines are applications requiring less than 186 kw (250 hp), which represent a large number of total units but only 25 to 35 percent of the total billings.

The applications selected for detailed analysis in Task II were a pressurized twin, a light twin, and a light single-engine utility helicopter.

1.2 Task II - Broad Scope Trade-Off Studies

The objective of this task was to identify the combination of engine cycle, configuration, and technology that forms the optimum engine for each aircraft application.

The engine trade-off studies evaluated 17 engines that varied in cycle and configuration and numerous component technology trades for those of the 17 that appeared most promising. The criteria that were used to evaluate the engines included:

- o Aircraft three-year total cost of ownership
- o Aircraft fuel consumption
- o Aircraft operating cost
- o Aircraft acquisition cost

The three-year total cost was the primary evaluation criterion. The study showed that a high turbine inlet temperature [1478°K (2200°F)] was superior in all applications studied and for all engine types. Turboprop engines were shown to be clearly superior to turbofan engines for the class of fixed-wing aircraft because of lower fuel consumption and smaller size.

Technologies that resulted in improved engine performance and low manufacturing cost were found to be essential for the GATE engine.

The optimum engine for the fixed-wing application was a single-shaft turboprop comprised of a single-stage centrifugal compressor producing a pressure ratio of 9.0, a reverse-flow annular burner and a cooled turbine having one radial and one axial stage. The engine rated a close second was a free-turbine turboprop comprised of a single-stage centrifugal compressor producing a pressure ratio of 9.0, a reverse-flow annular burner, a cooled radial gas generator turbine, and a two-stage uncooled axial power turbine.

The optimum engine for the light helicopter was a turboshaft version of the free-turbine engine.

The engine sizes required are:

- o Medi pressurized twin - 313 kw (420 shp)
- o Light twin - 242 kw (325 shp)
- o Light helicopter - 224 kw (300 shp)

A comparison of the above turboprop engines to current technology turboprops installed in the same aircraft yielded the following results:

- o 9 to 17-percent reduction in total 3-year cost of ownership
- o 17-percent reduction in mission fuel consumption
- o 15 to 18-percent reduction in aircraft acquisition cost
- o 16 to 18-percent reduction in operating cost
- o 6 to 8-percent reduction in aircraft gross weight.

A similar comparison to current reciprocating engines showed the following:

- o 20 to 28-percent reduction in total 3-year cost of ownership
- o 8 to 16-percent reduction in mission fuel consumption
- o 14 to 20-percent reduction in aircraft acquisition cost
- o 28 to 38-percent reduction in operating cost.
- o 20 to 25-percent reduction in airplane gross weight

1.3 Task III - Common-Core Concept Evaluation

The common-core concept evaluation task attempted to identify a common-core engine, which would be compatible with the single-shaft engine identified as optimum for the fixed-wing applications, and the free-turbine turboshaft identified as optimum for the rotary-wing applications.

The results of the study indicated that a common core for these two engines resulted in larger compromises than would be necessary if the optimum free-turbine engine was selected for both the fixed- and rotary-wing applications. The free-turbine engine is also compatible with a turbofan derivative.

1.4 Task IV - Technology Program Plan

Program plans were prepared for seven technology items identified as critical to the successful development of the GATE gas turbine engines. The seven technology programs are:

- Laminated, cooled radial turbine
- PM Titanium centrifugal compressor
- Clearance control
- Low-cost combustor and fuel nozzles
- Digital electronic fuel control
- High-work/low-speed power turbine
- Laser-hardened gears.

The program plans were limited to high-risk, high-payoff items which would not normally be developed in industry or Government-sponsored programs.

In addition to the component technology programs, an experimental engine program was recommended to provide for the integration of the components in an engine environment. NASA sponsorship of the integrated development of these components and demonstration of these components in an experimental engine program would provide the impetus for industry to undertake the development and production of the GATE engines.

SECTION II

2.0 Introduction

The recent history of aircraft engines has been characterized by the progressive introduction of turbine engines into small aircraft. The transition to turbine power in each succeeding category has resulted in safer, more comfortable, more reliable, and more productive aircraft. At this time, all segments of aviation have transitioned to turbine engines with two notable exceptions--small general aviation airplanes requiring less than 336 kw (450 hp) and single-engine helicopters requiring 224 kw (300 hp) or less. This segment of the market has been denied the advantages of turbine power because of the sizable cost difference between turbine and reciprocating engines.

The National Aeronautics and Space Administration, Lewis Research Center (NASA/Lewis) sponsored the study reported herein to investigate the feasibility of turbine engines for the smaller general aviation aircraft, and to identify the most effective technology program for developing the smaller turbine engines. The challenge of the General Aviation Turbine Engine (GATE) study is to determine if the advantages of turbine engines can be retained, while simultaneously achieving fuel consumption and engine cost levels required in this class of general aviation aircraft. The results of the GATE study provide added insight into the economics and performance requirements of this aviation segment and clearly shows the categories within the general aviation market segment where turbines and reciprocating engines have superior advantages.

The GATE study was a ten-month effort and consisted of the following tasks:

- Task I characterized and projected the 1988 general aviation market and selected aircraft applications where turbine engines appeared to offer advantages. Task I considered turboprop and turboshaft engines in the 112 to 746 kw (150 to 1000 shp) class and comparably sized turbofans.

- Task II consisted of broad scope trade-off studies to identify the optimum turbine engines for the applications selected in Task I. Task II was limited to consideration of engines in the 186 to 447 kw (250-600 hp) class. The aircraft applications included turbofan- and turboprop-powered medium and light twins and a turboshaft-powered light single-engine utility helicopter. A comparison of the GATE engines with reciprocating engines and current turbines was also accomplished.

- Task III evaluated the feasibility of a common core for the fixed- and rotary-wing applications.

- Task IV defined the technology programs necessary to develop the engines defined in Task II and includes both component development and an experimental engine program.

The technology level of the GATE engines was consistent with introduction into service in 1988.

SECTION III

Task I
Discussion - Market Survey

3.0 Market Survey

The objective of Task I was to forecast a 1988 market scenario for general aviation aircraft powered by engines in the 112 to 746 kilowatt (150 to 1000 horsepower) class. The forecast was to include the effects of regulatory factors such as noise, emissions, and safety, in addition to market needs as influenced by available engine size, performance, and cost. The identification of potential important market applications for gas turbine engines and corresponding typical mission profiles was the primary output of this task.

The major elements of the market survey task were:

- Market forecast
- Advanced technology gas turbine engine conceptual design
- Definition of gas turbine power classes for all general aviation categories
- Screening and selection of potential gas turbine applications
- Definition of aircraft characteristics and mission requirements.

The objective of the market forecast was to characterize the general aviation market with respect to category and features, and to project the annual 1988 production.

The conceptual design of advanced technology engines was to provide preliminary data for comparison to other engine types and provide basic data for preliminary aircraft design. The engine conceptual design effort provided preliminary engine sizing information to Cessna, the airframe subcontractor, for use in defining airplane characteristics, and was also the basis for economic feasibility studies and estimates of production volume.

The sea-level, static, power rating required for a particular gas-turbine-powered aircraft is a function of the mission performance requirements. A gas turbine engine may be larger or smaller than a reciprocating engine sized to provide the same mission performance, depending on the engine sizing point, mission, and whether the reciprocating engine is turbocharged or naturally aspirated. A preliminary definition of the gas turbine power classes that would be required to adequately cover the general aviation spectrum was made.

Screening and selection was conducted by considering every general aviation category, assuming the availability of gas turbine engines as defined in the conceptual design element of this task. Performance, safety, and operating cost evaluations were primarily subjective and were influenced by results of past studies. The cost of turbine engines and the effect of this cost on airplane acquisition cost was quantified. It was apparent very early in the program that engine cost was the primary obstacle to the introduction of gas turbines in the smaller general aviation aircraft. Turbine engine cost goals were established based on, (1) the conceptual engine designs prepared earlier in this task, and (2) detailed cost estimates prepared in prior studies for engines similar in size, performance, and configuration. The selection of applications for detailed study was based on a comparison between the engine cost objectives and the allowable turbine engine cost for each general aviation category.

Mission requirements and aircraft characteristics were provided by Cessna Aircraft Company for the fixed-wing aircraft and by the Bell Helicopter Company for the rotary-wing aircraft.

3.1 Market Forecast

3.1.1 Market Forecast - Fixed-Wing Aircraft

The fixed-wing aircraft market forecast was conducted by the Garrett Marketing Development Department and supported by Cessna Marketing. There were two parts to the market forecast:

- o Market Characterization
  - Categorization of general aviation fixed-wing aircraft
  - Data Collection
  - Demand Characteristics
- o Market Projections
  - Trend Analysis
  - Econometric Analysis

3.1.1.1 Market Characterization

The general aviation fixed-wing market can be grouped into 10 categories excluding current turboprops, turbojets, and turbofans. The ten categories are listed in Table 1, which also shows some general characteristics that are associated with each category.

The major categories identified, and as further subdivided by power class, cover the range of applications very thoroughly with respect to cost and capability. New categories do not appear likely by 1988. Some features of each category may change such as engine size, and the split between pressurized and non-pressurized

TABLE 1. MARKET CHARACTERISTICS.

- Two Place Light Single Engine (Cessna 150)
  - Trainer
  - Owned by FBO for 2-4 years
  - Low initial and operating cost
  - Establishes brand loyalty
  - Low power, low useful load
- Utility High Performance Single Engine (Cessna 207, Piper Super Cub)
  - Work horse; special duty applications (farms, ranches)
  - Functional and high useful load
  - Reliability and durability important
  - Price related to usefulness and not highly competitive
- Fixed Gear High Performance Single Engine (Cessna 182, Piper Cherokee)
  - High speed, high useful load, high power to weight ratio
  - Good aircraft for business or personal use
  - Very price competitive in given power class
- Four Place Light Single Engine (Cessna Skyhawk and Cardinal)
  - Low power, 112-149 kw (150-200 hp)
  - Low initial and operating cost
  - Personal and rental aircraft
- Light Retractables (Cessna Cardinal RG, Piper Arrow)
  - High speed
  - Low initial and operating cost
  - Functional
  - FBO, personal and business use
  - Very price competitive
- Heavy Retractable (Beech Bonanza, Cessna Centurion)
  - High performance (speed and altitude)
  - High useful load (6 passengers)
  - Quality and luxury important
  - Business airplane
  - Price competitive

TABLE 1. MARKET CHARACTERISTICS (CONTD)

- Agricultural (Cessna AG Truck, Rockwell Thrush)
  - Single engine specialty aircraft
  - Useful load important
  - Price related to ability to perform job
  - Reliability, durability, and low maintenance cost are important
- Light Twins (Beech Baron, Cessna 310)
  - Unpressurized
  - High speed, good fuel economy
  - Low maintenance
  - Price competitive
  - Top of the line for personal owner; popular with FBO's and corporate owners
  - Twin engine safety
- Cabin Class Unpressurized Twins (Piper Chieftain, Cessna 402)
  - High useful load (No. of passengers)
  - Unpressurized; operational altitudes under 3658 meters (12,000 feet)
  - Durability and low maintenance cost important
  - Commuter aircraft; high priority cargo; FBO use
- Pressurized Twins
  - High performance (altitude and speed)
  - High useful load
  - Quality and luxury important
  - Corporate use

aircraft, and turbocharged and non-turbocharged engines, but these distinctions were not considered important enough to warrant consideration.

Turbine engines will not change the character of the categories sufficiently to warrant special consideration. A high-speed, single-engine, turbofan-powered airplane is possible but the production potential for such an aircraft would be relatively small. Other highly specialized applications would probably be the result of the introduction of low-cost turbines but would not, of themselves, justify the development of such an engine or contribute greatly to its success.

In addition to the categorization and the general characteristics of each category, specific data on engine power class, acquisition cost (1977 average equipped price), number of seats, cruise speed, engine time between overhaul, and service ceiling was gathered for most models within each category. This data is contained in Tables 51 through 61 of Appendix I along with similar data for turboprops manufactured by General Aviation Manufacturers Association (GAMA) members. For each of these models or, in some cases, categories, production history and estimates through 1985 were available and provided the basis for market projections. The production estimates were obtained from manufacturers and from subscription forecasts such as Frost and Sullivan, DMS, and Forecast Associates.

The data obtained confirmed that the traditional relationship of price and demand did exist. Figure 1 shows the relationship between price and quantity sold for most general aviation fixed-wing aircraft. Aircraft were grouped in 20-percent price increments for the construction of this curve. There were three distinct segments along the curve:

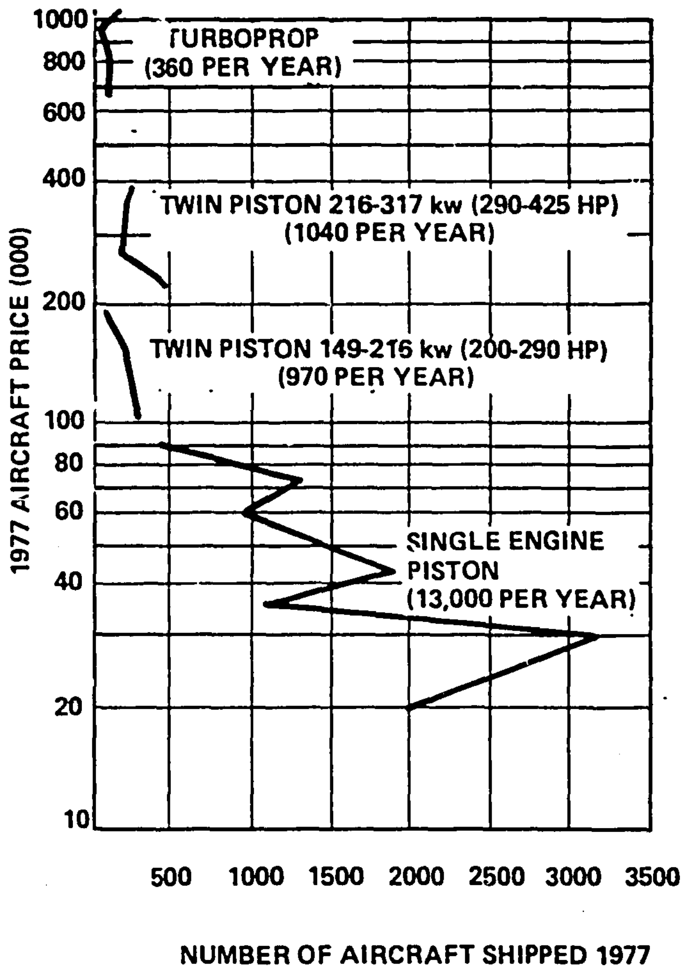


Figure 1. Demand Curve - Aircraft Price Versus Quantity

- Single engine-piston
- Twin-engine piston (heavy and light twin grouping)
- Turboprops

Analysis of Figure 1 suggested some inelasticity of the market, i.e., price could vary without affecting demand. A detailed elasticity analysis was not performed but discussion with industry representatives indicated that price increases of 10 percent or more could be absorbed without affecting demand if the "intangibles" of the buying decision are improved. This factor was important in the selection of turbine-powered applications for further study.

3.1.1.2 Market Projection

Market projections were made using two methods. The first was an analysis of historical unit shipments and a projection of these trends through the forecast period to 1988. The second was an econometric analysis based on the observed relationships between historical aircraft shipments and fluctuations in the economy. Only U.S. production was considered, and GAMA data was used for consistency. The forecast does not account for the impact of foreign manufacturers, which could become more important in the future, nor does it account for a change in the export growth rate. Exports could result in further increases in unit shipments over and above the forecast if the growth in disposable income in developing nations results in more demand for general aviation aircraft.

The historical trend analysis was performed for three groups:

- Single-Engine Piston
- Twin-Engine Piston
- Turboprop

In all three groups, unit shipments were cyclical but there appeared to be a consistent rate of growth over the 1955 to 1976 time period. Figure 2 shows unit shipments versus year for single-engine piston aircraft. Data was available from 1952 on, but only 1955 and later years were used to determine the trend line. The average annual compounded growth rate for single-engine aircraft is 4.3 percent. Over the same time period, the average annual compounded growth rate for twin-engine, piston aircraft is 4.4 percent, as shown in Figure 3. Figure 4 shows actual unit shipments and the growth trend for turboprops. Although data is available for 1964, only 1965 and later years were used to establish the growth trend. The average annual compounded growth rate is 9.2 percent, which is more than double the growth rate for the other two groups. The overall growth trend in unit shipments is 4.4 percent and shows the strong contribution of the single-engine segment, which accounts for more than 80 percent of total shipments. A projection of unit shipments to 1988, based on the above growth rates, is shown in Figure 5. Total units shipped in 1988 will increase from slightly over 15,000 in 1977 to almost 25,000 units in 1988.

The econometric analysis attempted to correlate unit shipments to an index of the economy. Prior work at Garrett has shown that general aviation shipments and billings correlate with pre-tax corporate profits. A formula was derived to predict unit shipments as a function of pre-tax corporate profits for 1955 through 1976. The correlation of GAMA historical data and unit shipments predicted from pre-tax corporate profits is shown in Figure 6. The degree of correlation or "goodness of fit" was not satisfactory at an r^{2}[(1)]

---

(1) $$r^2 = 1 - S^2_{y\cdot x}/S^2_y$$

$$S^2_{y\cdot x} = \sum_{i=1}^{n} \frac{(y_i - u_{ic})^2}{n-2}$$

$$S^2_y = \sum_{i=1}^{n} \frac{(y_i - \bar{y})^2}{n-1}$$

y_i = actual y
y_{ic} = computed y
n = number of data points
y = ordinate
$\bar{y}$ = average of all y_i

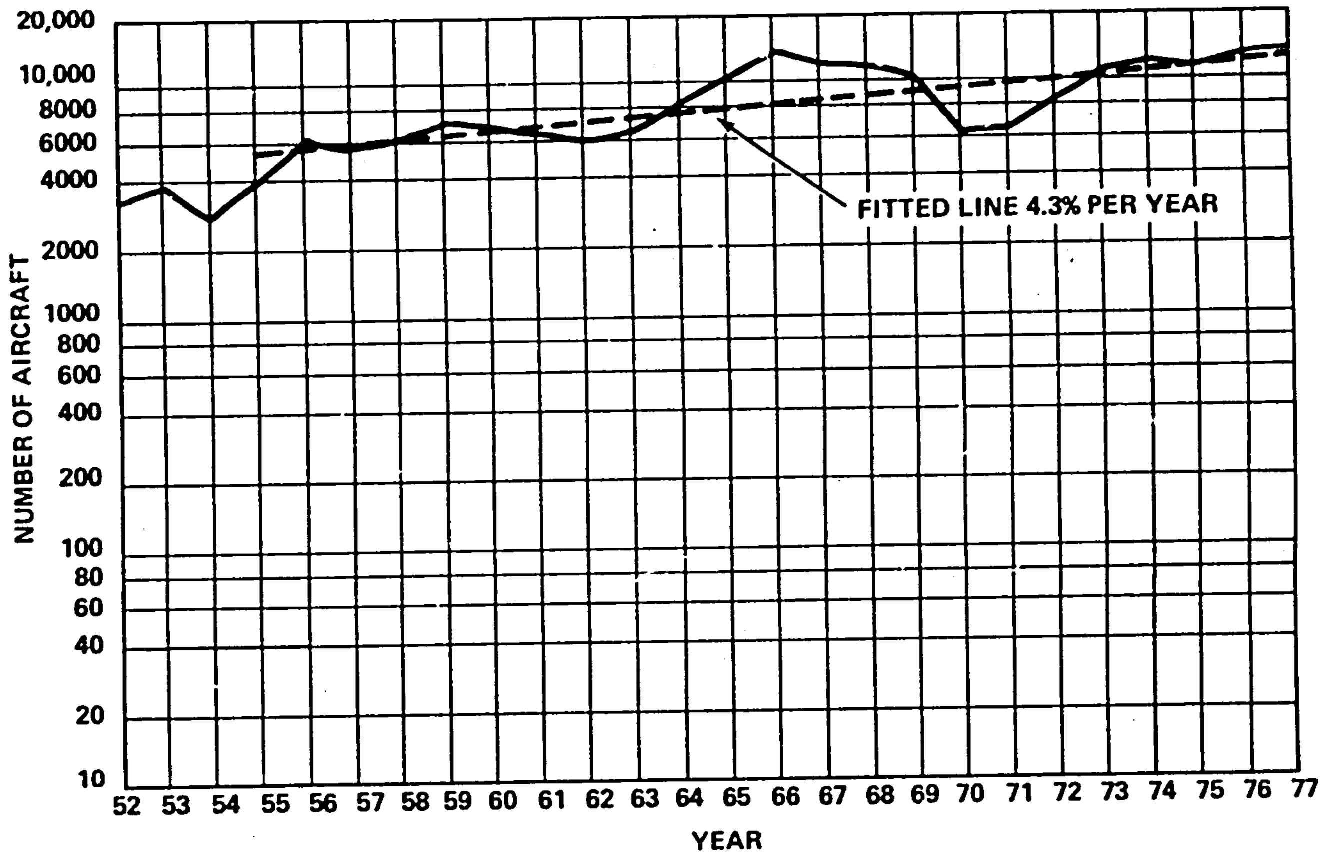


Figure 2. Single-Engine Aircraft Shipments.

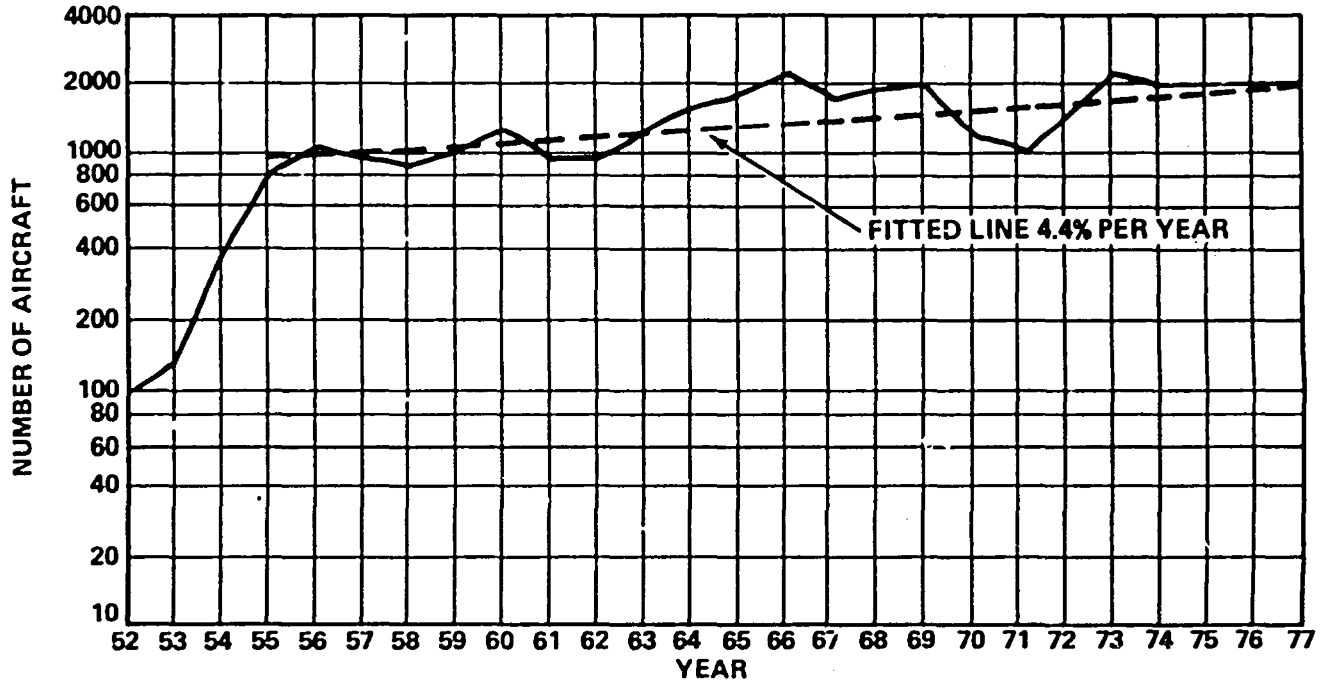


Figure 3. Twin-Engine Piston Aircraft Shipments

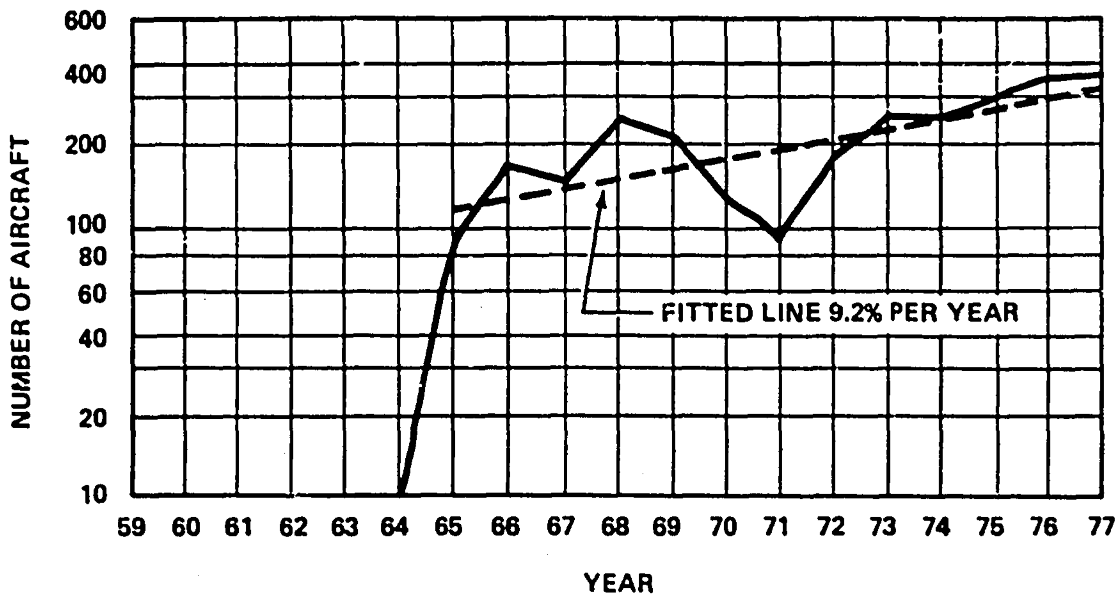


Figure 4. Turboprop Aircraft Shipments.

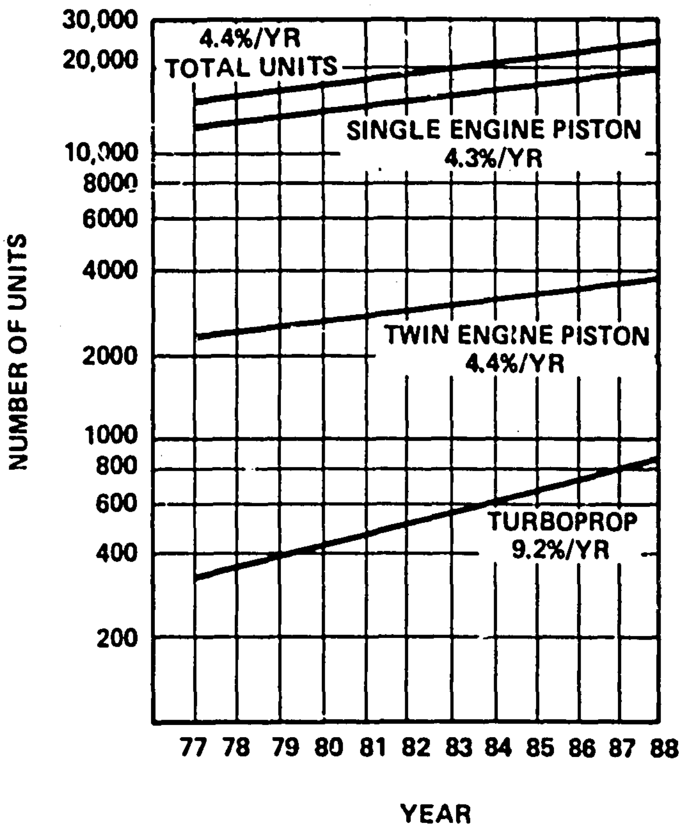


Figure 5. Forecast of Aircraft Unit Shipments by Market Segment.

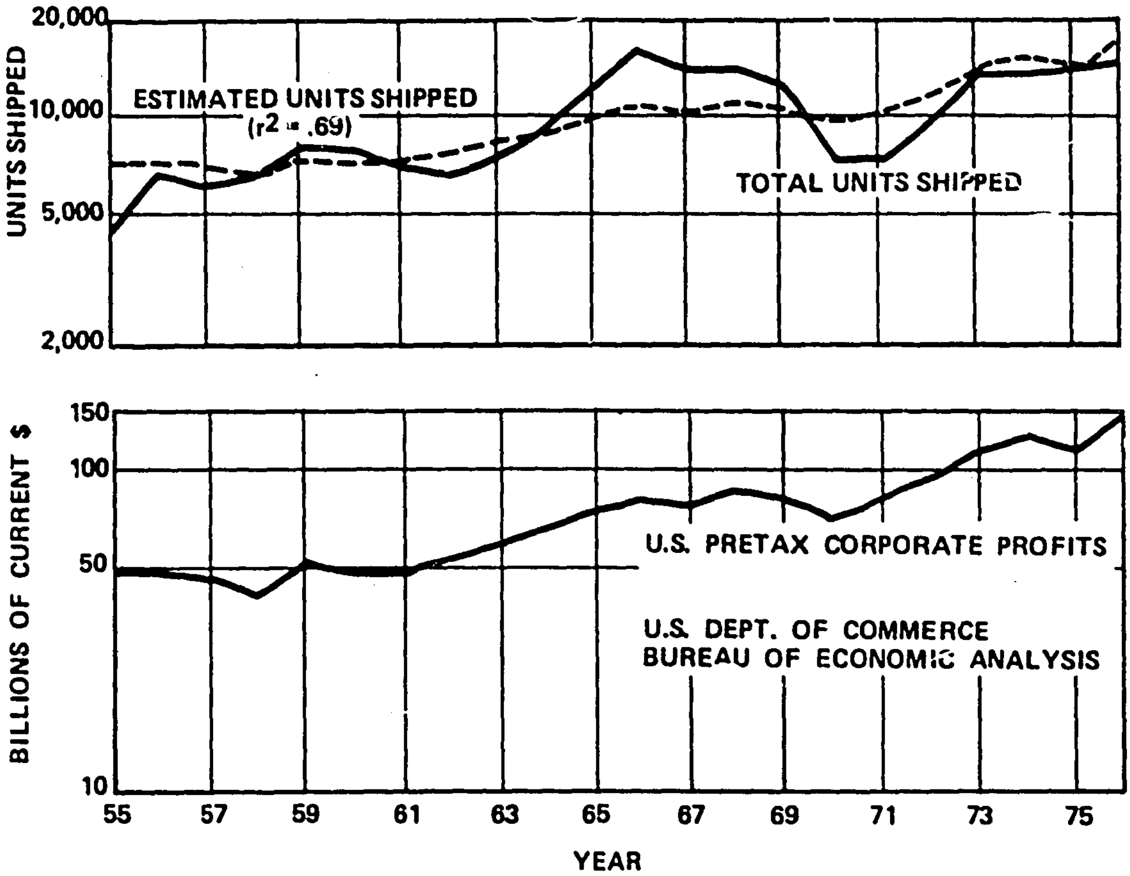


Figure 6. Aircraft Unit Shipments and Pretax Corporate Profits.

of 0.69. However, the correlation between pre-tax corporate profits and manufacturer's net billings was very good ($r^2 = 0.944$). These net billings, however, included turbofan and turbojet business aircraft sales, which use engines outside the size class studied in GATE. A procedure was developed for removing the contribution of turbofan and turbojet aircraft based on average unit prices for each segment, units shipped by segment, net billings by segment for recent years, and total yearly net billings for 1955 through 1976. The results of this analysis are shown in Figure 7. The solid curve shows total manufacturer net billings derived from historical data. The dashed line was predicted from the equation developed by regression analysis. The correlation factor, r^2, is 0.937.

A forecast of manufacturer net billings was derived in two ways. The first method was to project manufacturer net billings on the basis of pre-tax corporate profits. A forecast of pre-tax corporate profits to 1986 is available from Chase Econometrics. It was extrapolated to 1988 for the study. The results of using pre-tax corporate profits and the correlation shown in Figure 7 is shown as the broken line in Figure 8.

The second approach forecasted net billings by market segment. This forecast was derived by multiplying the unit shipments forecast by the average unit price of each segment. The average unit price was based on 1976 prices and inflated by a correlation between average price and the GNP deflator. The GNP deflator was forecast by Chase Econometrics to 1986.

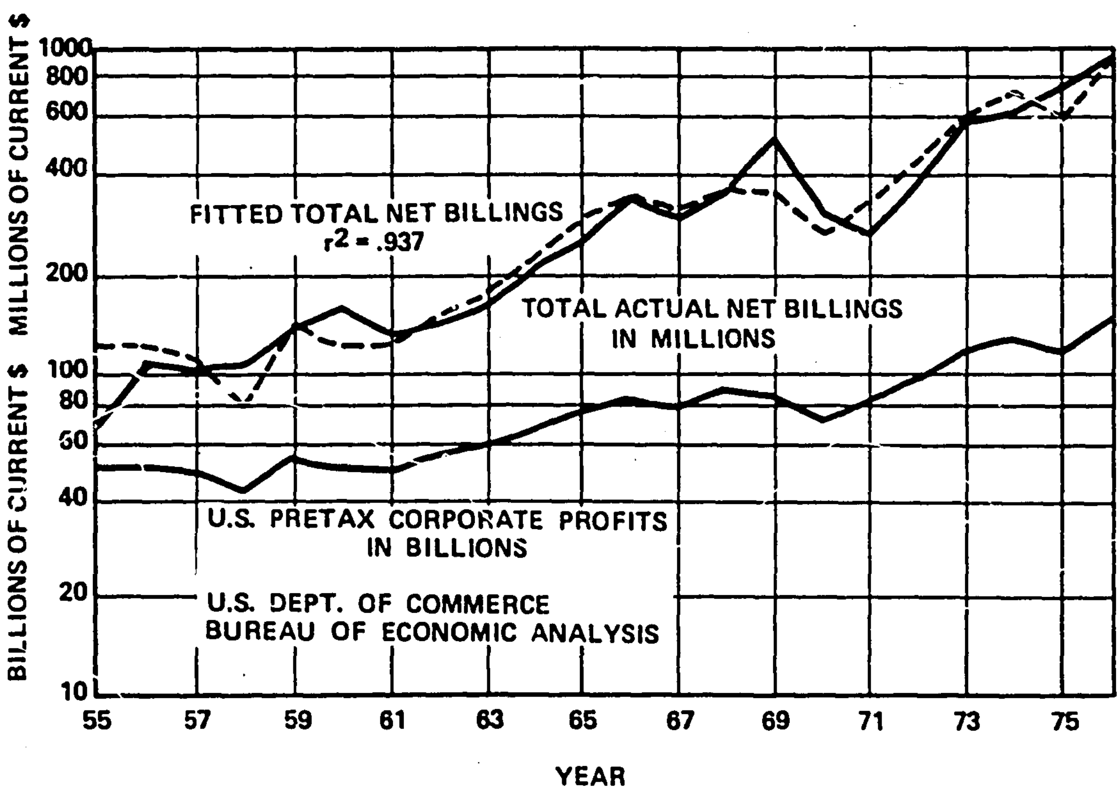


Figure 7. General Aviation Manufacturer Net Billings and Pretax Corporate Profits (Piston and Turboprop)

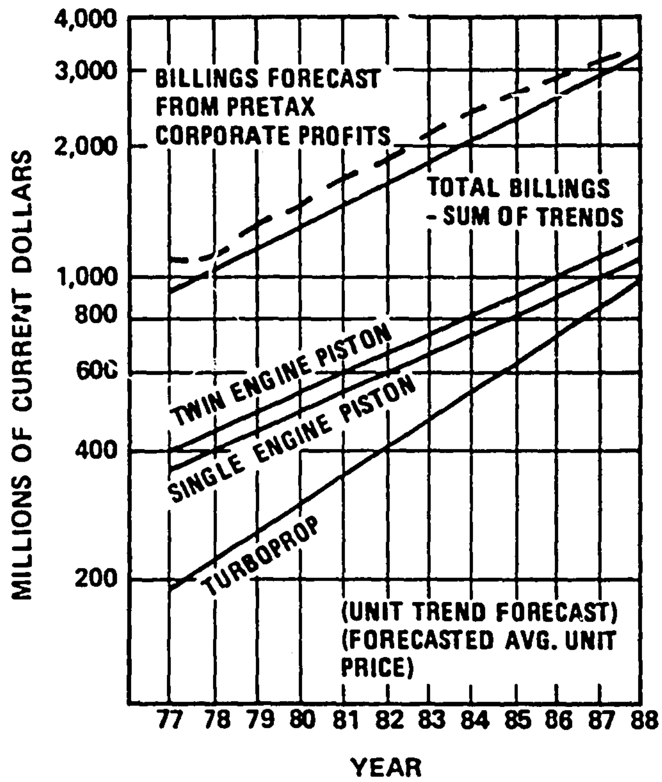


Figure 8. Forecast of Manufacturer Net Billings by Market Segment

The results of this approach are shown in Figure 8 also, by segment and the summation of the segments. The difference in total billings between the econometric method (pre-tax corporate profits) and the trend method ranges from 100 to 400 million dollars. The difference can be attributed to the method used or can be looked on as a growth potential in the market not predicted by trend analysis.

The remainder of the GATE study is based on the lower forecast, i.e., the unit-trend/average-unit-price forecast. This forecast projects manufacturer net billings of over 3 billion dollars by 1988 (then year dollars).

Forecasting by market segment also allowed an estimate to be made of the market segments in 1988. Table 2 shows the breakdown of unit shipments and billings for five selected years. In terms of unit shipments, current turboprops increase slightly at the expense of the single-engine category. The breakdown of billings changes drastically. Current turboprops in 1988 will account for the largest percent of the market in terms of billings.

3.1.2 Market Forecast - Rotary-Wing Aircraft

The rotary-wing aircraft market forecast was furnished by the Bell Helicopter Company. Unit shipments of light [under 4,540 kg (10,000 lbs) gross weight] civilian helicopters from 1963 to 1976 are shown in Figure 9. The market share for single-engine turbines, twin turbines, and piston engine aircraft is shown in addition to total shipments. Total shipments in 1976 were over 1000 units. The forecast through 1988, without considering the impact of a GATE program, is shown in Figure 10. In 1988, more twin turbines will

TABLE 2. FIXED-WING MARKET SEGMENTATION.

		1965	1970	1976	1981	1988
Units	Single	84%	82%	84%	82%	80%
	Twin	15	16	14	15	15
	Current Turbines	1	2	2	3	5
Billings	Single	44%	38%	39%	36%	30%
	Twin	48	45	39	40	33
	Current Turbines	8	16	22	23	37

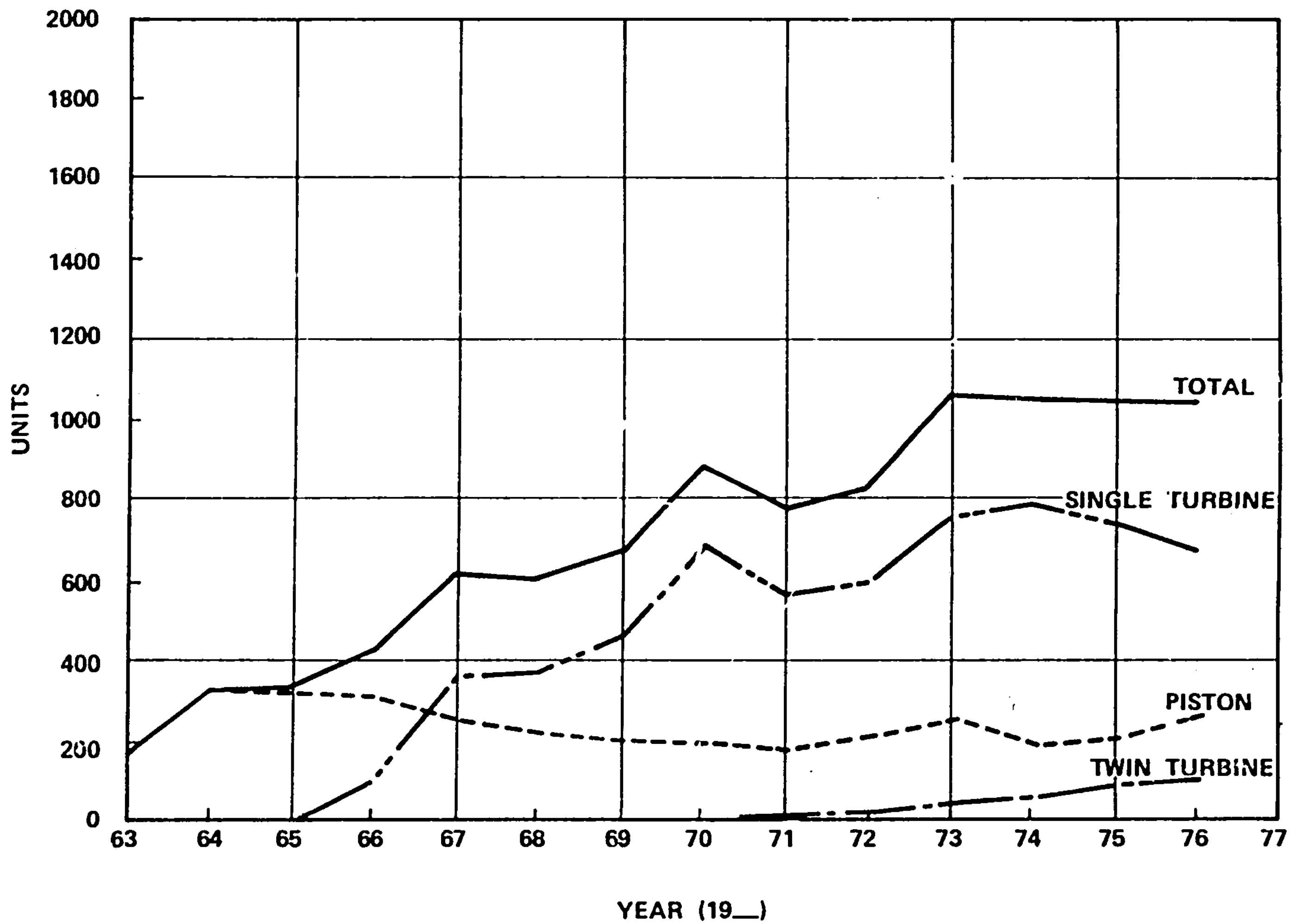


Figure 9. Historical Light Helicopter Sales.

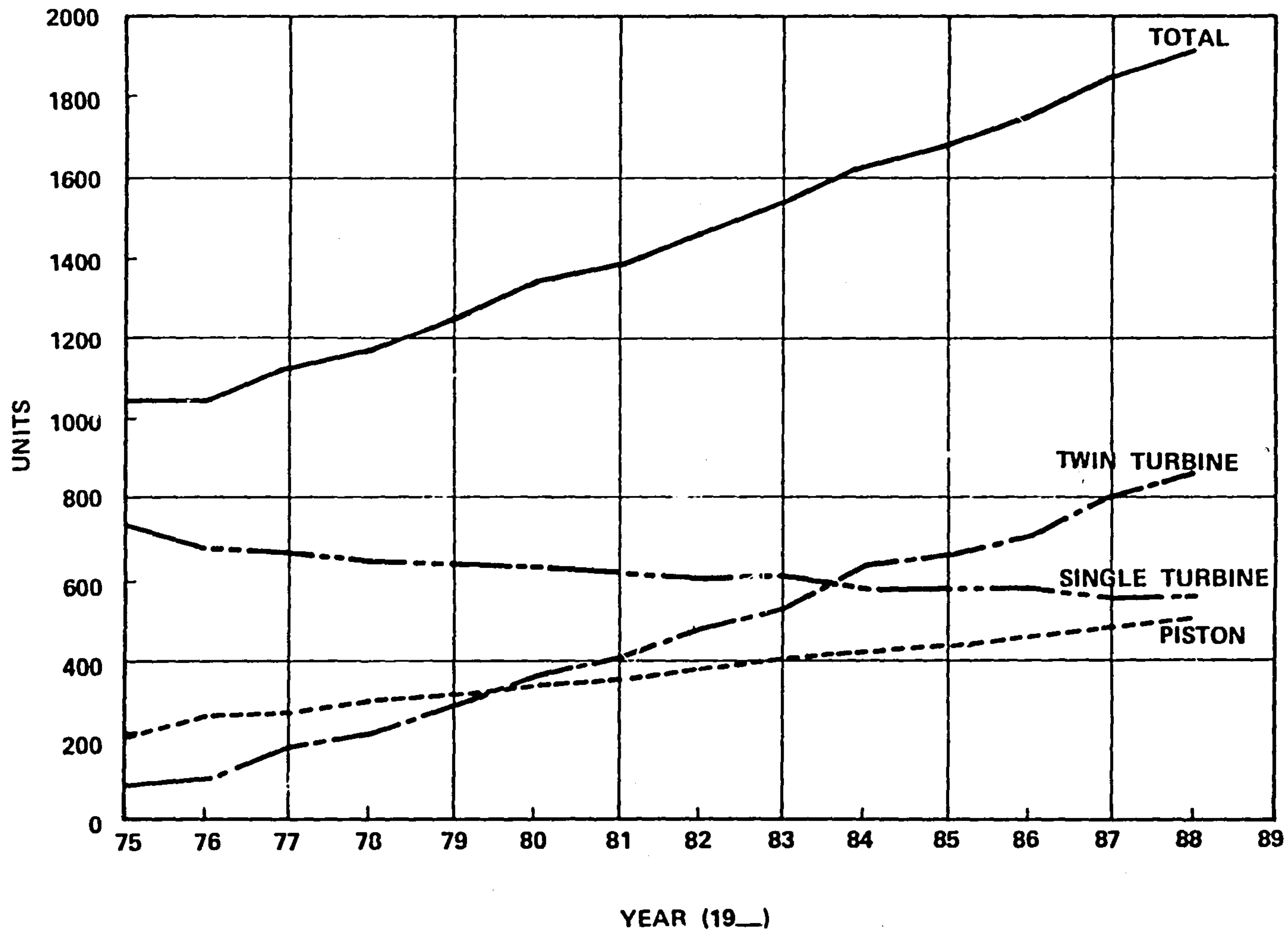


Figure 10. Light Helicopter Sales Forecast.

be delivered than either single turbine or piston engine aircraft. The 1988 forecast for total shipments is almost 2000 units per year.

The rotary-wing market is different from the fixed-wing market in that the conversion to turbine power is well on its way. Rotary-wing aircraft with turbine engines of less than 373 kw (500 hp) are common and represent a majority of the market. Tables 62 through 64 in Appendix I list the engine type, power, and the 1977 average equipped price of aircraft in the current light rotary-wing market.

In the fixed-wing market forecast with GATE, it was assumed that the turbine engine would be used on all applications where it was superior to the piston engine and was cost competitive. This assumption was not made in the rotary-wing forecast. Bell assumed an introduction of the GATE Engine in 1987 and forecast that portion of the market where it would be used. This forecast is shown in Figure 11. The forecast accounts for the continued, though declining, production of piston and older technology turbine-powered aircraft. For later use in engine cost estimates, the year 1992 was chosen to arrive at the GATE engine potential production for helicopters. Gate-powered unit shipments in 1992 include:

- 400 Singles (400 Engines)
- 280 Multi-Engine
  - 190 Twins (380 Engines)
  - 90 Tri-Engine (270 Engines)

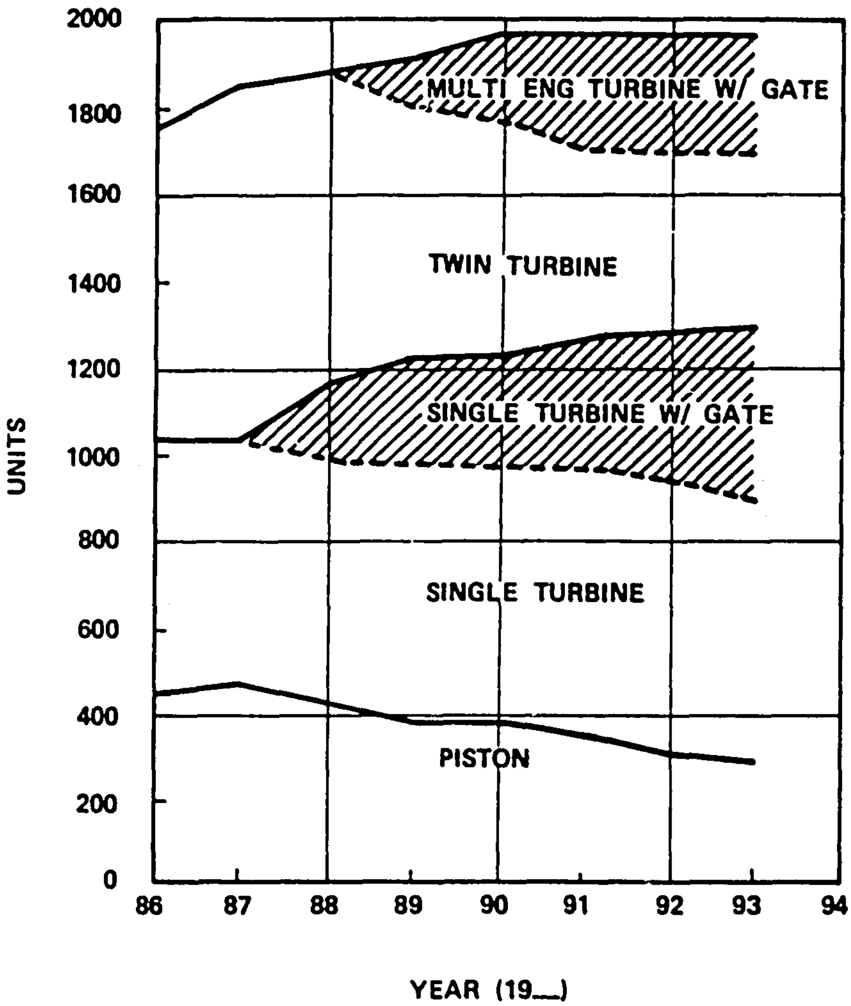


Figure 11. Forecast With GATE Engine.

The total GATE engine production is 1050 engines. The GATE engine size recommended by Bell is 261 ±56 kw (350 ±75 shp.) The criteria that the GATE engine would have to meet to realize the forecasted production are shown in Figure 12 and were suggested by Bell.

3.2. Engine Conceptual Design

The conceptual design of GATE engines was undertaken in Task I to allow preliminary engine cost targets to be set and to provide engine performance and size data to Cessna and Bell to enable them to define aircraft characteristics. Conceptual design focused on three types of engines:

- Turboprop
- Turboshaft
- Turbofan

The turboprop is shown in Figure 13 and consists of a single-stage centrifugal compressor developing a pressure ratio of 9:1, a reverse-flow annular burner, a single-stage cooled radial turbine, and a two-stage uncooled power turbine. Performance and cycle characteristics are shown in Table 3.

The baseline turboshaft engine was the same as the baseline turboprop except that the gearbox was eliminated. The turbofan engine, shown in Figure 14, uses the same core and low-pressure (LP) turbine as the turboprop and incorporates a geared fan, which produces a pressure ratio of 1.5:1. Performance and cycle characteristics are shown in Table 4.

A comparison of the turboprop and turbofan at the cruise design point selected for the conceptual design--6096m, 389 km/hr--(20,000 ft, 210 kts) showed a significant advantage for the turboprop. Based on an assumed propeller efficiency of 0.85 and equal

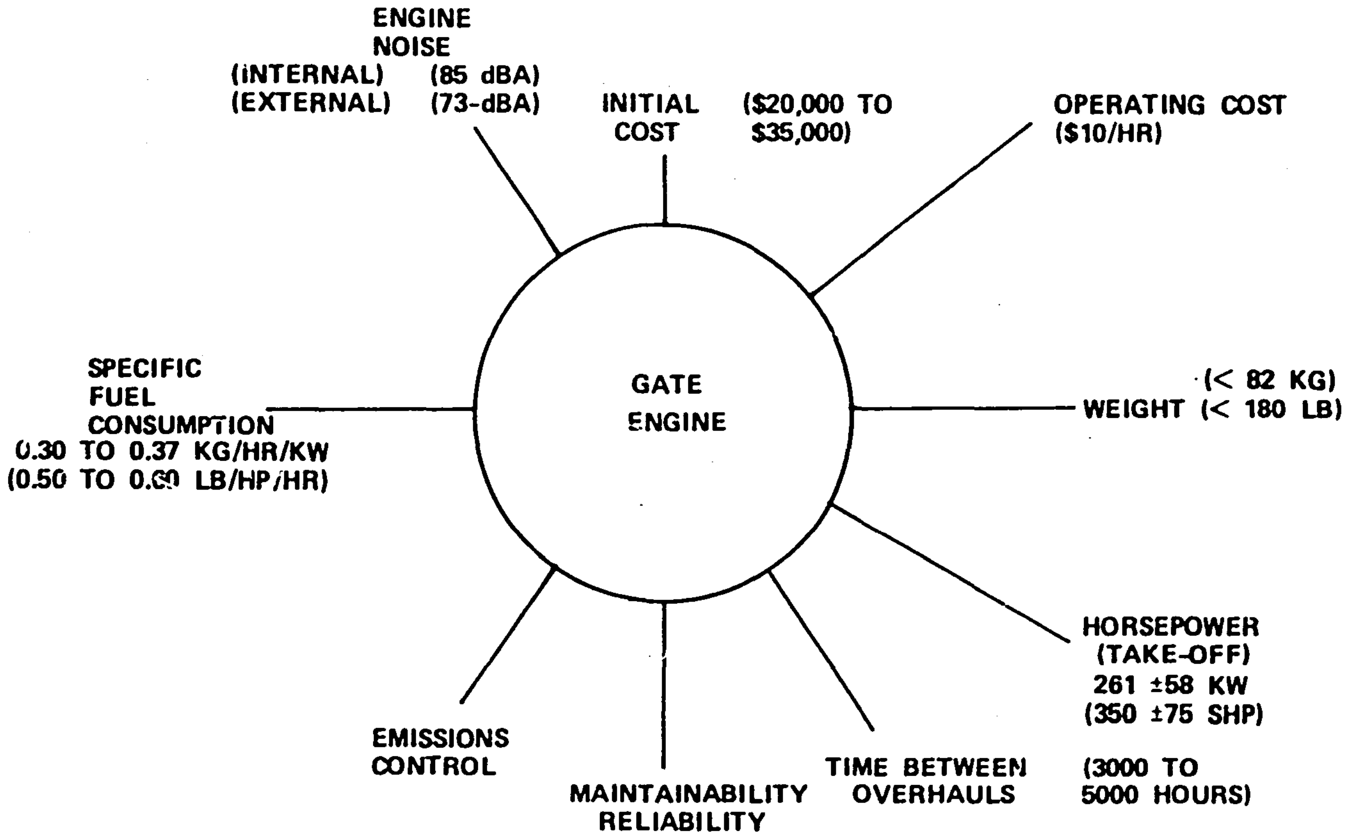


Figure 12. GATE Engine Criteria - Rotary-Wing Applications.

