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ADVANCED GENERAL AVIATION TURBINE ENGINE (GATE) STUDY

FINAL REPORT

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FOREWORD

The work described herein was conducted by Teledyne CAE with support from Bell Helicopter, Textron and Hamilton Standard, Division of United Technologies, and subcontracted support from Beech Aircraft Corporation.

TABLE OF CONTENTS

		Page
1.0	SUMMARY	1
2.0	INTRODUCTION	2
3.0	TASK I: MARKET ANALYSIS	3
	3.1 Preliminary Data Base	3
	3.1.1 Aircraft Categories	3
	3.1.2 Engine Performance	4
	3.1.3 Engine Cost, Weight and Scaling Data	5
	3.2 Market Research and Analysis - Beech: Fixed Wing Aircraft	7
	3.2.1 Aircraft - Engine Price Relationship Analysis	8
	3.2.2 Aircraft Price - Demand Approach	9
	3.2.3 Historical Trends	9
	3.2.4 Price-Demand Analysis	9
	3.3 Market Analysis - Bell: Rotary Wing Aircraft	10
	3.4 Alternate Cycles - Identifying Domains of Engine Superiority	11
	3.5 Noise and Emissions Regulations	13
	3.6 Market Forecast - Task I (Summation of Findings)	15
4.0	TASK II: TRADE-OFF STUDIES	17
	4.1 Parametric Performance Analysis	17
	4.1.1 Baseline Analysis	17
	4.1.2 Sensitivity Studies	18
	4.1.3 Cooling Effects	19
	4.1.4 Turbofan Performance Evaluation	20
	4.1.5 Parametric Performance Analysis Conclusions	20
	4.2 Sample Engine Performance Studies	21
	4.3 Component Analysis	23
	4.3.1 Compressor Component Studies	23
	4.3.2 Combustor	25
	4.3.3 Turbine Component Design	26
	4.4 Engine Configuration Layouts	28
	4.4.1 Performance Analysis	28
	4.4.2 Mechanical Design and Cost Analysis	29
	4.4.3 Alternate Configurations	31

TABLE OF CONTENTS (Cont'd.)

		Page
4.5	Fixed Wing Aircraft Point Design and Parametric Analysis	32
	4.5.1 Computerized Point Design Analysis	32
	4.5.2 Aircraft Price Analyses	34
	4.5.3 Noise Analyses	35
4.6	Engine - Aircraft Synthesis	35
4.7	L^2 C^2 Analysis - For Selection of Optimum Engines	37
4.8	GATE Point Design Aircraft With Reciprocating Power	38
4.9	Technology Applicability and Worth	40
	4.9.1 Technology Identification	40
	4.9.2 Technology Worth - Evaluation	42
4.10	Task II Conclusions	43
5.0	TASK III: COMMON CORE CONCEPT EVALUATION	45
5.1	Common Core Candidates	45
5.2	Free Turbine Design	46
5.3	Cost Analysis	46
6.0	TECHNOLOGY PROGRAM PLAN	48
7.0	CONCLUSIONS AND RECOMMENDATIONS	51

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	Areas of Power Plan Dominance	53
2	GATE Task I, Market Analysis Study Plan	53
3	GATE Turboprop	54
4	Installation - GATE Turboprop	54
5	GATE Turbofan	55
6	Installation - GATE Turbofan	55
7	Comparison of Task I Baseline GATE Turboprop With Current Technology	56
8	CR (Cost Ratio) Relationship	56
9	CR Formula and Base OEM Price	56
10	Relative Price Vs. Production Rates	56
11	Market Analysis Flow Chart	57

LIST OF ILLUSTRATIONS (Cont'd.)

Figure	Title	Page
47	AAAC 15 Turbine Design Study	77
48	CC 20 Turbine Design Study	77
49	AC 11.3 Free Turbine Design Study	78
50	Rotor Relative Temperature and Efficiency Vs. Wheel Speed	78
51	GATE Component Efficiencies Vs. Airflow	79
52	Basic Engine Configurations	80
53	Design 2010 Engine Layout	80
54	Installation - GATE Turboprop	81
55	Turbine Rotor Design Summary	81
56	Relative Cost and Power to Weight Ratio	82
57	Power Characteristics of a Differential Turbine Engine	82
58	Differential Turboprop Design 2011	83
59	Differential Turboshaft Design 2012	83
60	Airplane Size Vs. Cruise Velocity	84
61	Airplane Size Vs. Range - Category IIIP	85
62	Airplane Size Vs. Payload - Category IIIP	86
63	Airplane Size Vs. Take-Off Distance Cateogry IIIP	87
64	Airplane Size Vs. Landing Distance Category IIIP	88
65	Airplane Size Vs. Cruise Fuel Consumption	89
66	GATE Turboprop Powered Aircraft Three Views	90
67	GATE Turboprop Powered Aircraft Three Views	90
68	GATE Turboprop Powered Aircraft Three Views	91
69	GATE Twin Turboprop Powered Aircraft Three Views	91
70	Projected GATE Powered Aircraft Noise Levels Compared with 1976 GAMA Data	92
71	Engine Weight and Retain Price Vs. Power for Different Production Rates	93
72	Limited Life Cycle (L^2C^2) Features and Data Sources	94
73	Parametrics for L^2C^2 Analysis	94
74	Category II, 5 Year LC Summary	95
75	Category IV, 5 Year LC Summary	95
76	LC Vs. Fuel Cost	96
77	LC Vs. Fuel Cost	96
78	LC Vs. Fuel Cost	97
79	Applicability of Large and Other Engine Technologies to GATE	97
80	Typical Worth of Technology Over a 5 Year Period	98
81	GATE Fleet Yearly Cost Savings	98
82	Common Core Layouts	99
83	Two Frame Family Approach to a Common Core	99
84	Free Turbine Designs	100
85	Maximum Engine Price for Market Penetration	100
86	5 Year Demonstrator Plan	101