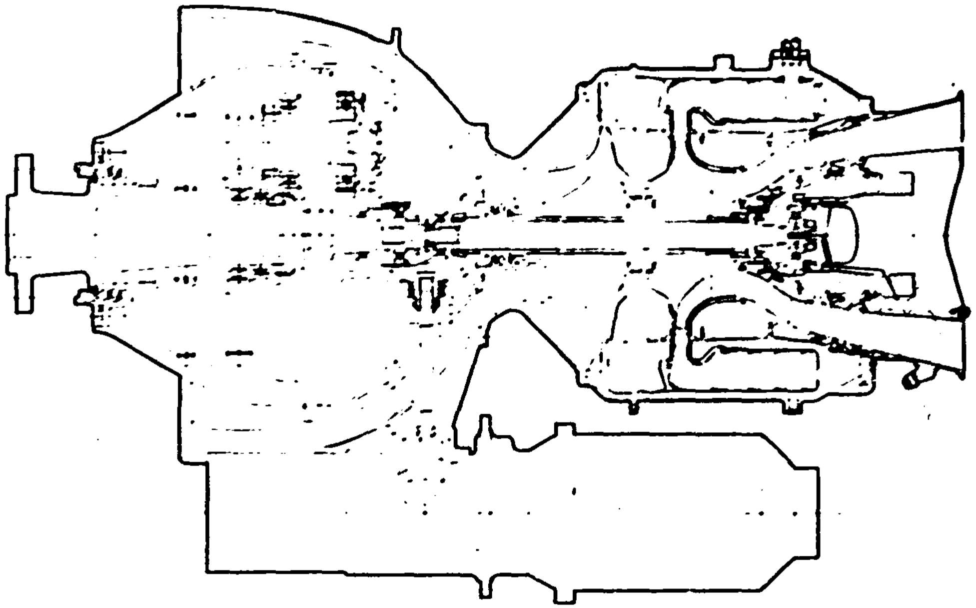


Figure 13. TPE Conceptual Design

TABLE 3. TPE CONCEPTUAL DESIGN

Standard Day
Uninstalled

Parameter	Value
Shaft Power	
SLS, T.O.	373 kw (500 shp)
6096m (20,000 ft), 389 km/hr (210 kts), max cruise	231 kw (310 shp)
Shaft Specific Fuel Consumption	
SLS, T.O.	0.0295 kg/hr/kw (0.484 lb/hr/hp)
6096m (20,000 ft), 389 km/hr (210 kts), max cruise	0.0283 kg/hr/kw (0.465 lb/hr/hp)
Cycle Characteristics,	
6096m (20,000 ft) 389 km/hr (210 kts), max cruise	
Corrected Airflow,	1.20 kg/sec (2.87 lb/sec)
Compressor Pressure Ratio	9:1
Turbine Inlet Temperature	1478°K (2200°F)
Nozzle Pressure Ratio	1.01
Weight,*	123 kg (271 lb)

*Including gearbox.

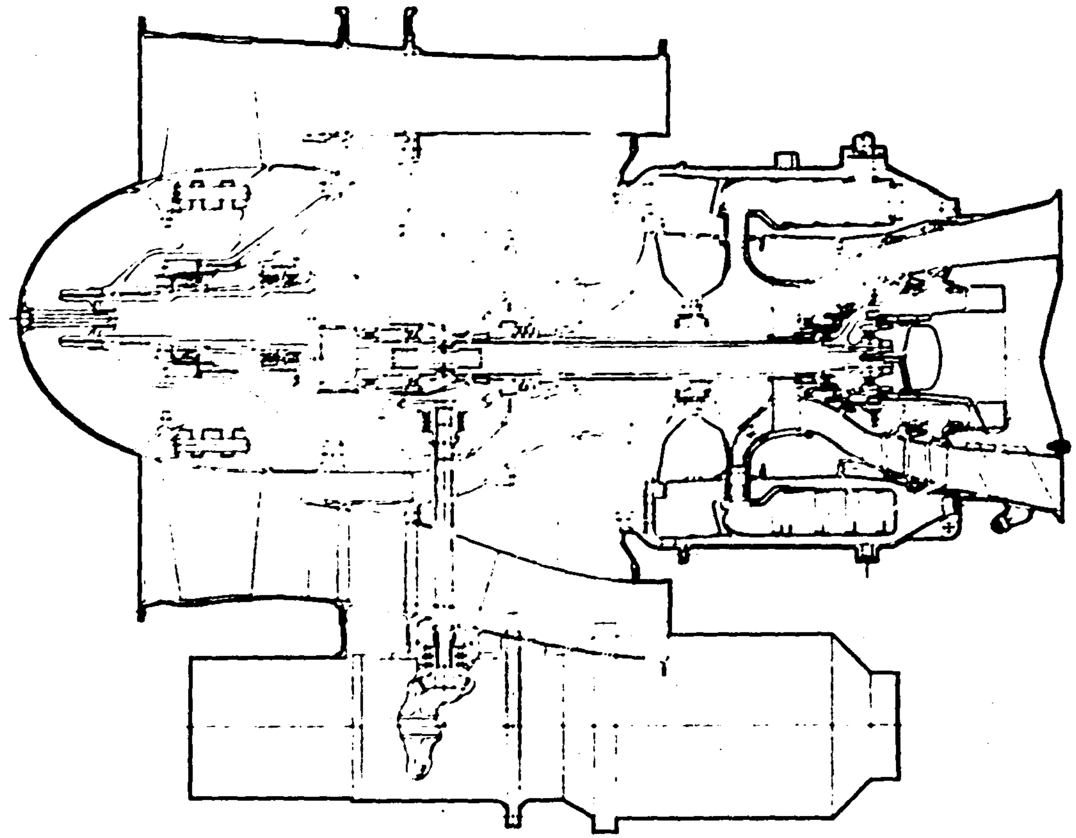


Figure 14. TFE Conceptual Design.

TABLE 4. TFE CONCEPTUAL DESIGN

Performance and Cycle Characteristics

Parameter	Value
Net Thrust	
SLS, T.O.	3275 N (736 lb)
6096m (20,000 ft), 389 km/hr (210 kts), max cruise	1406 N (316 lb)
Thrust Specific Fuel Consumption	
SLS, T.O.	0.041 kg/N-h (0.404 lb/hr/lb)
6096m (20,000 ft), 389 km/hr (210 kts), max cruise	0.060 kg/N-h (0.586 lb/hr/lb)
Cycle Characteristics,	
6096m (20,000 ft), 389 km/hr (210 kts), max cruise	
Inlet Corrected Airflow	16.21 kg/sec (35.7 lb/sec)
Compressor Corrected Flow	1.30 kg/sec (2.87 lb/sec)
Fan Pressure Ratio	1.5:1
Compressor Pressure Ratio	9.0:1
Turbine Inlet Temperature	1478°K (2200°F)
Bypass Ratio	8.0:1
Weight	84 kg (185 lb)

core size, the turboprop produces more net thrust at a lower thrust specific fuel consumption (fuel flow/propeller thrust) as shown in Table 5.

For equal thrust, again assuming 0.85 propeller efficiency, the turbofan would require a 30-percent greater core flow. If cruise speeds are greater than approximately 500 km/hr (270 knots), the advantage of the turboprop diminishes. However, the turboprop retains a fuel consumption advantage and would probably contribute to improved field performance.

3.3 Definition of Gas Turbine Power Classes

A preliminary estimate of turbine engine size typical of each general aviation fixed-wing category was required for an appraisal to be made of the suitability of turbine engines. Current airplanes within each of the 10 general aviation fixed-wing categories identified earlier can be segregated by engine power class. Engine power class includes the effects of turbocharging, i.e., a 224 kw (300 hp), naturally aspirated engine is in a different power class than a 224 kw (300 hp) turbocharged engine. Therefore, there are different turbine power classes for each airplane category.

It is not rigorous to generalize concerning the correlation between piston engine power required and turbine engine power required. The relationship depends on:

- Engine sizing point, e.g., cruise or takeoff
- Degree of turbocharging
- Turbine engine cycle
- Airframe/engine integration

To determine turbine power requirements precisely would require a detailed study of each application. However, it is possible to

TABLE 5. TURBOPROP AND TURBOFAN COMPARISON

6096m (20,000 Feet)
339 km/hr (210 knots)
Maximum power
Equal Core Size
0.85 Propeller Efficiency

	Turboprop	Turbofan
Corrected Core Flow	1.30 kg/sec (2.87 lb/sec)	1.30 kg/sec (2.87 lb/sec)
Shaft Power	231 kw (310 shp)	--
Net Thrust	1815 N (408 lb)	1406 N (316 lb)
TSFC	0.036 kg/N-hr (0.353 lb/hr/lb)	0.060 kg/N-hr (0.586 lb/hr/lb)

generalize sufficiently to allow screening of the various candidates and pick those where turbine engines offer potential.

Figure 15 shows a typical altitude lapse rate for a turbocharged reciprocating engine. A maximum power of 231 kw (310 hp) was arbitrarily selected. The performance is typical of all flight speeds. A variation of power with flight speed actually does occur but it is small and dependent on intake design and throttle setting.

The critical altitude of the engine was selected to be 6096 m (20,000 ft). To match the 231 kw (310 hp) reciprocating engine at 6096 m (20,000 ft), a turboprop engine has to provide 350 kw (470 hp) at sea-level, static, (SLS), standard day, maximum power. The dashed line, intersecting 231 kw (310 hp) at 6096 m (20,000 ft) is the turboprop lapse rate at 370 km/hr (200 kts) flight speed. At 370 km/hr (200 kts) at sea level, the engine produces 402.7 kw (540 hp). The 15-percent increase in power between 0 and 370 km/hr (0 and 200 kts) determines the power at sea-level static, i.e., 351 kw (470 hp). If a turboprop is sized in this manner, it provides equal or higher cruise power at all altitudes and higher takeoff power.

A slightly different situation exists when sizing a turboprop to replace a naturally aspirated reciprocating engine. Figure 16 shows a typical altitude lapse rate for a naturally aspirated reciprocating engine. The lower dashed line shows the altitude lapse rate at 370 km/hr (200 kts) of a turboprop sized to match reciprocating engine power at 3048 m (10,000 ft). The sea-level, static, maximum power of the turboprop in this case is 189 kw (253 hp). This is probably insufficient power to match takeoff performance of the reciprocating-engine-powered aircraft. The altitude lapse rate at 370 km/hr (200 kts) of a turboprop sized to provide 231 kw (310 hp) at sea level, static, takeoff is shown by the upper

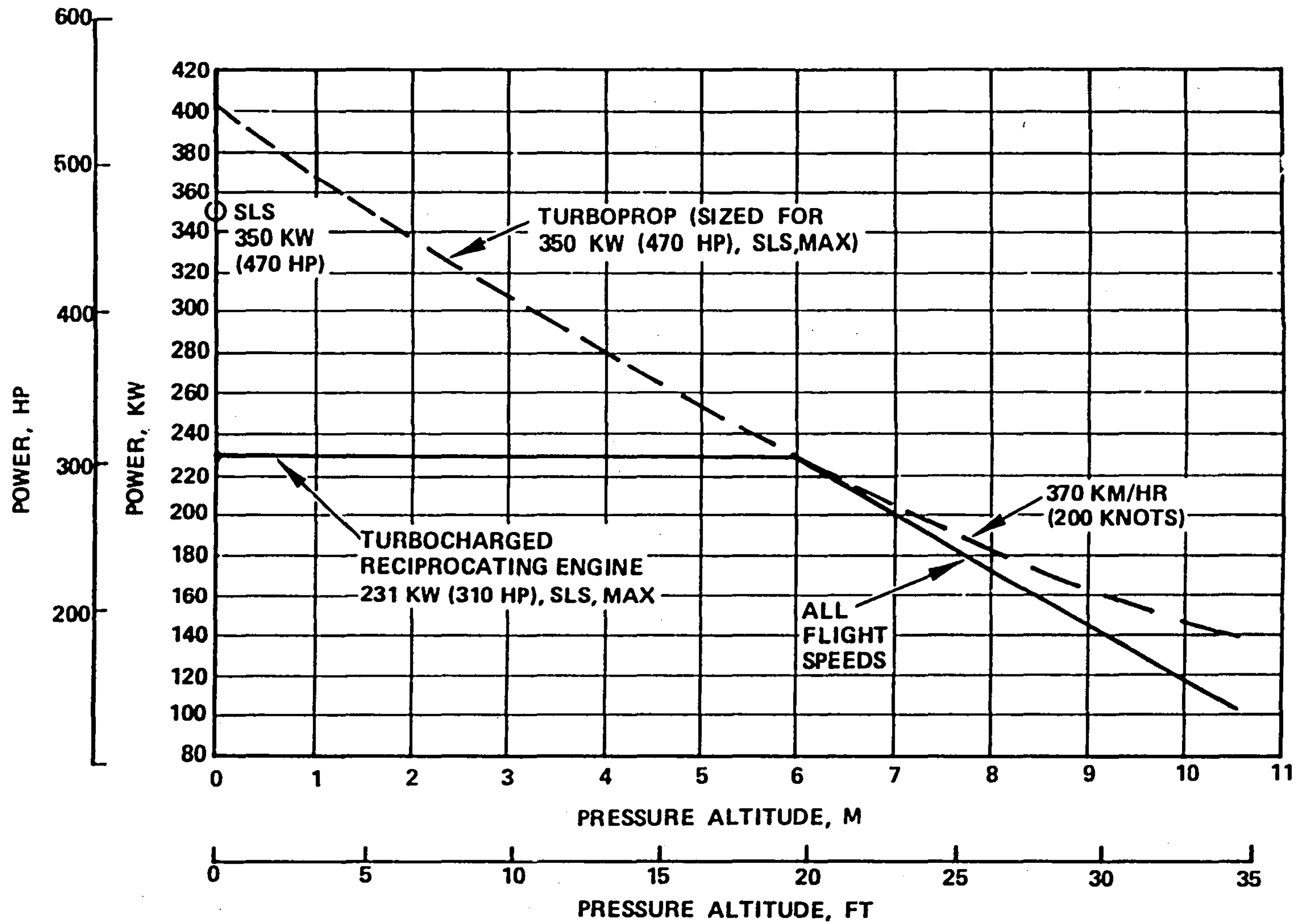


Figure 15. Engine Power Requirements

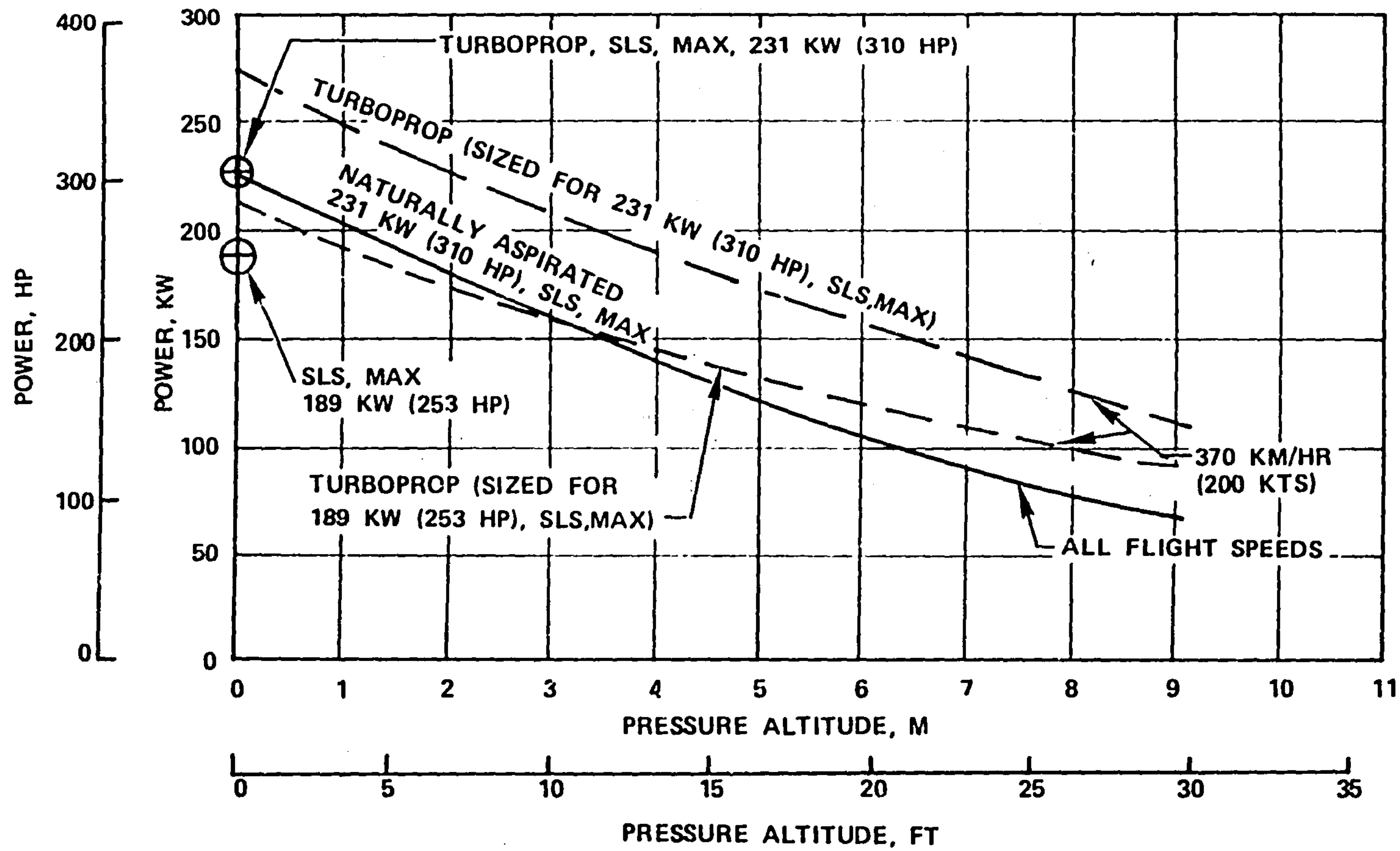


Figure 16. Engine Power Requirements

dashed line of Figure 16. Here it is apparent that the turboprop will have a higher cruise power for equal sea-level, static, takeoff power.

These two examples provided the correlation between the required power for reciprocating and turbine engines. For turbocharged engines, the turboprop must be 50-percent larger at sea-level, static, takeoff power and the turboprop must provide the same take-off power as a naturally aspirated engine. Table 6 shows the resulting equivalent turbine power for current power classes in each of the 10 general aviation categories. In some cases, a range is given to account for possible future changes in mission performance. It is emphasized that the correlation is only approximate and was accomplished solely to allow screening and selection of candidates for Task II, Trade-Off Studies.

As mentioned earlier, the rotary-wing engine size recommended by Bell is 280 ±56 kw (375 ±75 shp).

3.4 Screening and Selection

The objective of this element of the market survey was to identify the domain of superiority of the various engine types, particularly turbine engines.

Screening was limited to the 112 to 447 kw (150 to 600 hp) size class. Engines producing more than 447 kw (600 shp) were not screened because turbine engines are universally used in general aviation applications in this size class because of their superiority and the lack of competition from other types of propulsion systems. Also, U.S. engine manufacturers are heavily committed to the 447 to 746 kw (600 to 1000 shp) turboprop and turboshaft market, and will continue to develop the technology required for its growth. Finally, the U.S. Army's program to develop a demonstrator engine in the 447 to 746 kw (600 to 1000 shp) class will provide

TABLE 6. FIXED-WING TURBOPROP POWER CLASSES.

Airplane Category	Current Power Class		Equivalent Turbine Power Class	
	kw	hp	kw	hp
2-Place	75 112	100 150	75 112	100 150
Utility	112 149 224 224	150 200 300 300 TC	112 149 224-280 366-410	150 200 300-375 450-550
Fixed Gear High Performance	186 224 224	250 300 300 TC	168-205 224-280 336-410	225-275 300-375 450-550
4-Place	112 149	150 200	112 149	150 200
Light Retractables	149 149	200 200 TC	149 224	200 300
Heavy Retractables	186 224 224	250 300 300 TC	168-205 224-280 335-410	225-275 300-375 450-550
Agricultural	186 224 336 447	250 300 450 600	168-205 224-280 336-410 447	225-275 300-375 450-550 600
Light Twin	149 186 224 149 224	200 250 300 200 TC 300 TC	149.1 168-205 224-280 224 336-373	200 225-275 300-375 300 450-500
Cabin Class Twin	224 298	300 TC 400 TC	336-410 410-485	450-550 550-650
Pressurized Twin	224 298	300 TC 400 TC	373 447	500 600

TC - Turbocharged

much of the required future technology advancements. GATE technology development effort should be focused on the under 447 kw (600 shp) size class since the larger engine technology 447 to 746 kw (600 to 1000 shp) being developed by industry and the Army is not universally applicable to smaller engines. The under 447 kw (600 shp) class requires a primary emphasis on engine cost, which cannot be compromised for performance or weight.

Screening of candidate turbine engines was accomplished primarily on the basis of engine cost. Previous studies (Ref. 1, 2, and 3) had shown that performance and operating cost of gas turbines could be competitive with reciprocating engines but that the comparison must be made on a system basis, i.e., airplane and engine. This comparison is part of Task II. A method was derived which allowed a preliminary assessment of the feasibility of gas turbine engines with respect to engine cost and its effect on airplane cost.

The method derived required that target costs be established for advanced GATE Engines and allowable turbine engine costs be established for each airplane category. The comparison of the target costs and allowable costs will show those categories where turbine engines can compete.

Allowable turbine engine costs need definition because turbine engines can cost more than reciprocating engines and remain competitive for the following reasons:

- Based on earlier market survey results, gas-turbine-powered aircraft may command a 10-percent or greater premium

- Lower engine weight and decreased vibration and noise will result in lighter, less expensive airframes.

they believe the advantages of turbine will command/allow a 10% increase in price.

The 10-percent premium, a figure based on the judgment of AiResearch and Cessna marketing personnel, is justified because of the recognized superiority of turbines in the following areas:

- Lower interior noise and vibration
- Higher reliability and safety
- Improved takeoff/altitude/speed performance

Prior studies have shown that lower engine weight and decreased vibration and noise can result in airframe weight savings of 10 percent or more.

An additional factor that was considered in developing the allowable engine cost was the potential increase in reciprocating engine cost, because of technology advancements for improved performance and durability, lower weight, decreased vibration and noise, and lower emissions. Subsequent to completing this portion of the GATE study, the EPA published their intent to remove all emission requirements for small engines. Study results were not modified to reflect this and can be viewed as a necessary adjustment or a provision for future regulatory action.

3.4.1 Target Turbine Engine Original Equipment Manufacturer's (O.E.M.) Cost

The conceptual design studies indicated that turboprops are superior to turbofans in the aircraft categories being studied, in terms of fuel consumption and required engine size. This finding was not by any means based on a detailed and rigorous analysis. However, it suggested that engine cost screening could be done on the basis of the turboprop engine for fixed-wing aircraft. Turbofans may offer lower system cost than a turboprop engine plus propeller for a given core size but turbofans will require a larger core.

Screening for helicopter applications also follows the development of target costs for the turboprop. Turboshaft engine cost for helicopters should be lower than the turboprop cost at equal power, due to the elimination of gearbox cost.

Significant potential cost improvements were identified for GATE turboprops, relative to current-technology turboprops. Projections for 1983 component and manufacturing technology indicate improvements in performance that result in lower cost, and new fabrication techniques that promise dramatic decreases in labor and material requirements. The GATE turboprops can afford lower power-to-weight ratios than current turbine engines, and on a relative basis can have a lower quality cycle than larger engines of comparable technology. This flexibility in weight and performance is the basis for a successful Design-to-Cost (DTC) program. Many DTC programs are ineffective because little flexibility is allowed due to hard requirements for high performance and low weight.

Another major factor in cost improvement is the high volume production typical of the general aviation market segment being studied. The potential for large production releases, automated machining, and dedicated equipment offers significant cost reductions. Based on the above factors, GATE turboprop target costs were established as shown in Figure 17. The production quantities associated with these target costs are shown in Table 7. The data assumes the cost benefit associated with these high-production levels. A 90 percent learning curve is assumed.

The variation in production quantity and specific cost with power is a result of matching target and allowable engine cost, and is an iterative process. Target costs were initially based on a constant production volume. As the comparison between target and allowable engine cost was completed, estimates of production volume were made for those applications where the target cost was equal to or lower than allowable cost. Additional discussion of these production quantities is contained in subsequent paragraphs.

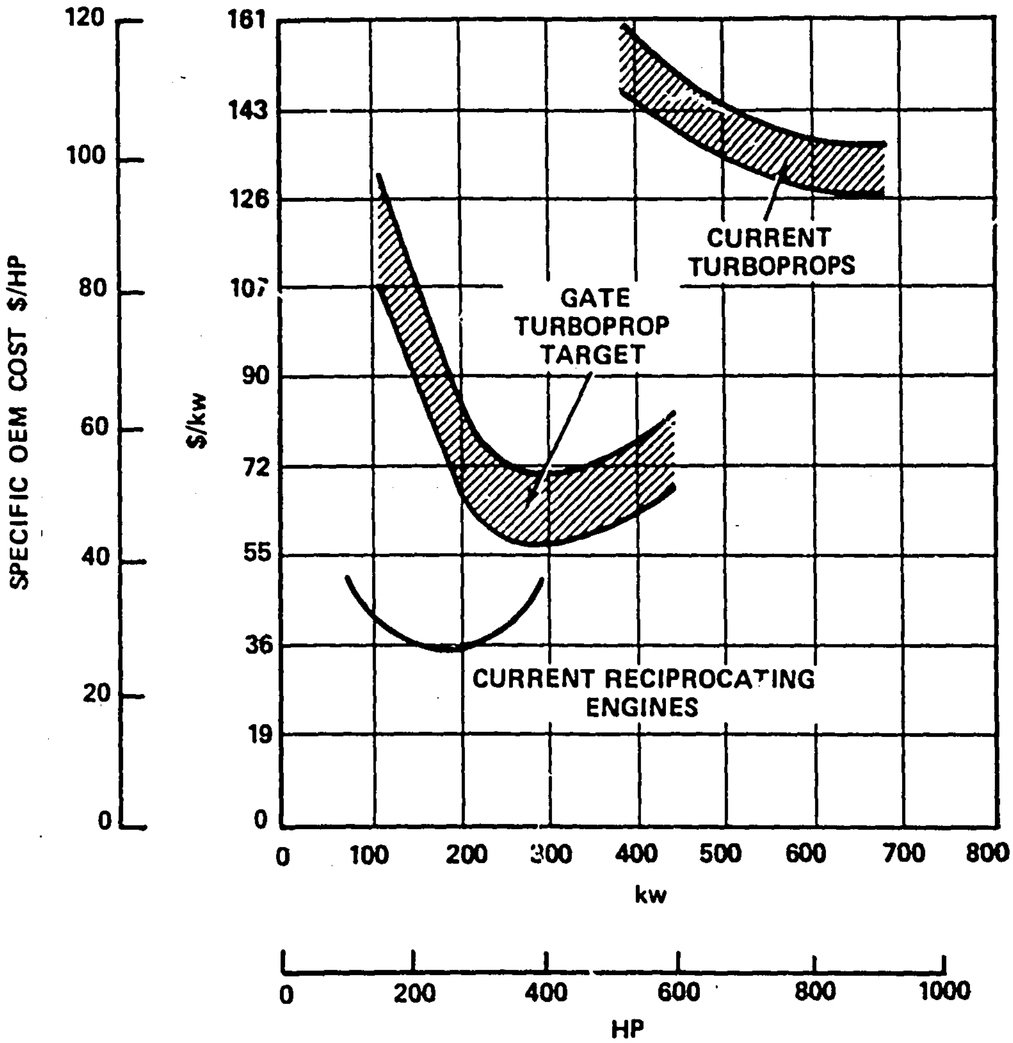


Figure 17. Estimated Engine O.E.M. Cost 1977 Dollars

TABLE 7. ENGINE PRODUCTION QUANTITIES - TARGET COST.

Power		
Kw	Hp	Annual Production Quantity
149	200	1250
186	250	2000
261	350	6200
373	500	2100
447	600	1600

Another source of variation in the specific cost versus power relationship shown in Figure 17 is the exponential scaling law issued by AiResearch for engine cost, namely:

$$\text{Engine cost} = \left(\frac{\text{Power}}{\text{Base Power}}\right)^{0.75} \text{(Base Engine Cost)}$$

As engines are scaled down, the specific cost increases, assuming that cycle quality and engine configuration remain the same.

Also shown in Figure 17 are the Original Equipment Manufacturer's (OEM) specific cost for current turboprops and an estimate of the specific OEM cost of current reciprocating engines. The GATE turboprop cost target represents a cost reduction of over 50 percent when compared to current production turboprops. Compared to the cost of reciprocating engines, the GATE turboprops are 25 to 100 percent higher. On a specific cost basis, turbines will probably be higher than reciprocating engines until common cores, high parts commonality, and product maturity of gas turbines increase to levels comparable to reciprocating engines.

3.4.2 Allowable Turbine Engine Cost

Given the difference in specific cost between the turbine and reciprocating engines, can the higher cost of turbines be justified and absorbed such that turbine-powered aircraft price is competitive with reciprocating-engine-powered aircraft price? To answer this question, it was necessary to determine the turbine engine OEM cost which would allow a competitive situation between gas turbines and reciprocating engines.

A simple procedure was developed to determine the allowable turbine engine OEM cost. In this procedure, the current aircraft dealer cost is first adjusted to reflect a 20-percent increase in current reciprocating engine OEM cost, to allow for reciprocating engine technology.

$$\begin{matrix}\text{ADJUSTED}\\ \text{CURRENT}\\ \text{DEALER}\\ \text{COST}\end{matrix} = \begin{matrix}\text{CURRENT}\\ \text{DEALER}\\ \text{COST}\end{matrix} + \begin{pmatrix}\text{RECIP}\\ \text{ENGINE}\\ \text{OEM}\\ \text{COST}\end{pmatrix}\begin{pmatrix}\text{RECIP}\\ \text{COST}\\ \text{INCREASE}\end{pmatrix}\begin{pmatrix}\text{OEM}\\ \text{MARKUP}\end{pmatrix}$$

Current dealer cost - Factory price with standard equipment

Reciprocating engine OEM cost - Estimated on basis of Figure 17

Reciprocating cost increases - 0.20 selected for increases due to noise, emissions, and advanced technology

OEM markup - Airframe markup factor on engine cost for direct and indirect cost, overhead, and profit (Factors over 2.0 were suggested. A factor of 1.5 was selected. The lower factor is conservative.)

For a single-engine airplane with a current dealer's cost of $36,000 and OEM engine cost of $5,000, the increase in current dealer's cost due to technology improvements in the reciprocating engine would be:

$$(\$5000)(0.2)(1.5) = \$1500$$

The adjusted current dealer's cost is:

$$\$36000 + 1500 = \$37500$$

The second step adjusts the airframe cost to reflect the lower gas turbine engine weight and decreased airframe weight due to lower noise and vibration.

$$\begin{pmatrix}\text{AIRFRAME}\\ \text{COST}\\ \text{(W/TURBINE)}\end{pmatrix} = \left[\begin{pmatrix}\text{CURRENT}\\ \text{AIRCRAFT}\\ \text{DEALER}\\ \text{COST}\end{pmatrix} - \begin{pmatrix}\text{RECIP}\\ \text{ENGINE}\\ \text{OEM}\\ \text{COST}\end{pmatrix}\begin{pmatrix}\text{OEM}\\ \text{MARKUP}\end{pmatrix}\right] \times \begin{matrix}\text{AIRFRAME}\\ \text{COST}\\ \text{REDUCTION}\\ \text{FACTOR}\end{matrix}$$

In this procedure, the airframe cost is the cost of the airplane less engine. The airframe cost reduction factor was assumed to be 0.90 or a 10-percent reduction in cost for turbine engines.

A new airplane cost or adjusted dealer cost with turbines is computed based on increasing the adjusted dealer cost by 10 percent, which is the assumed premium for turbine power.

Based on these three steps, the allowable turbine engine cost may be computed:

$$\begin{matrix}\text{AIRCRAFT DEALER}\\ \text{COST}\\ \text{(WITH TURBINES)}\end{matrix} = \begin{pmatrix}\text{AIRFRAME}\\ \text{COST}\\ \text{(W/TURBINES)}\end{pmatrix} + \begin{pmatrix}\text{ALLOWABLE TURBINE}\\ \text{ENGINE COST}\end{pmatrix}\begin{pmatrix}\text{OEM}\\ \text{ENGINE}\\ \text{MARKUP}\end{pmatrix}$$

or

$$\begin{matrix}\text{ALLOWABLE TURBINE}\\ \text{ENGINE OEM COST}\end{matrix} = \frac{\begin{pmatrix}\text{AIRCRAFT DEALER}\\ \text{COST (W/TURBINES)}\end{pmatrix} - \begin{pmatrix}\text{AIRFRAME}\\ \text{COST}\\ \text{(W/TURBINES)}\end{pmatrix}}{1.5}$$

The allowable turbine engine cost must be divided by two for twin-engine aircraft.

A specific example of this procedure is shown in Table 8. The reciprocating engine cost was obtained from Figure 17 for a 231 kw (310 hp) engine. The current dealer cost is an average of all models in the light-twin category.

TABLE 8. ALLOWABLE TURBINE COST EXAMPLE

Light Twin

Reciprocating Engine Cost	= 8550 (17,100/(2) Engines)	
Turbine Engine Premium	= 10%	
Current Dealer Aircraft Cost	=	136,496
Adjusted Current Dealer Aircraft Cost	= 136,496 + 0.2 (17,100)(1.5)	= 141,626
Dealer Aircraft Cost with Turbine Engines (TEDC)	= (1.1)(141,626)	= 155,789
Airframe Cost (AFC)	= [136,496 - (17,100)(1.5)] 0.9	= 99,761
Allowable Turbine Engine Cost (2 engines)	= (TEDC -AFC)/1.5	= 37,352
Allowable Turbine Engine Cost (each)	=	18,675

Tables 9, 10, and 11 list the data required to calculate the allowable turbine engine cost for each power class in all general aviation categories. The turbine power classes listed were discussed earlier. The average dealer cost is a unit shipment weighted average of the 1977 average dealer cost for every model. The current OEM engine cost is the 1977 cost to the airframe manufacturer for presently used reciprocating engines and was estimated by the cost/kilowatt relationship shown in Figure 17. The 1977 unit shipments were estimated in mid-1977 from available data for every model and were totaled by category. Final 1977 shipment data was conservative by approximately 10 percent. The 1988 unit shipments are projected from the 1977 shipments using the growth rates previously defined for single- and twin-engine aircraft. Since the forecasted trends were made for the general groupings of single-and twin-engine aircraft, projections by power class for each of the more specific categories are only approximate.

The data shown in Tables 9 and 10 was used to calculate the allowable turbine engine cost and the results were grouped by power class. These results are shown in Table 11. The allowable turbine engine cost assuming a 10-percent premium for turbine power and the 1988 annual production is shown. In addition, the cumulative production for each power class is shown. The total figures for both the single- and twin-engine categories differ slightly from the forecasts shown earlier. Previous data was based on GAMA data for the single and twin categories. The data shown in Tables 9 and 10 are based on forecasts for each manufacturer's model.

The results of the comparison between allowable and estimated engine cost is shown in Figure 18. This figure shows the GATE turboprop target cost, and the range of allowable engine cost in various power classes is superimposed. All categories in two power classes, 224 to 280 kw (300 to 375 hp) and 410 to 485 kw (550 to 650 hp), have allowble turbine engine costs that are greater than the

TABLE 9. SINGLE-ENGINE FIXED-WING MARKET

Airplane Category	Turbine Power Class		Average Dealer Cost (1977 $)	Current* OEM Engine Cost (1977 $)	1977 Shipments	1988 Shipments
	kw	(hp)				
2 Place	75	100	13,223	3700	1864	2964
	112	150	18,875	4500	424	674
Utility	112	150	17,300	4500	150	239
	149	200	19,700	5500	70	111
	168-205	225-275	32,400	6750	149	237
	224-280	300-375	38,563	8550	349	555
	336-410	450-550	53,500	8990	30	48
Fixed Gear High Performance	168-205	225-275	33,573	6750	1071	1703
	224-280	300-375	43,843	8550	460	731
	336-410	450-550	47,900	8990	240	382
4 Place	112	150	20,525	4500	2833	4504
	149	200	26,629	5500	1260	2003
Light retractables	149	200)	39,331	5500	788	1253
	224-280	300-375	49,600	5900	100	159
Heavy retractables	168-205	225-275	53,800	6750	170	270
	224-280	300-375	59,759	8550	1142	1816
	336-410	450-550	58,959	8990	358	569
Agricultural	168-205	225-275	30,500	6750	400	636
	224-280	300-375	40,942	8550	418	665
	336-410	450-550	52,400	--	250	398
	447	600	59,600	--	84	134
Total single engine aircraft					12,610	20,051

*Specific Cost Estimate

TABLE 10. TWIN-ENGINE, FIXED-WING MARKET

Airplane Category	Turbine Power Class		Average Dealer Cost (1977 $)	Current* OEM Engine Cost (Ea) (1977 $)	1977 Shipments	1988 Shipments
	kw	(hp)				
Light twins	168-205	225-275	112,037	6750	344	554
	224-280	300-375	136,496	8550	555	894
	336-410	450-550	157,692	8990	127	204
Cabin class	336-410	450-550	183,978	8990	91	147
(unpressurized)	410-485	550-650	253,600	14,600	200	322
Pressurized twins	336-410	450-550	199,048	8990	439	707
	410-485	550-650	319,904	14,600	257	414
	Total twin engine aircraft				2013	3242
	Total engines				4026	6484

*Specific Cost Estimate

TABLE 11. ALLOWABLE TURBINE ENGINE COST (1977 $).

Aircraft Category	Allowable Turbine Engine Cost 10% Premium, $	1988 Annual Production	
		Category	Cumulative
112 Kilowatt (150 hp) Class			
Four-Place	7777	4504	4504
Two-Place	7557	674	5178
Utility	7347	239	5417
149 Kilowatt (200 hp) Class			
Utility	8787	111	3367
Four-Place	9710	2003	3256
Light Retractable	11404	1253	1253
168-205 Kilowatt (225-275 hp) Class			
Agricultural		636	636
Light Twin	15029	1108	1744
Heavy Retractable	14733	270	2014
Fixed Gear High Perf.	12036	1703	3717
Utility	11880	237	3954
224-280 Kilowatt (300-375 hp) Class			
Rotary Wing		1050	1050
Agricultural		665	1715
Light Twin	18675	1788	3503
Heavy Retractable	17544	1816	5319
Light Retractable	16189	159	5478
Fixed Gear High Perf.	15421	731	6209
Utility	14718	555	6764
336-410 Kilowatt (450-550 hp) Class			
Agricultural		398	398
Pressurized Twin	23339	1414	1812
Cabin Class Twin	22334	294	2106
Light Twin	20582	408	2514
Heavy Retractable	17930	569	3083
Fixed Gear High Perf.	17202	382	3465
Utility	16456	48	3513
410-485 Kilowatt (550-650 hp) Class			
Agricultural		134	134
Pressurized Twin	37678	828	962
Cabin Class Twin	33258	644	1606

- Assumes helicopters and agricultural aircraft use turbine engines when available
- 1988 production based on forecasted growth (4.3% single; 4.4% twins)

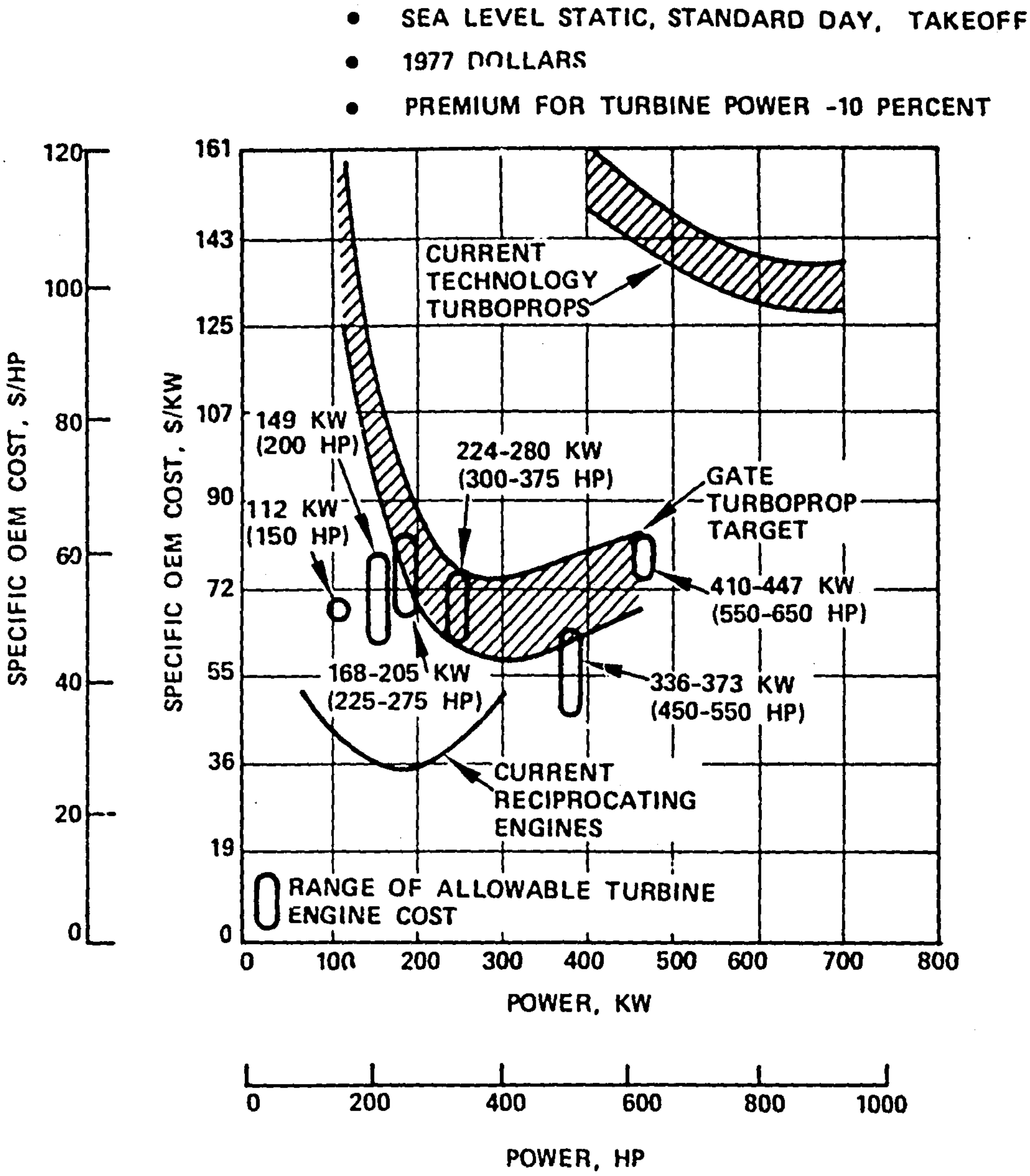


Figure 18. Estimated Engine O.E.M. Cost, 1977 Dollars.

GATE target costs. Two power classes, 112 kw (150 hp) and 149 kw (200 hp) do not have any categories that have allowable turbine engine costs equal to GATE target costs. GATE target costs would have to be decreased an additional 15 to 25 percent before these categories would be attractive for turbine engine propulsion. The two remaining power categories, 168 to 205 kw (225 to 275 hp) and 336 to 410 kw (450 to 550 hp) have some categories where the allowable costs exceed the target costs. Over 50 percent of the potential production in these categories could be powered by turbine engines. The potential turbine engine production for each power class is shown in Figure 19. In all cases, rotary-wing and agricul-tural applications are included because the results of the market survey indicate the applications would use a turbine engine if it were available at the GATE target levels. It was assumed that gas turbines developed as a result of GATE would be used in lieu of reciprocating engines based on allowable cost. This approach does not account for a retrofit market, nor does it allow for a change in the market growth rate as a consequence of the availability of GATE gas turbines. Immediate 100 percent penetration of the gas turbines in 1988 was also assumed, i.e., there is no start-up period during which production gradually builds.

The analysis of projected versus allowable cost was performed in Task I. In Task II, detailed cost estimates and more precise determination of power requirements were made. In general, the Task II results showed that engine cost was slightly lower than the target and required engine size was lower than estimated in Task I. Therefore, the potential turbine demand and number of categories where gas turbines are competitive are larger than predicted in Task I. Task I results as presented herein have not been updated based on the results of Task II.

Based on the market survey results and particularly the cost analysis, the applications selected for study in Task II were:

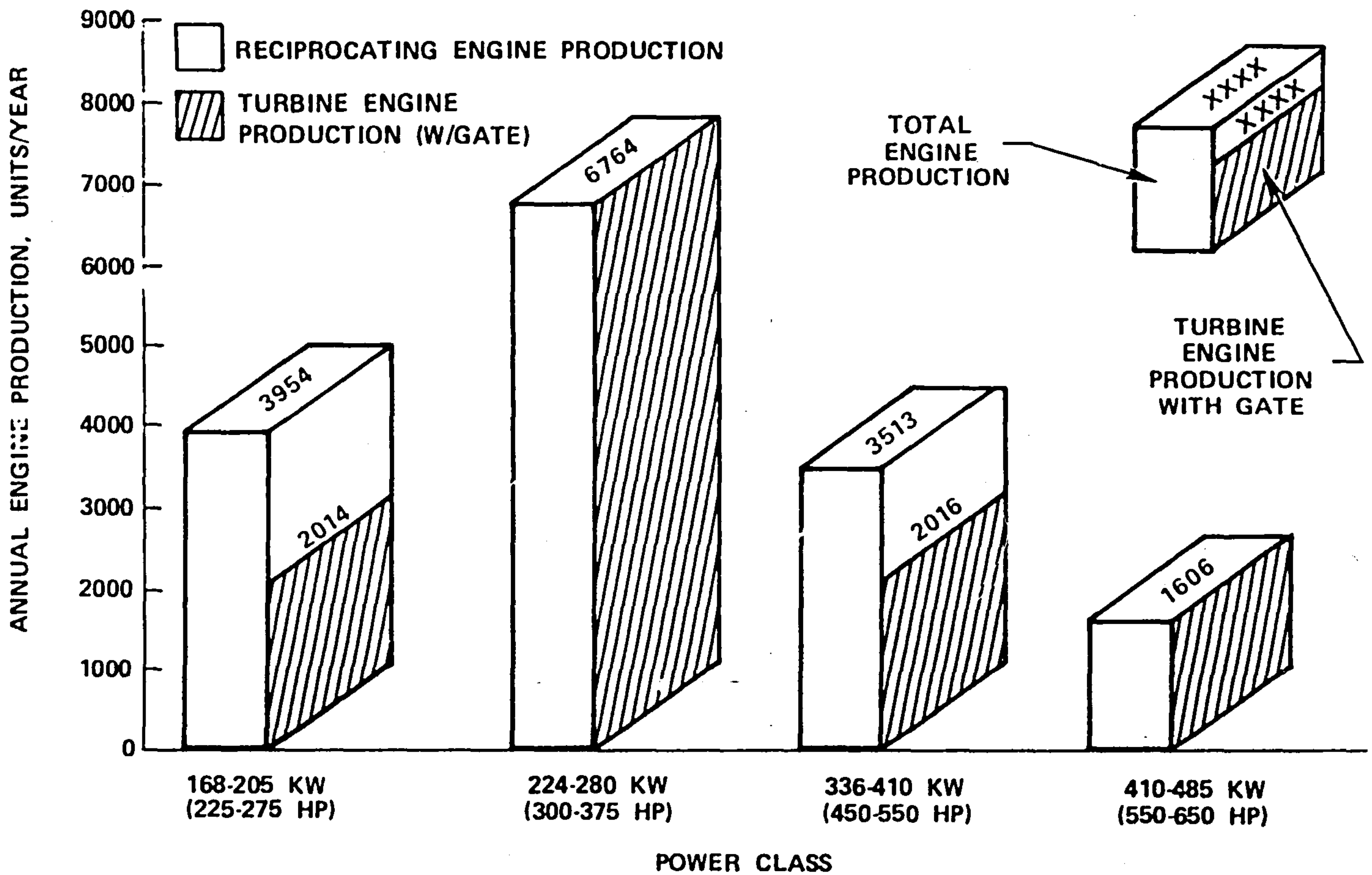


Figure 19. Potential Turbine Engine Demand (1988).

- Pressurized Twin
- Light Twin
- Single-Engine Utility Helicopter

The two fixed-wing applications chosen and the heavy retrac-tac table single-engine category had the highest potential production volume of all categories where turbine engines showed promise. It is recommended that the heavy, retractable, single-engine candidate be investigated in follow-on programs. The single-engine utility helicopter was chosen for study primarily because this segment of the market is currently dominated by reciprocating-engine-powered helicopters.

3.4.3 Other Engines Considered

The other types of engines that were considered in addition to turbines were:

- Reciprocating engines
  - Gasoline
  - Diesel
- Rotary engines

Only current and advanced gasoline reciprocating engines were retained after initial screening. Available information on advanced diesel and rotary engines indicates that they are considered potential propulsion systems for future general aviation aircraft and offer advantages in performance, weight, and durability. There is, however, very little specific information about their characteristics, cost, or how advancements will be made. A comparison including these engines would be desirable but without more specific data, a fair comparison cannot be made.

SECTION IV

TASK II

BROAD SCOPE TRADE-OFF STUDIES

4.0 OBJECTIVE

The objective of this task was to determine the optimum engine for the aircraft applications chosen in Task I, the Market Survey. The applications chosen were:

- o Pressurized Twin
- o Light Twin
- o Light Single-Engine Utility Helicopter

The tasks performed to define and select the optimum engine were:

- o Selection of candidate engine configurations and applicable advanced technology
- o Baseline engine definition
- o Aircraft sizing and sensitivity studies
- o Engine trade-off studies
- o Benefit analysis

PRECEDING PAGE BLANK NOT FILMED

4.1 Selection of Candidate Engine Configurations and Candidate Advanced Technology

4.1.1 Candidate Engine Configurations

The gas generator configurations selected for consideration during Task II are shown in Figures 20 and 21. Figure 20 shows gas generators compatible with free-turbine turboprops and turboshafts and two-spool turbofans. Figure 21 shows candidate single-shaft turboprop, turboshaft, and turbofan gas generators.

All the configurations shown in Figures 20 and 21 use reverse-flow annular combustors. Consideration was given to studying in-line, radial, and can-type combustors. They were eliminated because AiResearch has generally found that the reverse-flow annular combustor is competitive with or superior to the alternate configurations in the 186 to 447 kw (250 to 600 hp) class and when radial flow components are being used. The in-line combustor could be competitive with the reverse-flow combustor if turbine inlet temperatures considered exceeded 1589°K to 1644°K (2400°F to 2500°F). At turbine inlet temperatures higher than 1664°K (2500°F), cooling of the reverse-flow annular transition section is difficult. For specific applications, the radial or can-type combustors may offer some cost advantages and acceptable performance. However, they have a large effect on engine envelope. The GATE engines must be compatible with a variety of aircraft and the envelope of engines with radial or can-type burners could restrict the number of applications and/or affect aircraft design and performance.

Gas generator configurations utilizing all-axial compressors were eliminated from consideration. For core flow of less than 5 pounds per second, prior experience has shown axial-centrifugal or centrifugal compressors to be superior. A front drive, concentric

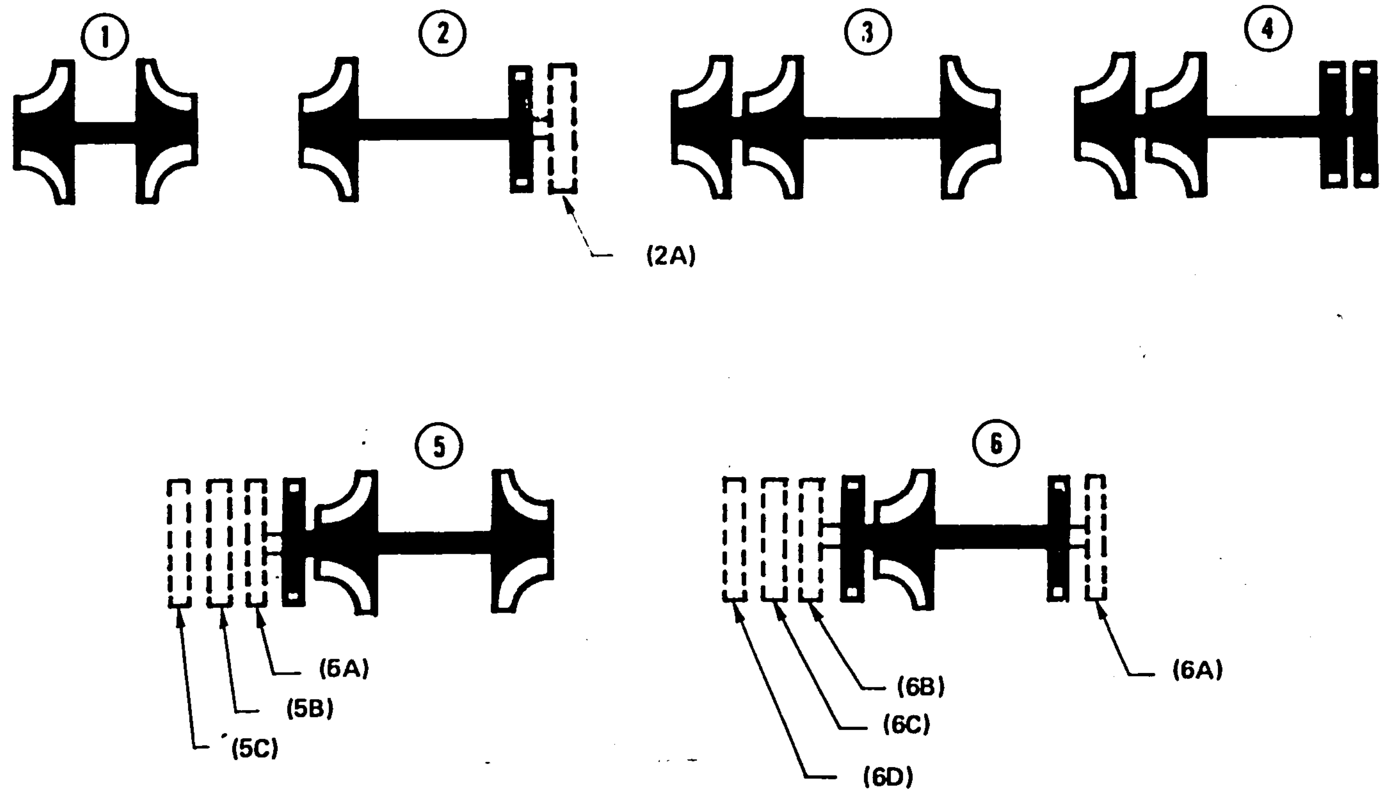


Figure 20. Candidate Free-Turbine Turboprops and Turboshafts and Two-Spool Turbofans

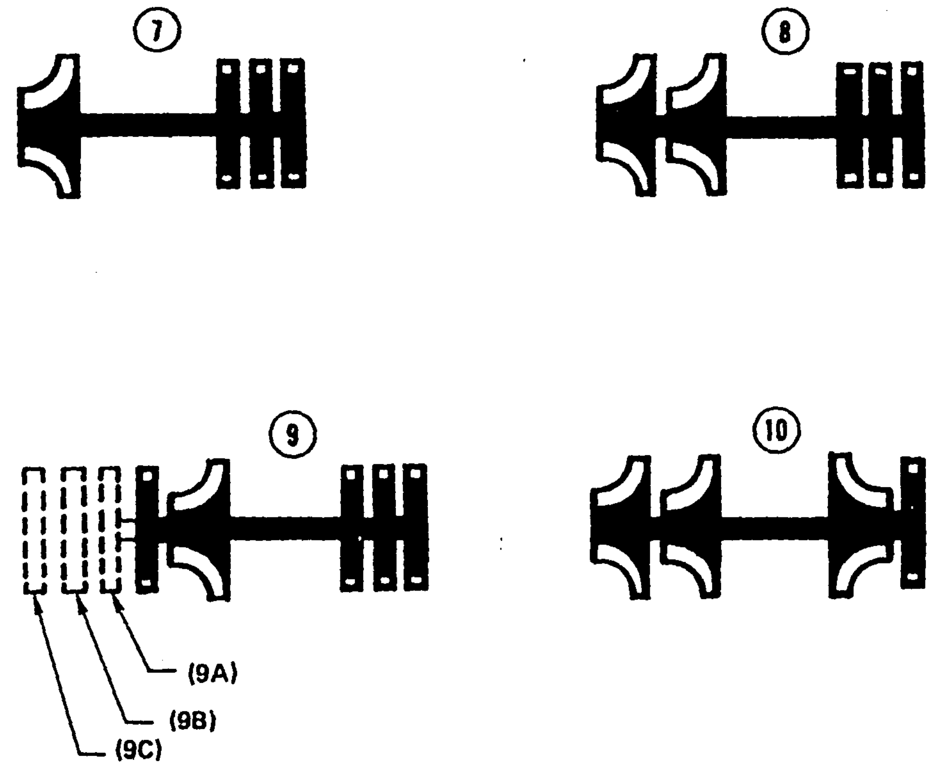


Figure 21. Candidate Single-Shaft Turboprop and Turbofan Gas Generators

shaft, low-pressure spool was the only configuration evaluated for the two-spool engines in Task II. This arrangement offers commonality among the turbofan, turboprop and turboshaft configurations and does not require special installation considerations. Low-pressure spool arrangements were limited to one- and two-stage turbines and, in the case of turbofans, to single-stage fan designs.

4.1.2 Advanced Technology

The advanced technology considered for the GATE engines is listed for each of the gas generator configurations in Figures 22 through 27.

4.1.2.1 Compressors

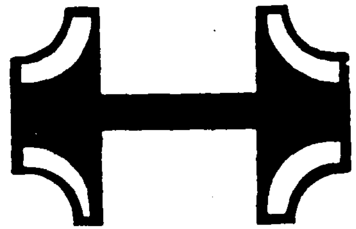
Three types of compressors were chosen for investigation, namely:

- Single-Stage Centrifugal
- Two-Stage Centrifugal
- Axial-Centrifugal

The single-stage centrifugal was evaluated over a pressure ratio range of 6 to 10. Materials and fabrication processes evaluated were:

- Cast Steel
- Cast Titanium
- Powder Metal Titanium (PM Ti)
- Powder Metal Titanium Aluminide
- Machined Titanium

The cast and powder metal approaches would allow use of sophisticated 3-D blading, while maintaining low cost.



COMPRESSOR

- P/P = 6-10
- CAST STEEL
- CAST TITANIUM
- PM TITANIUM
- PM Ti-Al
- MACHINED Ti

DIFFUSER

- CAST STEEL
- SHEET METAL
- PM Ti
- SINTERED PM VANES BRAZED TO CAST END WALLS
- DIE CAST STEEL
- CLEARANCE CONTROL

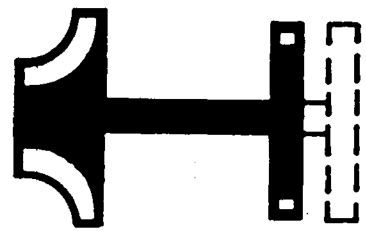
COMBUSTOR

- ANNULAR REVERSE FLOW
- 1255-1478°K (1800-2200°F)
- CERAMIC
- THERMAL BARRIER COATINGS
- ODS SHEET ALLOYS
- PHOTOETCHED/ LAMINATED CONSTRUCTION
- AIRBLAST NOZZLES

TURBINE

- 1255-1478°K (1800-2200°F) (COOLED AND UNCOOLED)
- CAST SUPERALLOY BLADE RING + PM SUPERALLOY HUB
- INTEGRAL CASTING
  - -AF2-IDA
  - -IN792 + H_f
- PM SUPERALLOY NET SHAPE
- LAMINATED SUPERALLOY
- THERMAL BARRIER COATING
- CERAMICS
- CLEARANCE CONTROL (ACTIVE AND PASSIVE)
- INTEGRAL-CAST DS BLADES EQUIAXED HUB

Figure 22. Gas Generator Configuration No. 1 Candidate Technology



COMPRESSOR

SEE FIGURE 22

DIFFUSER

SEE FIGURE 22

COMBUSTOR

SEE FIGURE 22

TURBINE

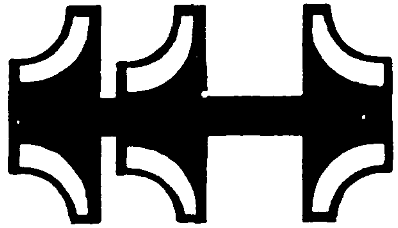
VANES

- LAMINATED SHEET ALLOY
- ODS EXTRUSIONS
- CERAMIC
- SUPERALLOY CASTINGS

BLADES

- INTEGRAL
  - CAST SUPERALLOY BLADES + PM SUPER-ALLOY HUB
  - CAST DS BLADES EQUIAXED HUB
  - CAST + HIP
  - LAMINATED
- INDIVIDUAL BLADES
  - DS BLADES
  - CONVENTIONAL CASTING
- SINGLE CRYSTAL
- CERAMIC

Figure 23. Gas Generator Configuration No. 2 Candidate Technology



COMPRESSOR		DIFFUSER		COMBUSTOR	TURBINE
1ST STAGE	2ND STAGE	1ST STAGE	2ND STAGE		
• P/P = 2.5-5.0	• P/P = 3.0-5.0	DIE-CAST ALUMINUM	SEE FIGURE 22	SEE FIGURE 22	SEE FIGURE 22
• CAST STEEL	SEE FIGURE 22				
• CAST TITANIUM					
• PM TITANIUM					
• PM Ti -Al					
• CAST ALUMINUM					
• MACHINED Ti					

Figure 24 Gas Generator Configuration No. 3 Candidate Technology

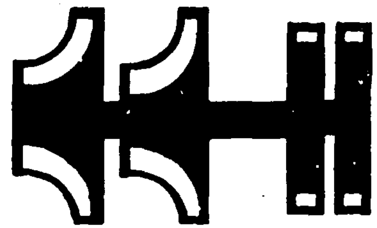
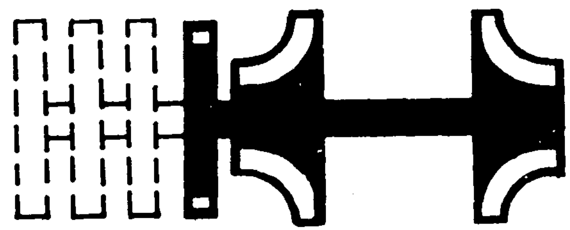
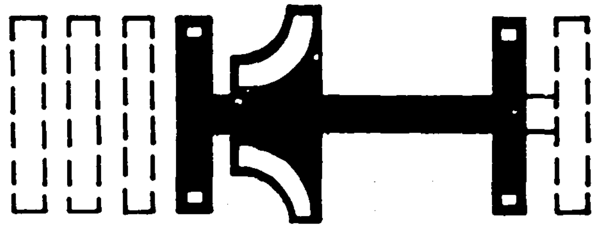


Figure 25. Gas Generator Configuration No. 4 Candidate Technology



COMPRESSOR		DIFFUSER	COMBUSTOR	TURBINE
AXIAL STAGES	CENTRIFUGAL STAGE			
• 1.2-1.4 P/P/STAGE • CAST INTEGRAL ROTORS AND STATORS • CAST INTEGRAL COMPRESSOR • PM Ti • PM Ti-Al	SEE FIGURE 22	SEE FIGURE 22	SEE FIGURE 22	SEE FIGURE 22

Figure 26. Gas Generator Configuration No. 5 Candidate Technology



COMPRESSOR	DIFFUSER	COMBUSTOR	TURBINE
SEE FIGURE 26	SEE FIGURE 22	SEE FIGURE 22	SEE FIGURE 23

Figure 27. Gas Generator Configuration No. 6 Candidate Technology

- Performance - Studies have shown that the powder metal approach would allow thinner blades and smaller radii and closer tolerances than casting approaches.

- Weight - The powder metal titanium approach would yield lower component weight as compared to cast steel designs. Cast titanium configurations would be competitive with PM Ti. Cast aluminum is not a candidate for the single-stage pressure ratios of 6 to 10.

- Cost - The cost of the cast configurations should be less than the PM Ti approach.

- Risk - The PM Ti approach, particularly for complex designs with a high number of blades and splitters, is considered high risk. The cast approach is lower risk but only if a lower performance level is accepted.

Machining the compressors is lower risk than either the cast or PM Ti approaches but is very expensive (2 to 4 times) particularly when compound curvature is required.

The two-stage centrifugal compressor was evaluated over a pressure-ratio range of approximately 8 to 16. Cast aluminum was considered for the first stage in addition to the materials and processes considered for the single-stage centrifugal compressor.

The axial-centrifugal compressor was evaluated over a pressure-ratio range of 8 to 16. Candidate materials and manufacturing approaches are:

- Cast integral rotors and stators (aluminum, steel, and, titanium)

- Cast integral compressor

- Powder-metal titanium rotors

- Powder-metal titanium aluminide rotors

4.1.2.2 Diffusers

Four types of diffusers were considered for the GATE engines:

- Vane island
- Vane
- Multi-vane
- Pipe

Trade-off studies included performance and cost. Materials and manufacturing processes included:

- Cast steel and titanium
- Powder metal (PM) titanium
- Sheet metal construction
- Sintered PM vanes brazed to cast or sheet metal side plates

The first-stage diffuser for the two-stage centrifugal compressor is die-cast aluminum. The selection was based on extensive trade-off studies conducted for the TPE331 Engine series.

4.1.2.3 Combustors

Annular, reverse-flow combustors operating at temperatures from 1255°K to 1478°K (1800°F to 2200°F) were evaluated. Materials considered for the combustors included:

- Hastelloy X
- HS188
- ODS sheet alloys
- Ceramics

Thermal barrier coatings and photoetched/laminated construction techniques were investigated.

4.1.2.4 Turbines

Gas generator turbines operating at rotor inlet temperatures of 1255°K to 1478°K (1800°F to 2200°F) were evaluated. At 1478°K (2200°F), the rotor and vane are cooled. At 1311°K (1900°F) the vane requires cooling and at 1255°K (1800°F) the turbine is uncooled.

Candidate materials and fabrication processes are:

- Integral castings using AF2-1DA and IN792 plus hafnium
- Integral PM superalloy net shape
- Laminated superalloy
- Ceramics

Turbine vane candidate materials and processes are:

- Photoetched/laminated superalloy sheet
- ODS extrusions
- Cast and hot-isostatic-pressed superalloy
- Ceramics

Axial turbine rotor candidate materials and processes include:

- Exothermic DS blades and powder metal superalloy hub.

- MAR-M 247 integral casting (DS blades and equiaxed hub).
- Hot-isostatic-pressed MAR-M 247 integral casting.
- Photoetched/laminated superalloy sheet.
- Ceramics.

4.1.2.5 Fans

Low cost and satisfactory performance in the fan component requires a low-cost manufacturing approach coupled with a mechanical design/materials approach that will meet bird ingestion requirements and allow the elimination of mid-span dampers. A pinned blade attachment appeared most promising as a mechanical design approach to satisfy the bird ingestion requirements without mid-span dampers. Material and fabrication approaches considered for the fan blades included:

- PM titanium
- PM steel
- Composite
- Cast steel
- Forged aluminum
- Forged steel
- Forged titanium

Material and fabrication approaches for the fan disk included:

- PM titanium
- PM steel

4.1.2.6 Low-Pressure Turbine

The low-pressure (LP) turbine configuration selected for all engines was an uncooled, shrouded, axial, cast design. Casting approaches considered were:

- o Investment
- o Rubber mold
- o AiRefrac*

Other variations that were considered in the LP turbine design were:

- o Elimination of tip shrouds
- o One piece casting of multi-stage turbine
- o Hot Isostatic Press (HIP) castings for improved properties and higher yield.

4.1.2.7 Gearboxes

In addition to conventional gears and housings, the following variations were evaluated:

- o Laser-hardened gears
- o Traction drives

4.2 Baseline Engine Design

Engine trade-off studies, which will be discussed in more detail in a later section, were conducted on a sensitivity basis. Changes in component performance, weight, and cost were related to

*Proprietary Process, AiResearch Casting Co.

changes in engine performance, cost, and weight, which in turn were related to changes in airplane performance, cost, and weight.

The sensitivities were derived for baseline engines and for airplanes sized using the baseline engines. Three baseline engines were designed. They included a turboprop, turboshaft, and turbofan. The three engines had a common core, which was selected on the basis of prior studies.

4.2.1 Turboprop Baseline

4.2.1.1 Description

A cross section of the turboprop baseline is shown in Figure 28. It is a two-spool, concentric-shaft, front-drive configuration comprised of a single-stage centrifugal compressor driven by a cooled single-stage radial turbine, a reverse-flow annular burner, a low-pressure two-stage axial uncooled turbine, and an offset two-stage reduction gearbox. The accessory gearbox is driven off the high-pressure spool and the engine is controlled by a low-cost, digital, electronic fuel control. In the component descriptions which follow, reference is made to current technology for comparison. Current technology is defined as that technology which could be committed to engineering development in 1978. As such, it is more advanced than technology in current production engines.

Characteristics of the single-stage centrifugal compressor are listed in Table 12. Three-dimensional blading is employed and the impeller is machined from a titanium forging.

The diffuser consists of 36 diffuser vanes followed by 58 deswirl vanes. Sheet metal construction is used.

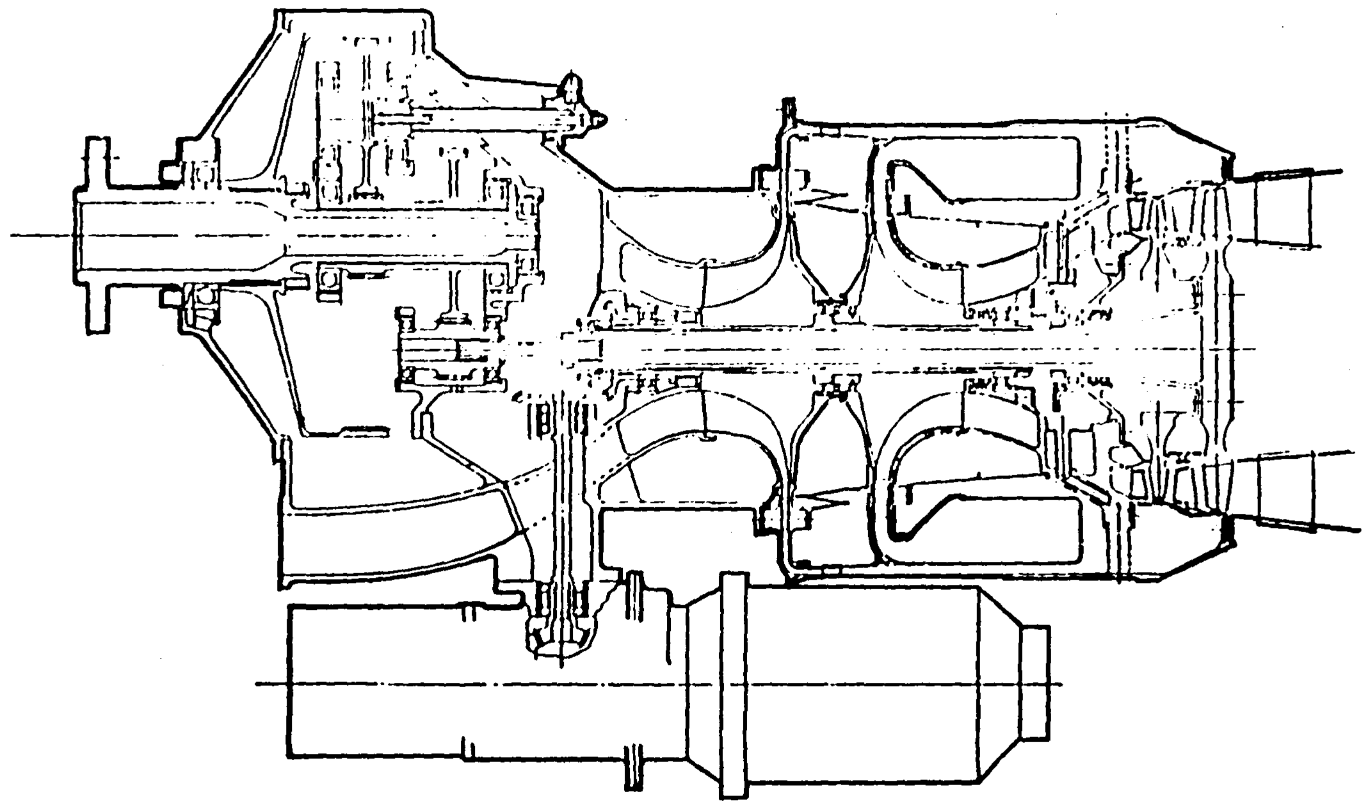


Figure 28. Baseline Turboprop Engine Design

TABLE 12. BASELINE TURBOPROP - COMPRESSOR CHARACTERISTICS

6100 m (20,000 ft), 389 km/hr 210 Knots, Max. Power

Type	Centrifugal
Tip Speed	661 m/sec (2166 ft/sec)
Pressure Ratio	9.0
Relative* Efficiency	+3.5 points
Axial Clearance	0.013 cm (0.005 in.)
Corrected Inlet Flow	1.30 kg/sec (2.87 lb/sec)
Impeller Exit Mach No.	1.199
Diffuser Exit Mach No.	0.15
No. of Blades (full)	20
No. of Splitters	20
Compressor Diameter	27.196 cm (10.707 in.)

*Relative to current technology 9:1 pressure ratio, single-stage, centrifugal compressor

Characteristics of the reverse-flow annular combustor are shown in Table 13. The combustor is rolled and welded from Inco 617. Ten airblast fuel nozzles investment cast in Hastelloy X are required. The operating temperature of this combustor is approximately 311°K (100°F) higher than current technology.

The turboprop baseline high-pressure turbine design is summarized in Table 14. The stator is an investment cast and brazed assembly of MAR-M 509. The rotor is machined from an AF2-1DA forging. Cooling passages are stem drilled (electrostream). The exducer is investment cast from MAR-M 247.

Design characteristics of the low-pressure turbine are listed in Table 15. The first-stage vane of the LP turbine is an integral investment casting in IN738 and the first-stage rotor is an integral investment casting in IN792. The second-stage vane and rotor are integrally cast from IN738. Both stages have integral shrouds.

4.2.1.2 Baseline Turboprop Cycle and Performance

The baseline turboprop cycle was selected based on prior studies and cycle selection studies performed in Task I. Cycle characteristics and performance at the engine design point (6100 m [20000 feet], 389 km/hr. [210 knots] true airspeed) and at sea-level static, standard day conditions, are shown in Table 16. A standard off-design thermodynamic model was used to predict engine performance throughout the flight envelope. This model includes representations of component performance, thermodynamic routines, and matching procedures.

4.2.1.3 Baseline Turboprop Weight and Cost

Detailed estimates of turboprop baseline engine weight and cost were not available at the point in the program when baseline engine data (size, weight, performance, and cost) was required for

TABLE 13. BASELINE TURBOPROP - COMBUSTOR CHARACTERISTICS

Sea Level Static, Standard Day, Maximum Power

Type	Reverse-Flow Annular
Inlet Pressure	78.12 N/cm^2 (113.3 psia)
Inlet Temperature	571.2°K (1028.1°R)
Inlet Flow	1.093 kg/sec (2.407 lb/sec)
Combustor Exit Temperature	1522°K (2739.7°R)
Temperature Rise	950.9°K (1711.6°R)
Reference Velocity	6.85 m/sec (22.47 ft/sec)
Heat Release Rate	617 $J/sec/m^3/Pa$ (6.04 $Btu/hr/atm/ft^3 \times 10^6$)
Pattern Factor	0.20
Liner Cooling, % Wa	42
Pressure Drop, % $\Delta P/P$	3.0
Efficiency	0.985

TABLE 14. TURBORPROP BASELINE HIGH-PRESSURE TURBINE CHARACTERISTICS

6100 m (20,000 ft), 389 km/hr (210 Knots), Max Power

Type	Radial
Specific Corrected Work, $\Delta H/\theta$	60,406 J/kg (25.97 Btu/lb)
Stage Work Coefficient, $\lambda_s = \frac{gJ\Delta H}{U_{tip}^2}$	0.914
Pressure Ratio (total-total)	2.492
Relative* Efficiency	+5.5 Points
Tip Speed	583 m/sec (1910 ft/sec)
Rotor Cooling Flow, % Wa	3.5
Exit Mach No., V/a'_{cr}	0.33
Clearance	0.038 (0.015 in.)
No. Blades	14
No. Vanes	17
Rotor Inlet Temperature	1477.6°K (2659.7°R)

*Relative to a current technology cooled axial turbine at equal work.

TABLE 15. BASELINE TURBOPROP LP TURBINE CHARACTERISTICS

6100 m (20,000 ft.), 389 km/hr (210 Knots), Maximum Power

Type	Axial
No. Stages	2-1/2
Specific Corrected Work, $\Delta H/\theta$	82,433 J/kg (35.44 Btu/lb)
Mean Work Coefficient, $\lambda_m = \frac{gJ\Delta H}{U_m^2}$	2.3
Pressure Ratio	3.8
Tip Speed	320.5 m/sec (1051 ft/sec)
Relative* Efficiency	+6 Points
Exit Mach No.	0.35
Clearance	0.038 cm (0.015 in.)
No. Blades	32
No. Vanes	33
Inlet Temperature	1209°K (2176.4°R)
Hub-to-Tip Radius Ratio, Exit	0.698

*Relative to a current technology uncooled, axial, two-stage turbine at equal work coefficient.

TABLE 16. TURBOPROP BASELINE CYCLE AND PERFORMANCE CHARACTERISTICS, UNINSTALLED

Altitude	6100 m (20,000 ft)	Sea Level
Speed	389 km/hr. (210 knots)	Static
Power Setting	Maximum Power	Maximum Power
Temperature	Standard	Standard
Shaft Power	239 kw (320 hp)	353 kw (473 hp)
Shaft Specific Fuel Consumption	0.278 kg/hr/kw (0.455 lb/hr/hp)	0.311 kg/hr/kw (0.511 lb/hr/hp)
Corrected Airflow	1.33 kg/sec (2.94 lb/sec)	1.22 kg/sec (2.693 lb/sec)
Net Jet Thrust	-15.13 N (-3.4 lb)	87.67 N (19.7 lb)
Compressor Pressure Ratio	9.0	8.3
Turbine Inlet Temperature	1478°K (2200°F)	1478°K (2200°F)
Nozzle Pressure Ratio	1.016	1.010
Gas Generator Speed, RPM	63,161	64,050
LP Spool Speed, RPM	28,000	28,000
Interturbine Pressure Drop, % $\Delta P/P$	1.0	1.0
Overboard Leakage, % Wa	0.5	0.5

C-2

airplane sizing and sensitivity studies. The goals established in Task I for cost and weight were therefore used. For the 353 kw (473 hp) baseline engine, this OEM cost goal was 60 dollars per kilowatt (45 dollars per horsepower). The weight goal for the baseline engine was 123 kg (270 lb). This goal, which translates to a relatively modest power-to-weight ratio, was set to allow meaningful tradeoffs with respect to cost. Detailed estimates, performed later in the program, resulted in a significantly lower weight.

4.2.2 Turboshaft Baseline

The turboshaft baseline had the same core and LP turbine design as the turboprop. The output gearbox was eliminated. It could be argued that the turboshaft cycle based on a single-stage centrifugal compressor would benefit from a slightly higher pressure ratio of approximately 10. This slight difference did not justify, however, the definition of a new baseline turboshaft. The turboshaft baseline engine is shown in Figure 29. Performance and component characteristics are identical to those previously listed for the baseline turboprop.

4.2.3 Turbofan Baseline

4.2.3.1 Description

A cross section of the turbofan baseline is shown in Figure 30. It is a two-spool, concentric-shaft, geared-fan, separately exhausted configuration. The gas generator or high-pressure spool is comprised of a single-stage centrifugal compressor driven by a cooled, single-stage radial turbine and a reverse-flow annular burner. The low-pressure spool is comprised of a single-stage axial fan driven by an uncooled, two-stage axial turbine through a simple, offset, reduction gearbox. The accessory gearbox is driven off the high-pressure spool and the engine is controlled by a low-cost, digital electronic fuel control.

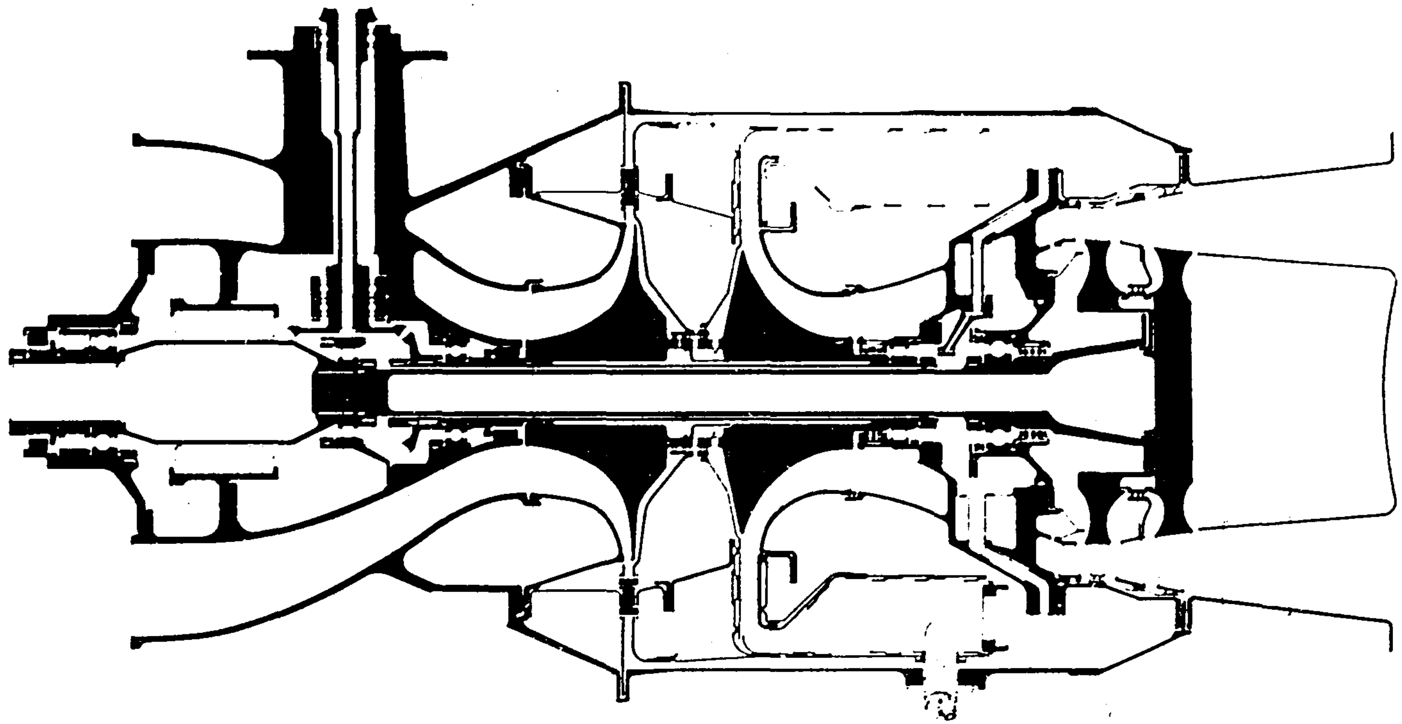


Figure 29. Turboshaft Baseline Engine - TSE Model 1060-1

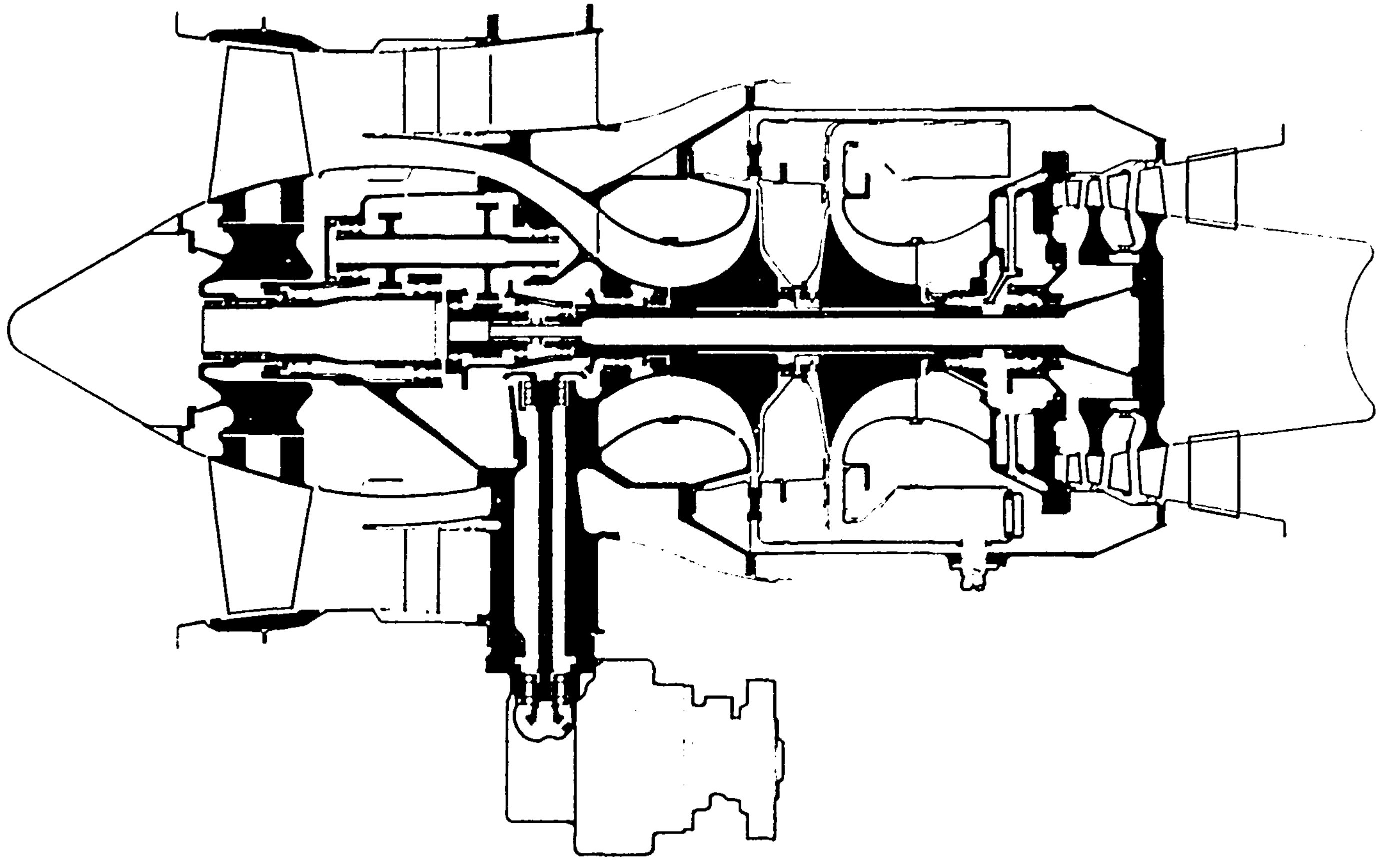


Figure 30. Turbofan Baseline Engine TFE Model 1054-2

The characteristics of the fan are shown in Table 17. The single-stage fan is comprised of a forged titanium hub and pinned, forged, titanium blades and stators.

The compressor is a 1.3:1 scale of the turboprop baseline compressor. Its characteristics are shown in Table 18.

The turbofan baseline combustor is a scale of the turboprop baseline combustor and its characteristics are listed in Table 19.

The high-pressure turbine is a scaled version of the turboprop high-pressure turbine and its characteristics are shown in Table 20.

The low-pressure (LP) turbine is a scaled version of the turboprop baseline LP turbine and its characteristics are identical to those listed in Table 15.

4.2.3.2 Baseline Turbofan Cycle and Performance

The baseline turbofan cycle was selected on the basis of commonality with the turboprop baseline gas generator and on the basis of prior studies and cycle selection work performed in Task I. Cycle characteristics and performance at the engine design point (6100m [20,000 feet], 389 km/hr [210 knots] true airspeed) and at sea-level static, standard day conditions, are shown in Table 21.

4.2.3.3 Baseline Turbofan Weight and Cost

The OEM cost and weight targets established in Task I were used for the turbofan baseline. The data, which was revised later in Task II, was found to be conservative. The Task I targets for the turbofan OEM cost and weight were \$6.74/N (\$30/lb) of thrust and 134 kg (296 lb), respectively.

TABLE 17. TURBOFAN BASELINE FAN CHARACTERISTICS

6100 m (20,000 Ft.), 389 km/hr (210 Knots), Maximum Power

Inlet Corrected Flow	21.08 kg/sec (46.43 lb/sec)
Bypass Ratio	8.0
Bypass Pressure Ratio	1.5
Core Pressure Ratio	1.5
Corrected Tip Speed	381 m/sec (1250 ft/sec)
Relative* Efficiency	+1.5 Points
Hub-Tip Radius Ratio	0.452
Fan Speed, rpm	15,739
No. of Blades	17
No. of Stators	39

*Relative to a current technology 1.5 pressure ratio, single-stage fan.

TABLE 18. TURBOFAN BASELINE COMPRESSOR CHARACTERISTICS

6100 m (20,000 Ft), 389 km/hr (210 Knots), Maximum Power

Type	Centrifugal
Tip Speed	648 m/sec (2124 ft/sec)
Pressure Ratio	9.0
Relative* Efficiency	+3.5 points
Axial Clearance	0.013 cm (0.005 in.)
Corrected Inlet Flow	1.69 kg/sec (3.73 lb/sec)
Impeller Exit Mach No.	1.199
Diffuser Exit Mach No.	0.15
No. of Blades (Full)	20
No. of Splitters	20
Compressor Diameter	31.01 cm (12.21 in.)

*Relative to current technology 9:1 pressure ratio, single-stage, centrifugal compressor.

TABLE 19. TURBOFAN BASELINE COMBUSTOR CHARACTERISTICS

SEA LEVEL STATIC, STANDARD DAY, MAX. POWER

Type	Reverse-Flow Annular
Inlet Pressure	109.9 N/cm^2 (159.5 psia)
Inlet Temperature	637.7°K (1147.8°R)
Inlet Flow	1.901 kg/sec (4.187 lb/sec)
Combustor Exit Temperature	1522.1°K (2739.7°R)
Temperature Rise	884.4°K (1591.9°R)
Reference Velocity	8.42 m/sec (27.6 ft/sec)
Heat Release Rate	638.94 $J/sec/m^3/Pa$ (6.25 $btu/hr/atm/ft^3 \times 10^6$)
Pattern Factor	0.20
Liner Cooling, % Wa	42
Pressure Drop, % ΔP/P	3.0
Efficiency	0.985

TABLE 20. TURBOFAN BASELINE HIGH-PRESSURE TURBINE

6100 m (20,000 Ft.), 389 km/hr (210 Knots), Maximum Power

Type	Radial
Specific Corrected Work, $\Delta H/\theta$	65,221 J/kg (28.04 Btu/lb)
Stage Work Coefficient, $\lambda_s = \frac{gJ\Delta H}{U_{TIP}^2}$	0.909
Pressure Ratio (total-to-total)	2.708
Relative* Efficiency	+5.5 Points
Tip Speed	607 m/sec (1990 ft/sec)
Rotor Cooling Flow, % Wc	3.6
Exit Mach No., V/a'_{cr}	0.33
Clearance	0.038 cm (0.015 in.)
No. of Blades	14
No. of Vanes	17
Rotor Inlet Temperature	1477.6°K (2659.7°R)

*Relative to a current technology, cooled, axial turbine at equal work.

TABLE 21. TURBOFAN BASELINE CYCLE AND PERFORMANCE

Altitude	6100m (20,000 ft)	Sea Level
Speed	389 km/hr (210 kts)	Static
Temperature	Standard	Standard
Net Thrust, lb	1740 N (391 lb)	4294 N (965 lb)
Thrust Specific Fuel Consumption	0.061 kg/N-hr (0.601 lb/hr/lb)	0.041 kg/N-hr (0.402 lb/hr/lb)
Fan Inlet Corrected Flow	21.10 kg/sec (46.48 lb/sec)	18.75 kg/sec (41.3 lb/sec)
Core Corrected Flow	1.69 kg/sec (3.73 lb/sec)	1.58 kg/sec (3.49 lb/sec)
Fan Pressure Ratio	1.5	1.4
Compressor Pressure Ratio	9.0	8.2
Turbine Inlet Temperature	1478°K (2200°F)	1478°K (2200°F)
Bypass Ratio	8.0	8.0
Compressor Speed, RPM	58,014	59,117
Fan Speed, RPM	15,736	15,075
Fan Duct $\Delta P/P$	0.025	0.025
Fan Nozzle Thrust Coefficient	0.985	0.985
Core Nozzle Thrust Coefficient	0.985	0.985

4.3 Aircraft Sizing and Sensitivity Studies

The definition of fixed-wing aircraft characteristics was subcontracted to Cessna Aircraft Company. Their task was to define the general requirements and detailed characteristics of the airplanes selected for study in Task II, namely, the pressurized twin and the light twin. The characteristics of turboprop- and turbofan-powered pressurized twins were defined. Two variations of the turbofan-powered aircraft were investigated, namely, an aft-fuselage-mounted engine and a wing-mounted engine. The characteristics as defined by Cessna were based on their experience and engine data provided by AiResearch. Also, Cessna supplied weight and drag correlations, which allowed the weight and drag breakdowns to be adjusted as mission performance and airplane synthesis was accomplished. During Task II, the General Aviation Synthesis Program (GASP) was used by AiResearch to size the aircraft and establish the power requirements and wing loading. The planform drag buildup and weight breakdown were not altered from those supplied by Cessna except as dictated by (1) the correlations for the effects of gross weight and wing loading, and (2) the modifications necessary to allow modeling the airplanes in GASP. In the latter case, Cessna was consulted and recommended the required modifications. Advanced technology airplanes were not defined. The designs provided by Cessna were slight extensions of current fixed-wing aircraft. Additional airframe advanced technology could be postulated for 1988 but it would be more difficult to separate the improvements due to the engine and those due to the advanced technology airframe.

The general characteristics and performance requirements of the designs supplied by Cessna are shown in Tables 22 and 23.

Design numbers were assigned for each of the airplanes, namely:

TABLE 22. GENERAL AIRCRAFT CHARACTERISTICS - GATE STUDY

Design No. Description Engine Type	1 Pressurized Twin Turbofan	1A Pressurized Twin Turbofan	2 Pressurized Twin Turboprop	4 Light Twin Turboprop
Estimated SHP/Thrust Class	6675N (1500 lbs)	→	373 kw (500 hp)	224 kw (300 hp)
Estimated Weights				
Gross	2860 kg (6300 lbs)	→	→	→
Empty	1544 kg (3400 lbs)	→	→	1317 kg (2900 lbs)
Approximate Wing Area	$16.7 m^2$ ($180 ft^2$)	→	→	→
Seating (Including Pilot)				
Maximum	6	→	→	→
Normal	6	→	→	→
Cabin Volume	$4.6 m^3$ ($165 ft^3$)	→	→	$3.6 m^3$ ($130 ft^3$)
Cabin Pressure Differential	$3.24 N/cm^2$ (4.7 psi)	→	→	0

TABLE 23. PERFORMANCE REQUIREMENTS - FIXED-WING AIRCRAFT - GATE PROGRAM

Design No.	1	1A	2	4
Speed				
Maximum	482 km/hr (260 kts)	→	→	444 km/hr (240 kts)
Maximum Cruise	444 km/hr (240 kts)	→	→	417 km/hr (225 kts)
Range*				
At Maximum Cruise	1556 km (840 NM)	→	→	2037 km (1100 NM)
At Speed for Min DOC**	1945 km (1050 NM)	→	→	2408 km (1300 NM)
Payload (Including Pilot)	518 kg (1140 lb)	→	→	345 kg (760 lb)
Service Ceiling				
Twin Engine	9150 m (30000 ft)	→	→	6100 m (20000 ft)
Single Engine	4575 m (15000 ft)	→	→	2135 m (7000 ft)
Rate of Climb				
Twin Engine (SL Std)	488 m/min (1600 ft/min)	→	→	→
Single Engine (SL Std)	92 m/min (300 ft/min)	→	→	→
Takeoff Distance (Flaps 0.255 rad (15 deg), SL Std)				
Ground Run	458 m (1500 ft)	→	→	336 m (1100 ft)
To 15 m (50 ft) Altitude	671 m (2200 ft)	→	→	488 m (1600 ft)
Landing Distance (Flaps 0.51 rad (30 deg))				
Ground Roll	259 m (850 ft)	→	→	229 m (750 ft)
From 15 m (50 ft) Altitude	610 m (2000 ft)	→	→	458 m (1500 ft)

*At 5490 m (18000 ft) for Nos. 1, 1A and 2, and 3050 m (10000 ft) for No. 4.

**Direct Operating Cost

- o Turbofan-Powered, Pressurized Twin (wing mounted) - Design 1

- o Turbofan-Powered, Pressurized Twin (aft fuselage mounted)- Design 1A

- o Turboprop-Powered, Pressurized Twin - Design 2

- o Turboprop-Powered, Light Twin - Design 4

Detailed fixed-wing airplane characteristics as defined by Cessna are listed in Appendix II. The characteristics as supplied formed the basis for modeling the pressurized twin and light twin for the General Aviation Synthesis Program (GASP) used for airplane sizing, mission analysis, and sensitivity studies.

4.3.1 Fixed-Wing Aircraft Sizing and Mission Analysis

Airplane sizing and mission analysis were performed assuming fixed mission performance requirements and varying airplane takeoff gross weight (TOGW), wing loading (W/S), and engine size to meet the mission requirements. The characteristics as supplied by Cessna were not varied except as required for changes in TOGW, W/S, and engine size. Specifically, wing and empennage geometric characteristics, fuselage dimensions, standard and optional equipment, and the high-lift system were unchanged. Wing area varied as TOGW and W/S were varied.

The weight breakdown as supplied by Cessna varied in the following groups:

- Wing
- Vertical Tail
- Horizontal Tail
- Main Gear
- Nose Gear
- Controls
- Retraction System

The following weight groups were not allowed to vary:

- Power Plant
- Nacelle
- Fuselage
- Standard Equipment
- Furnishings
- Exterior Finish
- Optional Equipment

The fuselage weight remains constant since its size is fixed by cabin volume, which is a function of the number of passengers. The nacelle and power plant group would have been varied as engine size varied. However, GASP contained routines for resizing the nacelle and associated equipment, which gave optimistic results. To avoid a major modification of GASP, engine weight was fixed and the results were adjusted at a later point in the study, based on engine weight sensitivities. The standard equipment group and optional equipment does not vary with gross weight for a particular aircraft category. Furnishings and exterior finish were also assumed to be fixed weights.

The drag polar, as supplied by Cessna, varied as the airplane was resized to account for change in wing area and a change in the relationship of aircraft wetted area to wing area. The change is consistent with the Cessna drag buildup.

Engine size varied as gross weight and wing loading varied. The wing loading initially supplied by Cessna was an estimate and was iterated to find the wing loading that resulted in the lowest gross weight while meeting all mission requirements.

Aircraft and engine sizing was accomplished by the General Aviation Synthesis Program (GASP). Installed engine performance maps based on the baseline engine off-design deck were utilized. Assumed engine installation losses were as follows:

	Pressurized Twin		Light Twin
	TFE	TPE	TPE
Bleed Air, kg/min/eng	2.0	2.0	0
(lb/min/eng)	(4.5)	(4.5)	0
Power Extraction, kw/eng	3.7	3.7	3.7
(hp/eng)	(5)	(5)	(5)
Total Pressure Recovery Ratio	0.995	1.0	1.0

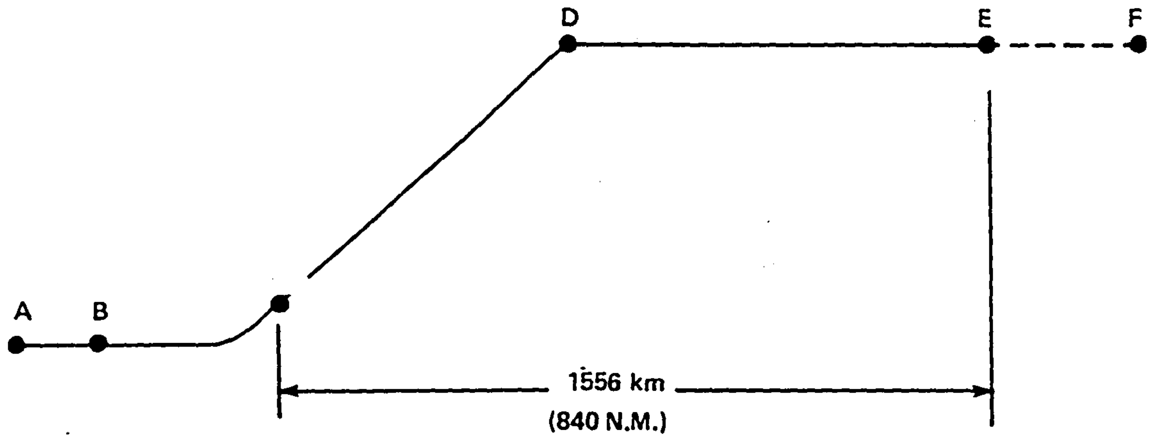
The bleed air rate decreased linearly at the rate of 0.23 kg/min/eng/305m (0.5 lb/min/eng/10,000 feet). The propeller efficiency, weight, and price were calculated by the propeller routine contained in GASP. These parameters were computed for a three-bladed propeller based on a fixed rotational speed and diameter of 2500 rpm and 1.9m (6.2 ft), respectively. The design characteristics of the propeller are:

Activity factor/blade	115
Design lift coefficient	0.5
Number of blades	3
Efficiency (cruise)	0.87

4.3.1.1 Pressurized Twin

Mission requirements for the Pressurized Twin (Designs 1, 1A, and 2) are shown in Figure 31. Airplanes were sized by GASP at wing loadings of 137 to 205 kg/m^2 (28 to 42 lb/ft^2). At each wing loading evaluated, the aircraft were sized to meet takeoff, cruise, and range requirements. Climb performance, landing distance, and service ceiling were evaluated as a function of wing loading.

The results of the wing loading study for Design No. 2 (turboprop medium pressurized twin) are shown in Figures 32 through 35. At each wing loading shown in these figures, the requirements of takeoff distances are met or exceeded and all wing loadings meet the range requirement of 1556 km (840 nm) at 5490 m (18,000 feet) and 444 km/hr (240 knots). A wing loading of 185 kg/m^2 (38.0 lb/ft^2) was selected on the basis of meeting the single-engine service ceiling requirement of 4575m (15,000 ft), as shown in Figure 32. At 4575 m (15,000 ft), a wing loading of 185 kg/m^2 (38.0 lb/ft^2) is the highest wing loading that allows a 31 m/min (100 ft/min) rate of climb. This figure also shows that the twin-engine rate of climb at 9150 m (30,000 ft) exceeds 31 m/min (100 ft/min) at all wing loadings. Figure 33 shows the variation of takeoff distance with wing loading. Below approximately 200 kg/m^2 (41 lb/ft^2), takeoff requirements are exceeded and the engines are sized by the cruise requirement. Above 200 kg/m^2 (41 lb/ft^2) the engines are sized to provide sufficient power for takeoff. Figure 34 shows the variation of installed power at sea level, static, standard day, takeoff power as a function of wing loading. At the selected wing loading, power is near minimum. Figure 35 shows the variation of gross weight and fuel consumed versus wing loading. Lower gross weights would result if a higher wing loading was selected but fuel consumption is close to minimum. At the selected wing landing, climb and landing requirements were exceeded.



SEGMENT	DESCRIPTION
A - B	TAXI - 5 MINUTES AT IDLE
B - C	TAKEOFF
C - D	CLIMB TO 5490m (18,000 FT)
D - E	CRUISE AT 5490m, 444 km/hr (18,000 FT, 240 kts)
E - F	RESERVES - 45 MINUTES AT CRUISE CONDITIONS

MISSION PERFORMANCE REQUIREMENTS (STD DAY)

SPEED
482 km/hr (260 kts) MAXIMUM

RATE-OF-CLIMB
SINGLE ENGINE, SL, MAX - 92m/min (300 FT/MIN)
TWIN ENGINE, SL, MAX - 488m/min (1600 FT/MIN)

FIELD PERFORMANCE (SL)
GROUND RUN - 458m (1500 FT)
TO 50 FT ALTITUDE - 671m (2200 FT)

SERVICE CEILING
SINGLE ENGINE - 4575m (15,000 FT)
TWIN ENGINE - 9150m (30,000 FT)

Figure 31. Mission Requirements - Pressurized Twin (Designs 1, 1A, and 2).

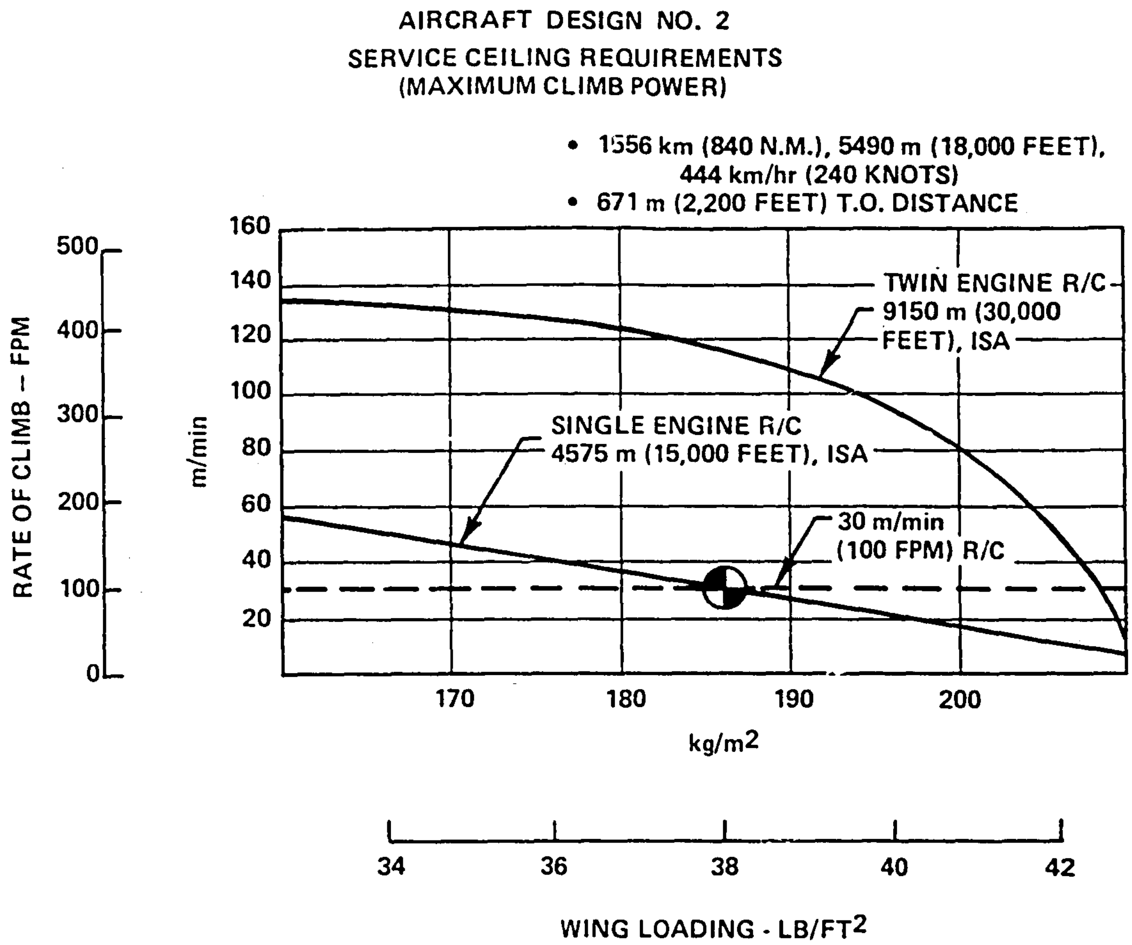


Figure 32. Turboprop-Powered Pressurized Twin.

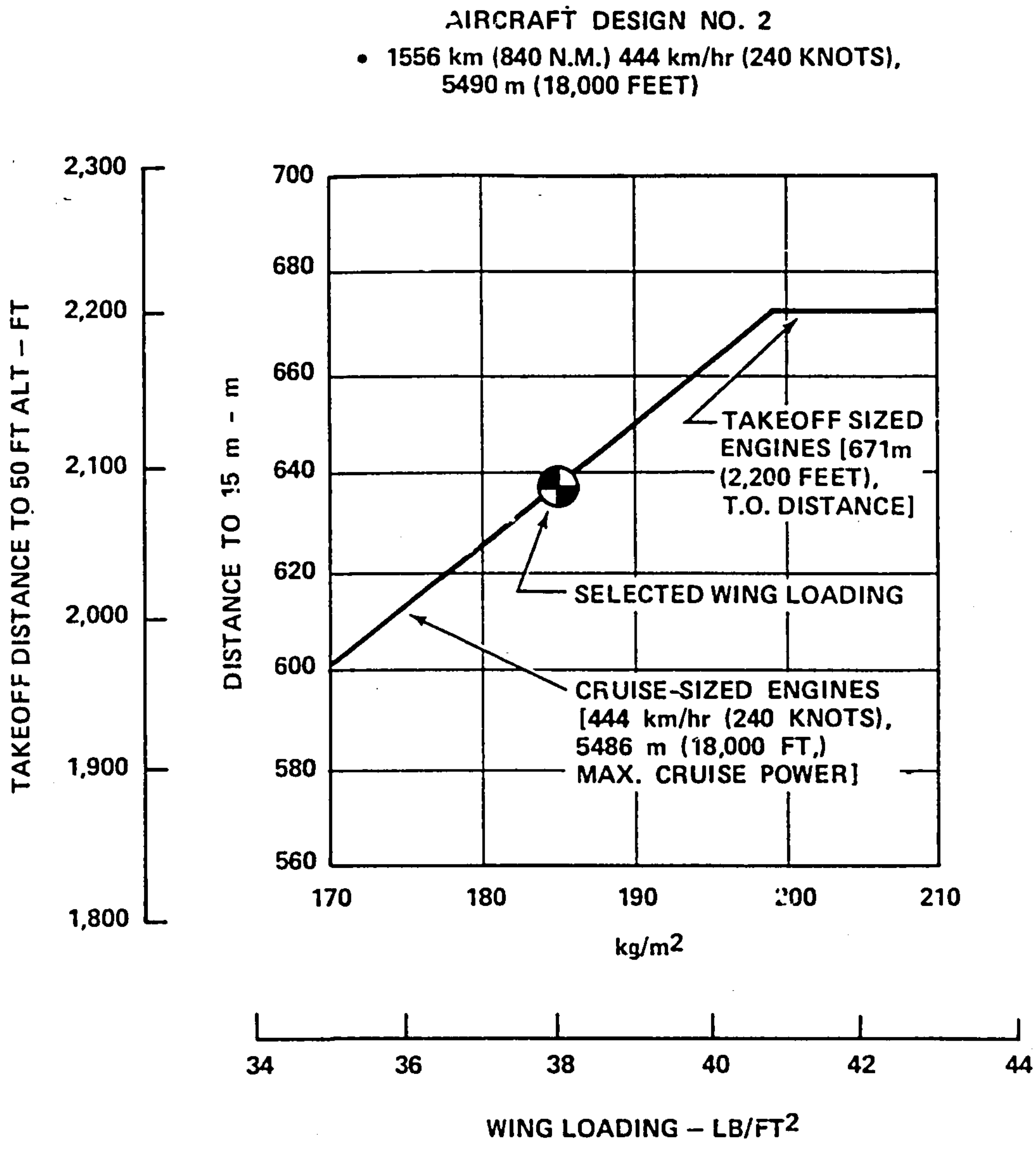


Figure 33. Turboprop-Powered Pressurized Twin-Engine Sizing

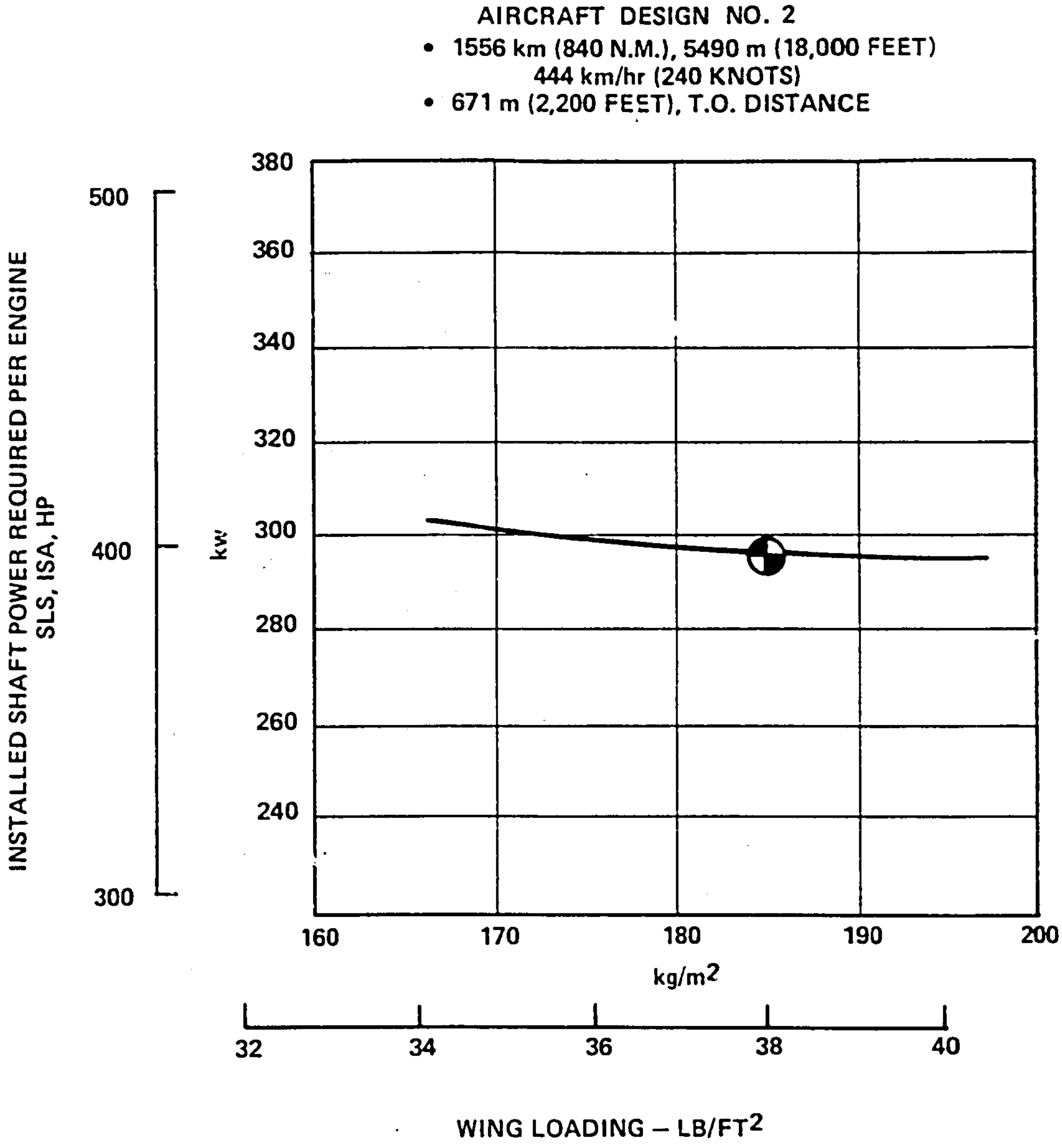


Figure 34. Turboprop-Powered Pressurized Twin-Engine Sizing

AIRCRAFT DESIGN NO. 2

- 1556 km (840 N.M.), 5490 m (18,000 FEET), 444 km/hr (240 KNOTS)
- 671 m (2,200 FEET), T.O. DISTANCE

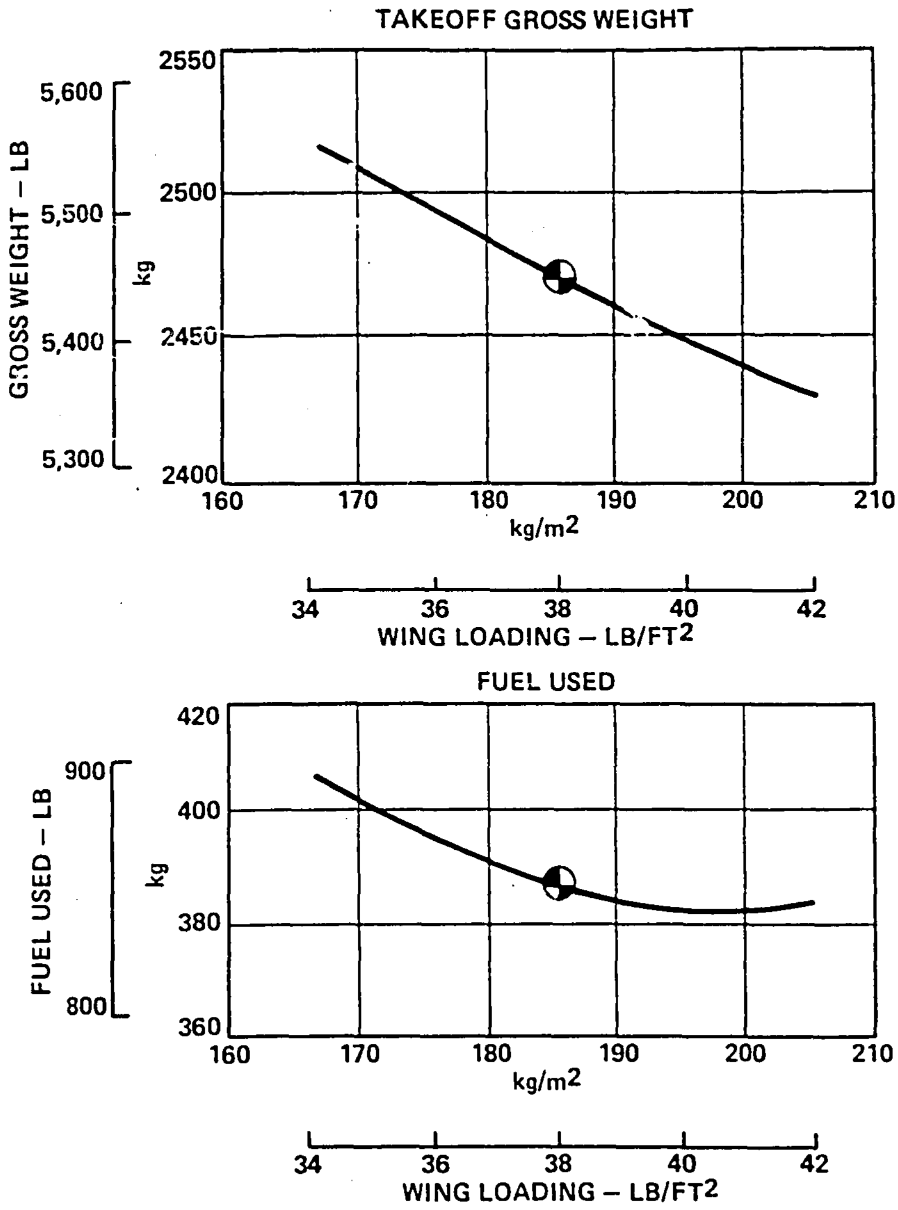


Figure 35. Turboprop-Powered Medium Twin Sizing.

For the turbofan-powered pressurized twins (Design No. 1), all wing loadings above approximately 155 kg/m^2 (32 lb/ft^2) allowed service ceiling and rate-of-climb requirements to be met. All wing loadings investigated resulted in acceptable landing performance. Figure 36 shows that acquisition cost is minimum at a wing loading of approximately 150 kg/m^2 (31 lb/ft^2), which is too low for performance requirements. Operating cost is minimum at approximately 165 kg/m^2 (34 lb/ft^2), as shown on Figure 37. Fuel consumption is minimum at approximately 185 kg/m^2 (38 lb/ft^2), as shown in Figure 38. The best compromise did not appear to be significantly different from the wing loading originally chosen by Cessna, namely 167 kg/m^2 (34.23 lb/ft^2).

Characteristics and performance of the turbofan- and turboprop-powered pressurized twins are shown in Table 24. At the selected wing loading, both configurations meet or exceed the maximum speed requirement of 482 km/hr (260 knots). There is a large difference between the turbofan- and turboprop-powered aircraft in gross weight, cruise fuel consumption, total mission fuel and engine core size required. For the speed and takeoff requirements of this application, the turboprop-powered configuration is clearly superior.

The effects of relaxed field performance and high-altitude cruise were investigated for the turbofan configuration. The results are also shown in Table 24. Takeoff distance was increased to 862 m (2800 ft) and the airplane was allowed to cruise at 7625 m (25,000 ft). The difference between the turboprop and turbofan versions decreases, although the turboprop is still superior. The range requirement on the turbofan was increased to 1637 km [884 NM (+5 percent)] to offset the increased altitude since the turboprop would also cruise more efficiently at 7625m (25,000 ft). Further improvements in the turbofan configuration may be possible if

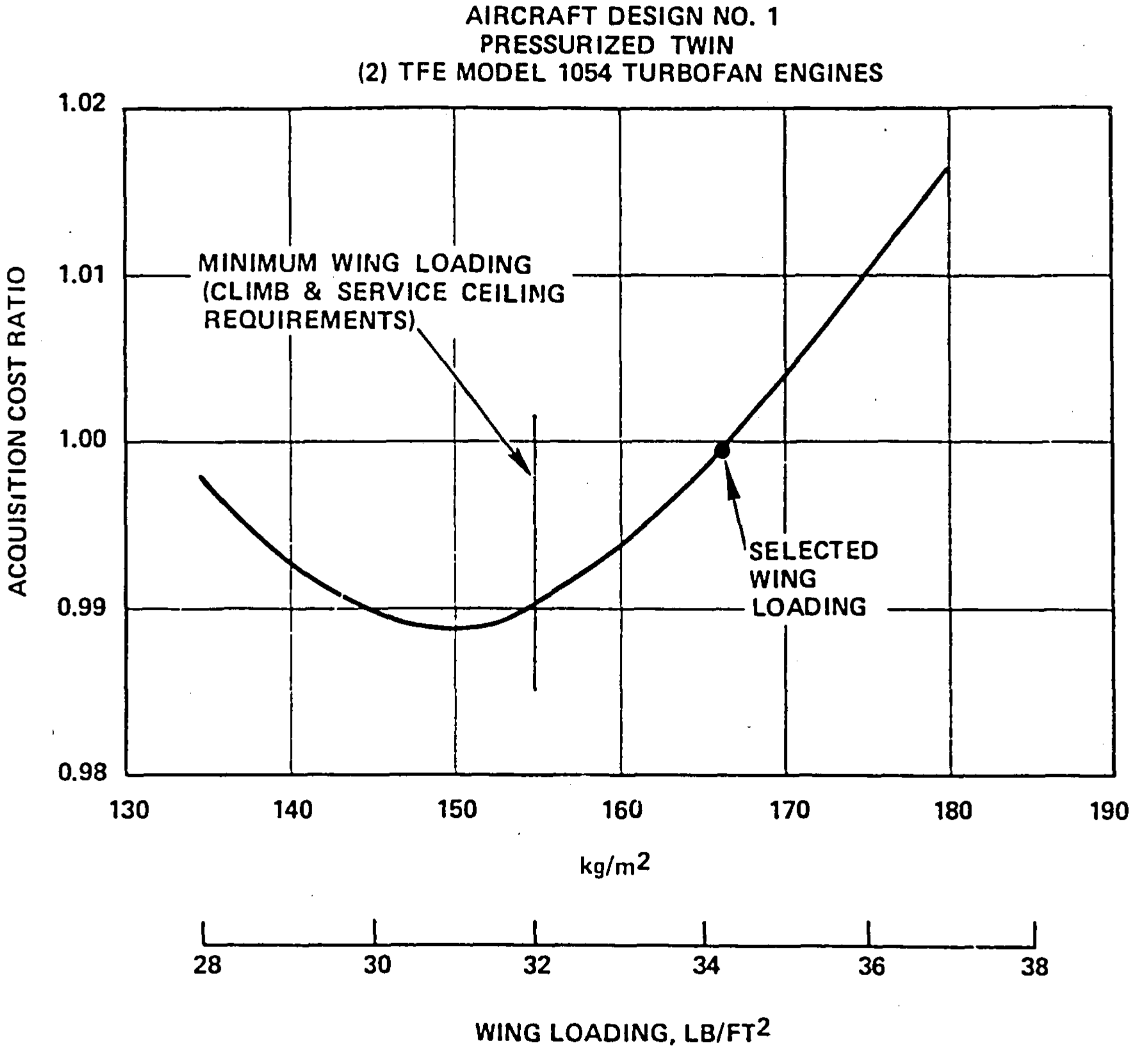


Figure 36. Relationship of Acquisition Cost to Wing Loading for Aircraft Design No. 1

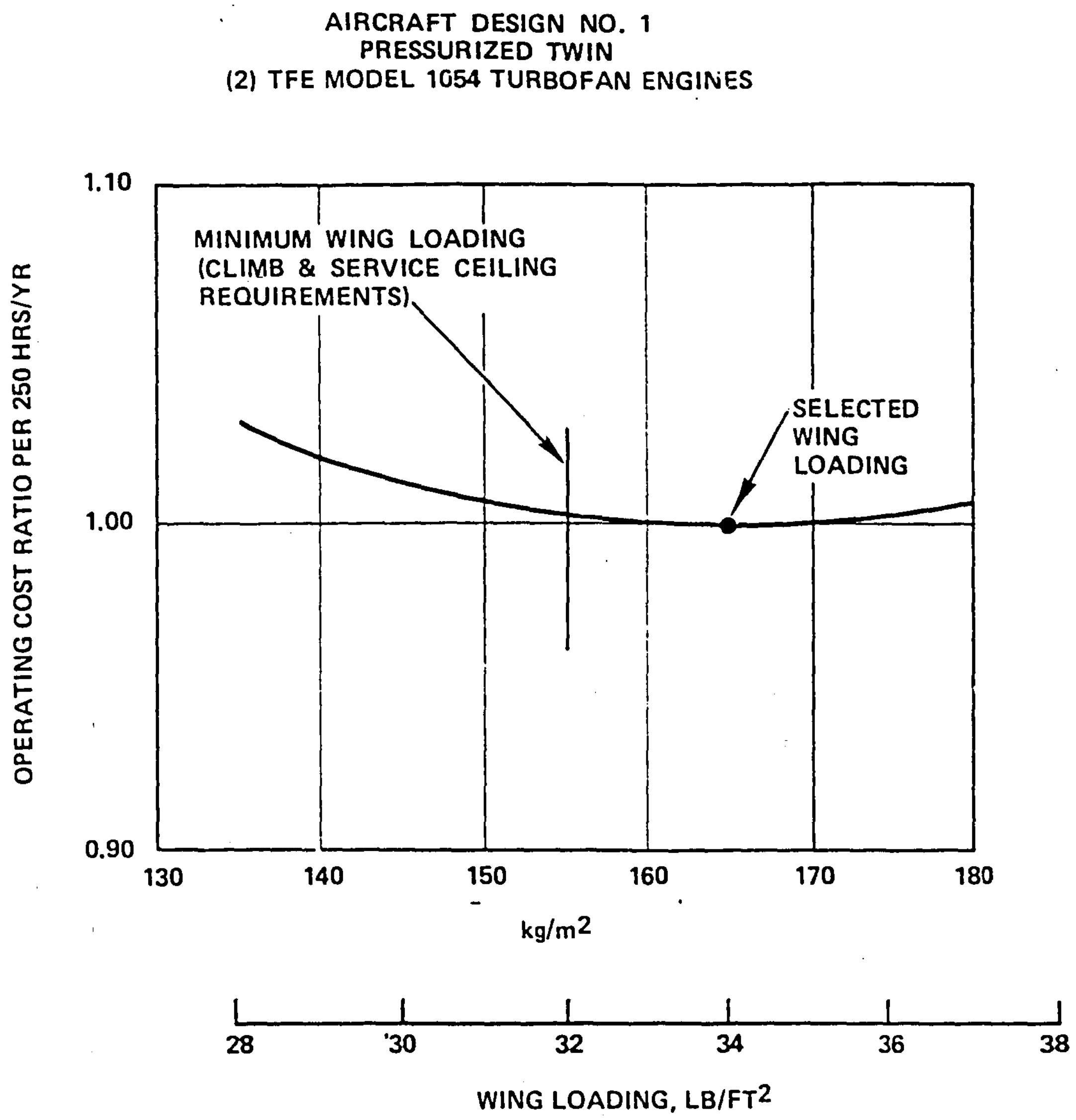


Figure 37. Relationship of Operating Cost to Wing Loading for Aircraft Design No. 1

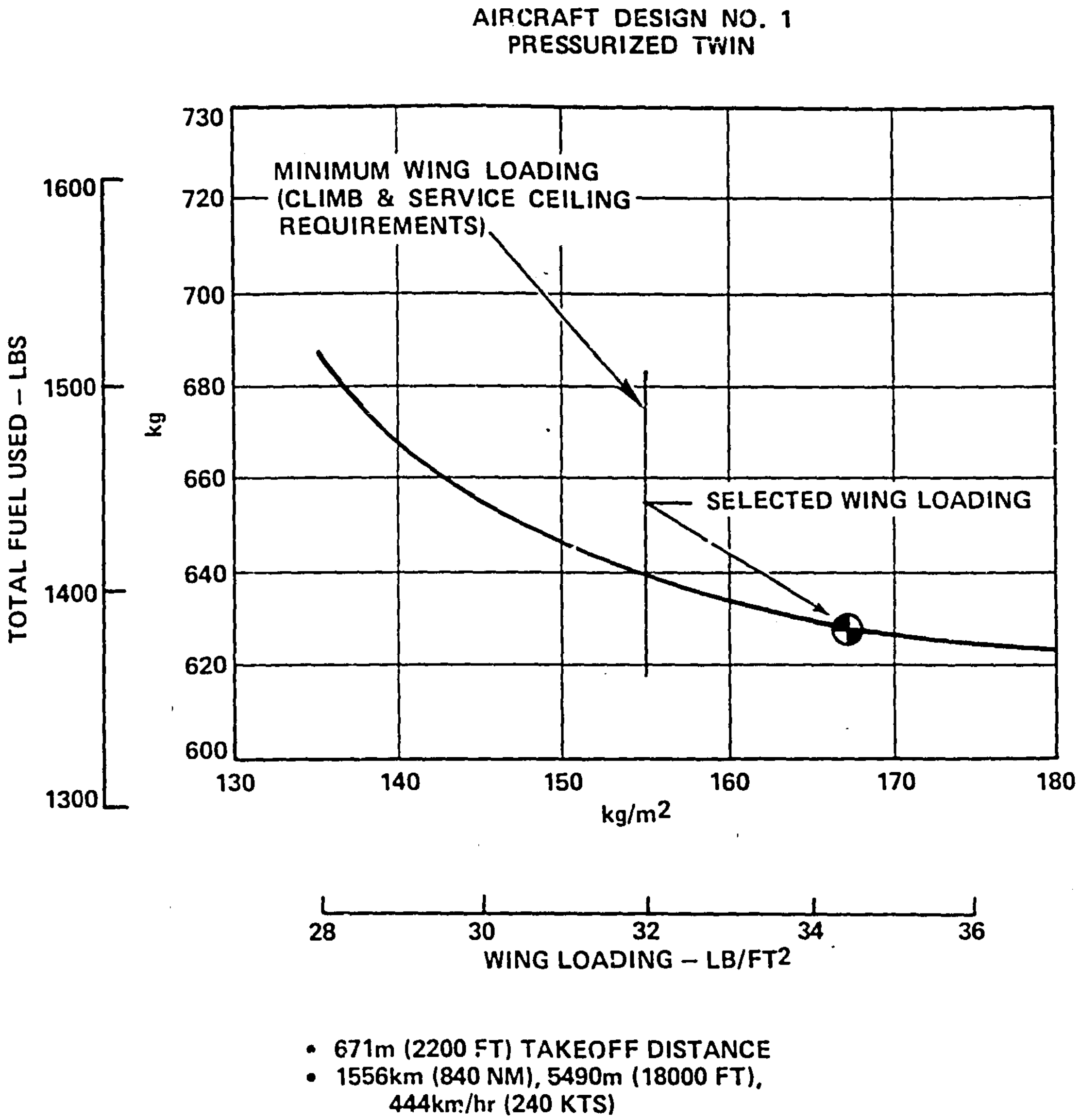


Figure 38. Mission Fuel Consumption

TABLE 24. AIRCRAFT SIZING SUMMARY

Aircraft Type Engine Type	Pressurized Twin Turbofan	Pressurized Twin Turboprop	Alternate Mission Pressurized Twin Turbofan
Takeoff Gross Weight	2825 kg (6223 lb)	2470 kg (5441 lb)	2706 kg (5960 lb)
Empty Weight	1550 kg (3413 lb)	1485 kg (3271 lb)	1524 kg (3357 lb)
Wing Loading	167 kg/m^2 (34.2 lb/ft^2)	185 kg/m^2 (38.0 lb/ft^2)	167 kg/m^2 (34.2 lb/ft^2)
Maximum Speed/Altitude	50[illegible]/6100 km/hr/m (275/20,000 kts/ft)	482/5490 km/hr/m ([illegible]50/18,000 kts/ft)	Not Available
Range at Cruise Speed/Altitude	1556 km (840 nm)	1556 km (840 nm)	1637 km (884 nm*)
Rate of Climb, 2 Engines	547 m/min (1795 ft/min)	607 m/min (1991 ft/min)	Not Available
Takeoff to 15m (50 ft), Std Day	649 m (2128 ft)	641 m (2100 ft)	854 m (2800 ft)
Cruise Fuel Consumption	212 l/hr (56.0 gal/hr)	132 l/hr (34.7 gal/hr)	171 l/hr (45 gal/hr)
Block Fuel	782 liters (206.4 gal)	492 liters ([illegible]27.2 gal)	694 liters (183 gal)
Engine SLS Takeoff Power/Thrust/Eng**	4895 N (1100 lb)	336 kw (450 hp)	3627 N (815 lb)
Engine SLS Core Airflow	1.81 kg/sec (3.9[illegible] lb/sec)	1.16 kg/sec (2.56 lb/sec)	1.34 kg/sec (2.95 lb/sec)

444 km/hr (240 kts), 7,625 m (25,000 ft)
**Uninstalled

cruise speed was increased. However, the resulting airplane is out of the category of the pressurized twin and cost could escalate sharply.

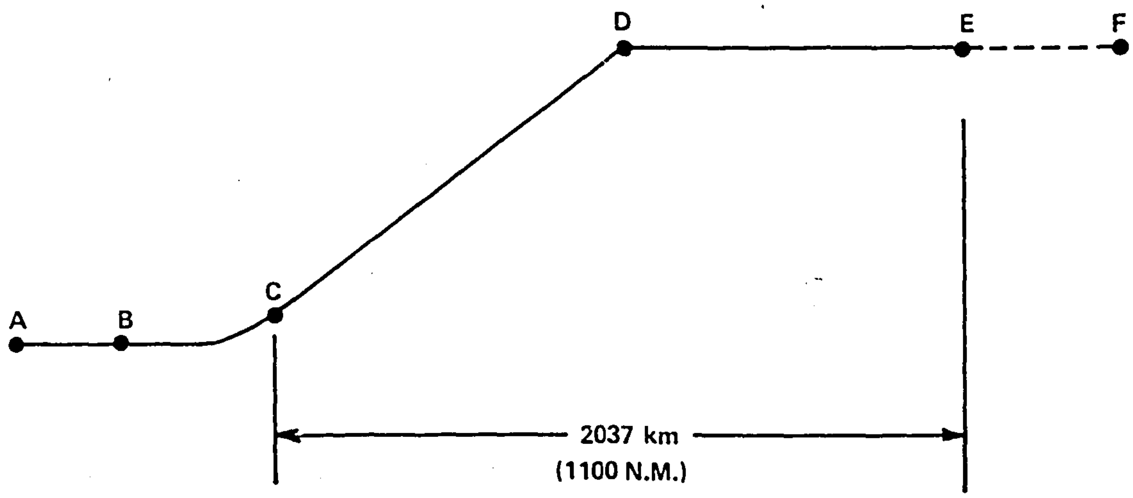
The comparison indicates that a competitive turbofan in this and smaller categories is unlikely unless takeoff distance is increased, cruise speed and altitude are raised, and the cost of sophisticated high-lift systems is acceptable.

4.3.1.2 <u>Light Twin</u>

Mission requirements for the light twin are shown in Figure 39. Airplanes were sized by GASP at wing loadings of 112 to 146 kg/m^2 (23 to 30 lb/ft^2) to meet takeoff, cruise, and range requirements. Climb performance, landing distance, and service ceiling were evaluated as a function of wing loading.

The results of this study for Design No. 4, the light twin, are summarized in Figures 40 through 42. All performance requirements were exceeded over the range of wing loadings investigated [112 to 146 kg/m^2 (23-30 lb/ft^2)]. The selection was therefore based on gross weight, fuel consumption, and engine size. On this basis, a wing loading of 139 kg/m^2 (28.4 lb/ft^2) was selected. This selection results in minimum gross weight, engine size, and fuel consumption. The variation of these parameters with wing loading is shown in Figures 40 and 41. Figure 42 shows the variation of takeoff distance with wing loading. At wing loadings below the selected value of 139 kg/m^2 (28 lb/ft^2), the engines are cruise sized. At higher wing loadings, the engines are takeoff sized.

Characteristics and performance of the light twin are shown in Table 25. At the selected wing loading, the airplane meets the 445 km/hr (240 knots) maximum speed requirement.



SEGMENT	DESCRIPTION
A - B	TAXI – 5 MINUTES AT IDLE
B - C	TAKEOFF
C - D	CLIMB TO 3048m (10,000 FEET)
D - E	CRUISE AT 3048m (10,000 FEET) 417 km/hr (225 KNOTS)
E - F	RESERVES - 45 MINUTES AT CRUISE CONDITIONS

MISSION PERFORMANCE REQUIREMENTS (STD DAY)

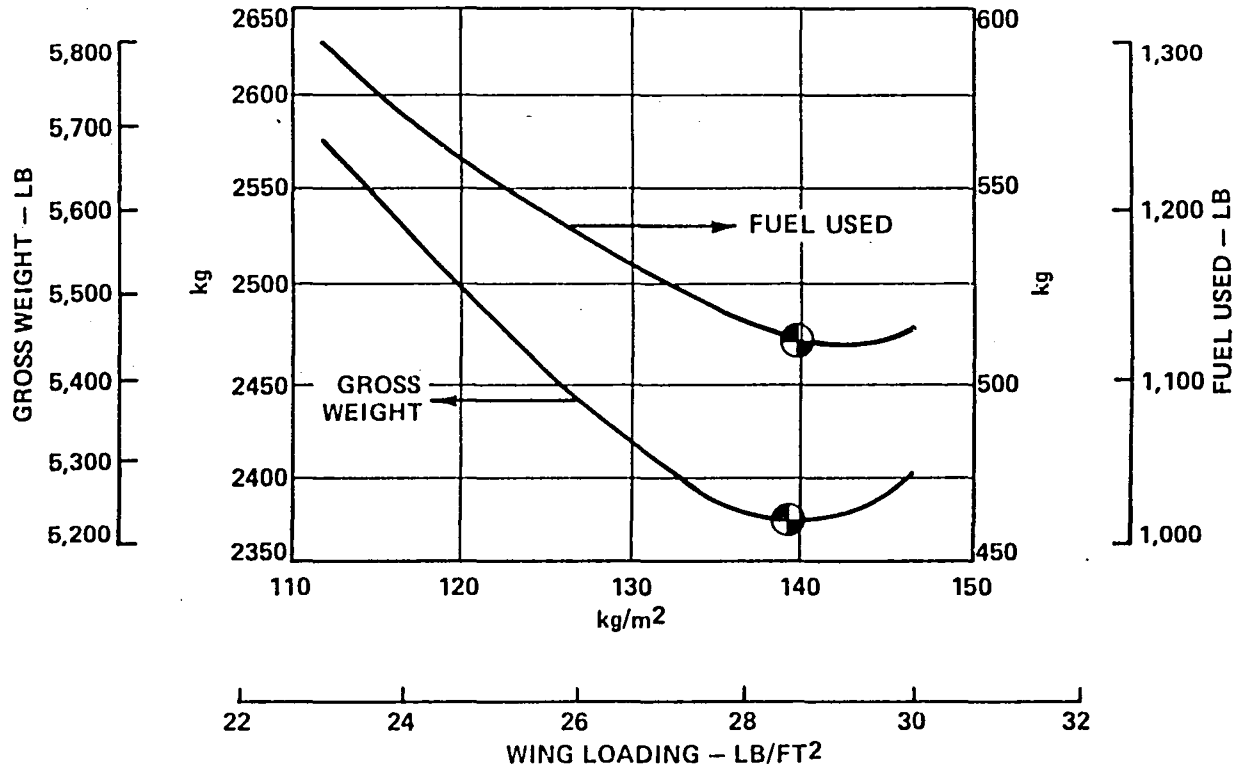
SPEED
444 km/hr (240 KNOTS) MAXIMUM

RATE-OF-CLIMB
SINGLE ENGINE, SL, MAX 92m/min (300 FT/MIN)
TWIN ENGINE, SL, MAX 488m/min (1600 FT/MIN)

FIELD PERFORMANCE (SL)
GROUND RUN 336m (1100 FEET)
TO 50 FT ALTITUDE 488m (1600 FT)

SERVICE CEILING
SINGLE ENGINE - 2135m (7000 FEET)
TWIN ENGINE - 6100m (20,000 FEET)

Figure 39. Mission Requirements - Light Twin



SIZED FOR
- RANGE - 2037 KM (1,100 NM) AT 3048M (10,000 FT) AND 417 KM/HR (225 KNOTS)
- T.O. DISTANCE OF 488M (1600 FT)

Figure 40. Turboprop Light Twin

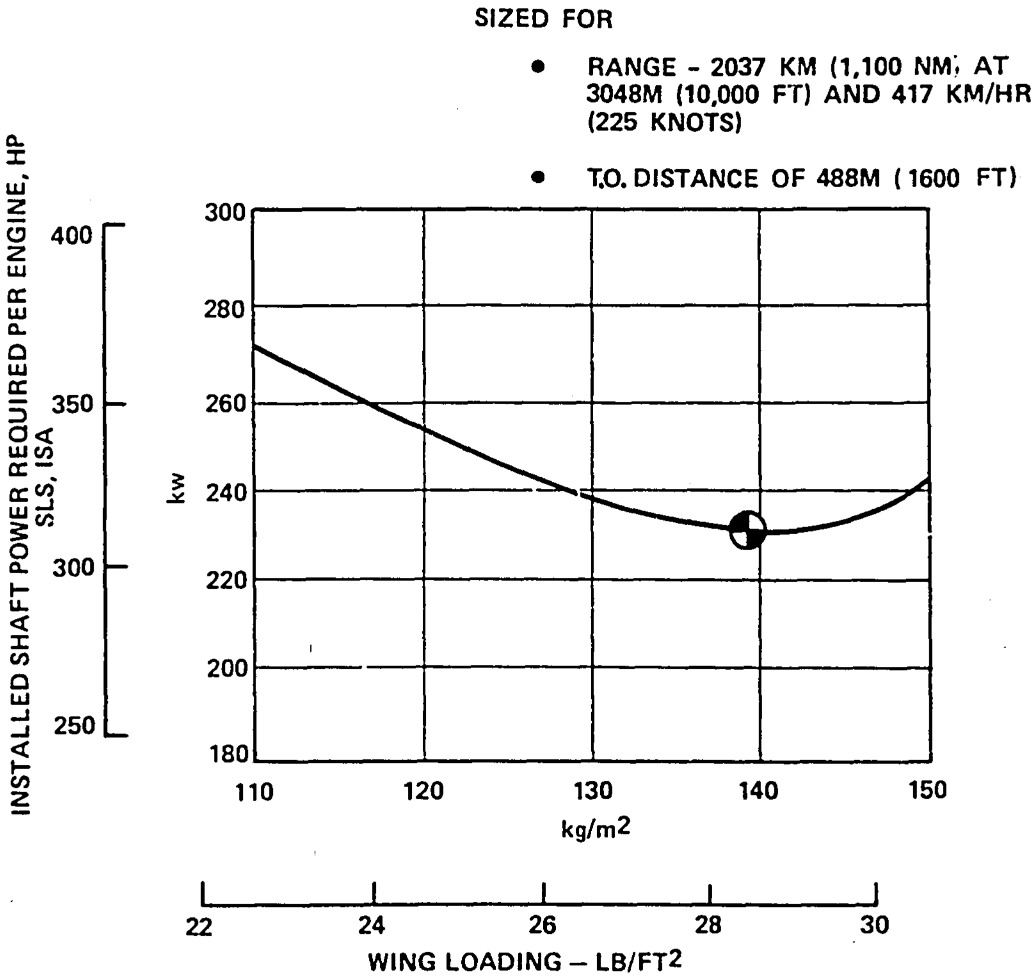


Figure 41. Turboprop-Powered Light-Twin Engine Sizing

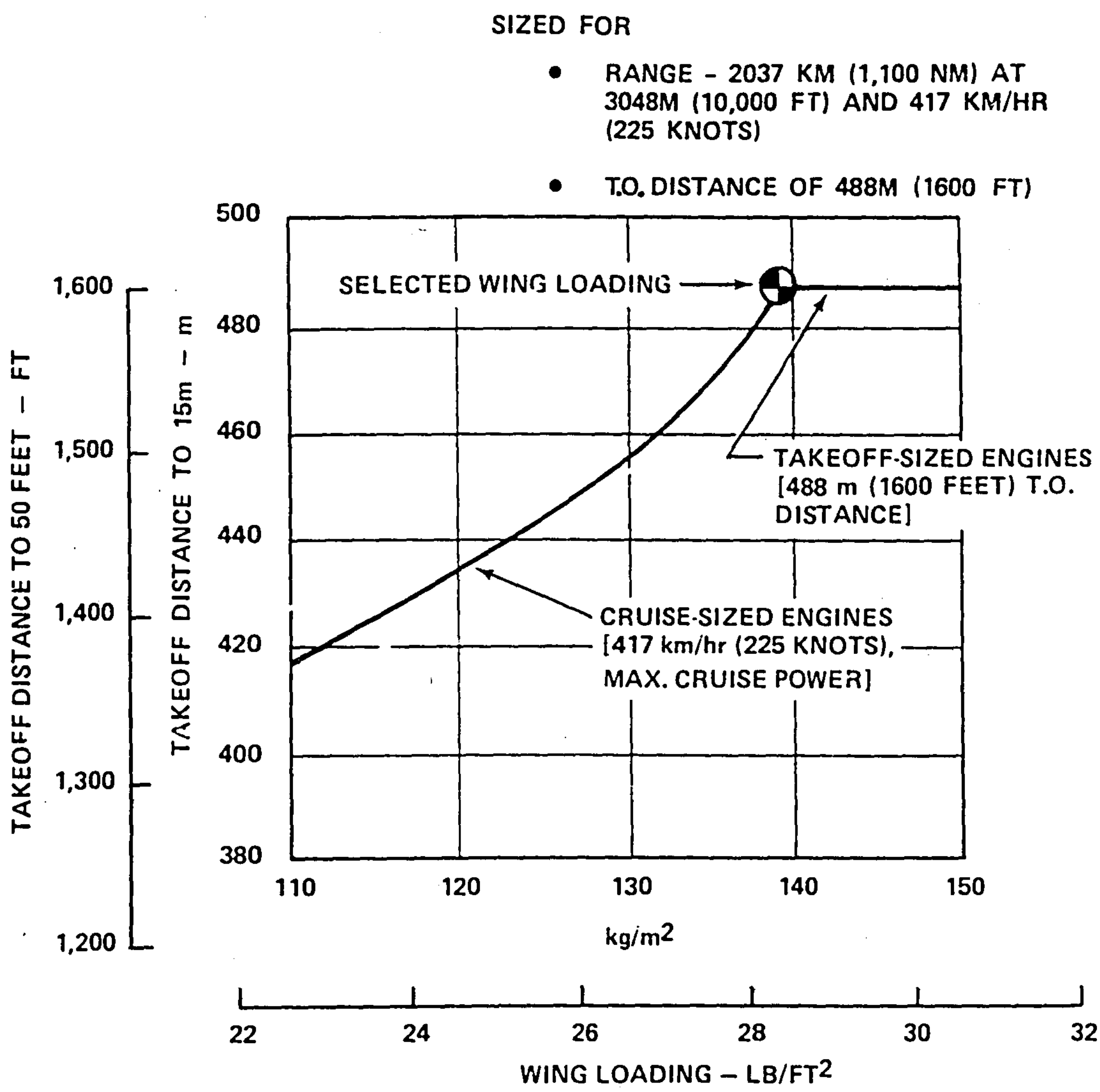


Figure 42. Turboprop Light-Twin Engine Sizing

TABLE 25. LIGHT-TWIN SIZING SUMMARY

Aircraft Type	Light Twin
Engine Type	Turboprop
Takeoff Gross Weight	2374 kg (5228 lb)
Empty Weight	1352 kg (2978 lb)
Wing Loading	139 kg/m^2 (28.4 lb/ft^2)
Maximum Speed/Altitude	444 km/hr - 3050m (240 kts - 10,000 ft)
Range at Cruise Speed/Altitude	2037 km (1100 NM)
Rate of Climb, 2 Engines	569 m/min (1864 ft/min)
Takeoff to 15m (50 Ft), Std Day	486 m (1595 ft)
Cruise Fuel Consumption	128 liters/hr (33.8 gal/hr)
Block Fuel	637 liters (168.2 gal)
Engine SLS Takeoff Power*	251 kw (336 hp)
Engine SLS Core Airflow	0.87 kg/sec (1.91 lb/sec)

*Uninstalled

4.3.2 Sensitivity Studies

The effects of engine weight and specific fuel consumption on aircraft characteristics were evaluated by resizing the aircraft with the use of GASP for changes in these parameters. The baseline aircraft described in 4.3.1 were used. For each of the changes, the aircraft were resized to meet the takeoff, range, and cruise conditions. The results of these sensitivity studies are contained in Appendix III.

4.4 Engine Trade-Off Studies

The majority of the engine trade-off studies were made using the turboprop baseline engine described in 4.2.1.1. This engine, hereinafter referred to as Engine A, is a free-turbine engine, and is comprised of a single-stage centrifugal compressor driven by a cooled radial turbine, a reverse-flow annular combustor, and a two-stage axial uncooled power turbine driving a two-stage reduction gearbox. Two groups of trade-off studies were conducted on this engine. The first group considered cycle and configuration and included the following items:

- o Cycle
- o Compressor type
- o High-pressure turbine type
- o Spool arrangement (single shaft versus free turbine)

The second group consisted of more detailed trade-offs on a component level and included the following:

- o Single-stage centrifugal compressor fabrication
- o Combustion system fabrication and fuel nozzles
- o High-pressure turbine fabrication and materials
- o Low-pressure turbine fabrication and materials
- o Single-stage versus two-stage power turbine

- Gearbox type and fabrication
- Sheet metal versus cast construction

As the trade-off studies were conducted, promising engine cycles and configurations were more fully defined and carried forward to an evaluation on a system or aircraft basis.

In addition to the turboprop engines, two turbofans and one turboshaft engine were defined. These three engines incorporated features identified in the turboprop studies.

4.4.1 Cycle and Configuration Trade-Off Studies

4.4.1.1 Cycle

The first cycle trade-off studies performed were accomplished for the baseline configuration, designated Engine A. The characteristics of Engine A are shown in Table 26. The maximum compressor pressure ratio for the single-stage centrifugal compressor was determined to be 10 for the technology level being investigated. The range of compressor pressure ratios investigated was 6 to 10. The variation in compressor efficiency assumed is shown in Figure 43. The efficiency shown is relative to the efficiency which could be achieved in a production compressor designed in 1977. Turbine rotor inlet temperature was also varied from 1255°K to 1478°K (1800°F to 2200°F). At 1255°K (1800°F), the turbine is uncooled, at 1311°K (1900°F) the turbine nozzle is cooled and at 1478°K (2200°F) the nozzle and rotor are cooled. Turbine efficiency varies with the level of turbine inlet temperature. Levels of turbine efficiency assumed relative to a 1977 radial design are shown in Figure 44. The results of design-point calculations at cruise conditions are shown in Figure 45. Shaft power and SFC are shown as a function of turbine inlet temperature and pressure ratio. For all turbine inlet temperatures, shaft power is near optimum at a pressure ratio of 9, with specific fuel consumption near minimum.

TABLE 26 TURBOPROP CANDIDATE ENGINE CHARACTERISTICS, SEA LEVEL, STATIC, STANDARD DAY, TAKEOFF POWER UNINSTALLED

Free Turbine Engines					
Gas Generator Turbine Type	Radial*			Axial*	
Compressor Type	1 Stage Centrifugal		2 Stage Centrifugal	1 Stage Centrifugal	
	Engine A	Engine B	Engine C	Engine D	Engine E
Turbine Inlet Temp, °K (°F)	1478 (2200)	1255 (1800)	1478 (2200)	1478 (2200)	1255 (1800)
Turbine Cooling	Yes	No	Yes	Yes	No
Compressor Pressure Ratio	8.3	8.3	12.0	8.3	8.3
Inlet Corrected Flow, kg/sec (lb/sec)	1.22 (2.69)	1.22 (2.69)	1.22 (2.69)	1.22 (2.69)	1.22 (2.69)
Power, kw (hp)	353 (473)	259 (347)	339 (454)	345 (463)	254 (340)
Shaft Specific Fuel Consumption kg/hr/kw (lb/hr/hp)	0.311 (0.511)	0.315 (0.517)	0.295 (0.484)	0.321 (0.528)	0.325 (0.533)
Engine Weight, kg (lb)	95 (210)	95 (210)	99 (219)	95 (210)	95 (210)
Engine OEM Cost,****$(1977)	39908	37434	42495	45891	39530

Single Shaft Engines				
Compressor Type	1 Stage Centrifugal			
Turbine Type	Radial/Axial**		All Axial***	
	Engine F	Engine G	Engine H	Engine I
Turbine Inlet, Temp, °K (°F)	1478 (2200)	1255 (1800)	1478 (2200)	1255 (1800)
Turbine Cooling	Yes	No	Yes	No
Compressor Pressure Ratio	7.6	7.6	7.6	7.6
Inlet Corrected Flow, kg/sec (lb/sec)	1.12 (2.47)	1.12 (2.47)	1.12 (2.47)	1.12 (2.47)
Power, kw (hp)	304 (408)	227 (304)	304 (408)	219 (294)
Shaft Specific Fuel Consumption kg/hr/kw (lb/hr/hp)	0.324 (0.533)	0.328 (0.538)	0.319 (0.523)	0.333 (0.547)
Engine Weight, kg (lb)	86.3 (190)	86.3 (190)	85.8 (189)	85.8 (189)
Engine OEM Cost,****$(1977)	37344	34426	46325	38882

*Two-stage axial LP turbine
**One radial stage and one axial stage
***Three axial stages
****Based on 1000 units per year

NOTE: Characteristics shown in this table are before improvements for advanced technology were incorporated.

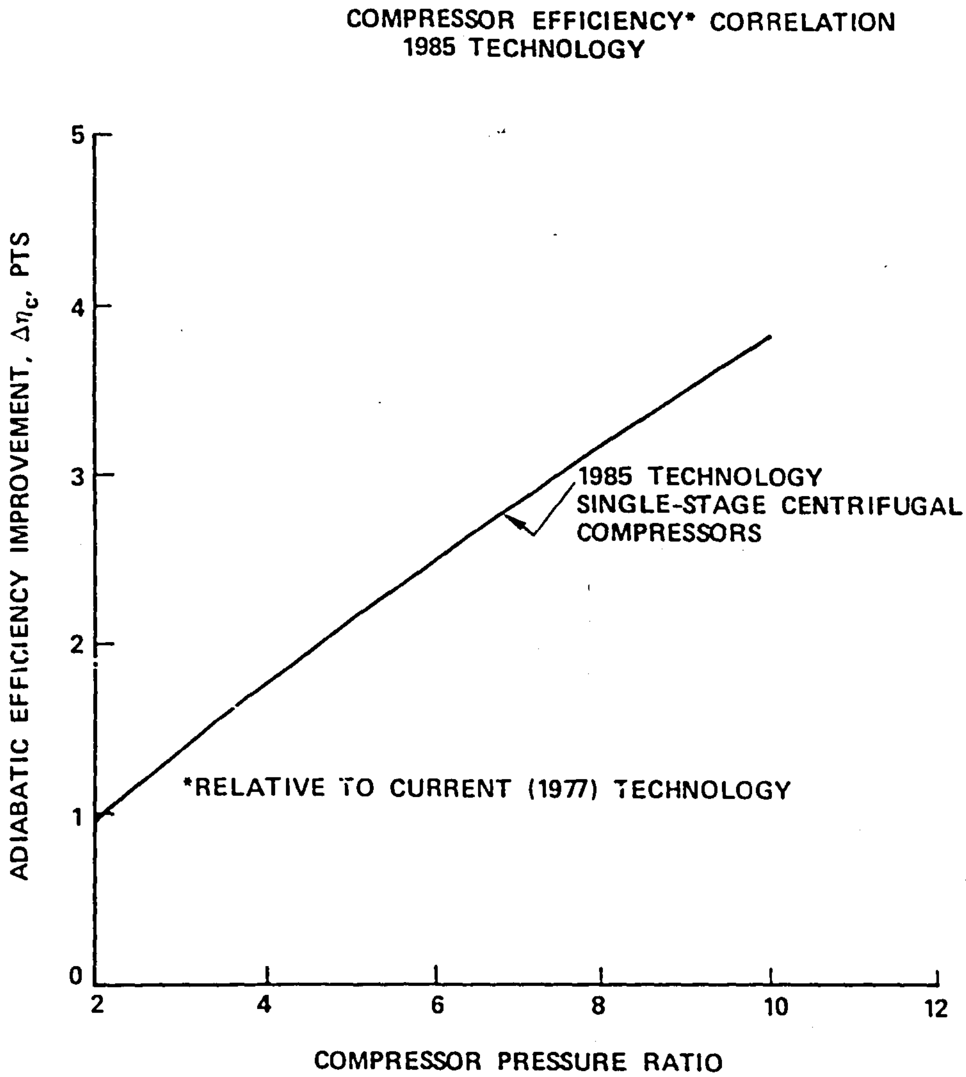


Figure 43. Compressor Efficiency 1985 Technology.

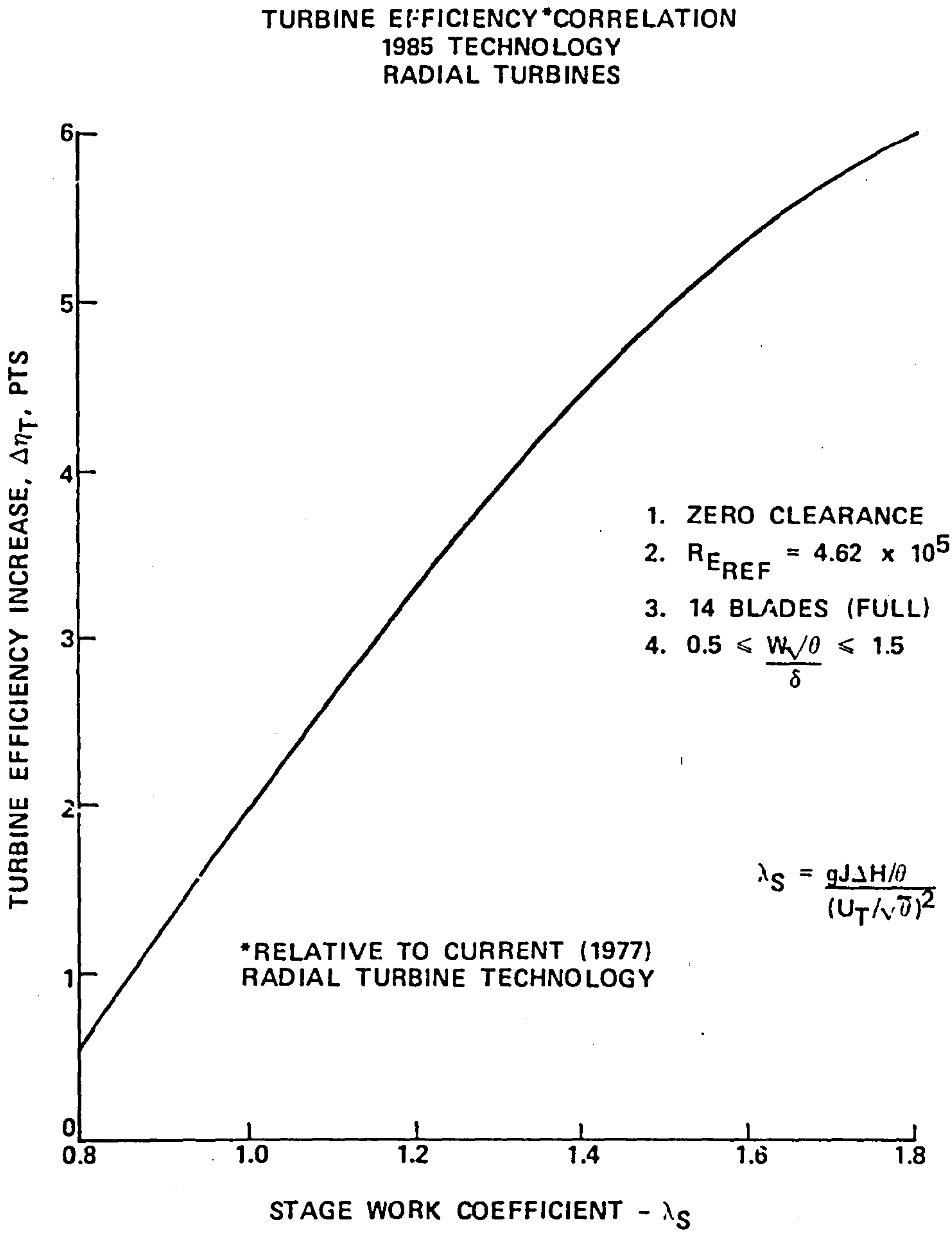


Figure 44. Turbine Efficiency, 1985 Technology.

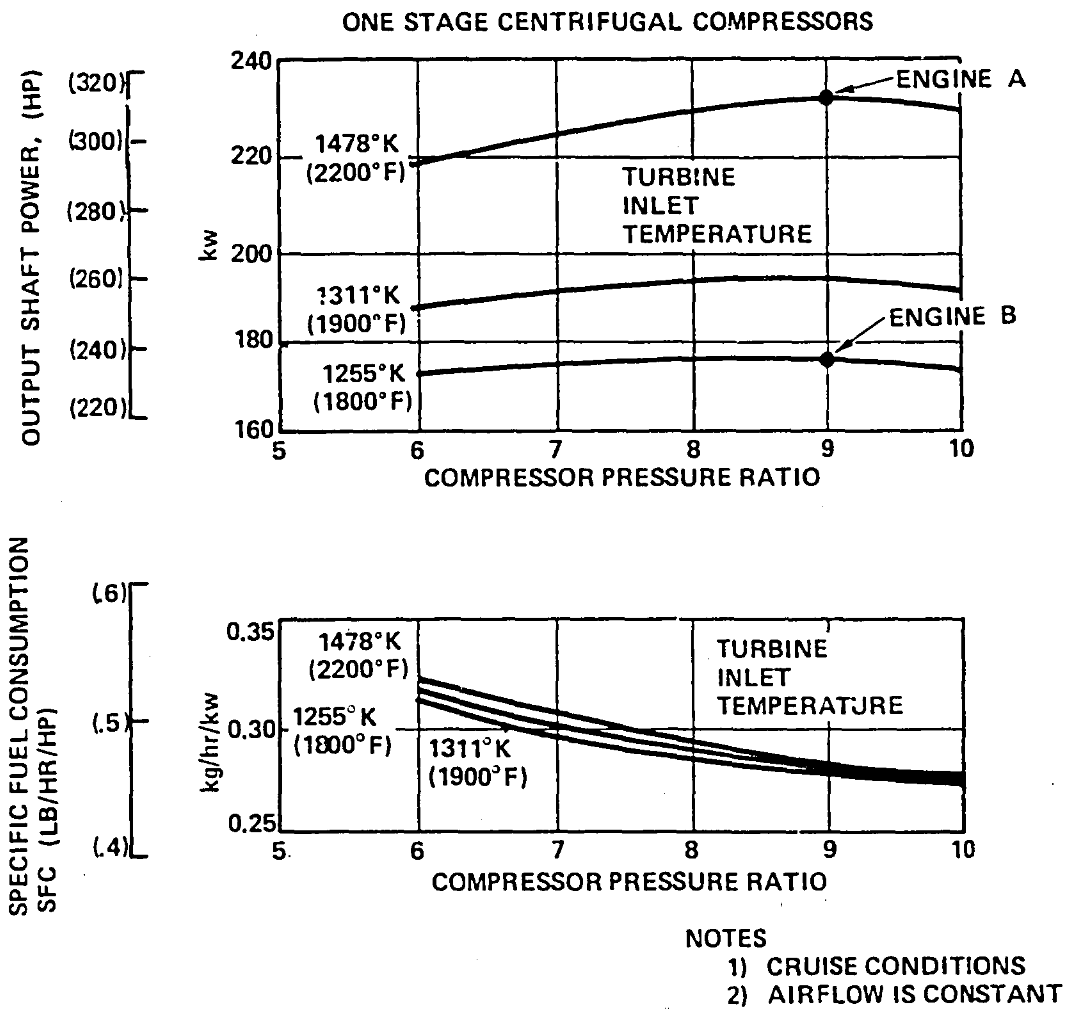


Figure 45. Turboprop Cycle Selection - Free-Turbine Engines

The selection of a pressure ratio of 9.0 can be made with confidence that factors such as cost and weight would not dictate a lower pressure ratio. Reducing the pressure ratio to 6.0 would increase the SFC 10 percent and the cost and weight would not be significantly different.

The selection of turbine inlet temperature is more complex, since differences in cost and weight were expected between the cooled and uncooled engines. To allow a complete evaluation of these differences, a more detailed definition of an uncooled version [1255°K (1800°F) T_4] of the baseline engine was accomplished. This uncooled version of the free turbine baseline was designated Engine B and its characteristics are shown in Table 26. Engine B has the same airflow as Engine A but produces less horsepower due to its lower temperature. Specific fuel consumption is only slightly higher. At equal airflow, the weight difference between Engines A and B was found to be insignificant but the cost of the uncooled engine at equal airflow was approximately 6 percent less. Cycle analysis results shown in Figure 45 show that a pressure ratio of 9:1 is near optimum for the uncooled engine in terms of specific power and specific fuel consumption.

Another cycle trade-off involved pressure ratios higher than could be obtained with a single-stage centrifugal compressor. At 1478°K (2200°F), the pressure ratio range was increased to a maximum pressure ratio of 16. Two-stage centrifugal and axial-centrifugal compressors were evaluated at cruise conditions. The adiabatic efficiencies of the two-stage centrifugal compressor and an axial-centrifugal compressor relative to 1977 designs are shown in Figure 46 for a corrected inlet flow of 5 pounds per second. This efficiency correlation was corrected for size effects for the GATE study.

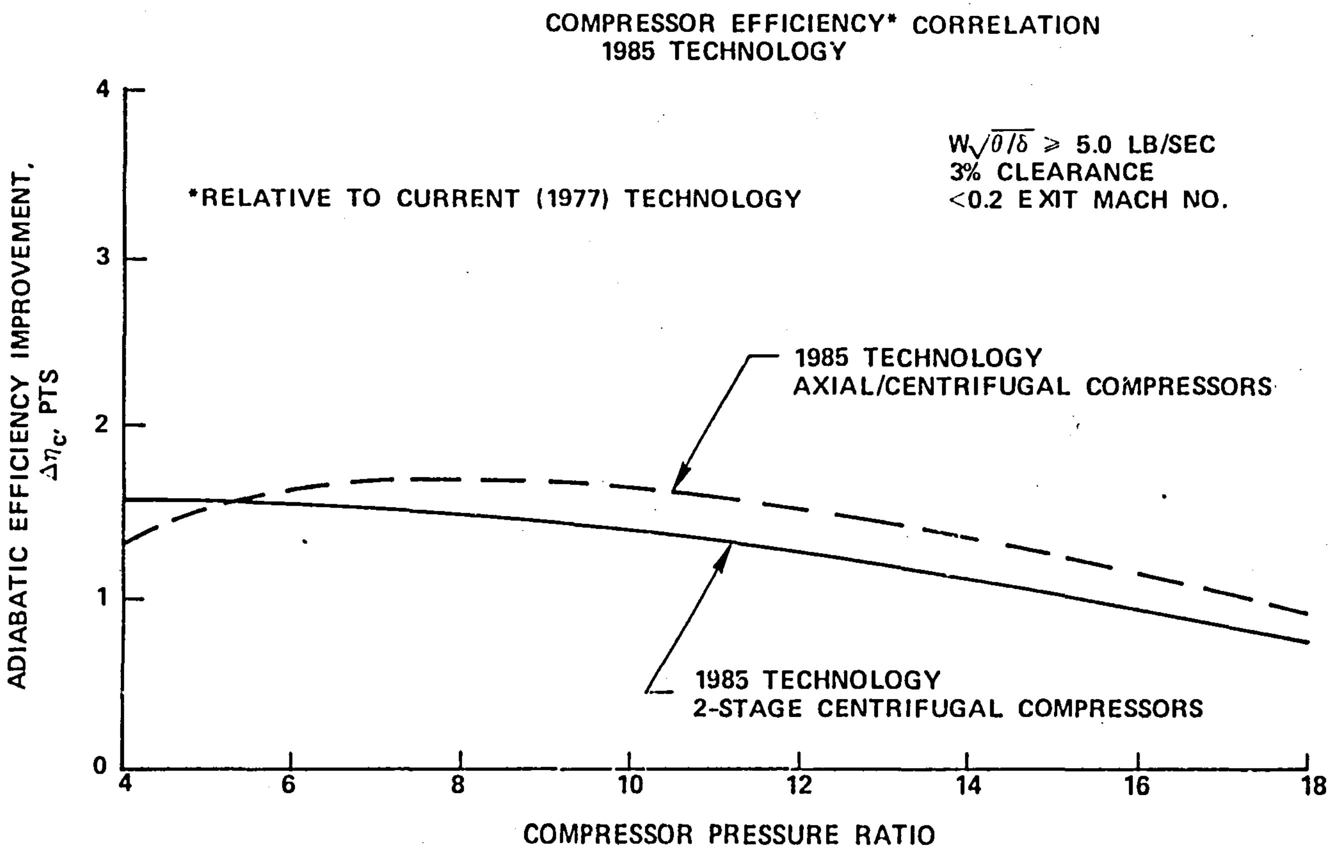


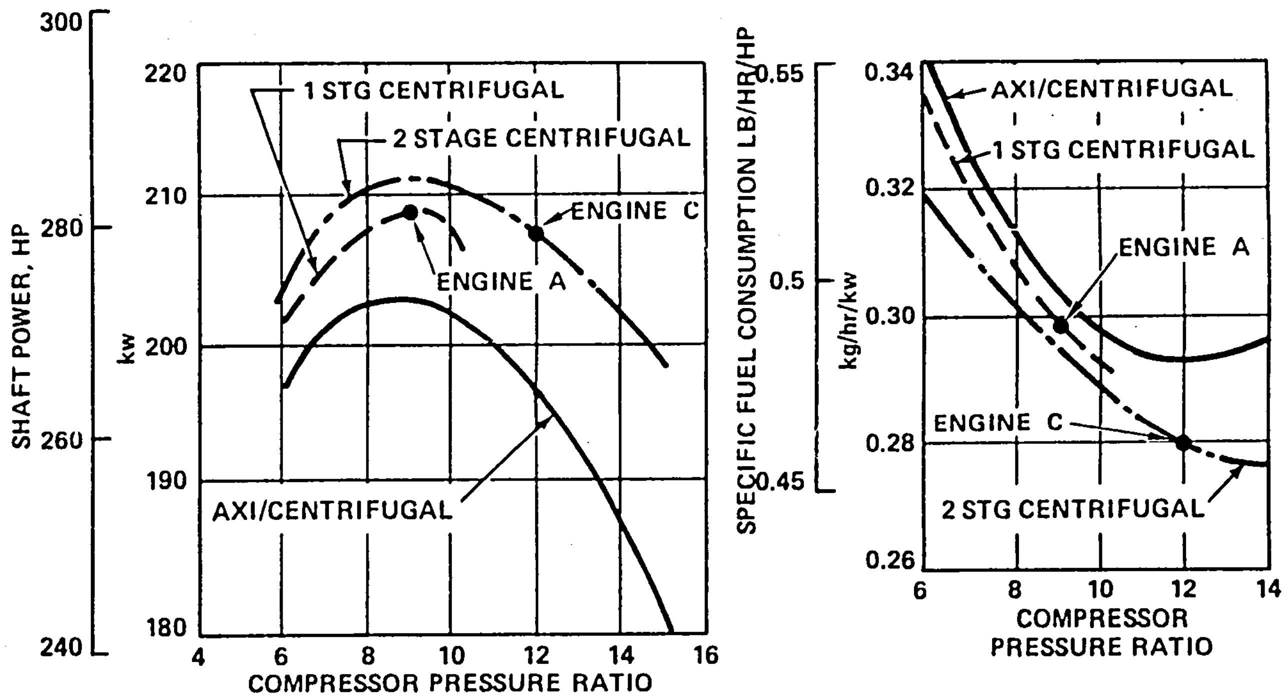
Figure 46. Compressor Efficiency, 1985 Technology

Figure 47 shows the results in terms of shaft power and SFC as a function of compressor pressure ratio for three compressor configurations. The single-stage data is shown for comparison, since this study was performed at a slightly different cruise condition than that used for Figure 45. The two-stage centrifugal compressor is clearly superior to the axial-centrifugal compressor, due to its higher efficiency. The difference in SFC between the single- and two-stage centrifugal compressors was significant (5 percent at 12.0 pressure ratio) and prompted the definition of Engine C for aircraft evaluation. Engine C has a two-stage centrifugal compressor in lieu of the single-stage centrifugal compressor and its characteristics are listed in Table 26. The pressure ratio selected for Engine C is 12.0. This provides near minimum SFC without incurring a large penalty in specific power. The axial-centrifugal compressor was not given further consideration.

Cross sections of Engines A and C are shown in Figure 48. The upper cross section shows the single-stage centrifugal compressor and the lower shows the two-stage centrifugal compressor.

4.4.1.2 Configuration Trade-Offs

Substitution of an axial high-pressure turbine for the radial high-pressure turbine was one of the configuration trade-offs. Figure 49 compares Engine A to Engine D, which is the cooled axial turbine version of Engine A. Characteristics of Engine D are listed in Table 26. The performance differences are due to lower axial turbine efficiency. The cost difference is due to the inserted blade design chosen for the axial turbine. An uncooled axial version, designated Engine E, was also defined to show the differences between cooled and uncooled cost when using axial turbines. Engine E is only 5 percent more expensive than Engine B, whereas Engine D is 15 percent more than Engine A.



NOTES: CRUISE CONDITION
T_4 = 1478°K (2200°F)
CONSTANT AIRFLOW.

Figure 47. Compressor Pressure Ratio Trade-offs

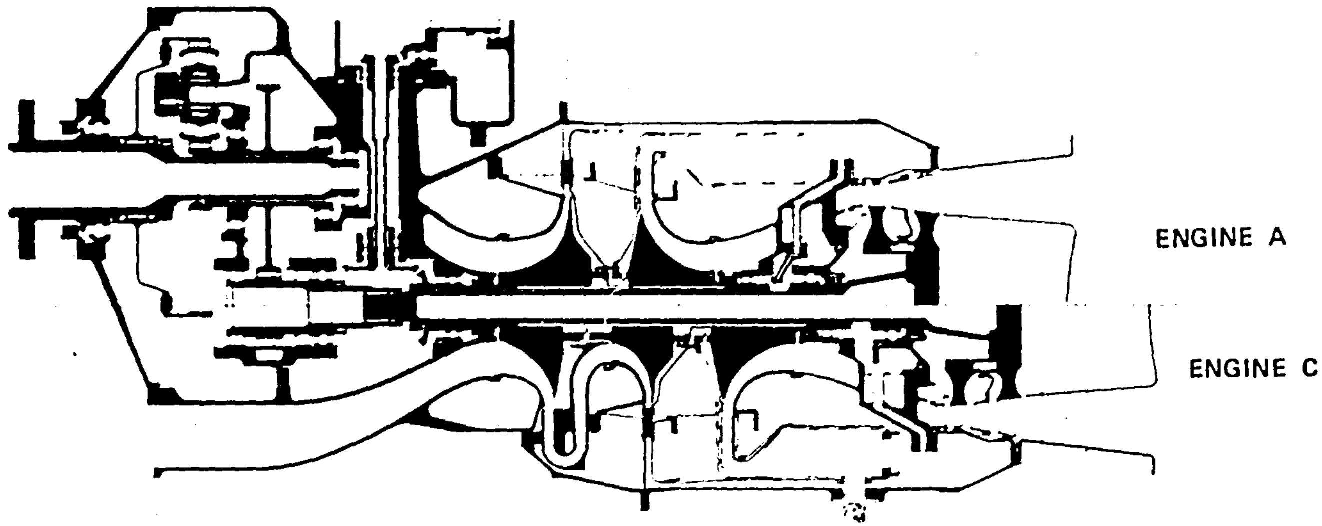


Figure 48. Free-Turbine Engines - Compressor Configurations

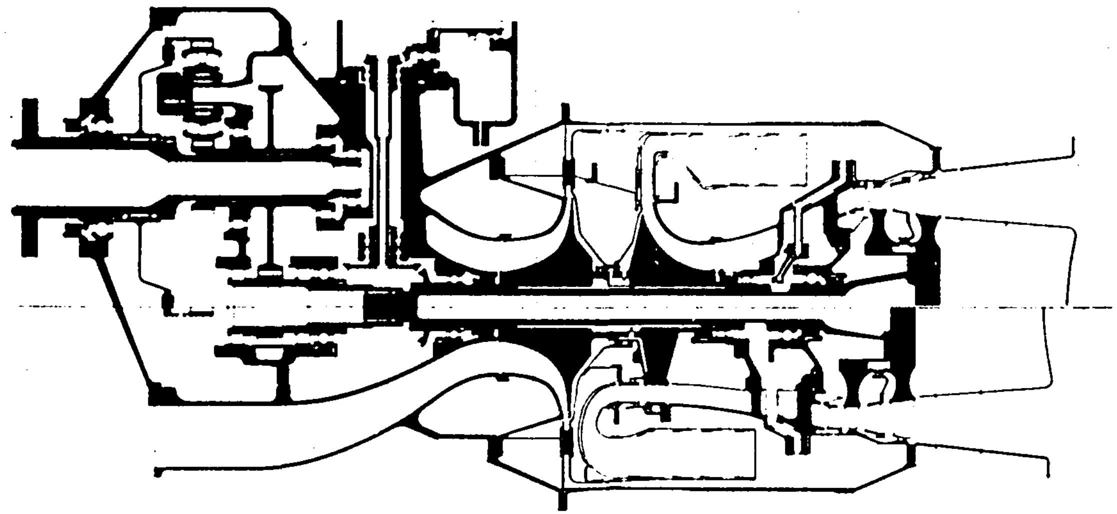


Figure 49. Free-Turbine Turboprops - Turbine Configurations

The major configuration trade-off was a change in spool arrangement from a free turbine (two shaft) to a single shaft. Past experience indicated that the single-shaft engine is less expensive than the free-turbine engine. Four single-shaft configurations were defined. Engine F is a 1478°K (2200°F) turbine inlet temperature engine comprised of a single-stage centrifugal compressor, a reverse-flow annular burner, and a two-stage turbine composed of one radial stage and one axial stage. Engine G is a 1255°K (1800°F) version of Engine F. Engines H and J are cooled and uncooled versions of Engine F with two stages of axial turbines substituted for the single radial stage. A comparison of Engines F and H is shown in Figure 50 and the characteristics of all four single-shaft engines are shown in Table 26. Although the sea-level, static, shaft power of the single-shaft engines is less than comparable free-turbine engines, they produce equivalent power at cruise conditions and have essentially the same core flow at their design points. On the basis of equal cruise power, the single-shaft engines are less expensive than comparable free turbines, although they have a slightly higher SFC.

4.4.2 Detailed Component Trade-Offs

4.4.2.1 Single-Stage Centrifugal Compressor

The single-stage centrifugal compressor incorporated in most of the engines defined earlier requires three-dimensional (3-D) blading to produce the high efficiency assumed. Presently, research compressors employing 3-D blading are machined and are very expensive. Blading formed from straight line segments can be machined less expensively on 5-axis machines but incur a performance penalty. The alternatives for low-cost manufacturing are power metal titanium (PM Ti) or casting (steel or titanium). Conventional castings result in large performance penalties. The powder metal approach promises mechanical properties

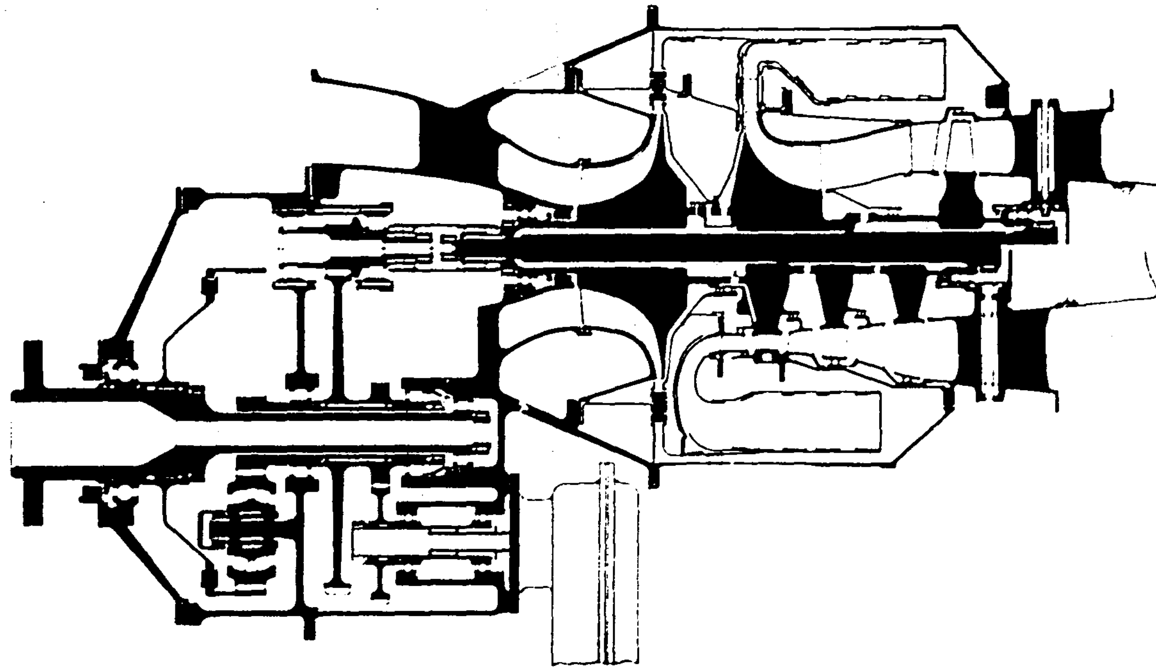


Figure 50. Single-Shaft Turboprops - Turbine Configurations

approaching those of a forging and efficiency levels equivalent to machined designs. A comparison of the three alternatives is shown in Table 27.

The major difference between the PM Ti compressor and the advanced cast compressor is approximately 4 percent in efficiency. If the efficiency of the cast compressor is improved, the cost of the cast part will increase due primarily to a lower yield of acceptable parts. The difference between the machined and PM Ti compressor is component cost. The PM Ti approach is higher risk since attainment of efficiencies equivalent to the machined design in PM Ti requires extensive research and development. The PM Ti approach was selected for all the candidate engines employing single-stage centrifugal compressors.

4.4.2.2 Combustion System

The combustion system, including fuel nozzles, did not require nor allow extensive trade-offs except with respect to the fuel nozzles. Ceramic combustors were eliminated because of their development status. Based on current ceramic combustor development programs, this approach will not be feasible for low-cost man-rated engines entering service in 1988. Ceramic materials could be used in non-man-rated engines by this time period. Good combustor durability at the 1478°K (2200°F) temperature level of Engine A will require advanced cooling schemes. The baseline design assumed that the cooling passages would be photoetched before the combustor is rolled and welded. Inco 617 was selected as the combustor material. Another candidate is oxide dispersion strengthened (ODS) sheet alloys. ODS sheet is more expensive than Inco 617 and would have to provide an increase in durability to be a successful candidate. The only change to the baseline combustion system resulting in a cost decrease was fuel nozzles. A low-cost airblast nozzle was conceived, which resulted in a one-percent reduction in engine cost.

TABLE 27. SINGLE-STAGE CENTRIFUGAL COMPRESSOR COMPARISON

Engine A
9:1 Pressure Ratio
1478°K (2200°F) Turbine Inlet Temperature

	Machined	PM Ti	Advanced Cast
Relative Efficiency	1.0	1.0	0.96
Relative SFC	1.0	1.0	1.04
Relative Specific Power	1.0	1.0	0.96
Relative Engine Cost*	1.0	0.96	1.03
Relative Engine Weight*	1.0	1.0	1.04

*For equal power

The improvements relative to the combustor and fuel nozzles are understated. Current production or development combustors in the 373 to 746 kw (500 to 1000 hp) class are operating at 1366°K (2000°F) or less rather than 1478°K (2200°F). Thus the baseline turboprop engine incorporates a combustor that is significantly improved relative to todays combustor. The 1478°K (2200°F) technology has been demonstrated as feasible in recent research programs. The transition from research to development or production status is a major task. It is complicated by the need to utilize alternate fuels such as diesel, synjet and broad specification kerosene. The ability to utilize these fuels may result in further improvements if the alternate fuel is less expensive, e.g. diesel.

4.4.2.3 High-Pressure Turbine

The high-pressure turbine in the baseline engine, Engine A, is a radial turbine comprised of Mar-M 509 cast nozzles, vanes brazed to Hastelloy "X" bands, and a forged and machined AF2-1DA wheel joined to a cast Mar-M 247 exducer. Cooling holes were stem or electrostream drilled. The advanced technology approach was laminated construction using photoetched 0.040-inch Waspalloy or Astroloy. The laminated approach results in a six percent savings in engine cost, a small increase in efficiency and a small decrease in cooling flow. Table 28 shows the results of the comparison between the baseline and the laminated approach.

The other advanced technology trade-off performed in the high-pressure turbine area focused on the axial high-pressure turbine selected for Engine D. The baseline configuration had segmented cast nozzle vanes and a rotor comprised of a forged and machined hub and inserted cast blades. The advanced technology approach consisted of laminated vanes and an integral laminated wheel constructed from photoetched 0.010- and 0.020-inch sheet. The sheet in the axial turbine is thinner gauge than in the radial

TABLE 28. RADIAL HP TURBINE COMPARISON

Engine A
9:1 Pressure Ratio
1478°K (2200°F) Turbine Inlet Temperature

	Baseline	Laminated
Relative Efficiency	1.0	1.014
Relative Cooling Flow	1.0	0.8
Relative SFC	1.0	0.99
Relative Specific Power	1.0	1.02
Relative Engine Cost*	1.0	0.94
Relative Engine Weight*	1.0	1.0

*For equal power

wheel to accommodate the higher curvature required. The thinner material results in higher proportionate cost. The change to laminated construction resulted in an increase in efficiency as well as a decrease in cost. Table 29 is a comparison of the baseline axial turbine design and the laminated high-pressure axial turbine.

The benefits identified for the laminated cooled radial turbine are applicable to Engine C, the two-stage centrifugal compressor design, as well as to Engine F, the cooled single-shaft engine employing a radial/axial turbine. The laminated cooled axial turbine is applicable to Engine H, the cooled single-shaft engine employing an all-axial turbine.

4.4.2.4 Other Trade-Offs

In addition to the trade-off studies discussed above, a number of other trade-off studies were conducted including the following:

- Clearance control
- Single-stage versus two-stage power turbine
- Conventional versus laser-hardened gears
- Sheet metal versus cast turbine plenum

The clearance-control trade-off study showed that efficiency could be increased 1.0 percent in the HP turbine and the LP turbine by reducing the turbine clearance from 0.015 to 0.010 inches. The cost penalty for achieving this reduction in clearance is very small if passive means such as abradables are workable.

A single-stage power turbine was investigated for the free-turbine engines but the reduction in efficiency offset the reduction in cost based on the airplane sensitivities developed earlier.

TABLE 29. AXIAL HP TURBINE COMPARISON

Engine D
9:1 Pressure Ratio
1478°K (2200°F) Turbine Inlet Temperature

	Baseline**	Laminated
Relative Efficiency	1.0	1.01
Relative SFC	1.0	0.99
Relative Specific Power	1.0	1.01
Relative Engine Cost*	1.0	0.94
Relative Engine Weight*	1.0	1.0

*For equal power
**Single stage axial, cooled, inserted blades

Gearbox cost reduction studies identified laser hardening as an alternative to conventional hardening. Estimates show a 3-percent reduction in engine cost due to a reduction in machining required on the laser-hardened gears.

A reduction in engine cost of two percent was identified for sheet metal fabrication of the turbine plenum as opposed to a cast/forged/s eʟ metal assembly. This item was not recommended as an advanced technology program since it should result from normal development.

In addition to the engine cost savings described above, further cost savings were assumed for items such as static structure, bearings, and shafting. These technologies are classified as low risk and should result from on-going company- and Government-sponsored R&D. The magnitude of the low-risk technology category was assumed to be a function of the remaining engine cost, after the cost of items that were specifically investigated was removed. Specifically, in the case of engine A, the components that were subjected to trade-off studies represented approximately one-third of the engine cost. For these components the application of advanced technology resulted in a 16-percent reduction in total engine cost. The application of advanced technology to the remaining components, which account for two-third of the engine cost, was assumed to result in additional cost savings of 8 percent.

4.4.2.5 Summary - Detailed Component Trade-Off Studies

The results of the detailed component trade-off studies identified cost reductions of 19-25 percent for Engines A through I listed in Table 26. For Engine A, the cost reduction is 24 percent and breaks down as follows:

Compressor	4%
Combustor	1%
HP Turbine	6%
Laser Hardened Gears	3%
Sheet Metal Turbine Plenum	2%
Low Risk Technology Category	8%
TOTAL	24%

Additional cost reductions due to advanced technology are implicit in the baseline engine. The candidate engines listed in Table 26 include advanced technology such as:

- o High efficiency, high-pressure-ratio compressor
- o High turbine inlet tmperature in the case of the cooled engines
- o Integrally cast shrouds on the low-pressure turbine
- o Low-cost digital electronic fuel control

The cost reductions due to these items were not evaluated in detail. An approximation of their contribution can be arrived at by comparing the baseline engine OEM cost with current production engine cost. Table 26 lists the OEM cost of the baseline engines before the cost reductions due to the advanced technology discussed in 4.4.2.1 through 4.4.2.4. For example, the specific cost of Engine A is approximately 84 dollars per horsepower. Current production turboprops at equivalent power and production volume would sell for 100 dollars per horsepower or more. Therefore, it can be inferred that the advanced technology in the baseline engine results in a cost reduction of 16 percent. Therefore, the maximum cost reduction due to advanced technology is the sum of the advanced technology benefits identified with respect to the baseline and the advanced technology included in the baseline. For Engine A, this is the sum of 24 and 16 percent for a total of 40 percent cost reduction due to advanced technology.

4.4.3 Turbofan and Turboshaft

Detailed engine trade studies were not performed on the turbofan and turboshaft engines with the exception of the fan component and cycle on the turbofan. The benefits identified in the turboprop engine trade studies were applied to the turbofan and turboshaft engines where appropriate.

Turbofan cycle optimization studies identified small improvements in performance. Figure 51 shows the results of fan pressure ratio and bypass ratio investigations. Fan pressure ratio should be reduced to 1.4 and bypass ratio increased to 10 for minimum thrust specific fuel consumption. Relative to the baseline cycle, this change would result in a 4-percent reduction in fuel consumption and no loss in cruise thrust. This decrease, however, is not sufficient to offset the difference between the fuel consumption of the turboprop and turbofan. Additional cycle work would involve the optimization of core pressure ratio and additional configuration work could include booster stages driven by the LP turbine, 2-stage centrifugal compressors, and axial/centrifugal compressors. None of these approaches, however, could significantly diminish the 61 percent difference in fuel consumption identified by the initial sizing results. Significant changes in the characteristics of the aircraft (higher speed and altitude, longer takeoff distances/more sophisticated high-life systems) would be necessary before the turbofan could compete with the turboprop.

- 6096 M, 389 KM/H (20000 FT, 210 KNOTS) ISA
- CORE PRESSURE RATIO - 9:1
- T4 = 1478°K (2200°F)

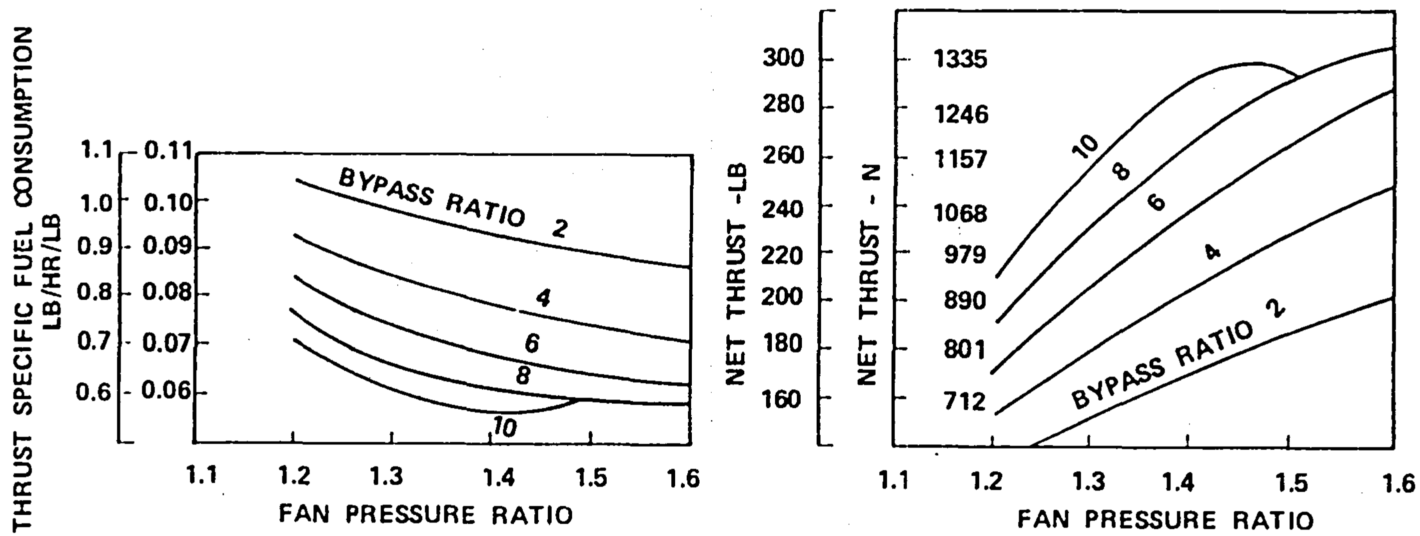


Figure 51. Turbofan Cycle Selection.

Two turbofan engines were defined and are designated Engines J and K. Engine J is the turbofan baseline engine defined earlier and Engine K is an uncooled version of it.

One turboshaft engine was defined and is designated Engine L. It is a turboshaft version of Engine A.

4.4.4 Summary - Engine Trade Studies

The application of advanced technology to the GATE engines identified performance improvements such as efficiency increases, reductions in cooling flows, and cost reductions. In addition to the advanced technology investigations, a study was also conducted to determine the effect of high volume production. The OEM engine cost listed in Table 26 assumed a production rate of 1000 units per year. Potential production of the GATE engines is 10,000 units per year. The scope of the GATE study did not allow a detailed study of the benefits of high volume production. Fortunately, data was available from the AiResearch GT601 gas turbine truck program. As part of the GT601 program, detailed estimates were made for cost reductions attributable to high volume production at the rate of 10,000 units per year. The GT601 gas turbine is a recuperated shaft engine in the 447 kw (600 hp) class. The benefit of high volume production was established for the GT601 by comparing estimates of engine costs at 1000 and 10,000 units per year. The major benefit identified is the reduction of set-up time through use of dedicated or captured machines. Setup is labor intensive and accounts for a large portion of the fabrication cost. Based on the GT601 studies, the cost of the advanced-technology engine can be reduced by 40 percent due to the decrease in fabrication cost associated with high-volume production.

Table 30 lists the cost reductions due to advanced technology and high volume production for the 12 candidate engines. Figure 52 summarizes the cost reductions with respect to current production

TABLE 30. O.E.M. COST OF THE TWELVE CANDIDATE ENGINES (1977 $)

	Free-Turbine Turboprop					Single-Shaft Turboprops				Turbofans		Turboshaft
	Cooled Radial	Uncooled Radial	2 Stg Centrif Cooled Radial	Cooled Axial	Uncooled Axial	Cooled Rad/Ax	Uncooled Rad/Ax	Cooled Axial	Uncooled Axial	Cooled	Uncooled	Cooled Radial
	A	B	C	D	E	F	G	H	I	J	K	L
Baseline,* $	39,908	37,434	42,495	45,891	39,530	37,344	34,426	46,325	38,882	47,878	45,618	35,937
Adv Tech Δ $	9575	7934	6495	10,558	7530	9344	6926	10,658	7382	10,545	9118	8270
Engine Cost Adv Tech*	30,333	29,500	34,000	35,333	32,000	28,000	27,500	35,667	31,500	37,333	36,500	27,667
High Vol + Adv Tech Engine Cost**$	18,200	17,700	20,400	21,200	19,200	16,800	16,500	21,400	18,900	22,400	21,900	16,600

*1000 units
**10,000 units

NOTES:

1. ENGINE A
2. CURRENT PRODUCTION ENGINE - $100/HP

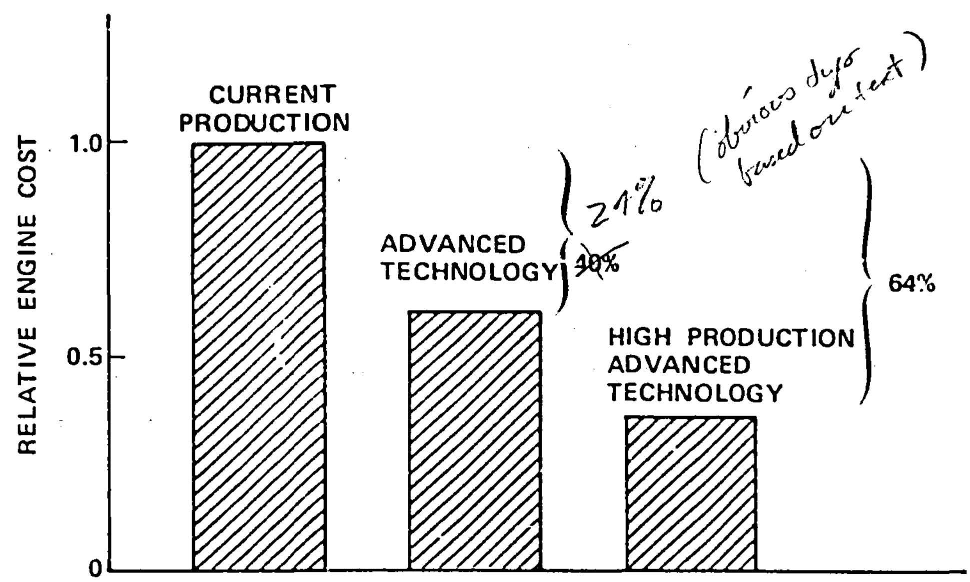


Figure 52. Engine Cost Reduction

engines. Approximately ~~40~~ 24 percent is due to advanced technology and ~~24~~ 40 percent is due to high-volume production. Note that Figure 54 shows engine cost reductions with respect to current production turboprops and not the GATE baseline engines used as the reference in Table 30. Table 31 lists the performance characteristics of the 12 engines after adjustments for advanced technology improvements in component performance and reduced cooling flows. All the turboprops and the turboshaft listed in Table 30 and Table 31 have identical core flows at their design points. The core flow of the turbofan is 30 percent higher.

The 12 candidate engines, as defined in Table 31, were evaluated in the next element of Task II - aircraft/engine trade-off studies.

4.5 <u>Engine/Aircraft Trade-off Studies</u>

The selection of the optimum engines for the medium pressurized twin and the light twin was made on the basis of the following criteria:

- Total three-year cost
- Operating cost
- Acquisition cost
- Fuel consumption

The twelve candidate engines described earlier were evaluated in the two aircraft configurations where appropriate. In addition to the twelve candidate engines, the performance, weight, and cost characteristics of the 1311°K (1900°F) versions of five of the engines previously discussed were defined. The characteristics of these engines are shown in Table 32.

TABLE 31. ENGINE CHARACTERISTICS WITH ADVANCED TECHNOLOGY IMPROVEMENTS

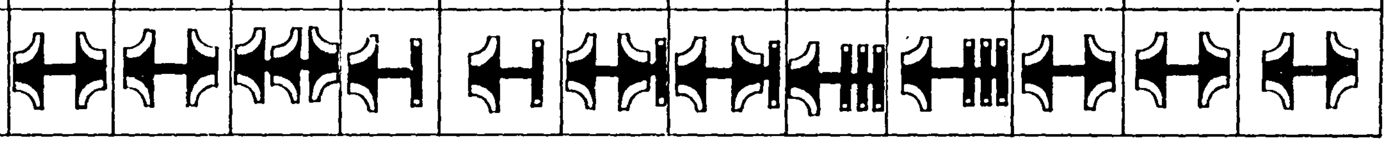
	Free-Turbine Turboprops					Single-Shaft Turboprops				Turbofans		Turboshaft
	Cooled Radial A	Uncooled Radial B	2 Stg Centrif Cooled Radial C	Cooled Axial D	Uncooled Axial E	Cooled Rad/Ax F	Uncooled Rad/Ax G	Cooled Axial H	Uncooled Axial I	Cooled J	Uncooled K	Cooled Radial L
SHP/F_N, kw SLS, TO, (HP)	365 (489)	265 (355)	357 (479)	350 (470)	260 (348)	318 (427)	236 (317)	324 (434)	233 (312)	4423N (994 lb)	3386N (761 lb)	365 (489)
SFC, SLS, TO kg/hr/kw	0.300	0.308	0.284	0.313	0.322	0.325	0.326	0.319	0.333	kg/N-hr 0.040	kg/N-hr 0.036	0.300
(lb/hr/hp)	(0.493)	(0.505)	(0.467)	(0.514)	(0.529)	(0.533)	(0.536)	(0.523)	(0.547)	lb/hr/lb (0.390)	lb/hr/lb (0.357)	(0.493)
Engine Weight kg (lb)	95 (210)	95 (210)	99 (219)	95 (210)	95 (210)	86.3 (190)	86.3 (190)	85.8 (189)	85.8 (189)	111 (245)	111 (245)	75 (165)
Engine Cost	18,200	17,700	20,400	21,200	19,200	16,800	16,500	21,400	18,900	22,400	21,900	16,600
$/kw or N	49.9	66.9	57.1	60.5	74.0	52.7	69.8	66.1	81.2	5.1	6.5	45.6
$/hp or lb	37.2	49.9	42.6	45.1	55.2	39.3	52.1	49.3	60.6	22.5	28.8	34.0
Gas Generator												

TABLE 32. 1311°K (1900°F) TURBINE ENGINE CHARACTERISTICS, SEA LEVEL, STANDARD DAY, TAKEOFF POWER, UNINSTALLED.

Engine Type	Turbofan	Free-Turbine Turboprop		Single-Shaft Turboprop	
Engine Designation	M	N	O	P	Q
Gas Generator Turbine	Radial	Radial	Axial	Rad/Ax	All Axial
Turbine inlet temperature, °K (°F)	1311 (1900)	1311 (1900)	1311 (1900)	1311 (1900)	1311 (1900)
Compressor pressure ratio	8.05	8.3	8.3	7.6	7.6
Fan pressure ratio	1.33	-	-	-	-
Bypass ratio	7.8	-	-	-	-
Compressor corrected flow, Kg/sec (lb/sec)	1.58 (3.47)	1.22 (2.69)	1.22 (2.69)	1.12 (2.47)	1.12 (2.47)
Net thrust/shaft horsepower	3605 N (810 lb)	295 kw (396 shp)	286 kw (383 shp)	260 kw (349 shp)	259 kw (347 shp)
Specific fuel consumption	0.037 kg/N-hr (0.363 lb/hr/lb)	0.294 kg/hr/kw (0.482 lb/hr/hp)	0.301 kg/hr/kw (0.494 lb/hr/hp)	0.306 kg/hr/kw (0.502 lb/hr/hp)	0.304 kg/hr/kw (0.499 lb/hr/hp)
Engine weight kg (lb)	111 (245)	95 (210)	95 (210)	86 (190)	86 (189)
Engine OEM cost $(1977)	22,200	18,000	20,200	16,700	20,200

4.5.1 Definition of Evaluation Criteria

4.5.1.1 Total Three-Year Cost

The market forecast established that owners of turboprop-powered aircraft and the larger twins trade-in their airplanes for newer or larger versions on the average of every 30 months. This was the basis for developing total cost on a three-year basis.

The real total cost for general aviation aircraft varies considerably depending on the type of owner - corporate, personal, etc., the tax situation of the owner, utilization, and other factors. Therefore, any total cost model can only provide data for comparisons on a relative basis. The total cost for the GATE airplanes is defined as the acquisition cost, plus the loan interest, plus the three-year operating cost, minus the trade-in price. The loan interest is based on a six-year loan at 10 percent interest and assuming 20 percent down. The three-year operating cost was based on 500 hours/year utilization. The resale value of the airplane was assumed to be 75 percent of the acquisition cost, which is approximately equivalent to the high wholesale "blue book" price at three years for an aircraft with a mid-time engine, i.e., halfway through the overhaul period. Since an engine overhaul reserve is maintained as part of the operating cost, the time on the engines is accounted for and no adjustment of the resale price is required. Tax advantages or the imputed interest (time value of money) on the down payment are not considered.

4.5.1.2 Operating Cost

The operating cost is separated into variable and fixed costs. Variable costs include:

- o Fuel and oil
- o Inspection and periodic maintenance
- o Engine overhaul reserve
- o Avionics reserve
- o Propeller overhaul reserve

Fixed costs include:

- o Hull insurance
- o Liability insurance

Tie-down and landing fees, local taxes, and other miscellaneous items, such as catering fees, were not included.

Fuel cost was based on the 1977 average jet fuel price of 70.85 cents per gallon. The oil cost for turbine engines was negligible. Inspection and periodic maintenance was based on a survey of Phoenix fixed base operators. The data received from this survey indicated that periodic inspection and maintenance costs after 250 hours of utilization for aircraft in the light-and medium-twin classes are as follows:

- o Ten hours airframe labor
- o Fifteen hours engine labor
- o $300 to $500 for parts
- o Labor cost, $17.50 per hour

These costs were for reciprocating-powered airplanes. On the same basis, turboprop-powered aircraft have reduced engine labor and parts cost. Typical periodic maintenance labor hours for current turboprops is 2.5 hours per 250 hours or 1 hour per 100 flight hours. The lower end of the parts cost range ($300) for the reciprocating-powered aircraft was selected for the turbine-powered aircraft. The parts cost for the reciprocating engines is believed to cover failures such as magnetoes, oil pumps, etc. The parts cost for the turboprop does not cover failures such as the fuel control, thermocouple harnesses, speed pickups etc., since these are relatively high cost items on a turbine engine. Detailed estimates of these costs are related to mean times between failure for these components, which were not estimated in this program. Some allowance for component failures is included in the overhaul reserve.

An allowance of 50 percent of the OEM engine cost at 3500 hours is provided for overhaul. Data on overhaul cost is available for AiResearch engines, as well as other gas turbines. The available data shows overhaul cost to vary between 15 and 60 percent of the original engine cost. The variance is due to different philosophies regarding replacement versus repair, remanufactured versus overhauled, and overhaul specifications. The higher side of the range was chosen not only to allow for realistic overhaul but also to provide for random component failures and periodic hot-end inspections. Hot-end inspections on current turboprops are required at between 1500 and 2000 hours. The effect on operating cost ranges between 4 and 18 cents per hour per engine. In the future, this cost may be reduced further through higher durability, on-the-wing inspection, and modular construction.

The avionics reserve was based on a formula used by Cessna. This formula computes the avionics overhaul reserve as 10 percent of the avionics options purchase price at 1000 hours. For example, if the avionics options are $30,000, the overhaul reserve is $3.00 per hour.

Available data suggests a propeller overhaul cost of 750 dollars for propellers used on current light and medium twins. Adequate data on time between overhauls was not available. However, recent studies suggest that there is no reason for the propeller not to have a TBO equal to or better than the engine. The TBO interval for the propeller was therefore selected to be 3500 hours.

Hull insurance yearly rates were obtained from Cessna and vary from 1.0 to 1.5 percent of the acquisition cost of the airplane on a sliding scale. A rate of 1.25 percent of the acquisition cost was assumed for all airplanes.

Liability insurance rates are a function of the number of passengers. According to this schedule, the annual rate for the medium pressurized twin and the light twin is 550 dollars per year.

4.5.1.3 Acquisition Cost

The acquisition cost of the airplanes is a function of the airframe weight and the maximum speed. The acquisition cost algorithm, shown below, was supplied by Cessna.

$$\text{Airplane Retail Price} = 0.008031\ (\overline{W}_E)^{1.76063} \times (V_{max})^{0.486512}$$

$$+ \text{[Retail Cost of Engine(s) Propeller, Optional Equipment]}$$

$\overline{W}_E$ = Standard Empty Weight minus the weight of the engine(s), propeller and optional equipment

$\overline{V}_{max}$ = Maximum speed (kts)

The retail cost of the engines and propeller is the OEM cost multiplied by 1.75.

4.5.2 Trade-off Studies

4.5.2.1 Turbine Inlet Temperature Trade-offs

The medium pressurized twin was evaluated with 1255, 1311, and 1478°K (1800, 1900, and 2200°F) versions of the turbofan engine and the free-turbine turboprop engine equipped with a single-stage compressor and a radial gas generator turbine. Tables 33 and 34 list

TABLE 33. TURBOFAN-POWERED MEDIUM PRESSURIZED TWIN, TURBINE INLET TEMPERATURE TRADE-OFFS

Engine Designation	J	M	K
Turbine Inlet Temperature, °K (°F)	1478 (2200)	1311 (1900)	1255 (1800)
Engine Net Thrust, SLS, T.O., N (lb)	4459 (1002)	4632 (1041)	4859 (1092)
Engine TSFC, SLS, T.O., kg/N-hr (lb/hr/lb)	0.039 (0.390)	0.037 (0.363)	0.036 (0.357)
Engine Weight, kg (lb)	121 (247)	140 (309)	160 (352)
Engine Cost, $ (1977)	22,500	26,800	28,700
Airplane Gross Weight, kg (lb)	2718 (5987)	2793 (6151)	2929 (6451)
Airplane Empty Weight, kg (lb)	1485 (3270)	1559 (3433)	1624 (3578)
Acquisition Cost, $ (1977)	250,497	266,847	280,672
Operating Cost, $/Hr (500 Hrs/Yr)	56.72	59.00	63.06
Total Cost, $ (1977)	197,806	209,049	220,886
Interest, $	50,099	53,369	54,134
3 Yr. Operating Cost, $	85,083	88,503	94,584
Trade-In, $	187,873	201,533	210,504
Fuel Consumption, liter/hr (gal/hr)	200.98 (53.03)	204.51 (53.96)	221.49 (58.44)

TABLE 34. TURBOPROP-POWERED MEDIUM PRESSURIZED TWIN, TURBINE INLET TEMPERATURE TRADE-OFFS

Engine Designation	A	N	B
Turbine Inlet Temperature, °K (°F)	1478 (2200)	1311 (1900)	1255 (1800)
Shaft Power, SLS, T.O., kw (hp)	312 (419)	339 (454)	356 (478)
Engine SFC, kg/hr/kw (lb/hr/hp)	0.300 (0.493)	0.302 (0.496)	0.308 (0.505)
Engine Weight, kg (lb)	84 (186)	113 (248)	131 (298)
Engine Cost, $ (1977)	16,200	19,900	22,100
Airplane Gross Weight, kg (lb)	2297 (5060)	2459 (5416)	2575 (5672)
Airplane Empty Weight, kg (lb)	1366 (3009)	1497 (3297)	1576 (3471)
Acquisition Cost, $ (1977)	202,854	229,553	245,741
Operating Cost, $/Hr (500 Hrs/Yr)	39.38	42.88	45.57
Total Cost, $ (1977)	150,357	167,616	178,944
Interest, $	40,571	45,911	49,148
3 Yr. Operating Cost, $	59,073	64,317	68,361
Trade-In, $	152,141	172,165	184,306
Fuel Consumption, liter/hr (gal/hr)	122.06 (32.21)	131.44 (34.68)	140.00 (36.94)

the characteristic data for these aircraft and Figures 53 and 54 show the relative values of the evaluation criteria and engine cost. The results show that the 1478°K (2200°F) turbine inlet temperature results in superior airplanes. The additional cost of the high-temperature components is offset by higher specific power or thrust, which results in smaller components and lighter weight. The effect of the smaller engines on aircraft drag and nacelle weight was not accounted for and would result in additional, though small, improvement. It is of interest to note that the difference between the 1478°K (2200°F) turbofan and the 1311°K (1900°F) turbofan is not as great as that between the 1478°K and 1311°K (2200°F and 1900°F) turboprops. If a turbofan-powered aircraft was of interest, more detailed turbine inlet temperature comparisons would be desirable, as well as further optimization of fan pressure ratio and compressor pressure ratio as discussed earlier.

4.5.2.2 Engine Configuration Trade-off Studies

The remaining engine configuration trade-off studies concentrated on the high-temperature configurations [1478°K (2200°F)]. The results are shown in Tables 35 and 36 for the pressurized and light twin and are summarized in Figures 55 and 56. In terms of the primary evaluation criterion, total cost, engine F (radial/axial single-shaft) is superior for both applications. The all-axial single-shaft engine, H, and the free-turbine engine, A, are within 5 percent of F. The two-stage centrifugal compressor configuration, engine C, by virtue of its high-pressure ratio and compressor efficiency, has the lowest fuel consumption in both applications. Operating cost differences between engines A, C, F and H are very small. Aircraft acquisition and engine cost show more pronounced differences.

If both applications and all evaluation criteria are considered, engines A and F appear to be the best selections, with the

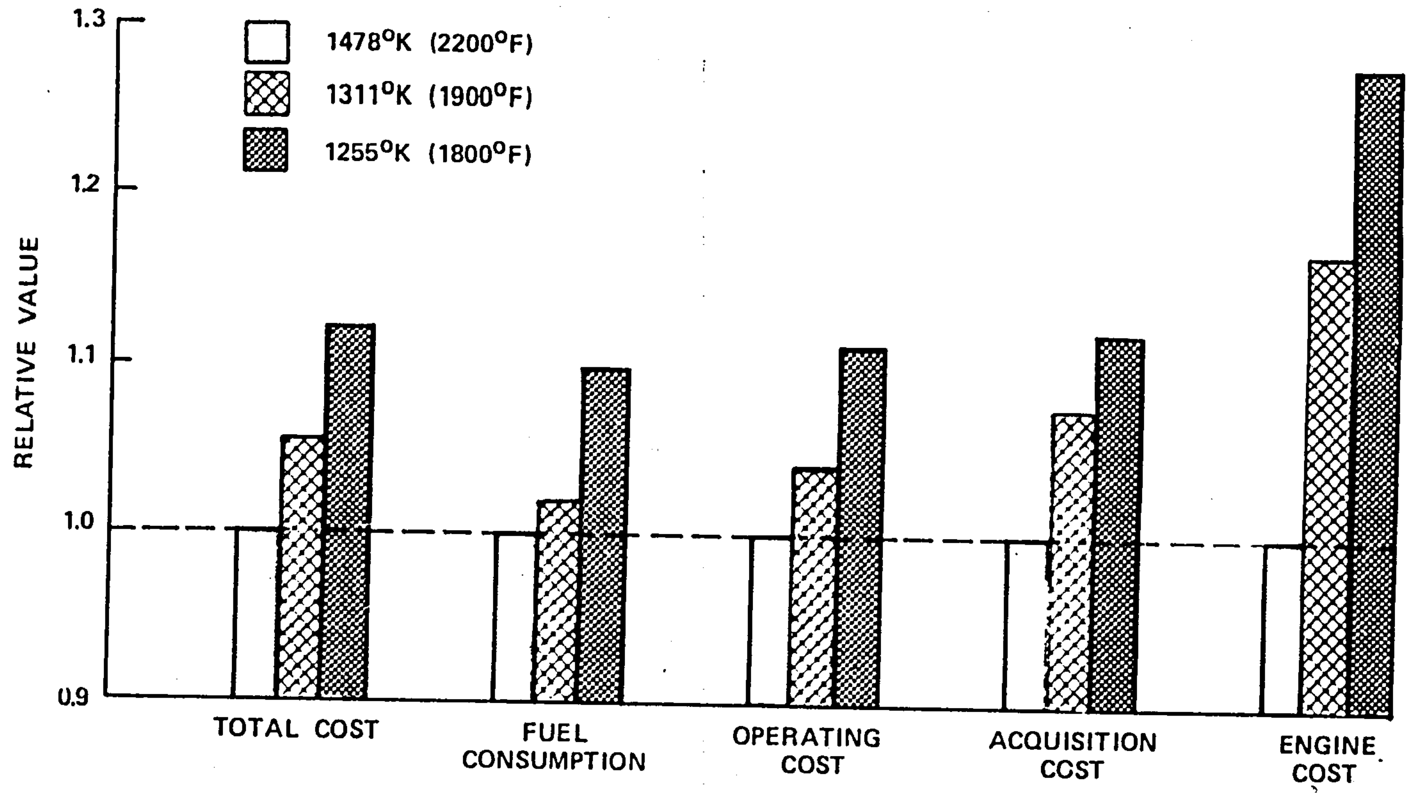


Figure 53. Turbofan Pressurized Twin Turbine Inlet Temperature Trade-Offs.

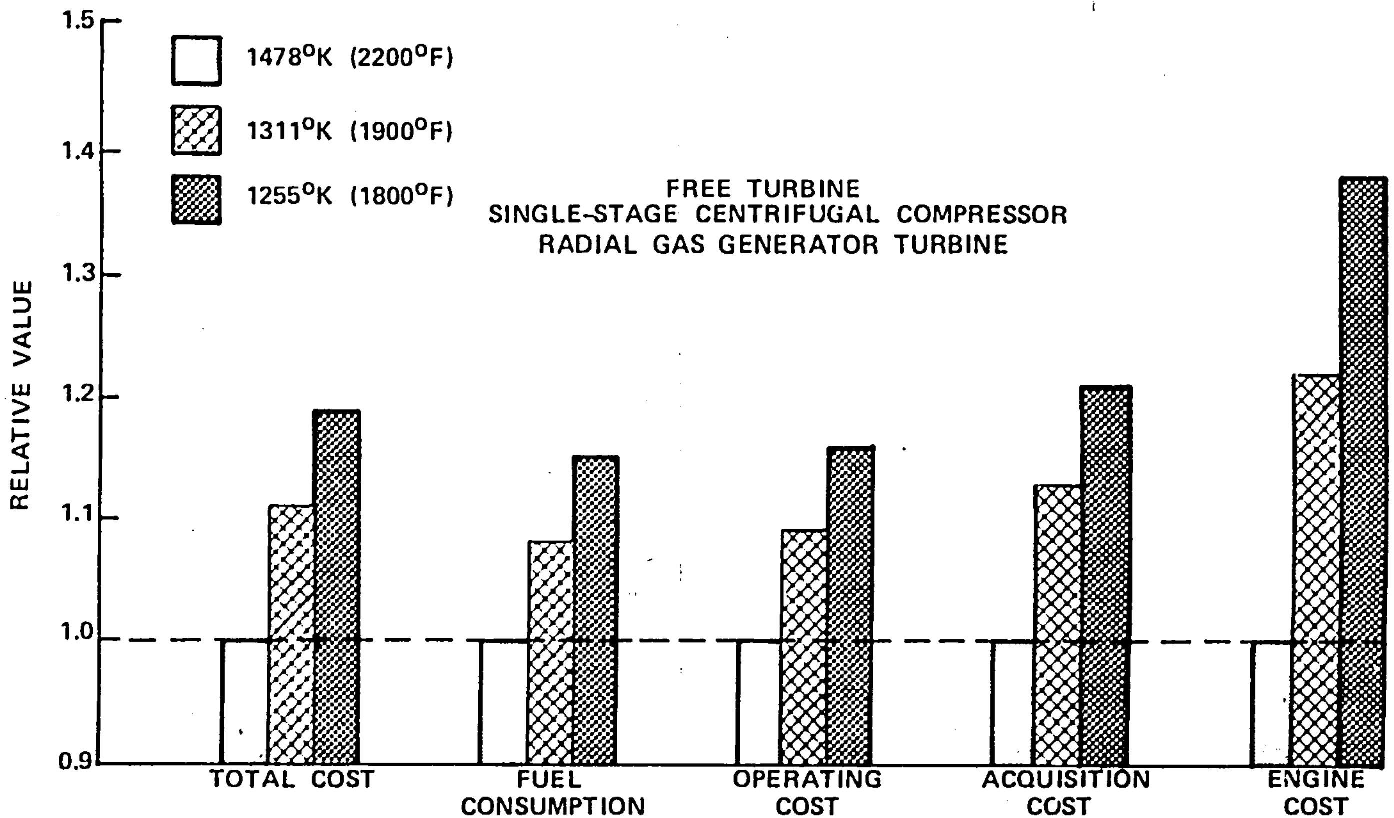
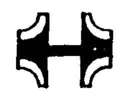


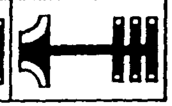
Figure 54. Turboprop Pressurized Twin Turbine Inlet Temperature Trade-Offs.

TABLE 35. PRESSURIZED TWIN, ENGINE CONFIGURATION TRADE-OFF STUDIES 1478°K (2200°F) ENGINES

Engine Type	Turboprop					Turbofan
	Free-Turbine			Single-Shaft		
Engine Designation	A	C*	D	F	H	J
Engine Net Thrust/Power, kw (hp)	312 (419)	318 (427)	314 (421)	274 (368)	256 (343)	4459N (1002 lb)
Engine SFC, kg/hr/kw (lb/hr/hp)	0.300 (0.493)	0.281 (0.462)	0.281 (0.514)	0.325 (0.533)	0.319 (0.523)	0.040 kg/N-h (0.390) lb/hr/lb
Engine Weight, kg (lb)	84 (186)	92 (202)	89 (195)	75 (165)	73 (160)	121 (247)
Engine Cost, $(1977)	16,200	18,700	19,500	15,000	17,900	22,500
Airplane Gross Weight, kg (lb)	2,297 (5,060)	2,285 (5,033)	2,339 (5,153)	2,245 (4,946)	2,223 (4,897)	2,728 (5,987)
Airplane Empty Weight, kg (lb)	1,366 (3,009)	1,384 (3,049)	1,381 (3,042)	1,319 (2,906)	1,309 (2,883)	1,485 (3,270)
Acquisition Cost, $(1977)	202,854	212,233	215,636	194,109	203,120	250,497
Operating Cost, $/Hr (500 Hrs/Yr)	39.38	39.21	41.89	38.81	39.30	56.72
Total Cost, $(1977)	150,357	154,313	159,865	145,568	150,355	197,806
Interest, $	40,571	42,446	43,127	38,822	40,625	50,099
3 Yr Operating Cost	59,073	58,809	62,829	58,218	58,950	50,099
Trade-In, $	152,141	159,175	161,727	145,581	152,340	187,873
Fuel Consumption, liter/hr (gal/hr)	122.08 (32.21)	116.05 (30.62)	128.48 (33.90)	121.96 (32.18)	119.01 (31.40)	200.98 (53.03)
Gas Generator						

*Two-Stage Centrifugal Compressor

TABLE 36. LIGHT TWIN ENGINE CONFIGURATION TRADE-OFF STUDIES 1478°K (2200°F) ENGINES

Engine Type	Turboprop				
	Free-Turbine			Single-Shaft	
Gas Generator Turbine	Radial	Radial*	Axial	Rad/Ax	Axial
Engine Designation	A	C	D	F	H
Engine Power, kw (hp)	244 (327)	241 (323)	251 (336)	240 (322)	239 (320)
Engine SFC, kg/hr/kw (lb/hr/hp)	0.300 (0.493)	0.281 (0.462)	0.313 (0.514)	0.325 (0.533)	0.319 (0.523)
Engine Weight, kg (lb)	64 (140)	68 (150)	68 (150)	65 (143)	63 (139)
Engine Cost, $(1977)	13,500	15,200	16,500	13,600	17,000
Airplane Gross Weight, kg (lb)	2243 (4,940)	2212 (4,872)	2285 (5,034)	2202 (4,851)	2179 (4,799)
Airplane Empty Weight, kg (lb)	1263 (2,781)	1267 (2,790)	1280 (2,820)	1238 (2,727)	1230 (2,710)
Acquisition Cost, $(1977)	178,706	183,917	190,767	174,923	186,141
Operating Cost, $/Hr (500 Hrs/Yr)	37.09	36.42	39.34	36.60	37.07
Total Cost, $(1977)	136,050	137,389	144,855	133,622	139,606
Interest, $	35,741	36,783	38,154	34,985	37,228
3 Yr. Operating Cost	55,632	54,627	59,009	54,906	55,605
Trade-In, $	134,030	137,938	143,075	131,192	139,608
Fuel Consumption, liter/hr (gal/hr)	119.46 (31.52)	112.56 (29.70)	125.26 (33.05)	117.07 (30.89)	112.94 (29.80)
Gas Generator					

*Two-Stage Centrifugal Compressor

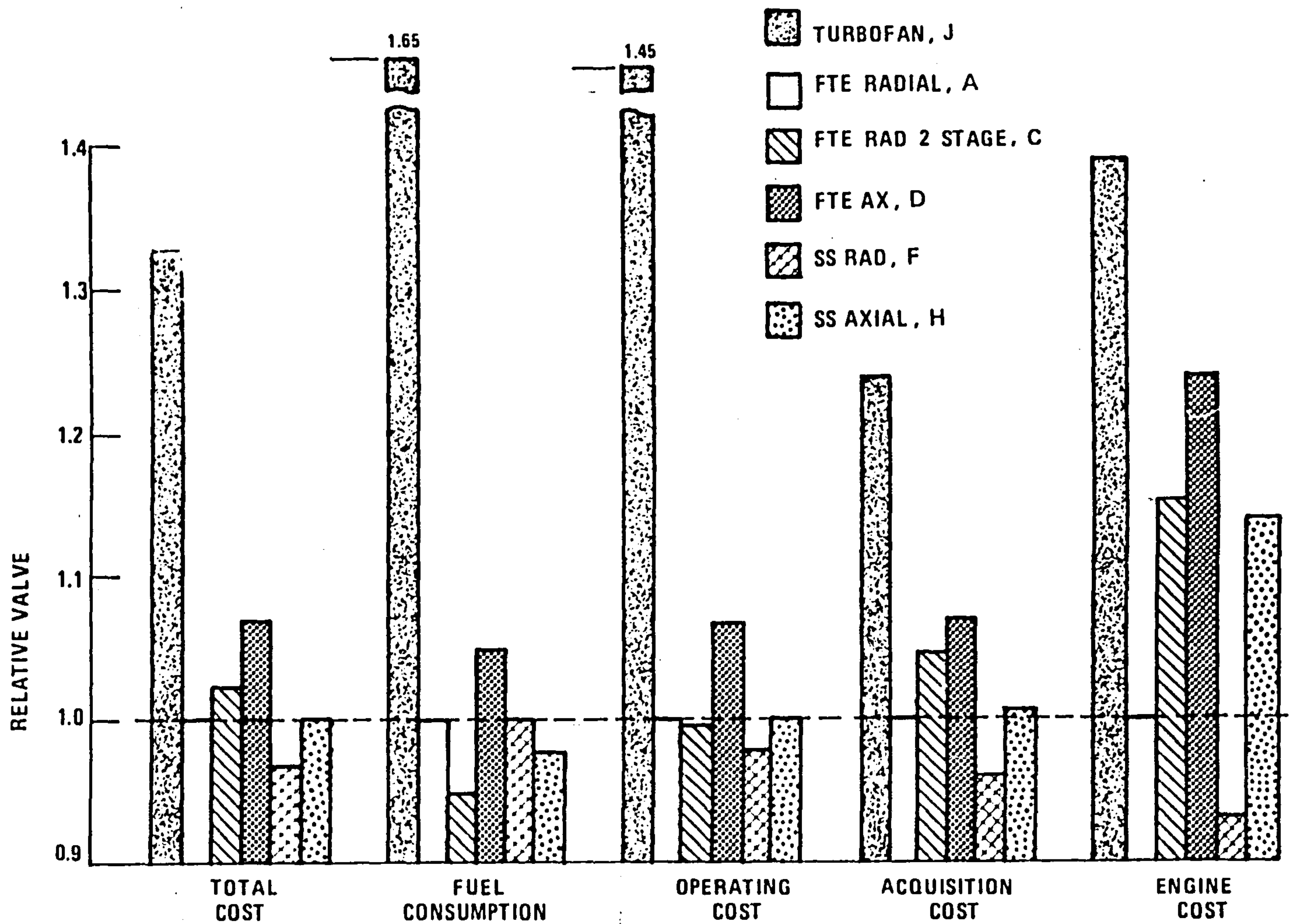


Figure 55. Trade Study Summary - Medium Pressurized Twin

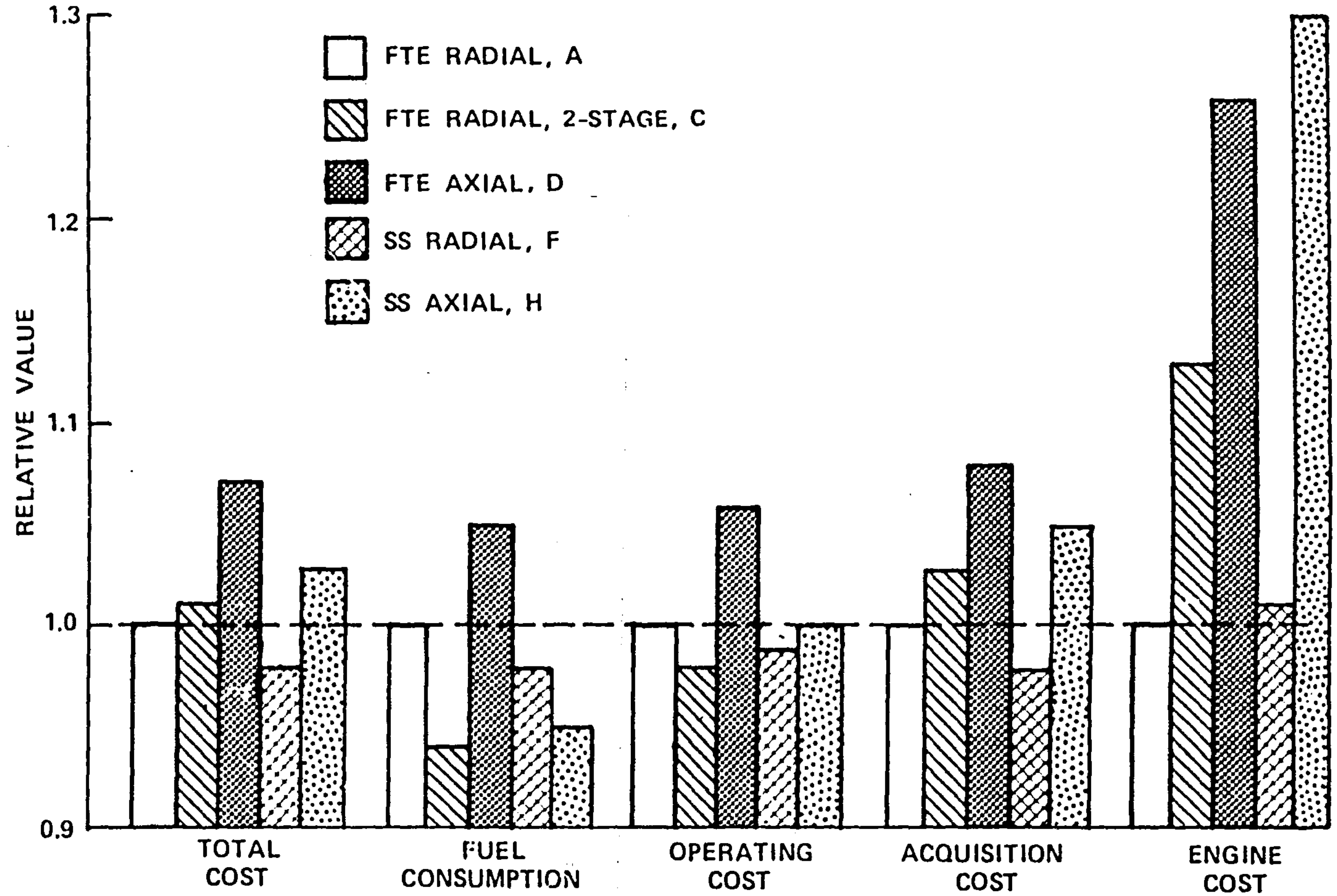


Figure 56. Trade Study Summary - Light Twin

fixed-shaft engine (F) having a slight edge. In considering other applications, particularly rotary wing, the single-shaft engine is not as attractive as the free-turbine engine. The rotary-wing applications are important since they represent at least 10 percent of the market and would probably be the first applications (in a turboshaft version) of an engine of this type.

To allow a choice between the two, Task III was oriented toward investigating the possibility of a common core, which would allow the fixed-wing market to enjoy the benefits of the single-shaft approach and give the rotary-wing market the free-turbine engine it requires.

4.6 <u>Benefit Analysis</u>

A benefit analysis was conducted to compare the GATE applications studied to aircraft powered by current technology turboprops, turboshafts, and reciprocating engines. Comparison to existing aircraft would be misleading, due to technology differences between the GATE aircraft and current aircraft. The GATE aircraft incorporate small improvements in aerodynamics and materials technology. The comparison was also done using the same ground rules for computing aircraft acquisition, operating, and total cost, and for identical missions.

4.6.1 <u>Current Technology Turboprop</u>

There is no suitable current technology turboprop that can be compared to the GATE engines. Turboprops employing recent technology are in the 447 to 746 kilowatt (600 to 1000 shaft horsepower) class and some of these are improved derivatives of engines designed 12 to 15 years ago. The Detroit Diesel Allison 250 Engine has been very successful and is at the upper end of the GATE size but is used primarily in turboshaft applications. It is a compact, durable, light-weight engine but only approaches the specific fuel consumption of the PT6, TPE331, and LTP101 in recent growth versions of approximately 447 kw (600 hp). A comparison of the 250 series with the GATE engines would show large benefits for the GATE designs but this approach would not yield a comparison to what could be achieved with readily available low-risk technology. To allow a fair comparison, a "current technology" engine was synthesized.

The turboprop configuration selected was a two-spool engine comprised of a two-stage centrifugal compressor, driven by a single-stage, axial, cooled turbine, a reverse-flow annular combustor, and a two-stage power turbine. Cycle characteristics and performance of the synthesized current-technology turboprop is compared to the GATE free-turbine engine (engine A). The results are shown in Table 37. The synthesized current-technology turboprop has lower fuel consumption than current gas turbines of comparable size, but is slightly heavier. The relatively low power-to-weight ratio is consistent with the philosophy followed on the GATE designs. Weight was traded in the GATE engines for lower manufacturing cost. The cost of the current-technology turboprop was derived by adding the increased costs of a two-stage centrifugal compressor, an inserted blade, cooled axial turbine, and a current electronic fuel control to the baseline cost of Engine A. This cost was then reduced by 40 percent for the effects of high-volume manufacturing.

Table 38 details the differences in cost, efficiency, specific fuel consumption, specific power, and weight by component. Note that cost and weight differences are not specified at equal power. The engines are compared as they are defined in Table 37. For equal power, the cost and weight differences would be greater. The advanced, high-pressure, radial turbine is a major contributor to the gains indicated. Compared with the current-technology axial turbine, the laminated radial turbine results in a 16-percent savings

TABLE 37. CURRENT TECHNOLOGY TURBOPROP CHARACTERISTICS

	Current Technology	GATE
Turbine Inlet Temperature, °K (°F)	1478 (2200)	1478 (2200)
Cycle Pressure Ratio	8.3	8.3
Compressor Corrected Flow, kg/sec (lb/sec)	1.22 (2.69)	1.22 (2.69)
Shaft Power, SLS, T.O., kw (hp)	315 (422)	365 (489)
Specific Fuel Consumption, kg/hr/kw (lb/hr/hp)	0.345 (0.567)	0.301 (0.493)
Engine Weight, kg (lb)	99 (219)	95 (210)
Engine Cost, $(1977)	27,671*	18,200*
No. of Compressor Stages	2	1
No. of HP Turbine Stages	1 Axial	1 Radial
No. of LP Turbine Stages	2	2

*For Production Quantities of 10,000/year

TABLE 38. ADVANCED TECHNOLOGY BENEFITS*
(DOES NOT INCLUDE SYSTEM EFFECTS)

Technology	ΔCost %	$\Delta\eta$ PTS	ΔSFC %	$\Delta\frac{SHP}{WA}$, %	ΔWT %
PM T_i Single-Stage Compressor	-4	-1.0	+1.4	-1.56	-4.3
Low-Cost Fuel Nozzles and Combustor	-1	0	0	0	0
Laminated High-Pressure Turbine**	-16	+9.8	-7.4	+9.4	0
High-Work/Low-Speed Power Turbine	0	+6.0	-7.0	+8.11	0
Electronic Control	-2	0		0	0
Laser-Hardened Gears	-3	-		0	0
Sheet Metal Turbine Plenum	-2	0		0	0
Other	-6	0		0	0
Total	-34		-13.0	+15.9	-4.3

*Relative to current technology engine (Table 37)
**Includes effects of turbine cooling and clearance control

in engine cost, a 9.8 percent increase in efficiency (improved relative to the initial value on page 84), and a 7.4 percent decrease in SFC. This table also does not include the airframe/engine synergistic effects, i.e., the total system benefits from the lower weight, improved efficiency, and higher specific power of the GATE engine.

The turbine inlet temperature selected for the current-technology engine is 339 to 366°K (150 to 200°F) beyond the capability of the latest TPE331 turbines and, as such, is somewhat beyond "readily available, low-risk technology".

The results of the comparison of the GATE free turbine engine (engine A) and the current-technology turboprop, as installed in the GATE airplanes, are shown in Table 39. The same propeller was used for the current-technology and GATE engines.

4.6.2 Reciprocating Engines

Currently, a number of reciprocating engine concepts are being investigated for aircraft applications. These include:

- Rotary engines
- Light-weight diesels
- Advanced spark-ignition engines

The rotary and diesel engines were considered only very briefly since current information on performance, durability, weight, size, and cost were not readily available. Both engine types could conceivably compete with the conventional, reciprocating, spark ignition engine but durability, performance, and weight are problems that must be surmounted.

Quantitative data on the advanced, reciprocating, spark ignition engines was also not readily available. Various projections have been made as to the level of fuel consumption improvement that will be possible. These projections range from 0 to 20 percent,

TABLE 39. COMPARISON OF GATE AND CURRENT TECHNOLOGY ENGINES

	Medium Pressurized Twin		Light Twin	
	Current Tech TPE	GATE Engine A	Current Tech TPE	GATE Engine A
Shaft Power, kw (hp)	327 (438)	312 (419)	253 (339)	244 (327)
Engine SFC, kg/hr/kw (lb/hr/hp)	0.345 (0.567)	0.300 (0.493)	0.345 (0.567)	0.300 (0.493)
Engine Weight, kg (lb)	103 (227)	84 (186)	80 (176)	64 (140)
Engine Cost, $(1977)	28,454	16,200	23,480	13,500
Airplane Gross Weight, kg (lb)	2501 (5510)	2297 (5060)	2393 (5271)	2243 (4940)
Airplane Empty Weight, kg (lb)	1465 (3226)	1366 (3003)	1357 (2990)	1263 (2781)
Acquisition Cost, $(1977)	238,699	202,854	218,735	178,706
Operating Cost, $(1977)/Hr	47.89	39.38	43.97	37.09
Total 3 Year Cost, $(1977)	165,555	150,357	164,386	136,050
Interest	47,740	40,751	43,747	35,741
3 Year Operating Cost, $(1977)	71,835	59,073	65,955	55,632
Trade-in, $(1977)	179,024	152,141	164,051	134,030
Fuel Consumption, liter/hr (gal/hr)	146.82 (38.74)	122.08 (32.21)	143.83 (37.95)	119.30 (31.52)

but factors such as durability and cost were not always considered. To compare reciprocating spark ignition engines to the GATE turbines, two levels of engine performance were assumed:

- Current technology
- Fuel consumption improvement of ten percent

Reciprocating engines representative of both levels of performance were evaluated in the GATE airplanes. The ground rules and assumptions followed in evaluating the reciprocating engines are listed in Table 40. The only change made in the basic empty weight breakdown of the airplanes is the change in engine weight and its effect on the weight of the wing, empennage, and landing gear. Nacelle and other engine-related weights were not changed and the propeller weight and cost were identical to those used for the gas turbines.

Specific fuel consumption for current-technology reciprocating engines at cruise conditions varies from 0.262 to 0.305 kg/hr/kw (0.43 to 0.50 lb/hr/hp). The 0.268 (0.44) level is typical of moderate sized engines.

Maximum cruise power for the reciprocating engines was limited to 75 percent of maximum power. Some current applications allow 79 percent of maximum but the majority recommend 75 percent for acceptable life.

The acquisition cost of the reciprocating-engine-powered aircraft was developed using the same equation supplied by Cessna for the GATE aircraft. The optional equipment and propeller cost was identical to that used for the gas-turbine-powered aircraft. The reciprocating engine cost was estimated using data developed in Task I. The 20-percent increase in reciprocating engine price assessed in Task I was not applied in Task II.

The major differences in operating costs were the fuel price, oil, the cost of engine overhaul, and inspection and routine maintenance costs. The price of aviation gasoline is the national average price for 1977. The cost of oil and the engine overhaul

TABLE 40. GROUND RULFS AND ASSUMPTIONS

Evaluation of Reciprocating Engines				
	Medium Pressurized Twin		Light Twin	
	Current Technology	Advanced Technology	Current Technology	Advanced Technology
<u>Engine</u>				
Type	Turbocharged	Turbocharged	Naturally Aspirated	Naturally Aspirated
Power-to-Weight Ratio	0.7	0.7	0.7	0.7
SFC, kg/hr/kw (lb/hr/hp)	0.268 (0.44)	0.241 (0.396)	0.268 (0.44)	0.241 (0.396)
Max Cruise Power	75% of Max Power	75% of Max Power	75% of Max Power	75% of Max Power
<u>Acquisition Cost</u>				
Basis	Cessna Equation	Cessna Equation	Cessna Equation	Cessna Equation
Propeller	*	*	*	*
Optional Equipment	*	*	*	*
Engine Cost, $/kw ($/hp)	44 (33)	44 (33)	39 (29)	39 (29)
<u>Operating Cost</u>				
Fuel Price, ¢/gal	77	77	77	77
Oil, $/Hr	0.45	0.45	0.45	0.45
TBO, hr	1500	1500	1500	1500
Engine Overhaul Cost	87% of O.E.M. Cost	87% of O.E.M. Cost	72% of O.E.M. Cost	72% of O.E.M. Cost

*Same As Gas Turbine

cost was obtained from data made available through Cessna dealers. They provide a service to potential customers called the Transportation Analysis Plan, which analyzes the operating cost of Cessna aircraft.

The results of the comparisons of the optimum GATE engine to the reciprocating-powered airplanes are shown in Table 41. The primary difference between the gas turbine and the reciprocating engine aircraft is engine weight. The difference in engine weight - approximately 454 kg (1000 pounds) - results in an empty weight increase of over 772 kg (1700 pounds). This increase in empty weight increases fuel required, the size of the engines, and the acquisition cost. The difference in operating cost is primarily due to the difference in engine overhaul reserve per hour and secondarily to higher fuel prices, lower volumetric energy content of aviation gasoline, and the higher inspection and routine maintenance costs of the reciprocating engine. The engine overhaul rate per hour of utilization is higher for the reciprocating engine due to:

- An overhaul period of less than half that of the gas turbine
- Higher percentage of the original engine price for overhaul
- An original engine cost equal to that of the gas turbine, due to higher power requirements

For the medium pressurized twin, the higher per hour overhaul rate accounts for 54 percent of the operating cost difference between the gas turbine and reciprocating engines. Fuel and oil cost, inspection, and insurance account for 29, 11, and 6 percent of the operating cost difference, respectively.

TABLE 41. COMPARISON TO RECIPROCATING POWERED AIRCRAFT

	Pressurized Twin			Light Twin		
	GATE Engine "A"	Current Technology Recip.	Advanced Technology Recip.	GATE Engine "A"	Current Technology Recip.	Advanced Technology Recip.
Engine Shaft Power, kw (hp)	312 (419)	346 (464)	338 (453)	244 (327)	283 (380)	277 (371)
Engine SFC, kg/hr/kw (lb/hr/hp)	0.3 (0.493)	0.268 (0.44)	0.241 (0.396)	0.300 (0.493)	0.268 (0.44)	0.241 (0.396)
Engine Weight, kg (lb)	84 (186)	301 (664)	292 (643)	64 (140)	250 (550)	243 (536)
Engine Cost, $(1977)	16,200	15,312	14,949	13,500	11,020	10,759
Airplane Gross Weight, kg (lb)	2297 (5060)	3097 (6821)	2997 (6601)	2243 (4940)	2815 (6200)	2715 (5980)
Airplane Empty Weight, kg (lb)	1366 (3009)	2117 (4664)	2068 (4555)	1263 (2781)	1846 (4065)	1800 (3965)
Airplane Acquisiton Cost, $(1977)	202,854	252,972	245,534	178,706	206,694	199,781
Operating Cost, $/Hr (500 Hrs/Yr)	39.38	63.63	59.88	37.09	51.32	48.26
Total 3 Year Cost $(1977)	150,357	209,289	200,308	136,050	169,989	162,297
Interest	40,751	50,595	49,107	35,741	41,339	39,956
3 Yr Operating Cost	59,073	95,451	89,817	55,632	76,977	72,396
Trade-in	152,141	189,729	184,151	134,030	155,021	149,836
Mission Fuel Consumption, liter/hr (gal/hr)	122.08 (32.21)	145.5 (38.4)	129.6 (34.2)	119.46 (31.52)	129.9 (34.3)	117.1 (30.9)

4.6.3 Current Technology Turboshaft

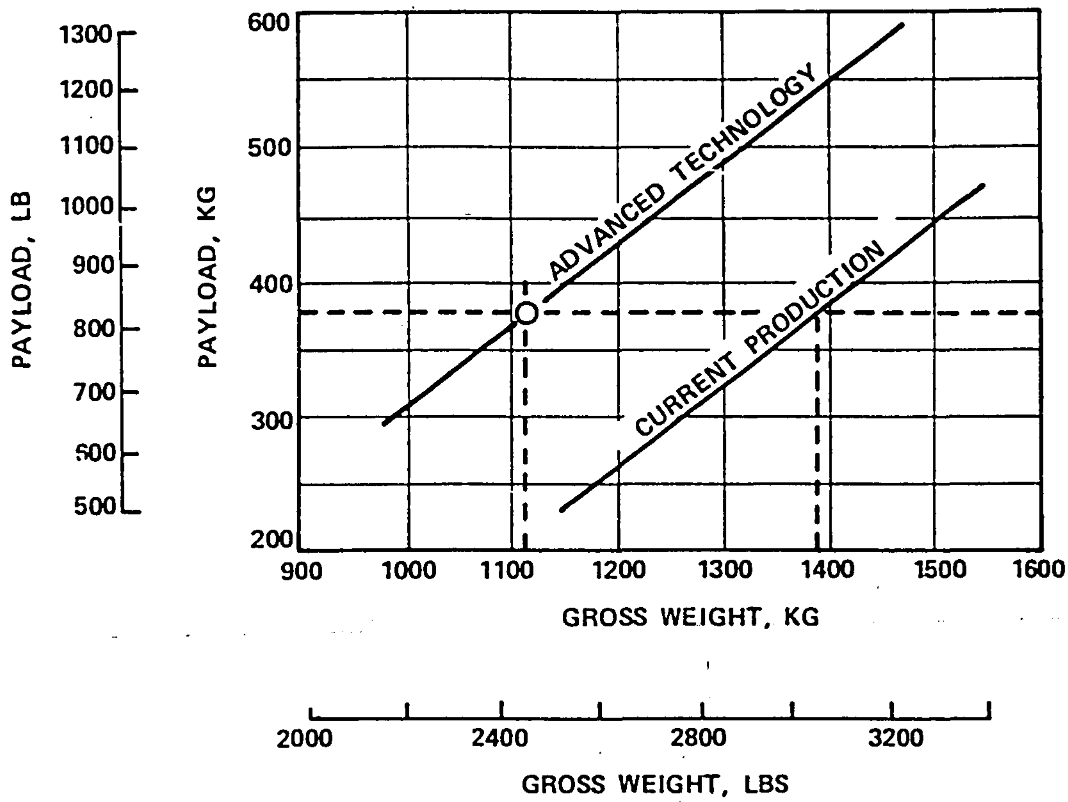
Analysis of the single-engine utility helicopter was a combined trade-off study and benefit analysis. The analysis was performed by Bell Helicopter. The turboshaft engine used in the analysis was engine L described in 4.5. The characteristics of the light helicopter and the results of sizing and mission analysis are listed in Table 42.

Bell compared the above results with a helicopter that used a current-production turboshaft engine. These results are shown in Figure 57. The engine characteristics of the advanced-technology engine (GATE) and the current production engine are shown at the bottom of the figure. At a constant payload of 377 kg (830 pounds), the advanced technology engine results in a helicopter that is 20-percent lighter. This reduction in gross weight translates to lower acquisition and operating costs, as well as markedly lower fuel consumption.

TABLE 42. SINGLE-ENGINE UTILITY HELICOPTER SIZING AND MISSION ANALYSIS RESULTS*

Parameter	Value	
Gross Weight, KG (LB)	1109	(2442)
Empty Weight, KG (LB)	549	(1210)
Payload, KG (LB)	377	(830)
Max Speed, KM/HR (KTS)	215	(116)
Cruise Speed, KM/HR (KTS)	189	(102)
Range, KM (N.M.)	611	(330)
Critical Altitude, M (FT)	1967	(6450)
SHP, SLS, T.O. Max Power, KW (HP)	204	(274)
Main rotor Diameter, M (FT)	10	(33)

*Bell Design Point No. 7



ENGINE CHARACTERISTICS		
	ADV TECH	CURRENT PRODUCTION
SFC, SLS, T.O.	0.29 KG/HR/KW (0.47 LB/HR/HP)	0.48 KG/HR/KW (0.78 LB/HR/HP)
POWER/WEIGHT	4.57 KW/KG (2.77 HP/LB)	3.51 KW/KG (2.13 HP/LB)

Figure 57. Comparison of a Turboshaft Version of the GATE Free-Turbine Turboprop with a Current-Production Turboshaft in a Light, Utility, Single-Engine Helicopter.

SECTION V

5.0 COMMON-CORE CONCEPT

The common-core concept study was envisioned as an effort to compromise engine requirements, as defined in the broad scope trade-off studies, and define a single gas generator, which would satisfy all requirements to a degree and achieve lower cost through parts commonality. It was anticipated that different types of engines would be optimum for the various applications, i.e.

- Turbofan
- Turboprop
- Turboshaft

The Task II results showed that all fixed-wing applications require a turboprop. Turbofans would not be competitive unless cruise speeds were increased and takeoff performance was relaxed. The most significant difference between optimum engines is believed to lie in the difference between turboprop and turboshaft configurations. The optimum engine for fixed-wing applications, by a small margin, is a single-shaft configuration. Although a single-shaft turboshaft is workable for single-engine rotary-wing applications, it introduces large compromises and may be unsatisfactory in twin-engine installations. The common-core concept study was therefore oriented toward determining if there was a common core that would approach the characteristics of the single-shaft engine in the fixed-wing applications, and was suitable for use as the core for a free-turbine turboshaft for rotary-wing applications.

The common core that resulted is shown in Figure 58 as are the turboprop and turboshaft engines which result from this common core. The common core is comprised of a single-stage centrifugal compressor, a reverse-flow annular combustor, and a radial inflow turbine.

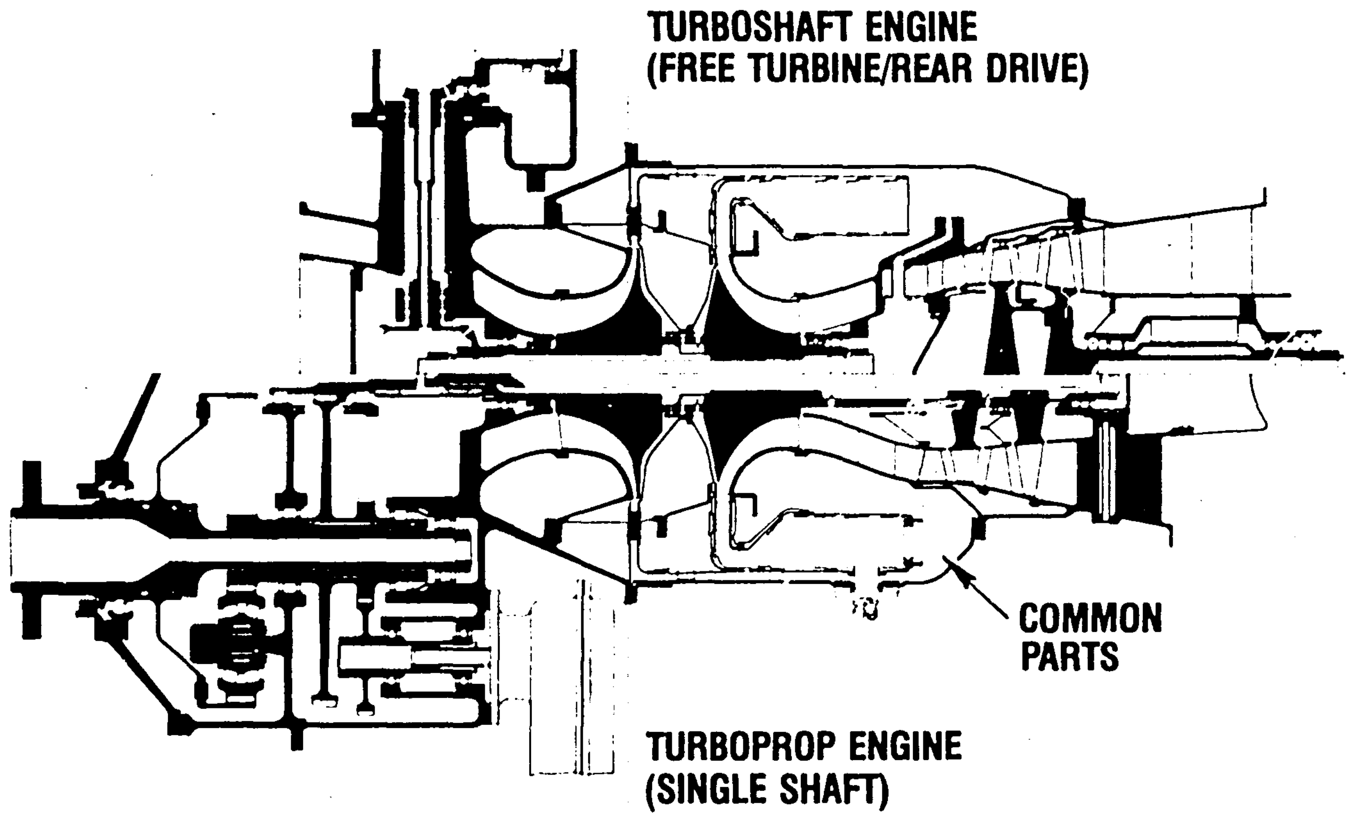


Figure 58. Common-Core Concept

The single-shaft engine shown on the lower half of the figure requires one more axial turbine stage than the optimum single-shaft turboprop with the radial/axial turbine shown in Figure 50. The additional turbine stage is the result of unloading the radial turbine in the optimum single-shaft engine. The radial turbine must be unloaded so that it is compatible with the turboshaft engine shown in the upper half of Figure 58. This engine is a rear-drive, free-turbine turboshaft. The radial turbine in the optimum engine drives the compressor and also supplies part of the output power. As a part of a common core for the free-turbine turboshaft, it only needs to drive the compressor.

The benefits of the common core are:

- o Increased parts commonality
- o Increased turbine efficiency due to more lightly loaded stages.

The disadvantages are:

- o Additional turbine stage in single-shaft version (cost and weight)
- o High-temperature power-turbine bearing compartment in free-turbine turboshaft
- o A common-core turbofan is not easily derived.

The common-core approach would provide a single-shaft engine for the fixed-wing aircraft and a free-turbine turboshaft for the helicopter. However, a preliminary study indicates that the superiority of the common-core, single-shaft engine over the non-common-core, free turbine engine (Figure 48) would be diminished and the relative difference would be very small, due primarily to the cost of the additional turbine stage.

On the basis of this analysis, Engine A, which is a free-turbine engine comprised of a single-stage, centrifugal compressor and radial turbine, is recommended as the preferred engine configuration. It is close to optimum, offers turbofan derivatives, and is compatible with rotary-wing applications.

SECTION VI
TECHNOLOGY PROGRAM PLAN

6.0 Program Scope

An integrated program approach is recommended to establish technology readiness for general aviation turboprop and turboshaft engines in the 298 kw (400 shp) class. The scope of the recommended experimental program is shown in Table 43. The first task consists of a preliminary design of an experimental engine incorporating the advanced technology components to be demonstrated. The advanced component test hardware will be designed in parallel. Each of these components will be extensively evaluated in full-scale component test rigs. The high-pressure spool components will then be further evaluated in a gas generator core. The core performance is critical in establishing a successful technology demonstration. The highest pressures and temperatures are encountered in the core and significant performance improvements can be made as a result of optimization of the gas generator component system. After separate component testing, the low-pressure turbine system and output reduction gearbox will be combined with the high-pressure core to form the complete experimental engine. Additional evaluation tests will be conducted to demonstrate the technology readiness for full-scale development. System analysis and engine definition will be performed throughout the program to insure that engine design trade-offs do not result in undue compromises in aircraft cost or capability.

6.1 Preliminary Design

The preliminary design effort will establish the configuration of the experimental engine. The engine cycle will be defined and the components sized in order to establish the design requirements for each of the GATE advanced technology components. The experi-

TABLE 43. GATE EXPERIMENTAL PROGRAM PLAN - PROGRAM SCOPE.

- o Preliminary Design
- o Component Technology Development
  - o High-Pressure Turbine
    - \- Rotor
    - \- Nozzle
  - o Compressor
  - o Clearance Control
  - o Combustion System
  - o Low-Cost Digital Electronic Control
  - o High-Work/Low-Speed Power Turbine
  - o Laser Hardened Gears
- o Gas Generator Technology Development
- o Experimental Engine Technology Development
- o Engine System Analysis and Definition

mental engine design will be based on a front-drive, concentric shaft, free-turbine, turboprop engine configuration, as shown in Figure 59. The nominal takeoff power rating for the engine will be approximately 313 kw (420 hp).

Design objectives will be established for each of the components. These objectives will be compatible with the overall engine technology required. The experimental engine will be designed as a demonstrator only and would not necessarily, in all areas, have flight-weight or production-type components. In areas where new technology is not being developed, the components will be designed with an objective of best program economy, while ensuring that the experimental engine will provide a representative demonstrator for both steady-state and dynamic operation.

6.2 Component Technology

6.2.1 High-Pressure Turbine

The high-pressure turbine is an integrally cooled radial turbine designed for a rotor inlet temperature of 1478°K (2200°F). Both the nozzle and rotor are of low-cost laminated construction. The objective is to provide the technology for a small, cooled, radial turbine with a 9.8 percent efficiency improvement over current, small, cooled, axial turbines, while reducing engine cost by 17 percent. The critical elements of technology to be addressed are shown in Table 44. Figure 60 shows the program plan and schedule for the component technology development.

6.2.1.1 Rotor Task

Advanced process research will address the need for a low-cost sheet alloy with high stress-rupture strength. Candidates are Astroloy and AF2-1DA. As shown in Figure 61, the conventional rolling process has a yield of only 35 percent when making photoetch

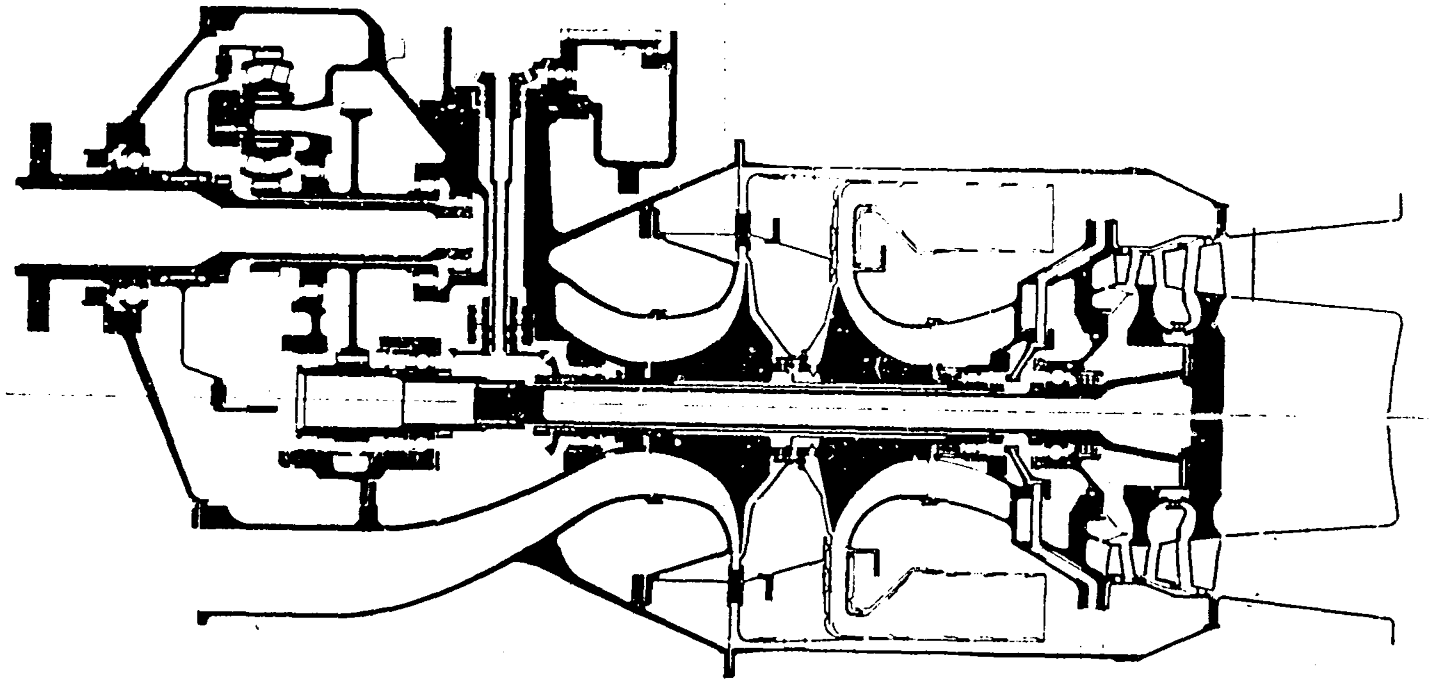


Figure 59. Free-Turbine Turboprop

TABLE 44. LAMINATED RADIAL GAS GENERATOR TURBINE

MATERIALS AND PROCESSING

- o Low-Cost AF2-1DA Sheet (Rotor)
- o Low-Cost AF2-1DA or ODS Material (nozzle)
- o Low-Cost/High Strength Bonding
- o Non-destructive Evaluation Techniques
- o Photoetching Process for ODS Materials
- o Material Characterization
- o 3-D ECM

AERODYNAMICS

- o Minimize Clearance Losses
  - -- Shroud Treatment
  - -- Decreased Clearance
- o Minimize Cooling Penalty (Tip Discharge)
- o 3-D Blading
  - -- Decreased Incidence Loss
  - -- Increased Blade Loading
- o Reduced End Wall Losses
  - -- 3-D Velocity Diagram
  - -- 3-D End Walls

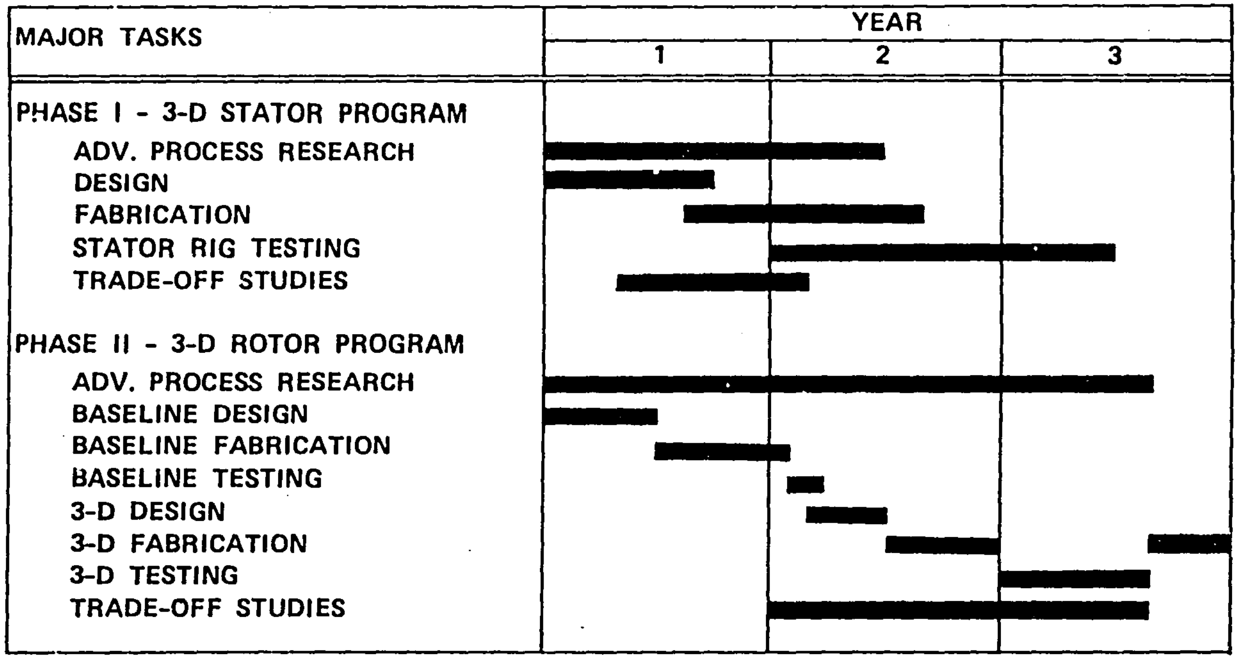


Figure 60. Cooled Laminated Radial High-Pressure Turbine

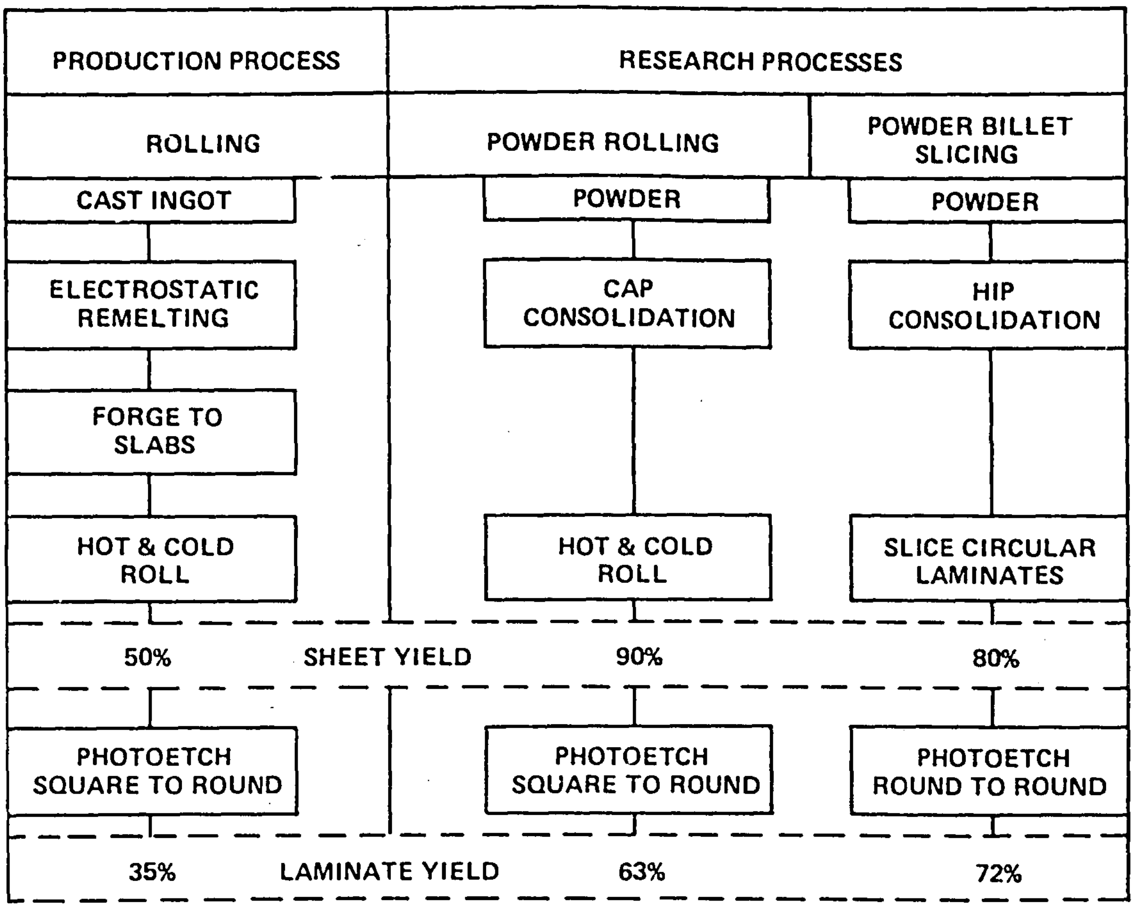


Figure 61. Sheet Alloy Processes

quality sheet stock. The powder rolling process and powder billet slicing method have projected yields of 63 percent and 72 percent, respectively. Development of either of these processes would remove the cost barrier and allow use of the high-strength Astroloy or AF2-1DA material.

Both of the advanced sheet alloy forming processes will be evaluated by small-scale pilot processing. The most promising approach will be selected and an adequate quantity of material fabricated for the final gas generator and experimental engine test components.

New methods of bonding the sheet alloys will be evaluated to obtain high bonding strength using a low-cost method. Two methods will be evaluated: (a) sputtering and (b) electroless nickel plating. After initial evaluation using small bonded test stacks, the superior method will be selected and further optimized by bonding larger test stacks.

Nondestructive test methods using computer enhancement techniques will be optimized with the use of known defect test samples. Additionally, the electrochemical method (ECM) of final machining the airfoil surface will be optimized to permit fully three-dimensional reproduction of the desired aerodynamic shape. All of these processing advancements will be used to fabricate a turbine rotor to be used in the second series of gas generator tests.

The objectives of the aerodynamic technology program may be summarized as:

- o Refine performance effects of increased rotor blockage resulting from internal cooling.

- o Determine the performance effects of coolant airflow discharge into the main gas stream.
- o Determine clearance effects on performance of a cooled radial turbine.
- o Define shroud treatment to reduce clearance losses.
- o Evaluate approaches to increase blade loading so that fewer blades and proportionally less cooling air will be required.
- o Evaluate methods to decrease incidence losses by 3-D design methods.

The baseline tests will assess rotor blockage effects, performance effects of coolant airflow discharge, and clearance criteria.

Data from the baseline tests will be combined with advanced analytical methods and used to make a final 3-D design. The baseline test series will be repeated on the 3-D design and additional tests will be made to evaluate blade loading and incidence losses. Flow predictions will be confirmed by use of Laser Doppler Velocimeter (LDV) test methods. Three test series are planned with modifications to optimize performance.

6.2.1.2 Nozzle Task

The initial program will test nozzles in conjunction with the baseline rotor. Both integral and segmented, cooled nozzle designs will be tested. Predictions of performance, cost, and life will be made for both designs. Laminated construction will be used for both designs. Performance will be evaluated in a test rig based on stator exit pressure surveys and torque measurements on a down stream rotor.

After testing the integral stator, the segmented stator will be tested to assess the leakage effects. Cooling flow shall be varied in each test to determine the effects of the quantity of cooling flow on nozzle performance. A final test shall be conducted on either the integral or segmented nozzle to assess the performance effect of smoothing the laminated vane surface.

Trade-offs must be accomplished in order to select the optimum nozzle laminated sheet material. Candidates are Astroloy, AF2-1DA and oxide-dispersion-strengthened (ODS) material such as MA956E. The effort would involve preliminary sheet fabrication, photoetch, and bonding method development to assess the relative merits of the candidate materials. The selected material would be used for final hardware, which will be tested in conjunction with the 3-D rotor.

The orthotropic material properties of the selected laminated material will be established, including strength, elastic modulus, Poisson's ratio, low- and high-cycle fatigue, and creep /creep rupture.

Trade-off studies will be made of the 3-D design approach to obtain an optimum balance of performance and cost. A cost versus performance design trade-off will also be accomplished for 3-D end walls versus 2-D end walls.

6.2.2 Compressor

The advanced technology compressor component is a 9:1 pressure ratio, single-stage, centrifugal compressor fabricated to essentially net shape from powder metal titanium. The objective is to provide the technology for improving the efficiency of the compressor by 3.5 points relative to a current technology 9:1 single-stage machined centrifugal compressor, while reducing cost to the point where it is competitive with cast designs.

The critical elements of the compressor technology are shown in Table 45 Figure 62 shows the program plan and schedule for the component design and evaluation. In the first task, two or more candidate PM titanium processes will be evaluated to determine the one most suitable for meeting the GATE compressor requirements. Impellers of an existing configuration will be made from each process and a comparison made of properties, shrinkage, blade-shape reproduction, surface finish, and potential production cost.

Concurrently, the baseline GATE compressor will be designed. The design will be compatible with an existing test rig. The compressor shall be fabricated by machining and tested for performance in the component rig. It is anticipated that five tests will be conducted including impeller modifications and diffuser redesigns.

Prototype fabrication of the GATE impeller design will establish the process limitations and provide information for a redesign of the impeller. The redesigned impeller will be fabricated both by machining and the PM titanium process.

Tests shall be run to compare the performance of the machined and PM titanium impellers. A final test is anticipated with a redesigned diffuser.

Using all the available data, cost and performance trade-offs will be made to determine if any design changes are required for the compressor to be carried into gas generator testing.

6.2.3 Clearance Control

Clearance control on small engines is exceedingly important because the clearance performance loss penalties are relatively greater than on large engines. However, small engine clearance control is difficult because of various factors:

TABLE 45. REQUIRED COMPRESSOR TECHNOLOGY - 9:1 SINGLE STAGE.

- 3-D Blading for High Efficiency
  - High Tip Speeds
  - High Inducer Mach Number
- 3-D Diffuser Research
- Improved Surge Margin
- PM Ti Technology

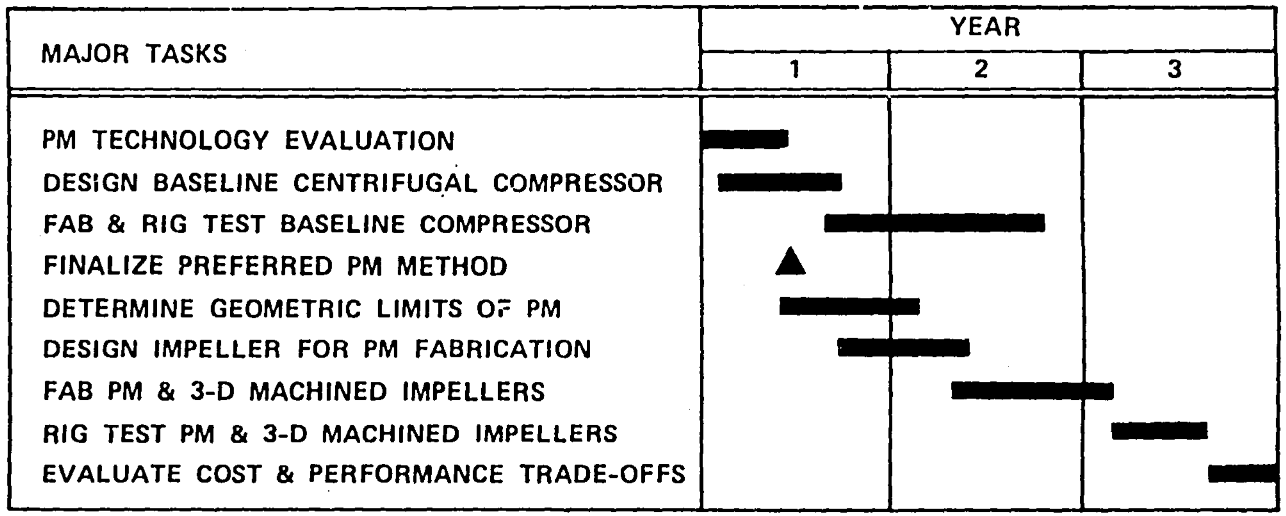


Figure 62. PM Titanium Centrifugal Compressor

- Tolerances do not scale
- Small engines have larger thermal gradients
- High-speed rotor systems have more critical speed problems
- Rotor excursions are relatively larger
- Conventional abradable systems cause relatively high tip wear
- Clearance control means must be simple and low cost

The major technology tasks that must be addressed for substantially improved clearance control are shown in Table 46. The technology program plan is summarized in Figure 63. Design concepts will be evaluated to establish viable candidate approaches to clearance control. Dynamic thermal analysis methods will be used to evaluate candidate clearance control concepts during transient operation.

In order to minimize operating clearances, controlled growth structure approaches shall be analyzed considering selection of optimum material expansion rates. Materials with thermal expansion coefficients that vary with temperature will be considered. Effective use of cooling air will be analyzed as an additional method of controlling differential expansion rates of structure and rotating components. Although emphasis will be on non-active clearance control because of the GATE Engine low-cost emphasis, simple active clearance control methods will also be considered and trade-offs made on cost versus performance. Selected controlled-growth approaches will be designed, fabricated, and tested in an existing engine, using dynamic clearance measurement instrumentation.

TABLE 46. CLEARANCE CONTROL TECHNOLOGY.

- Controlled Growth Structures
  - Variable Expansion Rate Materials/Designs
  - Effective Use of Cooling Air
  - Dynamic Simulation of Small Engines
- Rotor Damping
- Shroud Treatment
  - Grooves
  - Cooling Flow Discharge
- Abradable Materials
  - Tip Wear
  - Life

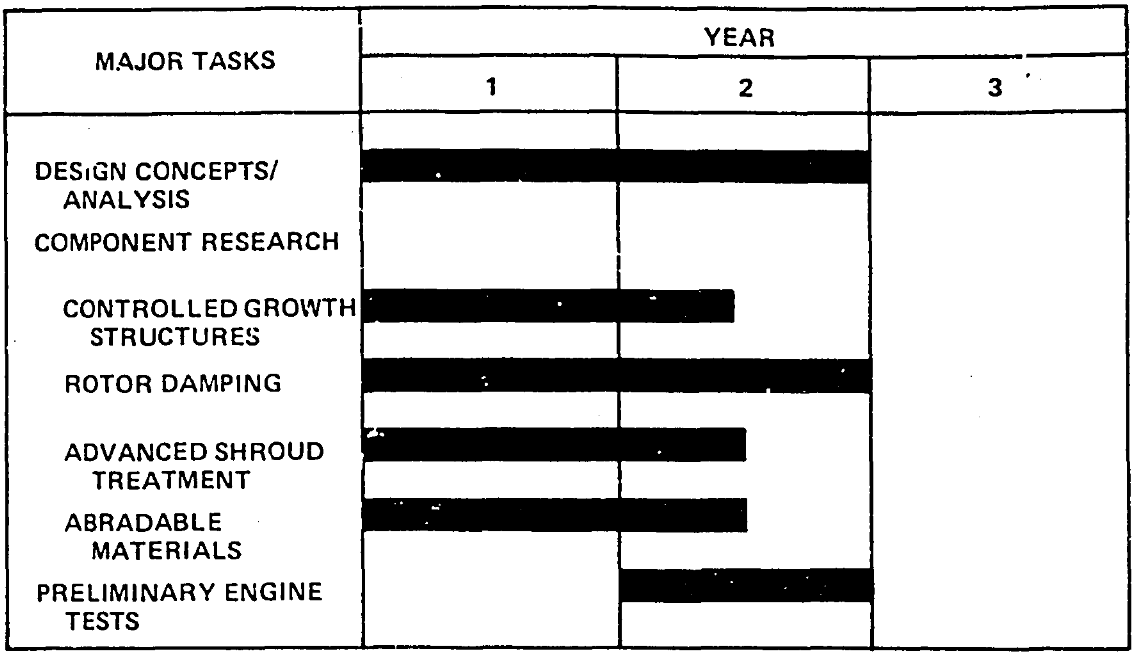


Figure 63. Clearance Control

Reduced rotor excursion is desirable to allow both closer rotor-face operating clearances and smaller seal clearances in order to improve performance. Rotor system damping methods will be evaluated to select concepts that offer the pontential of reducing rotor excursions when operating through critical speeds. This will include evaluation of shafting designs, bearing support structure, and hydraulic and/or mechanical bearing damping systems. Candidate systems will be designed, fabricated, and tested on a dynamics test rig to determine the optimum system approach.

Investigations shall be made into reducing effective clearance. Two approaches will be considered. In the first, the effect of grooves or labyrinths in compressor and turbine shrouds will be analyzed and tested in component test rigs to establish their effect on performance. The effect of boundary layer bleed in the compressor shroud/diffuser interface will be analyzed and tested to determine whether any performance benefit exists.

Alternate methods of high-pressure turbine cooling flow discharge shall be studied and any promising methods will be tested in a component test rig.

Abradable materials will be evaluated including investigation of rotor tip configuration alternatives and rotor tip hardening methods. Promising combinations of abradable shroud materials and rotor tip configurations and materials will be evaluated and tested in existing engines.

Additional testing using existing engines shall be accomplished combining the most promising approaches derived from the controlled-growth structures, rotor damping, shroud treatment, and rotor-tip/abradable-shroud efforts. This testing will provide for the determination of performance effects of zero engine time and after limited running.

6.2.4 Combustion System

The GATE combustion system consists of a reverse-flow annular combustor combined with a minimum number (8-10) of low-cost air-blast fuel nozzles. The combustor outlet temperature required to provide a turbine rotor inlet temperature of 1478°K (2200°F) is 1522°K (2280°F). The system will require low-cost combustor construction and low combustor wall temperatures with minimum gradients for long life. Technology for good starting, operating, and relight characteristics, with either Jet A (current jet fuel), broad specification, synthetic or diesel fuels is required. The critical elements of combustor system technology are shown in Figure 64. Figure 65 shows the program plan and schedule for combustor component development.

A full-scale, baseline, combustion system will be designed using advanced empirical/analytical design methodology. The design requirements will be consistent with the GATE Engine and will emphasize minimum fuel impingement on walls to reduce the carbon forming tendency. An objective is a 30-percent improvement in exit pattern factor from current technology. The improved pattern factor can be achieved with proper matching of fuel nozzle characteristics and combustor flow field with the use of advanced analytical modeling. Two alternate advanced wall cooling schemes will be designed for comparison with the baseline design. Low-cost photo-etch fabrication methods will be used in these advanced cooling schemes.

Approximately ten tests on the baseline combustor will be accomplished to optimize its performance characteristics. Six additional tests are planned on the advanced wall cooling configurations. Based on test evaluations and life-cycle cost predictions, the most promising configuration will be selected for further evaluation over the entire operating envelope. Six tests

OBJECTIVE	TECHNOLOGY ADVANCEMENT					
	LINER COOLING	PRIMARY ZONE DESIGN	CARBON FORMATION	STABILITY	INJECTOR DESIGN	EFFICIENCY
REDUCED CHANNEL HEIGHT	X	X	X	X	X	X
INCREASED DURABILITY	X	X			X	
LOWER PATTERN FACTOR	X	X			X	
ALTERNATE FUEL CAPABILITY		X	X		X	

- EMPIRICAL/ANALYTICAL COMBUSTOR DESIGN METHODOLOGY
- IMPROVED FILM EFFECTIVENESS
  - COOLING SCHEMES
  - LOW-COST FABRICATION
- PRIMARY ZONE DESIGN

Figure 64. Combustor Technology

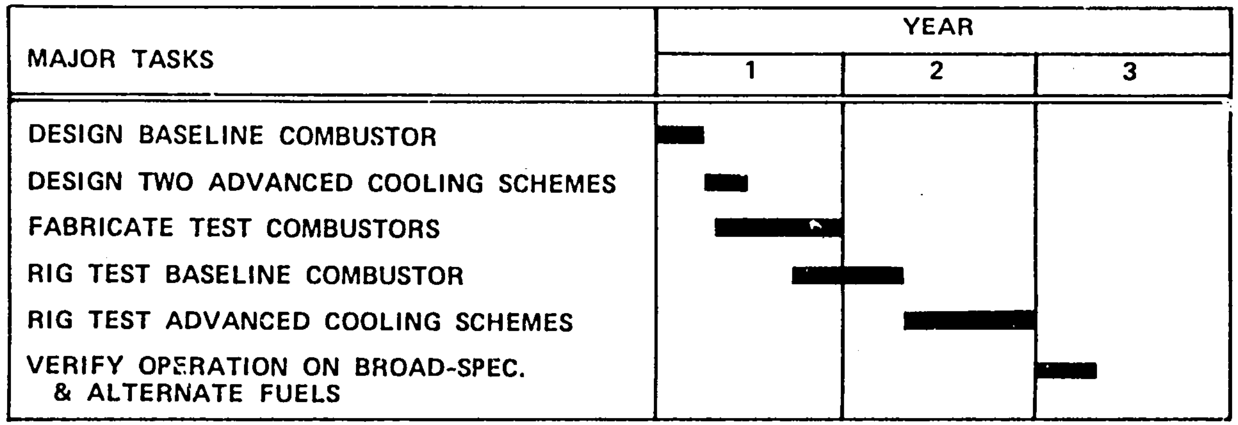


Figure 65. Low-Cost Combustor, 1478°K (2200°F)

are expected for this final optimization. Finally, combustor performance will be demonstrated with Jet A, broad specification kerosene fuel, diesel fuel, and an additional fuel to be specified by NASA.

Critical elements of the low-cost airblast nozzle component technology are shown in Table 47. Figure 66 shows the program plan and schedule. Conceptual design will be done on several candidate airblast atomizers. Three designs will be selected based on cost and performance projections. These designs will be evaluated to determine spray characteristics. One or two of the best configurations will be selected for further evaluation in combustor rig testing on the baseline combustor. One configuration will be selected for further evaluation along with the baseline combustor in the baseline gas generator. A comparison of gas generator test and rig test results will be made and used to accomplish the final optimization of the combustion system on the component test rig. Starting characteristics and limited endurance evaluation will be conducted on the baseline gas generator and any required improvements would be incorporated into the final component rig evaluation tests.

6.2.5 Low-Cost, Digital, Electronic Control

Control systems for small general aviation gas turbine engine applications must be low cost and reliable. The least expensive, most reliable control is a simple, hydromechanical type provided there are few sensed parameters, outputs, or automatic features, and a relatively high pilot workload is acceptable. The cost and weight penalty of hydromechanical mechanization of features such as torque limiting, automatic starting and sequencing, automatic transfer and protection, and provisions for optimum engine performance, noise abatement, and emission reductions is very high.

TABLE 47. LOW-COST AIRBLAST NOZZLE TECHNOLOGY.

- Eliminate Air Assist
- Design for High Production Quantity
- Simplify Piloting Requirements
- Improve Spray Quality
- Improve Functional Reliability
- Alternate Fuel Capability

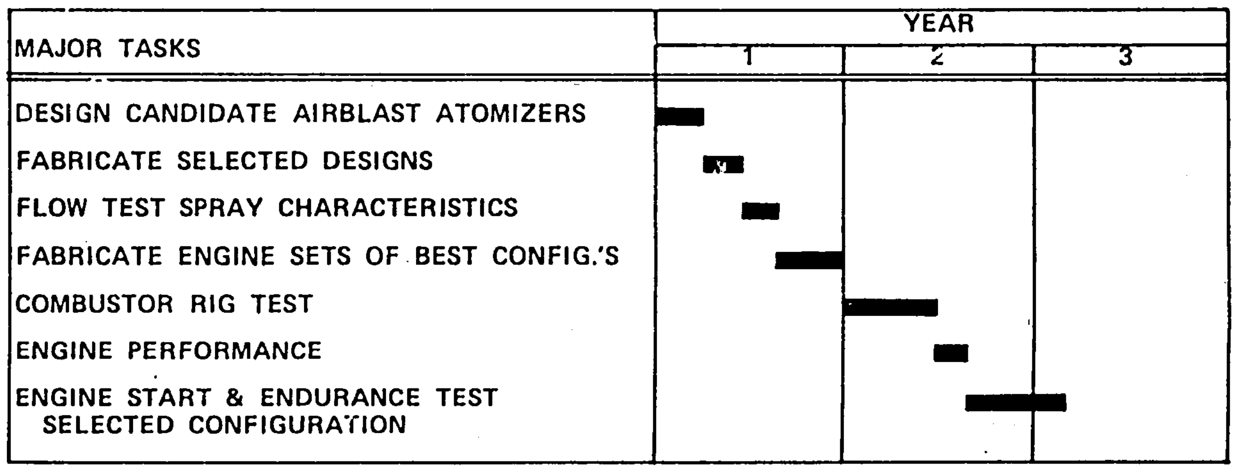


Figure 66. Low-Cost Airblast Fuel Atomizers

The only feasible approach to a control that provides these features and retains low cost and high reliability is a digital electronic control. The current philosophy of a full authority electronic control with hydromechanical backup will be retained. Since a gas turbine requires no electrical power to sustain operation, the backup control should not require electrical power to function.

A low-cost, high-reliability fuel control offering automatic sequencing and protection will require new approaches to closed-loop control, advanced microprocessors, and resolution of the temperature and vibration environment problems of the electronic hardware. Cost reduction will result from advances in microprocessor design and reducing the number of sensors and output devices.

The critical elements of the technology are shown in Table 48. Figure 67 shows the program plan and schedule for the component technology development.

The objectives of this program are to:

(a) Continue the control philosophy trade-off study - The additional cost and weight of a backup hydromechanical control must be continually substantiated versus reliability.

(b) Finalize the selected approach and mechanization study. Determine the electronic/hydromechanical/fluidic split. Select the optimum closed-loop control.

(c) Sensor and output devices definition - Characteristics, life, cost, and physical size as related to gas path blockage.

TABLE 48. LOW-COST DIGITAL ELECTRONIC CONTROL

- Low-Cost Electronic Control Required To Meet GATE Fuel Control Requirements.
- Low-Cost Approach to Prime Control and Hydromechanical or Fluidic Backup Required
- Closed-Loop Control Philosophy
- Microprocessor Design
- Sensor and Output Device Definition Compatible with Engine Size and Cost Objectives

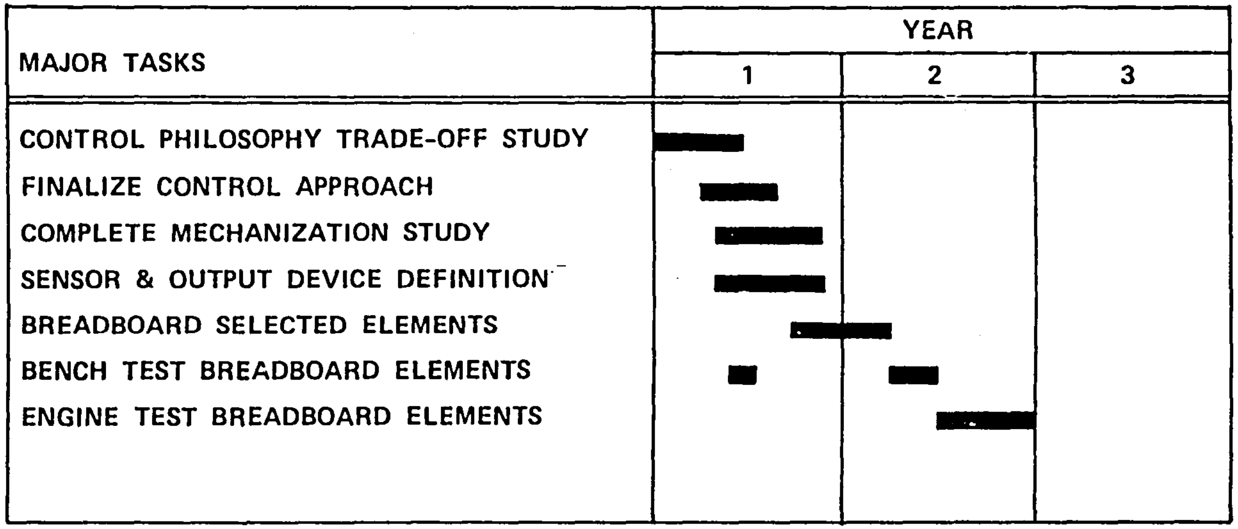


Figure 67. Low-Cost Digital Electronic Control

(d) Breadboard selected elements for bench and engine tests/ designs will be compatible with the existing TPE331 turboprop control system, thus obtaining actual relative performance type data.

The reprogrammable feature of the electronic control will allow the electronic breadboard to be tested on the TPE331 Engine and on the baseline gas generator as well. This will permit an early determination of the control characteristics under actual engine transients as well as on the GATE gas generator. As a result of testing, modifications will be made to optimize the control performance for the GATE requirements.

6.2.6 High-Work/Low-Speed Power Turbine

The GATE power turbine, as is typical in small engines, is required to run at lower than optimum aerodynamic speed because of critical speed limitations. Experience has shown that a wide margin must be held between the operating range and critical speeds in order to achieve high bearing system reliability and avoid excessive seal and tip clearances. A high turbine work coefficient is then required to minimize the number of stages and their cost. The power turbine technology will include an objective of a 5 to 6 point improvement in turbine efficiency, to be accomplished utilizing low-cost cast rotors with integral tip shrouds to minimize clearance losses. Currently, low-cost cast designs are unshrouded. Shrouded designs require inserted blades which is an expensive design.

Problems to be addressed in improving efficiency in the high-work design include:

- High blade-row turning
- Low stator and rotor reaction due to high inlet velocity

- High exit swirl requiring downstream turning vanes
- High Mach numbers

The program is based on an advanced two-stage,high-work, low-blade-speed design with exit guide vanes. The critical technology tasks that will be accomplished are shown in Table 49. Figure 68 shows the program plan and schedule for the component technology effort. The analysis task will establish the design method and conduct the trade-offs required to optimize the design. Using these results as a baseline, a design will be made for rig test evaluation. The baseline design will be made compatible with machined components to allow early initiation of testing and facilitate rapid modifications. Three tests are planned to optimize the stator and deswirl vane settings.

Concurrently, an integral, shrouded, cast, turbine assembly design shall be made. Processing technology iterations will be conducted to optimize the method of casting the integral shrouded rotors. The final task includes three tests of the cast version of the turbine to assess any differences in performance from the machined version and to evaluate clearance effects.

Based on all of the available data, cost and performance trade-offs will be conducted to evaluate the need for any design changes necessary prior to experimental engine testing.

6.2.7 Laser-Hardened Gears

The long life and high reliability requirements of propulsion engines requires hardening of gear teeth with the use of methods such as carburizing. Quenching after carburizing results in distortion. This distortion is corrected by final grinding operations that amount to nearly 37 percent of the gear cost. The technology advancement for the GATE Engine gears consists of replacing carburizing with laser contour hardening. Additional cost savings, not

TABLE 49. HIGH-WORK/LOW-SPEED POWER TURBINE.

Aerodynamic Technology

- Define Loss Correlations for High Turning/Low Reaction (2-D Analysis and Available Data)
- Optimize 3-D Velocity Diagram
- 3-D Blade Design
  - Solidity
  - Blade Loading
  - Stack and Contour
- 3-D Vane Design
  - Lean
  - End Wall Contour
  - Exit Guide Vane Optimization
- Clearance Effects
  - Tighter Clearances
  - Shroud Treatment

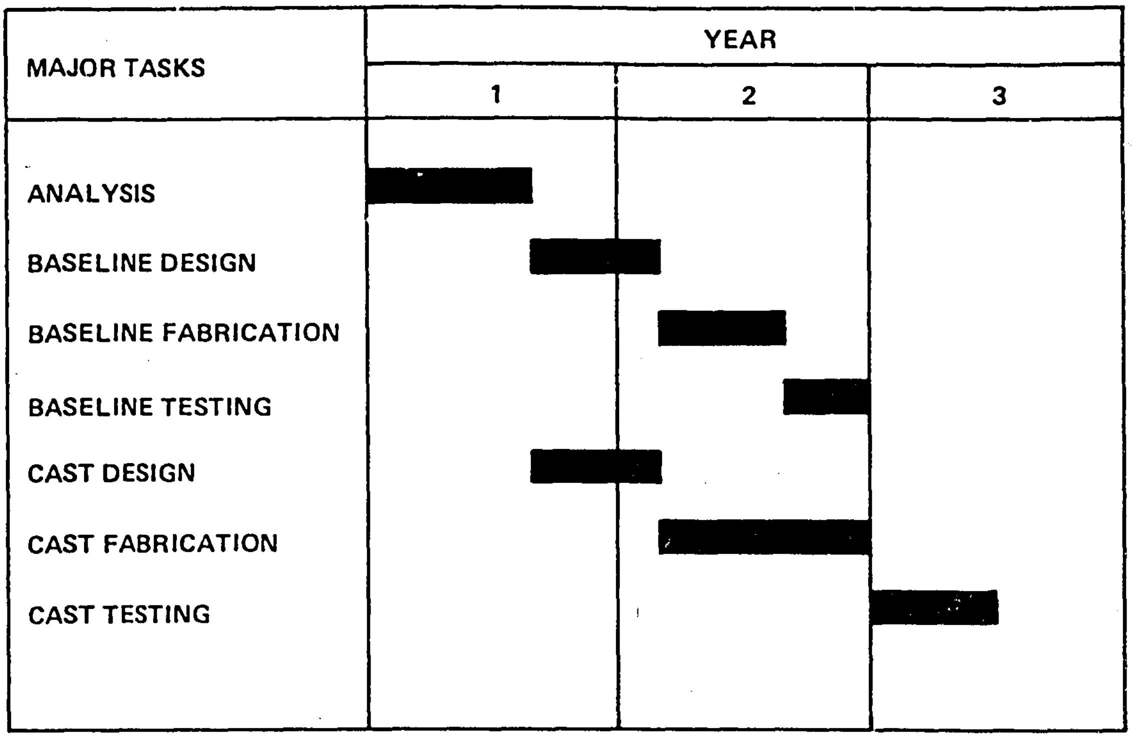


Figure 68. High-Work/Low-Speed Power Turbine

quantified, will accrue due to elimination of copper plating and stripping operations, deleting the requirement for use of natural gas, and reduced material requirements. The laser hardening process is highly compatible with automation and promises extended gear life due to improved surface hardness through closer control over case depth and the ability to have ductile material layers between hardened zones.

The initial program task consists of an experimental effort to optimize the laser hardening technique. An investigation would be made of the desired gear material characteristics followed by selection of candidate material(s). Material coatings to enhance the laser hardening will be evaluated and the best coating selected. Laser hardening experiments will be conducted on sample gears for sequential tooth hardening, hardening teeth sequentially opposite each other, and simultaneous scanning of the entire gear. Resulting material property characteristics and gear distortion will be evaluated for each of these techniques, and the best method selected for further evaluation. Gears made using the best hardening method will be designed, fabricated, and tested in a gear test rig for approximately 100 hours Results will be evaluated followed by fabrication of gears for endurance testing. These gears will be tested on a piggy-back basis on either an APU or propulsion engine test wherein a substantial number of hours may be accumulated. Following endurance testing, the gears will be comparatively evaluated with respect to conventional gears.

6.2.8 Gas Generator

The gas generator effort will ensure early discovery of critical component integration requirements. Figure 69 shows the program plan for the gas generator. After completion of the experimental engine preliminary design and the initial components design, the design of the baseline gas generator will be initiated. It

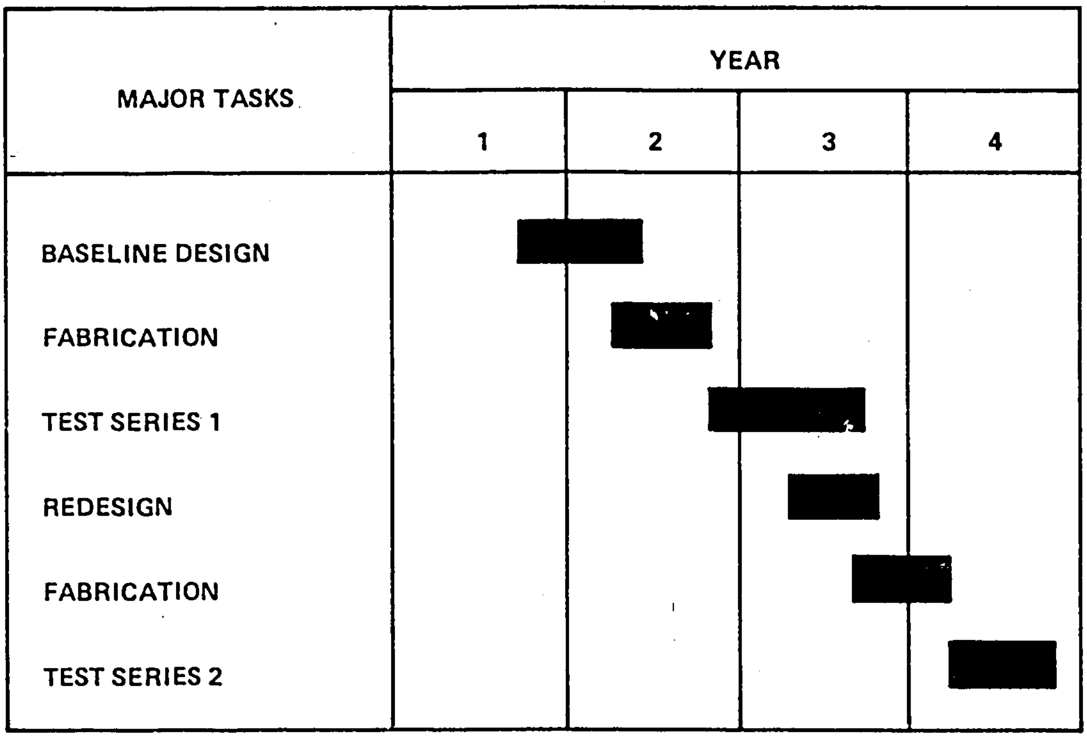


Figure 69. Gas Generator Program Plan

will include the baseline machined compressor, the baseline combustor, and the baseline high-pressure turbine, and will provide an engine environment test bed for the fuel atomizers, electronic control, and gas generator clearance control features.

The baseline gas generator will be tested prior to the completion of the component test efforts. This will substantially reduce program risk and provide early data to substantiate the component test data in an actual engine environment. The integrity of the gas generator design will be proven to ensure successful evaluation of the final components in the second gas generator test series.

Extensive performance, mechanical, and thermal instrumentation will provide data for comparison with design predictions during the baseline test series. The test series will include the following:

- o Mechanical checkout
- o Starting
- o Combustor performance
- o Clearance-control evaluation
- o Transient control operation
- o Structure temperature survey
- o Performance evaluation

A total of 75 hours of testing is planned for the baseline gas generator test series. The baseline gas generator design will be modified to incorporate any desirable changes indicated by the initial testing, and will incorporate the final component configuration established in the component test effort.

This modified gas generator test series will include the following:

- Controls evaluation
- Turbine cooling evaluation
- Clearance control system
- Performance testing
- Alternate fuel tests
- Transient thermal cycles
- Limited durability testing

A total of 125 hours is expected to be accumulated during this second test series.

6.2.9 Experimental Engine

The experimental engine effort will demonstrate the technology readiness of the GATE components and provide the final data needed to assess the GATE engine performance and production potential. The experimental engine will consist of an integration of the GATE gas generator and the low-spool components. The experimental engine program schedule is shown in Figure 70.

The design of the low-spool components shall include the low-pressure turbine and exhaust system, the low-pressure turbine shaft and bearing system, and an output power gear system. The experimental engine will not represent a final production engine design but will be a test bed to integrate components to the extent necessary to assess overall performance, component interactions, and mechanical system technologies.

The experimental engine design will begin near the completion of the final gas generator design effort. Two experimental engines will be fabricated. Engine Serial No. 1 will emphasize performance, combustion, and controls testing, and engine Serial No. 2 will emphasize mechanical and durability testing.

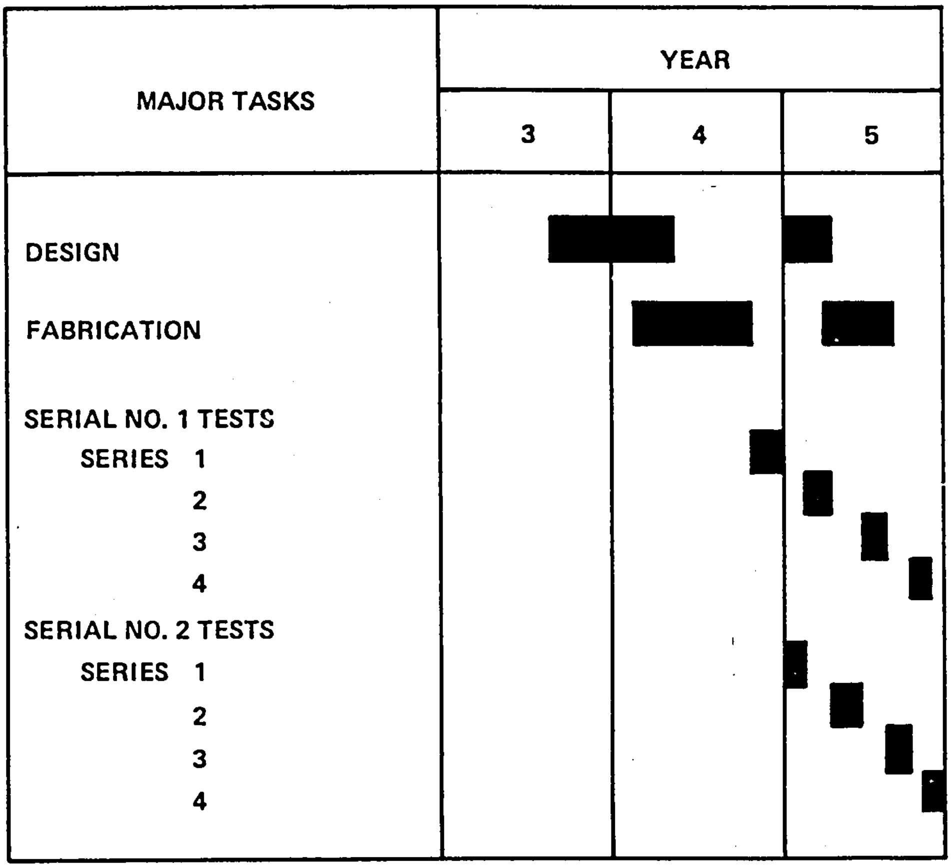


Figure 70. Experimental Engine Program Schedule

The test plan for the two experimental engines is shown in Figure 71. Four test series are planned on each engine with necessary modifications incorporated as testing progresses. A total of 400 hours testing is planned to be accumulated utilizing the two engines.

6.2.10 Engine System Analysis and Definition

Throughout the GATE experimental program, analysis will continue to refine and update the previous engine definition. The results of component, gas generator, and experimental engine testing of the GATE design will be evaluated; and engine cost, life, weight, performance characteristics, and trade-offs will be updated. Technology from other sources such as company efforts will be evaluated for applicability to the GATE Engine. Using the updated engine characteristics, the GATE engine performance and economic benefits in an aircraft system will be updated.

6.2.11 Schedule

The schedule of each of the program elements has been described. Figure 72 shows the overall program schedule and relationship of the program elements. The program schedule and task interrelationships are based on minimizing program risk with an economical program approach. An engine preliminary design is accompiished early to ensure compatibility of the components in the gas generator and experimental engine. Gas generator testing is started as soon as initial component readiness is established. Early gas generator results will insure that final component testing is properly directed. Final gas generator testing is completed prior to experimental engine testing and will minimize experimental engine test problems. System analysis and definition continues throughout the program to ensure proper assessment of available data and help direct the design and test efforts. Program milestones and reviews

	MECHANICAL CHECKOUT	PERFORMANCE TEST	PERFORMANCE WITH BLEED	COMBUSTOR PERFORMANCE	MECHANICAL	ENGINE CYCLIC DURABILITY	EXHAUST EMISSIONS	CLEARANCE CONTROL	THERMAL TRANSIENTS	TURBINE COOLING	CONTROL COMPATIBILITY	HEAT REJECTION	TORQUE SENSOR	TELEMETRY DATA	NOISE	DURABILITY DEMONSTRATION
ENGINE SERIAL NO. 1																
TEST SERIES 1	X				X											
TEST SERIES 2		X	X	X				X			X					
TEST SERIES 3		X	X	X				X			X					
TEST SERIES 4		X		X			X				X			X	X	
ENGINE SERIAL NO. 2																
TEST SERIES 1	X	X			X											
TEST SERIES 2				X	X			X	X	X	X					
TEST SERIES 3					X	X		X	X	X		X	X	X		
TEST SERIES 4																X

Figure 71. Experimental Engine Test Plan

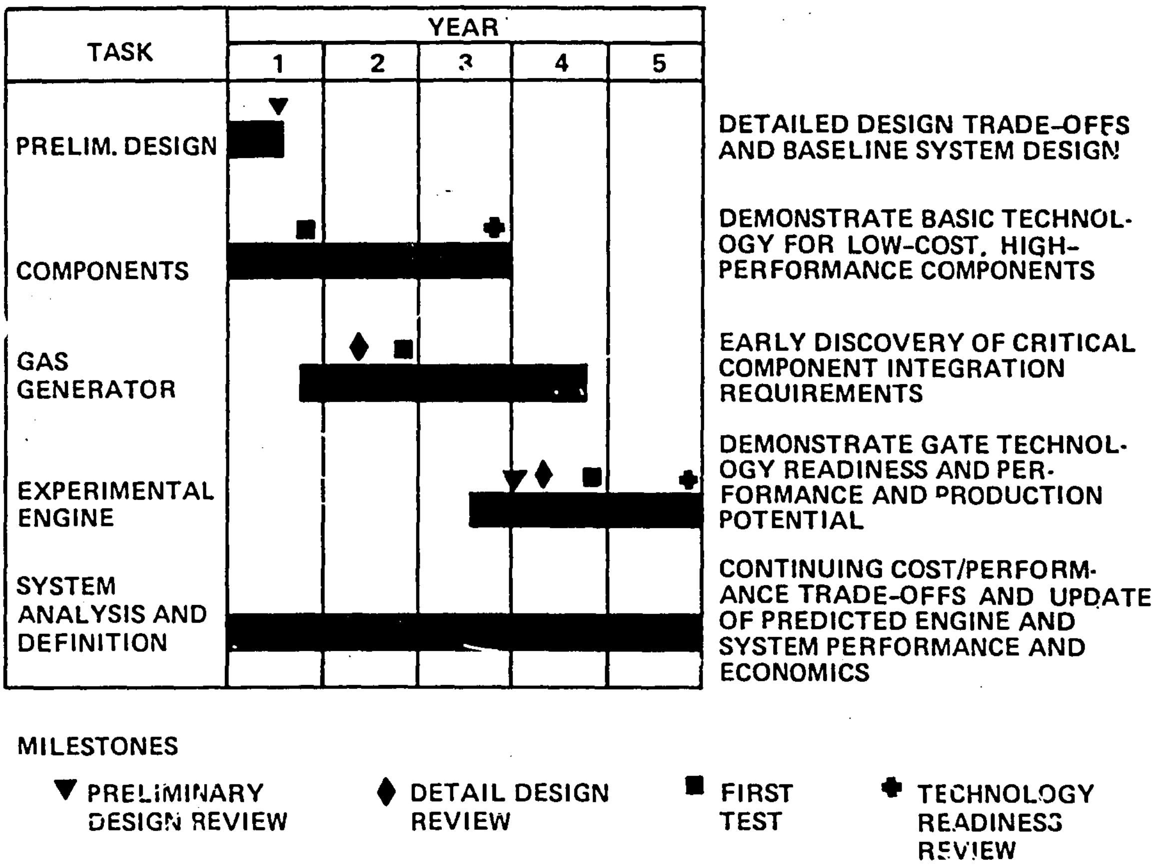


Figure 72. Recommended GATE Experimental Program

with NASA to obtain approval of the approach are indicated in the overall program plan.

6.2.12 Technology Development - Benefit Analysis

The critical components identified in the previous paragraphs are high-risk development items but have significant payoff with respect to the GATE engine. To quantify this payoff each component was evaluated with respect to the cost of demonstrating technology readiness and the payoff of the particular component to the engine and aircraft application. A summary of the evaluation is shown in Table 50. The improvements in engine weight and cost are on a system basis, i.e., GATE engines are compared to current-technology engines at the power level required to meet performance requirements. This comparison, therefore, includes synergistic airplane/engine effects, which were not included in Table 38. The improvements in component efficiency and specific fuel consumption are independent of applications. The benefit/cost ratio is the 20-year fleet total cost savings for the pressurized twin divided by the cost to demonstrate technology readiness. A benefit analysis for clearance control and the combustor was not conducted. Clearance control was assumed in component design in order to achieve the tight-clearances desired.

TABLE 50. PAYOFF RELATIVE TO CURRENT TECHNOLOGY TURBINE ENGINE.

	$\Delta\eta$ PTS	Δ Engine Cost, %	Δ Engine Weight, %	Δ Engine SFC, %	Benefit/Cost Ratio
HP Laminated Turbine	+9.8	-21	-7	-7.4	561
PM Titanium Single-Stage Compressor	-1.0	-4	-6.0	+1.4	232
Low-Cost Fuel Nozzles	-	-1	0	0	144
Electronic Control	-	-2	0	0	132
High-Work/Low-Speed LP Turbine	+6.0	-5	-7.0	-7.0	498
Laser-Hardened Gears	-	-3	0	0	226
Total		-36	-20	-13.0	402 (Avg)

NOTES: 1) Changes are relative to a hypothetical current-technology turbine engine (Table 37)

2) Clearance control benefits are included in the above.

SECTION VII

7.0 CONCLUSIONS

This report summarizes the results of the General Aviation Turbine Engine Study. Small gas turbine engines in the 336 kw (450 hp) class were defined and evaluated in appropriate aircraft. The performance and economics resulting from the use of these engines were evaluated, and comparisons were made between aircraft powered by reciprocating and turbine engines. Identical aircraft technology levels were assumed in all aircraft comparisons. Overall conclusions that were drawn as a result of the study program are:

- The general aviation market was predicted to continue to grow at current rates.

- Compared to current-technology reciprocating engines and current-technology turboprops, significant reductions in aircraft fuel consumption and weight were projected with the 1988 GATE technology engines. Reduced aircraft initial cost and operating cost were also estimated, based on projections of new technology and high manufacturing quantities. The barrier technology which must be overcome through development of new technologies is the achievement of this low manufacturing cost without major sacrifice in performance.

- A turboprop engine is the most suitable propulsion system for the medium- and light-twin aircraft investigated. Turbofans at the flight speeds, altitudes, and takeoff distances stipulated have higher fuel consumption and require larger engines than do turboprops and therefore are more costly.

- A single-shaft turboprop is slightly superior to a free-turbine turboprop for the aircraft studied but the difference is slight and the free-turbine engine is the most likely choice if the needs of the rotary-wing market are considered.

- High-temperature engines [1478°K (2200°F)] are superior to lower temperature engines [1255 to 1311°K (1800 to 1900°F)].

- Study results indicated that a GATE turboshaft would allow a reduction in helicopter gross weight of 20-percent when compared to a helicopter designed with a current-production turboshaft.

- Component research and development integrated with an experimental engine program is required to realize the benefits of the GATE engines.

APPENDIX I

GENERAL AVIATION MARKET DATA

During Task I, data was compiled on each of the ten reciprocating-engine-powered fixed-wing categories, the turboprop category, and the three rotary-wing categories. This data includes, for most models, the engine model and rated power, the 1977 average equipped price, number of seats, cruise speed, engine time between overhaul, and service ceiling. This data is displayed in Tables 51 through 64.

TABLE 51. TWO PLACE LIGHT SINGLE ENGINE.

Aircraft Manufacturer and Model	Engine Type	Engine kw (hp)	Aircraft Avg. Equip. Price 1977	No. of Seats Standard	Cruise Speed At Ceiling (Recommended) km/hr. (mph)	Engine TBO Hours	Service Ceiling m (ft.)
Beech Sport 19	LYC 0-320-E3D	112 (150)	29,376	2	198 (123)	1200/2000	3,553 (11,650)
Bellanca Citabria	LYC						
ECA	0-235-C1	858 (115)	19,010	2	198 (123)	2000	3,660 (12,000)
GCAA	0-320-A2D	112 (150)	22,575	2	208 (129)	1200/2000	5,185 (17,000)
KCAB	IO-320-E2A	112 (150)	23,460	2	208 (129)	1200/2000	5,185 (17,000)
Bellanca Decathlon	LYC IO-320-E1A	112 (150)	26,705	2	219 (136)	1200/2000	4,880 (16,000)
Cessna 150/152	CONT 0-200-A	75 (100) 75 (100)	18,255	2-1/2	195 (121)	1800	4,667 (15,300)
Grumman-American Trainer	LYC 0-235-L2C	858 (115)	19,853	2	200 (124)	2000	3,889 (12,750)
Cherokee Piper Cruiser PA28-140	LYC 0-320-E3D	112 (150)	24,615	2	203 (126)	1200/2000	3,338 (10,950)

TABLE 52. UTILITY HIGH PERFORMANCE SINGLE ENGINE.

Aircraft Manufacturer and Model	Engine Type	Engine kw	(hp)	Aircraft Avg. Equip. Price 1977	No. of Seats Standard	Cruise Speed At Ceiling (Recommended) km/hr.	(mph)	Engine TBO Hours	Service Ceiling m	(ft.)
Bellanca Scout	LYC 0-360-C2A	134	(180)	26,600	2	196	(122)	2000	4,423	(14,500)
Skywaggon Cessna 180	CONT 0-470-U	172	(230)	43,552	6	253	(157)	1500	5,399	(17,700)
AG Carryall Cessna 185	CONT IO-520-D	224	(300)	49,252	6	227	(141)		4,087	(13,400)
Cessna 207	CONT IO-520F	224	(300)	64,610	7	264	(164)	1200/1500	4,057	(13,300)
Cessna Turbo 207	CONT TSIO-520M	231	(310)	70,455	7	298	(185)	1400	7,930	(26,000)
Maule Rocket	CONT IO-360	157	(210)	21,245	4	390	(242)	1200/1500	5,490	(18,000
Piper Super Cub PA18	LYC 0-320-A2A	112	(150)	24,140	2	185	(115)	1200/2000	5,795	(19,000)

TABLE 53. FIXED GEAR HIGH PERFORMANCE SINGLE ENGINE

Aircraft Manufacturer and Model	Engine Type	Engine kw	Engine (hp)	Aircraft Avg. Equip. Price 1977	No. of Seats Standard	Cruise Speed At Ceiling (Recommended) km/hr.	Cruise Speed At Ceiling (Recommended) (mph)	Engine TBO Hours	Service Ceiling m	Service Ceiling (ft.)
Cessna Skylane 182	CONT 0-470-U	172	(230	44,745	4 1/2	267	(166)	1500	5,033	(16,500)
Cessna 206	CONT IO-520-F	224	(300)	57,685	6	272	(169)		4,514	(14,800)
Cessna Turbo 206	CONT TSIO-520M	231	(310)	63,135	6	309	(192)	1400	8,235	(27,000)
Cessna Reims Rocket FR-172	CONT IO-360D	157	(210)	No Price Given				1200/1500		
Cherokee PA28-235 Piper Pathfinder	LYC 0-540-B4B5	175	(235)	47,325	4	233	(145)	1200/2000	4,133	(13,550)
Piper Cherokee PA32-260	LYC 0-540-E4B5	194	(260)	54,235	7	254	(158)	1200/2000	3,904	(12,800)
Piper Cherokee PA32-300	LYC IO-540-K1G5	224	(300)	58,005	7	282	(175)	2000	4,956	(16,250)

TABLE 54. FOUR PLACE LIGHT SINGLE ENGINE.

Aircraft Manufacturer and Model	Engine Type	Engine kw	Engine (hp)	Aircraft Avg. Equip. Price 1977	No. of Seats Standard	Cruise Speed at Ceiling (Recommended) km/hr	Cruise Speed at Ceiling (Recommended) (mph)	Engine TBO Hours	Service Ceiling m	Service Ceiling (ft.)
Beech Sundowner	LYC O-360-A4K	134	(180)	37,373	4	227	(141)	1200/2000	3,843	(12,600)
Cessna Skyhawk 172	LYC O-320-H2AD	119	(160)	30,050	4 1/2	225	(140)	2000	4,331	(14,200)
Cessna Cardinal 177	LYC O-360-A1F6D	134	(180)	39,195	4 1/2	242	(150)	1200/2000	4,453	(14,600)
Cessna French Skyhawk Reims F-172	CONT O-300-D Built by Rolls Royce	108	(145)	26,850						
Cessna Hawk XP	CONT IO-360K	145	(195)	38,680	4 1/2	243	(151)	1200/1500	5,185	(17,000)
Cherokee Piper Warrior 151	LYC O-320-D3D	112	(150)	27,285	4	203	(126)	1200/2000	3,874	(12,700)
Piper Warrior 161 (Warrior II)	LYC O-320-D3G	119	(160)	28,700	4	235	(146)		3,965	(13,000)
Cherokee Piper Archer PA-28-181	LYC O-360-A4M	134	(180)	33,930	4	243	(151)	1200/2000	4,163	(13,650)
Grumman Cheetah AA5A	LYC O-320-E2G	112	(150)	31,294	4	237	(147)	1200/2000	3,858	(12,650)
Grumman Tiger AA5B	LYC O-360-A4K	134	(180)	36,780	4	258	(160)	1200/2000	4,209	(13,800)

TABLE 55. LIGHT RETRACTABLES.

Aircraft Manufacturer and Model	Engine Type	Engine kw (hp)	Aircraft Avg. Equip. Price 1977	No. of Seats Standard	Cruise Speed at Ceiling (Recommended) km/hr (mph)	Engine TBO Hours	Service Ceiling m (ft)
Beech Sierra C-24-R	LYC IO-360-A1B6	149 (200)	53,594	6	254 (158)	1200/1600	4,697 (15,400)
Cessna Cardinal 177-RG	LYC IO-360-A1B6D	149 (200)	50,095	4	274 (170)	1200/1600	5,216 (17,100)
Mooney Ranger M20C	LYC O-360-A1D	134 (180)	44,185	4	264 (16[illegible])	1200/2000	5,033 (16,000)
Mooney Executive M20F	LYC IO-360-A1A	149 (200)	48,960	4	288 (179)	1200/2000	5,734 (18,800)
Mooney 201 M20J	LYC IO-360-A1B6D	149 (200)	55,310		314 (195)	1200/1600	5,734 (18,800)
Piper Arrow II PA 28R 200	LYC IO-360-C1C	149 (200)	47,850	4	266 (165)	1200/1600	4,575 (15,000)
Piper Arrow III PA 28R 201	LYC IO-360-C1C6	149 (200)	50,320	4	264 (164)	1200/1600	4,941 (16,200)
Piper Turbo Arrow III PA 28R 201T	CONT TSIO-360F	149 (200)	54,975	4	319 (198)	1400	6,100 (20,000)
Rockwell 112 (112B)	LYC IO-360-C1D6	149 (200)	61,295	4	262 (163)	1200/1600	4,590 (15,050)
Rockwell 112 TCA	LYC TO-360-C1A6D	157 (210)	65,295	4	301 (187)	1200	6,100 (20,000)

TABLE 56. HEAVY RETRACTABLES.

Aircraft Manufacturer and Model	Engine Type	Engine kw (hp)	Aircraft Avg. Equip. Price 1977	No. of Seats Standard	Cruise Speed at Ceiling (Recommended) km/hr (mph)	Engine TBO Hours	Service Ceiling m (ft)
Beech Bonanza A36	CONT IO-520-BA	213 (285)	96,545	6	311 (193)	1200/1500	5,063 (16,600)
Beech Bonanza V35	CONT IO-520-BA	213 (285)	89,355	5	319 (198)	1200/1500	5,444 (17,850)
Beech Bonanza F33	CONT IO-520-BA	213 (285)	84,224	5	319 (198)	1200/1500	5,447 (17,858)
Bellanca Viking 17-31A	LYC IO-540-K1E5	224 (300)	68,259	4	306 (190)	2000	5,551 (18,200)
Bellanca Turbo Viking 17-31 ATC	LYC IO-540-K1ES	224 (300)	79,090	4	357 (222)	2000	7,320 (24,000)
Cessna Centurion	CONT IO-520-L	224 (300)	71,335	6	317 (197)	1200/1500	5,277 (17,300)
Cessna Turbo Centurion	CONT TSIO-520R	231 (310)	77,455	6	367 (228)	1400	8,693 (28,500)
Piper Lance PA 32R-300	LYC IO-540-K1G5D	224 (300)	72,120	6	293 (182)		4,453 (14,600)
Rockwell 114	LYC IO-540-T4B5D	194 (260)	70,800	4	291 (181)	2000	5,307 (17,400)

TABLE 57. AGRICULTURAL.

Aircraft Manufacturer and Model	Engine Type	Engine kw (hp)	Aircraft Avg. Equip. Price 1977	No. of Seats Standard	Cruise Speed at Ceiling (Recommended) km/hr (mph)	Engine TBO Hours	Service Ceiling m (ft)
Cessna AG Carryall	CONT IO-520-D	224 (300)	55,205	6	227 (141)	1200/1500	4,087 (13,400)
Cessna AG Wagon 188	CONT IO-520-D	224 (300)	51,485	1	182 (113)	1200/1500	3,386 (11,100)
Cessna AG Truck	CONT IO-520-D	224 (300)	54,310	1	209 (130)	1200/1500	3,386 (11,100)
Grumman AG Cat	P & W R985AN1	336 (450)	69,005		190 (118)	1400	4,270 (14,000)
Piper Pawnee 235 PA-25-235D	LYC 0-540-B2C5	175 (235)	39,880	1	183 (114)	1200/1500	3,965 (13,000)
Piper Pawnee 260 PA-25-260D	LYC 0-540-G1A5	194 (260)	42,350	1	187 (116)	1200/2000	4,819 (15,800)
Piper Brave 285 PA-36-285	CONT TIARA 6-285	213 (285)	54,305	1	237 (147)		3,965 (13,000)
Piper Brave 300 PA-36-300	LYC IO-540-K1G5	224 (300)	55,605	1	227 (141)	2000	3,660 (12,000)
Rockwell Thrush S2R600	P & W R1340AN1	447 (600)	78,500	1	200 (124)	900	4,575 (15,000)

TABLE 58. LIGHT TWINS.

Aircraft Manufacturer and Model	Engine Type	Engine kw (hp)	Aircraft Avg. Equip. Price 1977	No. of Seats Standard	Cruise Speed at Ceiling (Recommended) km/hr (mph)	Engine TBO Hours	Service Ceiling m (ft)
Beech Baron 58	CONT IO-520C	213 (285)	187,115	6	370 (230)	1200/1500	5,673 (18,600)
Beech Baron E55	CONT IO-520C	213 (285)	167,351	6	370 (230)	1200/1500	5,826 (19,100)
Beech Baron B55	CONT IO-470L	194 (260)	142,844	6	348 (216)	1200/1500	5,887 (19,300)
Beech Baron 58TC	CONT TSIO-520L	231 (310)	214,666	6	446 (277)	1400	7,625 (25,000)
Cessna Skymaster 337	CONT IO-360G	157 (210)	102,155	6	309 (192)	1200/1500	5,490 (18,000)
Cessna 310	CONT IO-520M	213 (285)	152,440	6	359 (223)	1500	6,024 (19,750)
Cessna T310	CONT TSIO-520B	213 (285)	170,880	6	412 (256)	1400	8,357 (27,400)
Piper Aztec PA23	LYC IO-540-C4B5	186 (250)	137,835	6	325 (202)	1200/2000	5,368 (17,600)
Piper Seneca PA34R	CONT TSIO-360E	149 (200)	102,180	6	353 (219)	1400	7,625 (25,000)
Rockwell Shrike	LYC IO-540-E1B5	216 (290)	242,700	8	327 (203)	1400	5,917 (19,400)
Aerostar 600	LYC IO-540-K1F5	216 (290)	171,170	6	441 (274)	2000	6,466 (21,200)
Aerostar 601	LYC IO-540-S1A5	216 (290)	189,170	6	467 (290)	1800	9,181 (30,100)

TABLE 59. CABIN CLASS UNPRESSURIZED TWINS.

Aircraft Manufacturer and Model	Engine Type	Engine kw (hp)	Aircraft Avg. Equip. Price 1977	No. of Seats Standard	Cruise Speed at Ceiling (Recommended) km/hr (mph)	Engine TBO Hours	Service Ceiling m (ft)
Cessna 402	CONT TSIO-520-E	224 (300)	225,675	10	386 (240)	1400	7,985 (26,180)
Cessna Titan 404	CONT GTSIO-520-M	280 (375)	321,665	10	399 (248)	1200	7,930 (26,000)
Piper Navajo PA31-310	LYC TIO-540-A2C	231 (310)	232,490	8	398 (247)	1500/1800	8,022 (26,300)
Piper Navajo Chieftain PA31-350	LYC TIO-540-J2BD	261 (350)	263,485	10	409 (254)	1600	8,052 (26,400)

TABLE 60. PRESSURIZED TWINS.

Aircraft Manufacturer and Model	Engine Type	Engine kw (hp)	Aircraft Avg. Equip. Price 1977	No. of Seats Standard	Cruise Speed at Ceiling (Recommended) km/hr (mph)	Engine TBO Hours	Service Ceiling m (ft)
Beech Duke 60	LYC TIO-541-E1C4	283 (380)	330,090	6	443 (275)		9,150 (30,000)
Beech Baron 58TC	CONT TSIO-520L	231 (310)	265,908	6	452 (281)	1400	7,625 (25,000)
Cessna Pressurized Skymaster	CONT TSIO-360C	168 (225)	146,155	5	380 (236)	1400	6,100 (20,000)
Cessna 340	CONT TSIO-520N	231 (310)	225,245	6	430 (267)	1400	9,089 (29,800)
Cessna 414 Chancellor	CONT TSIO-520N	231 (310)	271,870	7	412 (256)	1400	9,562 (31,350)
Cessna 421 Golden Eagle	CONT GTSIO-520N	280 (375)	381,000	8	448 (278)	1200	9,211 (30,200)
Piper Navajo 425	LYC TIGO-541-E1A	317 (425)	390,255	8	407 (253)	1200	8,845 (29,000)
Aerostar 601 P	LYC IO-540-S1A5	216 (290)	247,940	6	467 (290)	1800	8,037 (26,350)

TABLE 61. TURBOPROPS.*

Aircraft	Engine	kw	hp	1977 Average Equipped Price
Beech King Air Super 200	PT6A-41	634	(850)	1,128,200
Beech King Air B100	TPE331-6-252B	533	(715)	956,000
Beech King Air A100	PT6A-28	507	(680)	926,100
Beech King Air E90	PT6A-28	410	(550)	807,500
Beech King Air C90	PT6A-21	410	(550)	614,900
Piper Cheyenne	PT6A-28	462	(620)	665,000
Rockwell 690 A/B	TPE331-5-251K	535	(718)	781,190
Merlin III A	TPE331-303	626	(840)	1,078,070
Merlin IV A	TPE331-303	626	(840)	1,175,970
Metro II	TPE331-303	701	(940)	1,055,900
Cessna Conquest	TPE331-8	466	(625)	850,000

*Manufactured by Gamma member.

TABLE 62. HELICOPTERS - SINGLE ENGINE PISTON

Aircraft Manufacturer and Model	Engine Type	Engine kw	Engine hp	Aircraft 1977 Avg. Equipment Price
(1) Robinson R22	LYC-O-320	92	(124)	
(2) Brantly B2B	IVO-360-A1A LYC	134	(180)	$48,950
(3) Enstrom F-28A	LYC HIO-360-C1A	153	(205)	64,500
(4) Hughes 300 C	HIO-360-D1A LYC	142	(190)	65,450
(5) Enstrom 280 Shark	HIO-360-C1A LYC	153	(205)	71,000
(6) Enstrom F-28C	LYC HIO-360-E1AD	153	(205)	71,000
(7) Brantly 305	IVO-540-B1A LYC	227	(305)	79,950
(8) Enstrom F280C	HIO-360-E1AD LYC	153	(205)	76,000
(9) Hiller UH-12E	VO-540-C2A LYC	227	(305)	78,000

TABLE 63. HELICOPTERS - SINGLE ENGINE TURBINE

Aircraft Manufacturer and Model	Engine Type	Engine kw	Engine hp	Aircraft 1977 Avg. Equipment Price
(10) Hughes 500D Model 500 (369)	Allison T-63 250-C20B	298	400	$209,000
(11) Bell 206B	Allison 250-C20	298	400	212,500
(12) Aerospatiale Astar 350 SA350 Ecureuil	(1) Arriel or (1) LTS 101	441-485	592-650	235,000
(13) Aerospatiale Gazelle SA341		440	590	300,000
(14) Bell 206L	Allison 250-C20B	313	420	309,500

TABLE 64. HELICOPTERS - TWIN ENGINE TURBINE

Aircraft Manufacturer and Model	Engine Type	Engine kw	Engine hp	Aircraft 1977 Avg. Equipment Price
(15) MBB BO-105C B2	Allison 250 C20/20B	313	420	$ 385,000
(16) Agusta A-109 A-109A	(2) Allison 250-C30	336	450	700,000
(17) Bell 222	LTS-101	447	600	750,000
(18) Aerospatiale Dauphin 2 SA365	(1) Arriel/SM365 (2) LTS 100/SA366	317	425	620-865,000
(19) Sikorsky S-76	Allison 250-C30	522	700	

APPENDIX II

AIRCRAFT DESIGN CHARACTERISTICS

1.0 FIXED-WING AIRCRAFT

During Task I and early in Task II, the Cessna Aircraft Company, Pawnee Division, defined the characteristics of the aircraft to be used in the GATE study. These characteristics were used to model the airplanes for the General Aviation Synthesis Program (GASP). GASP resized the airplanes as required for wing loading changes and changes in takeoff gross weight required to meet the mission requirements. Checks were performed during the GASP analysis to ensure that fidelity to the original characteristics, as supplied by Cessna, were maintained.

Table 65 shows the weight breakdown of the four designs studied. Designations are as follows:

Design No.	Description
1	Turbofan-Powered (wing mounted) Medium Pressurized Twin
1A	Turbofan-Powered (fuselage mounted) Medium Pressurized Twin
2	Turboprop-Powered Medium Pressurized Twin
4	Light Twin

Cessna's weight breakdown philosophy is explained in NASA CR-151973, "Conceptual Design of Single, Turbofan-Engine-Powered Light Aircraft", Section 3.2.4, pages 42-46. The methodology has been modified for the GATE study, based on larger Cessna models, in order to handle the medium-twin configurations. The powerplant installation weight was based on engine data supplied to Cessna

TABLE 65. WEIGHT BREAKDOWN, KG (LB)

Components	Configurations			
	1	1A	2	4
Wing Includes control surfaces, attachment hardware, fairing, carry-thru in fuselage	283.9 (625.4)	283.9 (625.4)	283.9 (625.4)	271.9 (598.9)
Power Plant Installation (See Table 66) Includes everything supported by engine mount, intake and exhaust systems, filters, pumps, controls	322.9 (711.4)	313.5 (690.6)	426.4 (939.2)	332.5 (732.4)
Nacelle Includes cowling, attachment, engine mount	145.3 (320.0)	63.0 (138.8)	145.3 (320.0)	90.1 (198.4)
Vertical Tail	20.8 (45.8)	25.0 (55.1)	20.8 (45.8)	16.6 (36.5)
Horizontal Tail	30.9 (68.0)	34.6 (76.2)	30.9 (68.0)	26.1 (57.5)
Main Gear Assembly Includes tires, wheels, brakes, gear legs, shocks	71.6 (157.7)	71.6 (157.7)	71.6 (157.7)	69.0 (152.0)
Nose Gear Assembly	25.8 (56.8)	25.8 (56.8)	25.8 (56.8)	24.9 (55.0)
Retraction System Includes actuators, valves, lines, pumps, selectors, reservoirs, fluids	47.1 (103.7)	47.1 (103.7)	47.1 (103.7)	44.5 (98.0)
Fuselage Includes structure, doors, hatches, windows, attachment fittings, brackets, floors	292.7 (644.8)	292.7 (644.8)	292.7 (644.8)	234.3 (516.0)
Controls Flight and engine	52.5 (115.6)	52.5 (115.6)	52.5 (115.6)	50.8 (112.0)
Equipment Electrical, battery, box, regulator, basic instruments	93.3 (205.6)	93.3 (205.6)	93.3 (205.6)	91.7 (202.0)
Furnishings Includes seats, restraint systems, ventilation system, soundproofing	147.8 (325.5)	147.8 (325.5)	147.8 (325.5)	134.4 (296.0)
Exterior Finish	15.2 (33.5)	15.9 (35.2)	15.1 (33.2)	12.9 (28.5)

TABLE 65. WEIGHT BREAKDOWN, KG (LB) (Contd)

Components	Configurations			
	1	1A	2	4
Dry Empty Weight (DEW)	1549.9 (3413.8)	1466.9 (3231.0)	1653.2 (3641.3)	1399.8 (3083.2)
Basic Empty Weight (BEW)	1660.0 (3656.4)	1557.0 (3473.6)	1763.3 (3883.9)	1517.5 (3342.6)
Assumed Gross Weight (GW)	2860.2 (6300.0)	2860.2 (6300.0)	2860.2 (6300.0)	2724.0 (6000.0)
Constants				
a_1, kg (lb)	549.2 (1209.7)	458.5 (1010.0)	753.3 (1659.2)	607.5 (1338.2)
a_2, kg/m^2 (lb/ft^2)	2.859 (0.58603)	3.266 (0.66916)	2.859 (0.58603)	3.304 (0.67695)
a_3 (dimensionless)	0.13518 (0.29775)	0.13616 (0.29991)	0.13518 (0.29775)	0.12616 (0.27789)
a_4, $1/m^2$ ($1/ft^2$)	0.0000193 (0.0002078)	0.0000183 (0.0001974)	0.0000193 (0.0002078)	0.0000185 (0.0001991)

early in Task I and was revised as the detailed engine weight became available. The difference between dry empty weight and basic empty weight includes optional equipment and unusable fuel and oil. The assumed gross weight was based on the basic empty weight plus payload (passengers plus baggage minus optional equipment) and Cessna's estimate of the fuel required. The constants a_1 through a_4 were supplied by Cessna to allow Garrett to check the wing weight calculated by GASP as TOGW and W/S varied. Use of these constants is explained in the previously cited reference. The propulsion system weight breakdown is detailed in Table 66.

Wing and empennage geometric characteristics are shown in Table 67. Cessna recommended a basic wing having an aspect ratio of 7 and a taper ratio of 0.7, with a thickness-to-chord ratio varying linearly from 0.17 at the root to 0.13 at the tip. The basic wing design was adapted to each application by adding wing root plugs to achieve the desired wing area. The addition of the wing root plugs increases aspect ratio and decreases taper ratio.

Optional equipment lists for each of the configurations are shown in Tables 68 and 69. The items selected are those included in Cessna's popular "-II" factory installed accessory packages. The prices are listed for each item installed separately and must be adjusted for factory-installed packages. A package installation reduces the total cost by 17 percent. The weights of the optional equipment are charged against the payloads stipulated in the design requirements.

Drag polars for all configurations are shown in Table 70. They are for the wing areas selected by Cessna and with the gear retracted. The drag polars supplied by Cessna were used to calibrate the GASP drag subroutines. The equivalent flat plate area of the landing gear is 3.5 sq. ft. based on a nose gear tire size of 6.00-6 and a main gear tire size of 6.50-10. The flap system lift/

TABLE 66. POWER PLANT INSTALLATION DETAILS WEIGHT, KG (LB)

Components	Configurations 1	1A	2	4
Engine	134.4 (296.0)	134.4 (296.0)	123.0 (271.0)	90.8 (200.0)
Propeller	-- --	-- --	53.6 (118.0)	40.4 (89.0)
Spinner	-- --	-- --	3.6 (7.9)	2.3 (5.0)
Starter Generator	12.3 (27.0)	12.3 (27.0)	12.3 (27.0)	12.3 (27.0)
Propeller Pitch Control	-- --	-- --	1.4 (3.0)	1.4 (3.0)
Hydraulic Pump and Propeller Governor	-- --	-- --	3.5 (7.6)	3.5 (7.6)
Pressure Switch and Voltage Regulator	0.73 (1.6)	0.73 (1.6)	0.73 (1.6)	0.73 (1.6)
Oil Pressure Transducer	1.1 (2.4)	1.1 (2.4)	1.1 (2.4)	1.1 (2.4)
Drain Tubes	1.1 (2.4)	1.1 (2.4)	1.1 (2.4)	1.1 (2.4)
Electric Boost Pumps (2)	3.6 (8.0)	3.6 (8.0)	3.6 (8.0)	3.6 (8.0)
Unfeathering Pump	-- --	-- --	1.1 (2.4)	1.1 (2.4)
Oil Cooler and Mount	3.4 (7.5)	3.4 (7.5)	3.4 (7.5)	3.4 (7.5)
Control Linkage on Engine	0.18 (0.4)	0.18 (0.4)	0.18 (0.4)	0.18 (0.4)
Tailpipe	4.7 (10.4)	0.0 (0.0)	4.7 (10.4)	4.5 (9.9)
TOTAL (Per Engine)	161.5 (355.7)	156.8 (345.3)	213.2 (469.6)	166.3 (366.2)

TABLE 67. WING AND EMPENNAGE GEOMETRIC CHARACTERISTICS

Configuration	Wing				Horizontal Tail					Vertical Tail				
	Area m^2 (ft^2)	AR	λ	Sweep	Area m^2 (ft^2)	Tail Dist cm (in.)	AR	λ	Sweep rad (deg)	Area m^2 (ft^2)	Tail Dist cm (in.)	AR	λ	Sweep rad (deg)
1	17.17 (184.06)	7.71	0.67	0	4.38 (47.08)	508 (200)	3.98	0.60	0.1493 (8.53)	2.68 (28.85)	523 (206)	1.458	0.338	0.753 (43)
1A	17.17 (184.06)	7.71	0.67	0	4.90 (52.74)	459.7 (181)	5.35	1.00	0.00	3.22 (34.63)	445 (175)	1.227	0.369	0.875 (50)
2	17.17 (184.06)	7.71	0.67	0	4.38 (47.08)	508 (200)	3.98	0.60	0.1493 (8.53)	2.68 (28.85)	523 (206)	1.458	0.338	0.753 (43)
4	16.75 (180.09)	7.60	0.68	0	3.73 (40.16)	406 (160)	4.19	0.67	0.1113 (6.36)	2.16 (23.26)	432 (170)	1.495	0.348	0.753 (43)

TABLE 68. CONFIGURATIONS 1 AND 2 - OPTIONAL EQUIPMENT LIST.

(Taken from the Pressurized Model 340II)

Item	Price (1977)	Weight kg (lbs)
400B Nav-O-Matic (AF-550A)	$ 8,595.00	14.98 (33.0)
Basic Avionics Kit	1,135.00	2.72 (6.0)
300 Series Avionics System-TSO'd	8,115.00	27.69 (61.0)
400 Transponder (RT-452A) - High Altitude	795.00	3.18 (7.0)
400 DME (RTA-476A) Distance Measuring Equipment	3,495.00	6.81 (15.0)
Indicator, Economy Mixture	610.00	1.04 (2.3)
Controls, Dual	680.00	3.45 (7.6)
Cabin Pressure Control System, Variable (Exchange)	1,895.00	0.91 (2.0)
Fuel System, Auxiliary-Wing 239 liters (63 gallons)	4,680.00	30.55 (67.3)
Ground Service Plug Receptacle	295.00	2.50 (5.5)
Light, Landing, RH	430.00	2.72 (6.0)
Light, Taxi	80.00	0.68 (1.5)
Lights, Strobe (Three)	1,295.00	4.99 (11.0)
Locator Beacon, Economy	250.00	1.27 (2.8)
Nose Wheel Fender	75.00	0.45 (1.0)
Static Dischargers (set of five)	135.00	0.09 (0.2)
Indicator, Outside Air Temperature (Electric)	150.00	0.45 (1.0)
	$32,710.00	104.5 (230.2)

TABLE 69. CONFIGURATION 4 - OPTIONAL EQUIPMENT LIST.

(Taken from the Model 310II and Turbo 310 II)

Item	Price (1977)	Weight kg (lbs)
400B Nav-O-Matic (AF-550A)	$ 8,595.00	14.98 (33.0)
Basic Avionics Kit	1,010.00	2.27 (5.0)
300 Series Avionics System-TSO'd	8,115.00	27.69 (61.0)
400 Transponder (RT-459A) - High Altitude	795.00	3.18 (7.0)
Indicator, Outside Air Temperature (Electric)	150.00	0.45 (1.0)
Indicator, Economy Mixture	610.00	1.04 (2.3)
Controls, Dual	540.00	2.50 (5.5)
Door, Baggage-Large Size (Exchange)	660.00	4.81 (10.6)
Fuel System, Auxiliary-Wing [239 liters (63 gallons)]	4,365.00	27.33 (60.2)
Ground Service Plug Receptacle	225.00	2.32 (5.1)
Light, Landing, RH	410.00	2.72 (6.0)
Light, Taxi	80.00	0.68 (1.5)
Lights, Rotating Beacon (on rudder)	310.00	0.68 (1.5)
Locator Beacon, Economy	250.00	1.18 (2.6)
Nose Wheel Fender	75.00	0.45 (1.0)
Static Dischargers (set of five)	120.00	0.09 (0.2)
Seating Arrangement - Option 1	2,285.00	19.75 (43.5)
	$28,595.00	112.14 (247.0)

TABLE 70. ESTIMATED DRAG POLAR FOR THE GATE STUDY CONFIGURATIONS

Configuration	S_{REF} m^2 (ft^2)	b_{Wing} m (ft)	AR	S_{WET} m^2 (ft^2)	f m^2 (ft^2)	e	C_{D_o}	$\frac{dC_D}{dC_L{}^2}$
1	17.11 (184)	(37.67)	7.71	83.42 (897)	0.39 (4.22)	0.765	0.0229	0.0540
1A	17.11 (184)	(37.67)	7.71	88.12 (947.5)	0.41 (4.45)	0.758	0.0242	0.0544
2	17.11 (184)	(37.67)	7.71	82.49 (887)	0.45 (4.79)	0.750	0.0260	0.0551
4	16.74 (180)	(36.983)	7.60	69.75 (750)	0.38 (4.05)	0.769	0.0225	0.0545

drag characteristics supplied by Cessna would have required re-programming GASP. A comparison of the six options contained in GASP indicated that GASP option No. 3 (Split Flap) approximated the Cessna data satisfactorily.

Three-view drawings of the four aircraft used in the GATE study are shown in Figures 73 through 76.

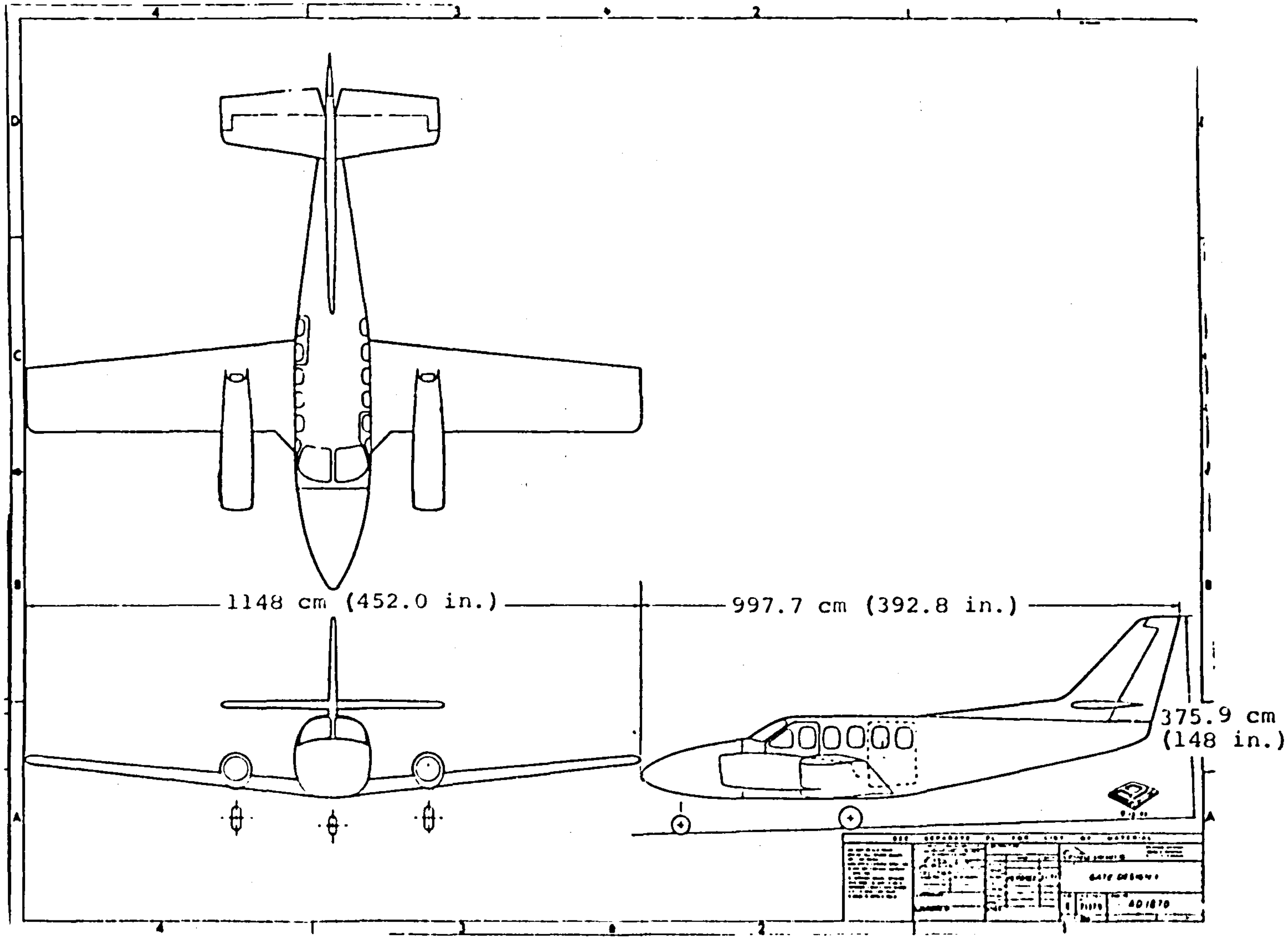


Figure 73. GATE Design No. 1

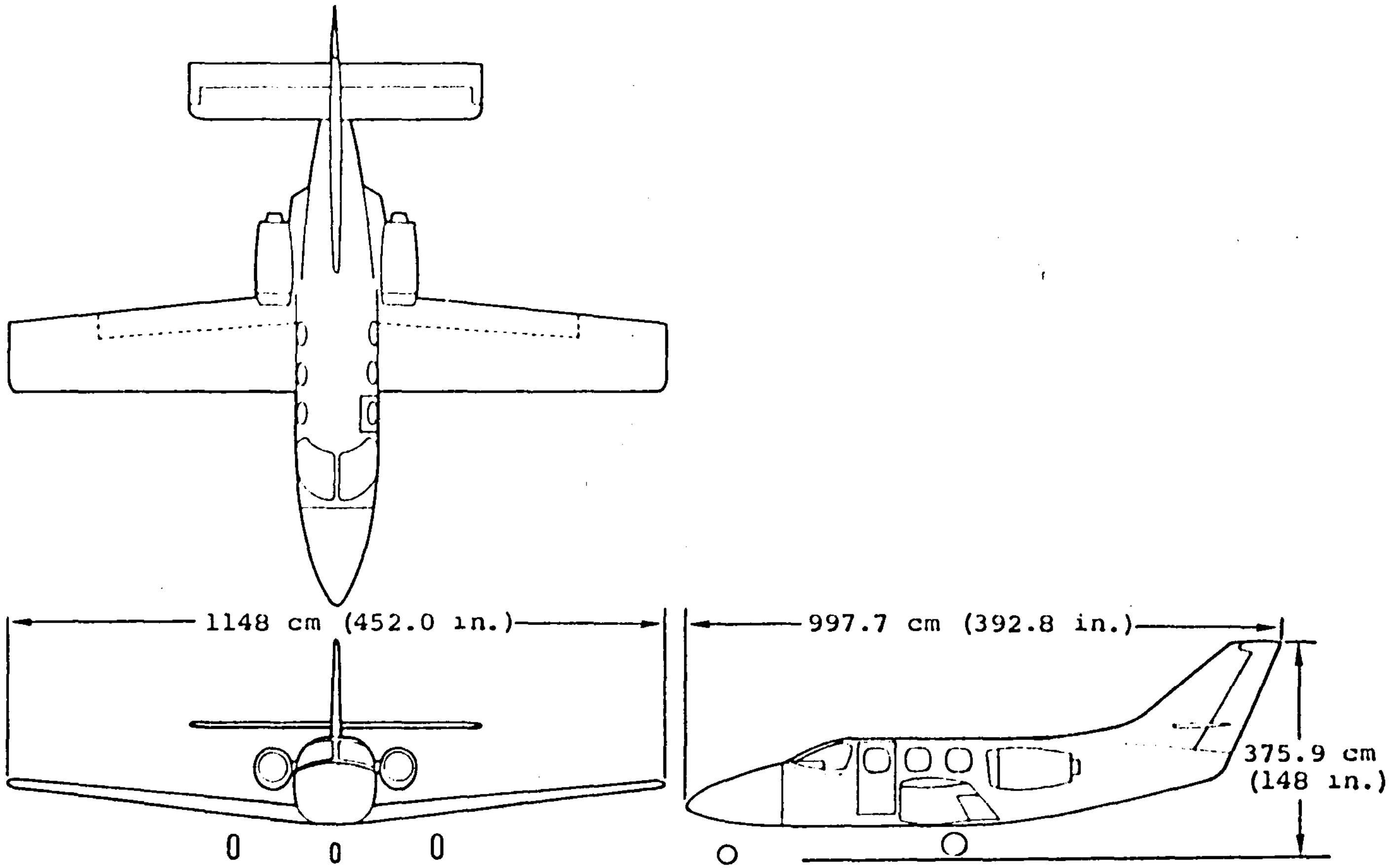


Figure 74. GATE Design No. 1A

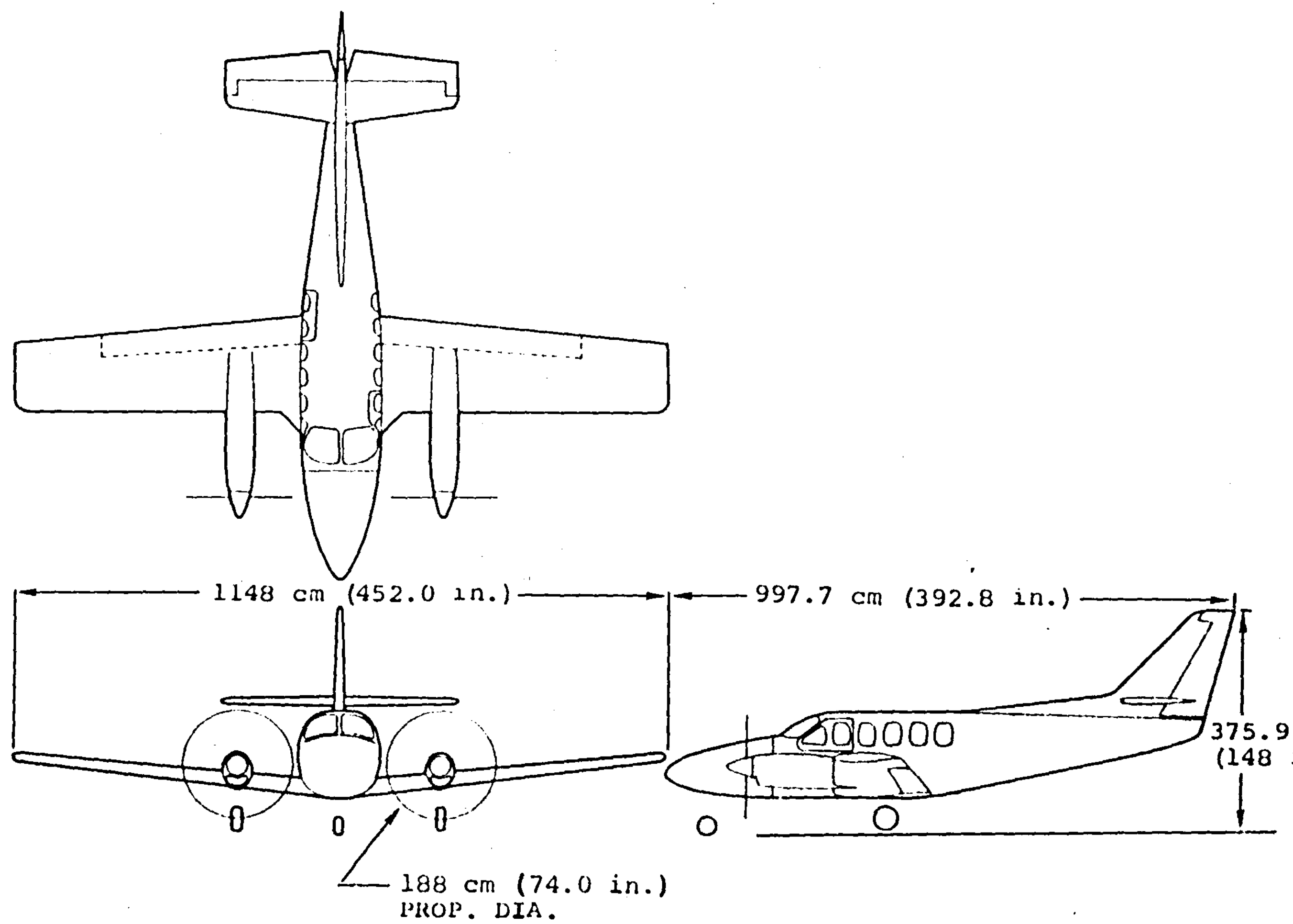


Figure 75. GATE Design No. 2

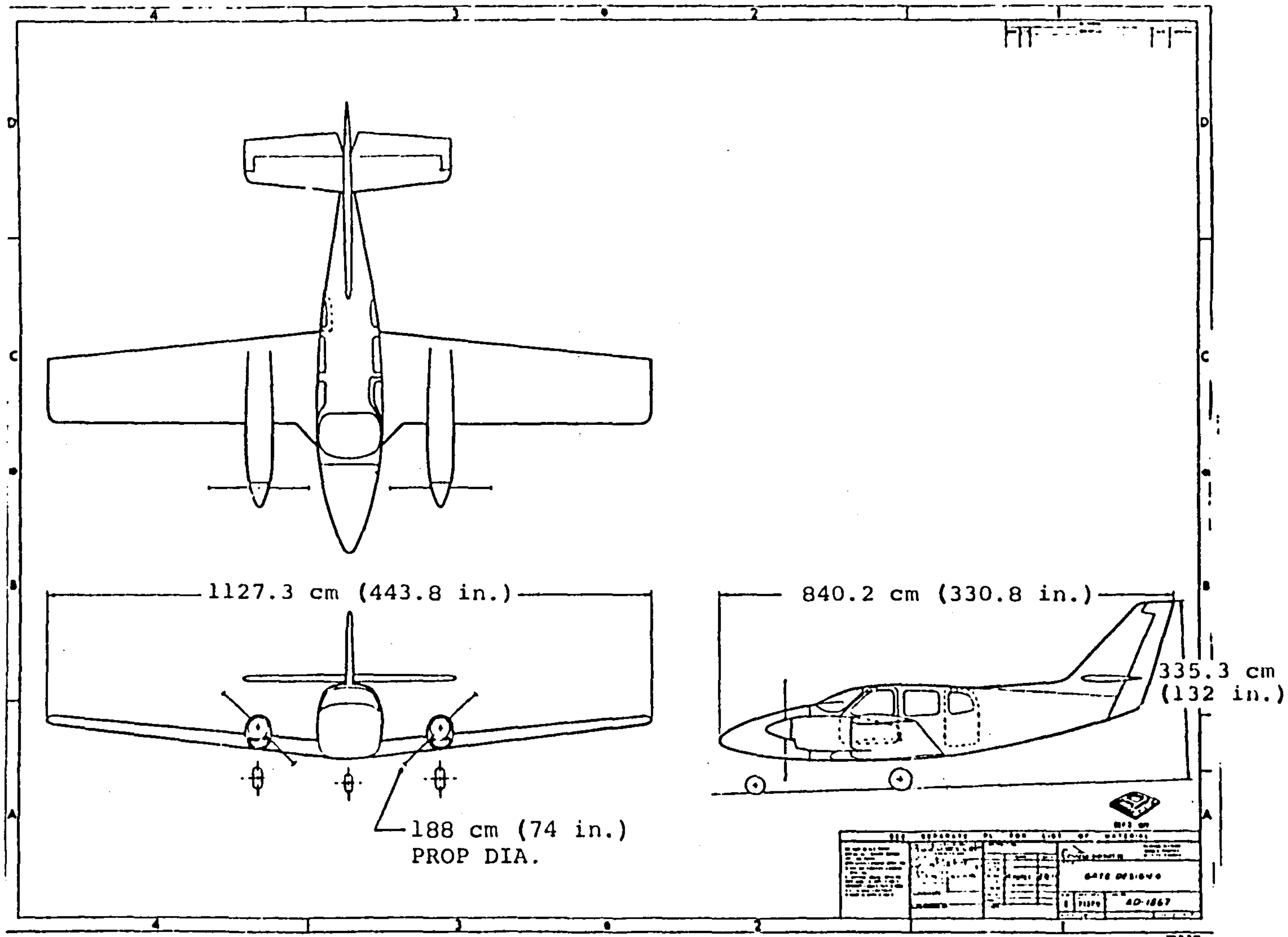


Figure 76. GATE Design No. 4

APPENDIX III

SENSITIVITY DATA

As described in Section 4.0, sensitivity data was developed for each of the three baseline aircraft. Specifically, the relationship of empty weight, gross weight, fuel weight and power or thrust required to engine weight and specific fuel consumption was defined. Base values for the sensitivities were:

Design	Pressurized Twin Turboprop 2	Pressurized Twin Turbofan 1	Light Twin Turboprop 4
Gross Weight	2470 kg (5441 lb)	2825 kg (6223 lb)	2374 kg (5228 lb)
Empty Weight	1485 kg (3271 lb)	1550 kg (3413 lb)	1352 kg (2978 lb)
Fuel Weight	468 kg (1030 lb)	758 kg (1670 lb)	590 kg (1300 lb)
Thrust or Power SLS,TO	336 kw (450 hp)	4579 N (1029 lb)	251 kw (336 hp)
Engine Weight	123 kg (271 lb)	134 kg (296 lb)	91 kg (200 lb)
Specific Fuel Consumption*	0.31 kg/hr/kw (0.51 lb/hr/hp)	0.065 kg/N.h (0.64 lb/hr/lb)	0.31 kg/hr/kw (0.51 lb/hr/hp)

*Cruise conditions, installed shaft or thrust SFC as appropriate.

Figures 77 through 82 show sensitivity data for the three baseline aircraft.

Engine sensitivity data was also developed during the program and is included in Tables 71 and 72. These data were generated for the baseline turboprop and turbofan engine.

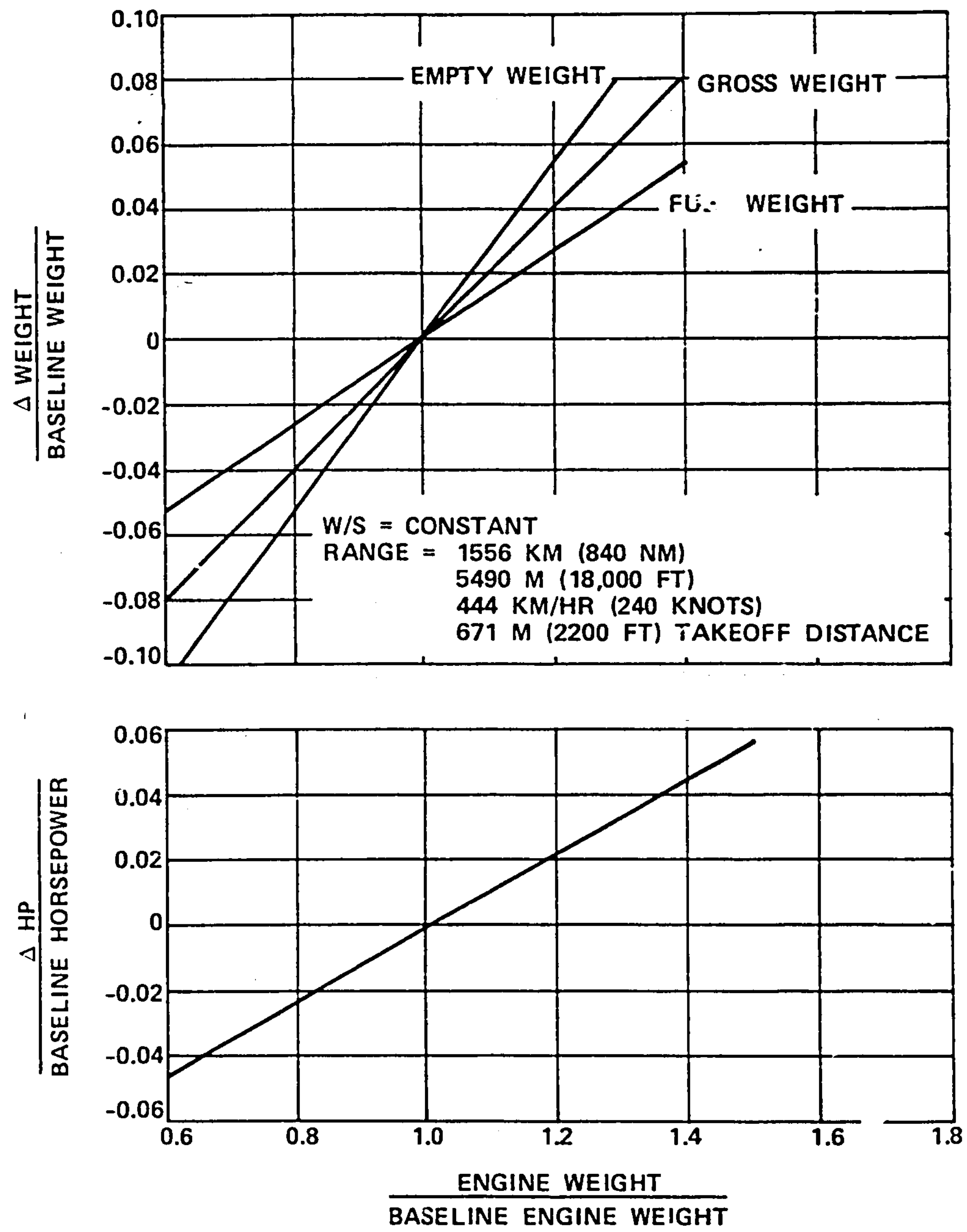


Figure 77. Engine Weight Sensitivities, Turboprop Pressurized Twin, Design No. 2.

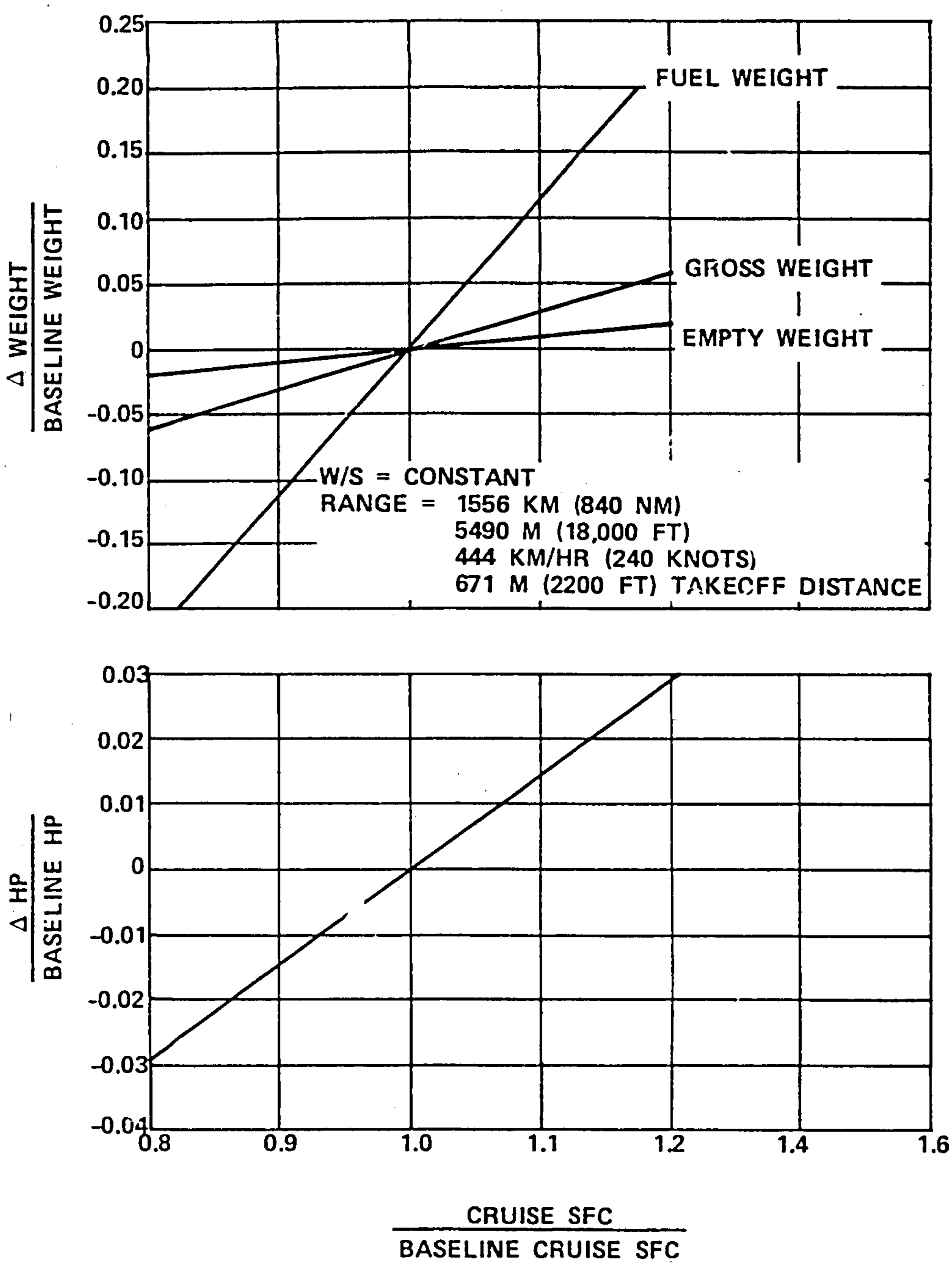


Figure 78. Fuel Consumption Sensitivities, Turboprop Pressurized Twin, Design No. 2.

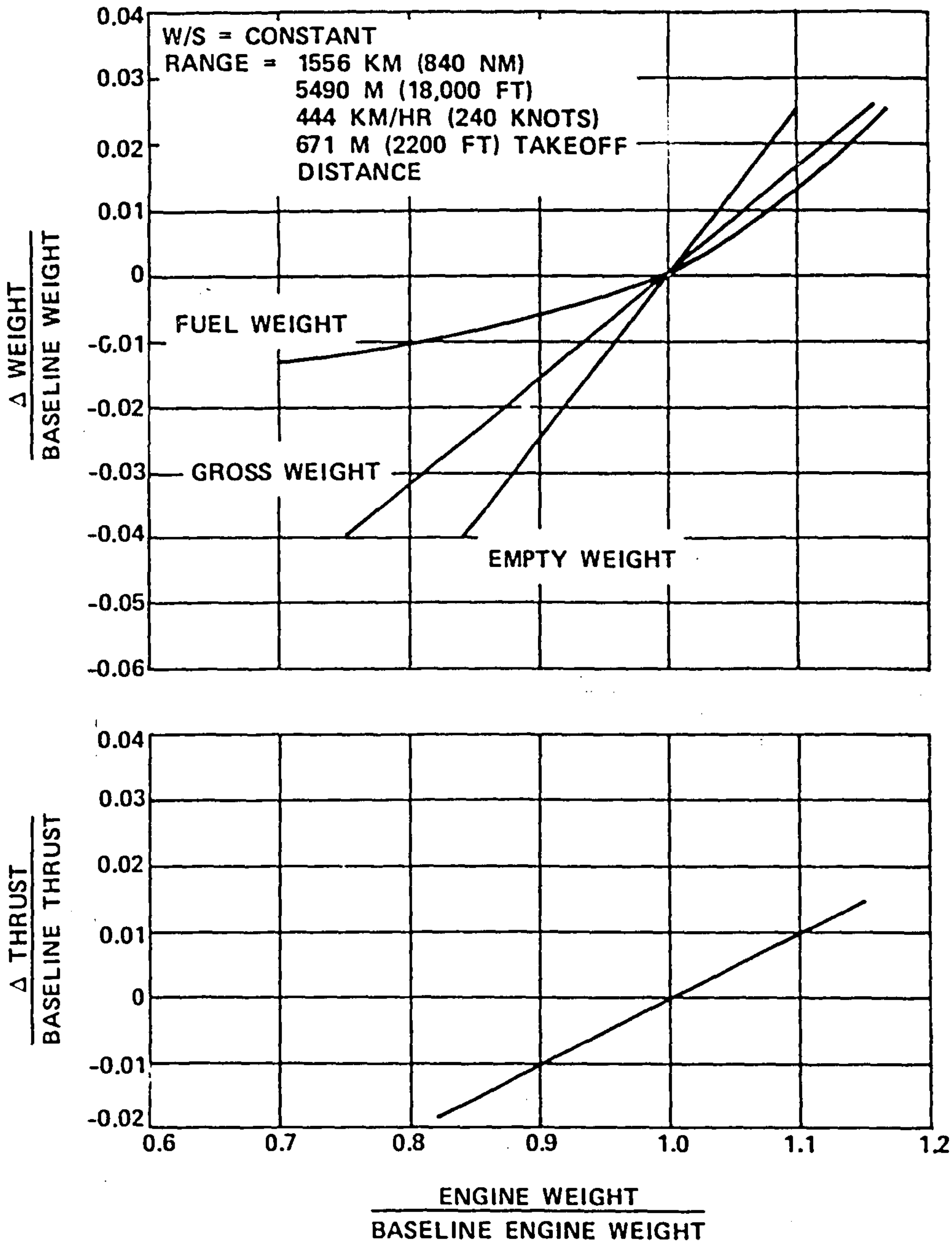


Figure 79. Engine Weight Sensitivity Studies, Turbofan Pressurized Twin, Design No. 1.

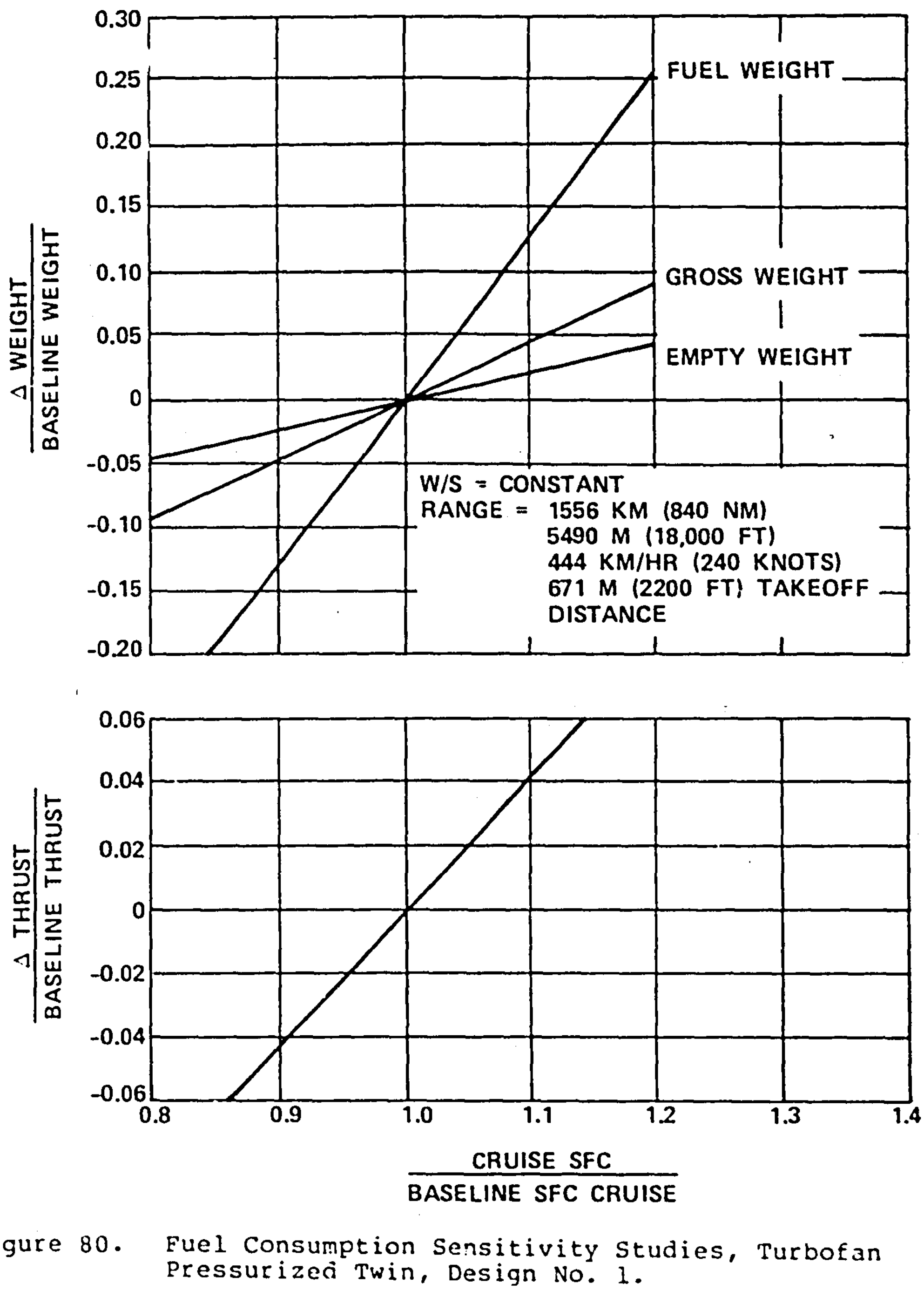


Figure 80. Fuel Consumption Sensitivity Studies, Turbofan Pressurized Twin, Design No. 1.

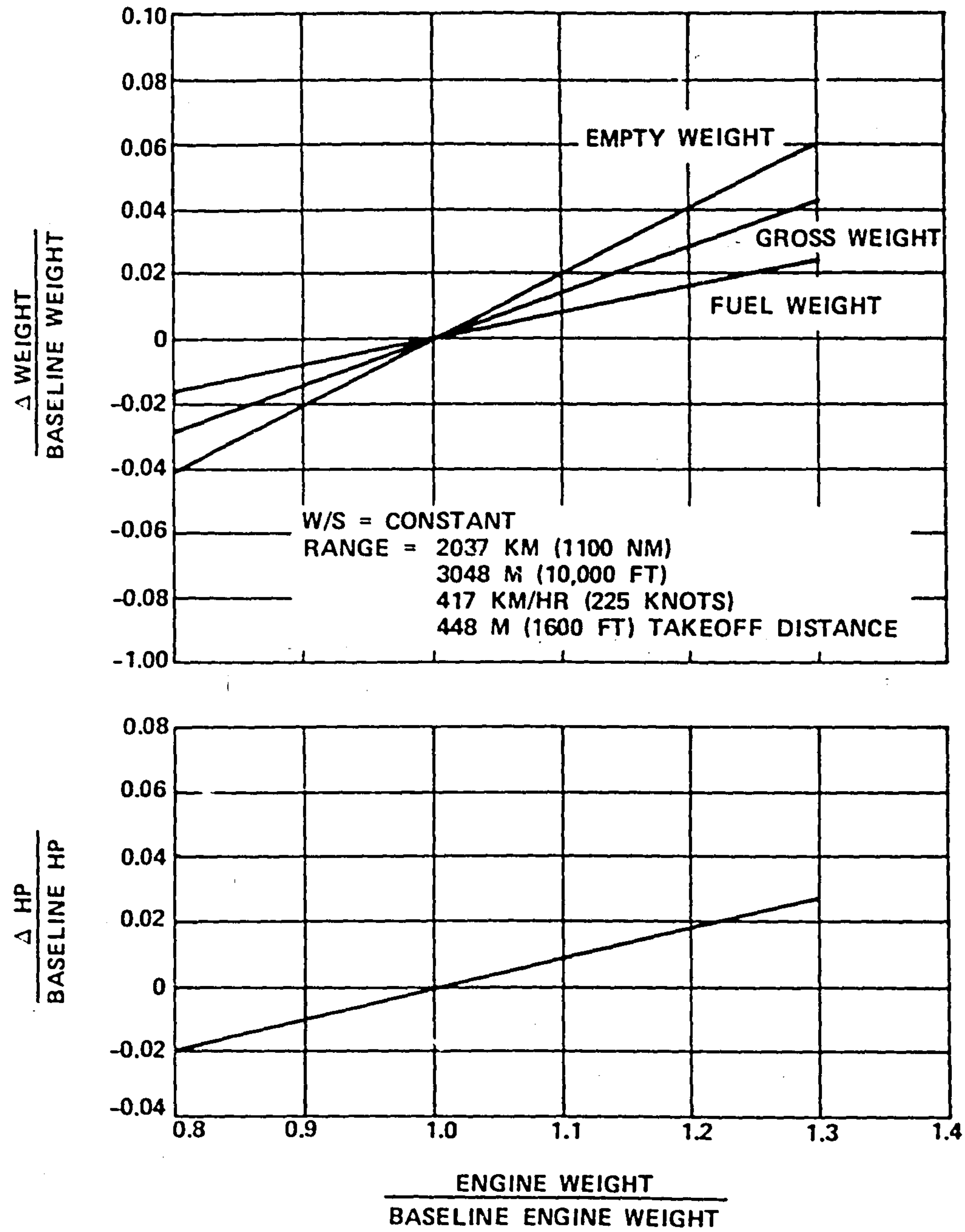


Figure 81. Engine Weight Sensitivities, Turboprop Light Twin, Design No. 4.

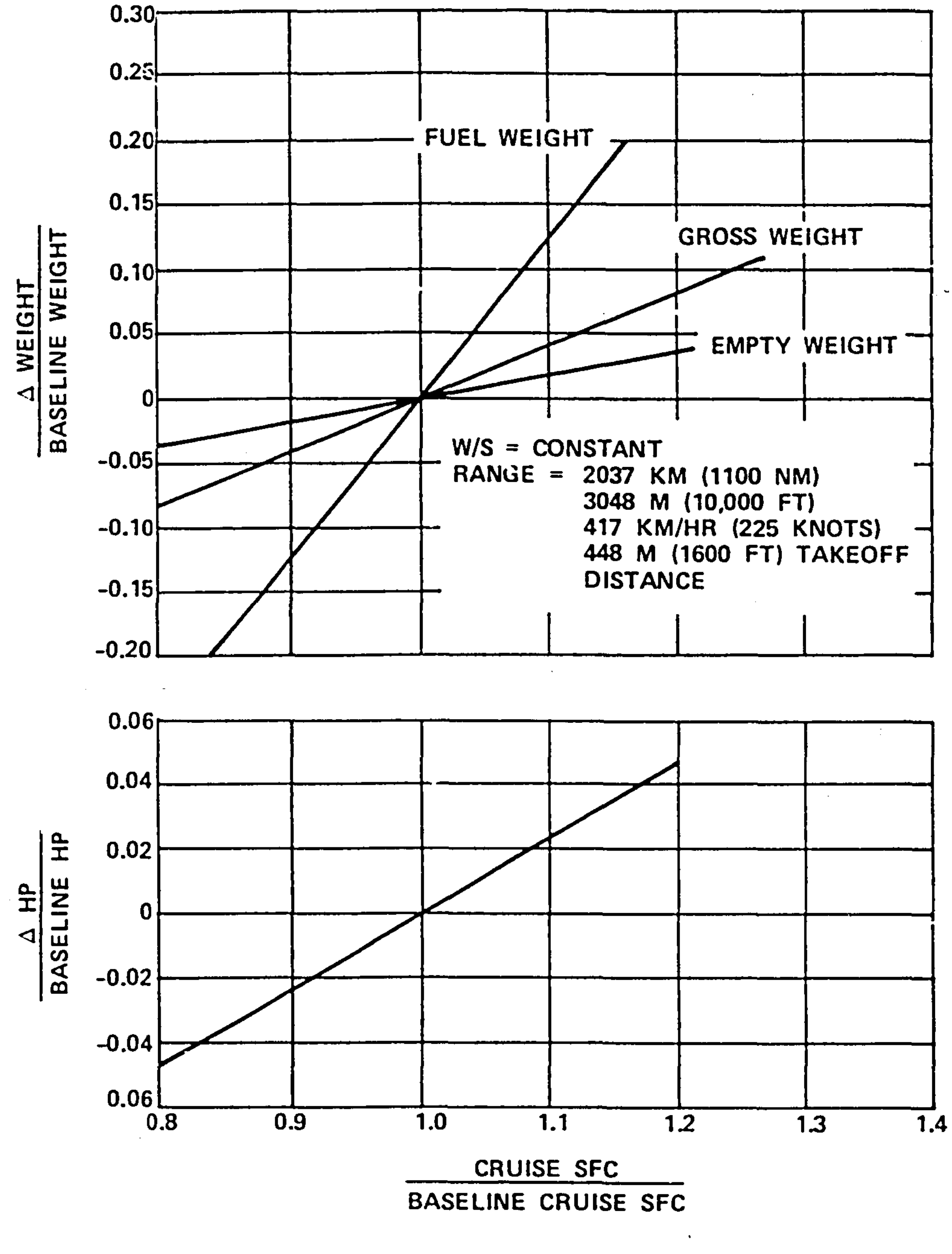


Figure 82. Fuel Consumption Sensitivities, Turboprop Light Twin, Design No. 4.

TABLE 71. 1478°K (2200°F) BASELINE TURBOPROP SENSITIVITY OF PERFORMANCE TO COMPONENT PARAMETERS 6100 M (20,000 FT), 389 KM/HR (210 KTAS), STD DAY (ENGINE A).

Parameter	Base Value	Δ Value	Δ% Power	Δ% SFC
Ram recovery	1.0	-0.02	-3.32	1.36
Compressor efficiency (ΔT/T=C)	Base	-0.02	-2.63	2.72
Compressor efficiency ΔP/P=C)	Base	-0.02	-2.18	1.52
Pressure ratio	9.0	-0.8	-1.21	2.74
Compressor bleed	0.043	+0.02	-4.01	1.90
Turbine cooling flow	Base	+0.02	-3.04	0.90
Burner ΔP/P	Base	+0.02	-1.31	1.34
Burner leakage	Base	-0.02	-3.70	3.82
HP turbine efficiency	Base	-0.02	-1.28	1.29
HP-LP turbine ΔP/P	Base	+0.02	-1.28	1.29
Horsepower extraction (GG)	5	+5	-1.56	1.58
HP turbine leakage	Base	+0.02	-1.97	2.00
Power turbine efficiency	Base	-0.02	-2.28	2.34
Horsepower extraction (P.T.)	0	+5	-1.70	1.73
Turbine diffuser ΔP/P	Base	0.02	-1.28	1.30

TABLE 72. 1478°K (2200°F) BASELINE TURBOFAN SENSITIVITY OF PERFORMANCE TO COMPONENT PARAMETERS 6100 M (20,000 FT), 389 KM/HR (210 KTAS), STD DAY (ENGINE J)

Parameter	Base Value	Value	Δ% Thrust	Δ% TSFC
Ram recovery	0.995	-0.02	-5.78	+3.85
Fan efficiency (ΔT/T=C)	Base	-0.02	-2.51	+1.67
Fan efficiency (P/P=C)	Base	-0.02	-1.76	+1.34
Fan pressure ratio	1.5	-0.05	-3.81	+1.67
Fan duct ΔP/P	Base	+0.02	-3.02	+3.01
Fan-Comp ΔP/P	Base	+0.02	-2.91	+10.84
Comp efficiency (ΔT/T=C)	Base	-0.02	1.84	+1.84
Comp efficiency (P/P=C)	Base	-0.02	-1.89	+11.00
Comp pressure ratio	9.0	-0.8	-0.05	+1.84
Fan duct leakage	Base	-+0.02	-2.79	+2.84
Compressor leakage	Base	+0.02	-3.58	+1.51
Turbine cooling flow	Base	+0.02	-2.43	+0.17
Burner ΔP/P	Base	+0.02	-0.89	+0.84
HP turbine efficiency	Base	-0.02	-1.23	+1.17
HP turbine leakage	Base	+0.02	-1.84	+1.84
Horsepower extraction	5	+5	-0.64	+0.50
HPT-LPT ΔP/P	Base	0.02	-0.87	+0.84
LP turbine efficiency	Base	-0.02	-1.48	+1.34
LP turbine leakage	Base	+0.02	-0.47	+0.33
Turbine diffuser, ΔP/P	Base	+0.02	-0.89	+0.84
Core thrust coefficient	0.985	-0.02	-0.49	+0.50
Fan thrust coefficient	0.985	-0.02	-2.84	+2.84
Bypass ratio	8.0	-2.0	-8.85	+9.7

REFERENCES

1. Merrill, G. L., G. A. Burnett, C. C. Alsworth, et al., A Study of Small Turbofan Engines Applicable to General Aviation Aircraft Final Report, NASA CR 114630, September 1973.

2. Hildenbrand, R. W., G. L. Merrill, and G. A. Burnett, Study of Small Civil Turbofan Engines Applicable to Military Trainer Airplanes Final Report, NASA CR 137575, April, 1975

3. Merrill, G. L., Study of Small Turbofan Engines Applicable to Single-Engine Light Airplanes, NASA CR 137944, September 1976

End of Document