LIST OF TABLES

Table No.		Page
I	Task I Aircraft Types	102
II	Initial Turboprop Engine Performance Postulations at Cruise	103
III	Initial Turboprop Engine Power and Airflow at Sea Level Static	104
IV	Initial Turbofan Engine Performance Postulations	104
V	Baseline Turboprop Scaling Data	105
VI	Baseline Turbofan Scaling Data	106
VII	Component Relative Cost	106
VIII	General Avaiation Market and Growth Trend Summary	107
IX	Project Light Helicopter Market	107
X	Missions for GATE Powered Light Helicopters	107
XI	Helicopter Aircraft Capability with GATE	108
XII	1988 GATE Powerplant Capabilities	109
XIII	GATE Emissions	109
XIV	1988 Turbine Power Market Forecast	110
XV	Matrix of Advanced Technology Efficiency Assumptions	111
XVI	Range of Cooling Bleed Loss Assumptions	112
XVII	Data Matrix for the Turbofan Parametric Analysis	112
XVIII	Typical Performance at 107 KN	113
XIX	1985 State-of-the-Art Compressor Summary	114
XX	Candidate Engine Component Data at Cruise	115
XXI	Candidate Engine Cruise Performance	116
XXII	Maximum Thermodynamic Horsepower at Sea Level Static	117
XXIII	Turboprop Scaling Data	118
XXIV	Design 2010 Critical Speed Summary	119
XXV	Relative Cost Summary for Four Basic Engine Configurations	119
XXVI	OEM Cost for the Four Basic Engine Designs	120
XXVII	Q-Fan$_{(tm)}$ Design Parameters	120
XXVIII	Relative Cost Summary (For Equal Weight) for Design 2011 - Differential Turboprop and Design 2012 - Differential Turboshaft	121
XXIX	Comparison of a Differential Turbine Design to a Single Shaft Design	121
XXX	Baseline Aircraft/Engine Characteristic for Point Designs	122
XXXI	Baseline Aircraft Point Design Characteristics	123
XXXII	Point Design Aircraft Price Analysis	124
XXXIII	Aircraft Parametrics - Linear Influence Coefficients	124
XXXIV	Aircraft Synthesis Analysis Results	125

LIST OF TABLES (Cont'd.)

Table No.		Page
XXXV	LC Final Schedule Definitions	125
XXXVI	Comparison of GATE 1988 Category II Aircraft With Turboprop Vs. Reciprocating Power	126
XXXVII	Comparison of GATE 1988 Category IV Aircraft With Turboprop Vs. Reciprocating Power	127
XXXVIII	Comparison of GATE 1988 Category II Aircraft With Turboprop Vs. Reciprocating Power	128
XXXIX	Comparison of GATE 1988 Category IV Aircraft With Turboprop Vs. Reciprocating Power	129
XL	Aircraft Improvements With GATE Turboprop Over Recip Engines	130
XLI	Summary of Common Core Approach	130
XLII	Two Frame Family Performance Summary	131
XLIII	Relative Cost Summary (For Each Weight) for Design 3013-AC 11.3 Common Core	132
XLV	AC 11.3/CO Cost Summary	133
XLVI	Relation of the Common Core Engine Price to the Projected Fixed Wing and Helicopter Market	134
XLVII	Core Engine Cost Features Compared to Current Technology	135

REFERENCES 136

APPENDIX A - LIST OF SYMBOLS AND ABBREVIATIONS 137

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SECTION 1.0

SUMMARY

A 5-task study program was conducted to develop a market scenario, to evaluate the benefits of gas turbine power in general aviation aircraft in the late 1980's, and to outline the technologies requisite to meeting the market needs. The study spanned fixed and rotary wing aircraft in the 726 kg to 3629 kg (1600 to 8000 lb.) take-off gross weight (TOGW) markets.

Task I showed that potential U.S. national engine sales of 31,500 per year (95 percent fixed wing, 5 percent helicopter) could exist for defined categories of the market. A primary constraint is the ability to produce engines with a sales price approaching current reciprocating engines. Fuel conservation, installation, safety, comfort, and environmental improvements would accrue if the market could be created via reduced engine prices.

These features were used as input in Task II to evaluate a spectrum of engine configurations; optimum aircraft-engine types and payoffs were developed for each aircraft category, based on a (limited) life cycle cost criterion. It was determined that a combination of advanced component design features, a low cost manufacturing and materials technology approach, and high rate production would produce engine designs to meet the price, performance, and durability objectives.

Task III provided the derivation of a common core engine applicable across the spectrum, and the benefits and tradeoffs associated with it. A 9:1 pressure ratio single stage compressor, combined with a novel reverse flow vaporizer plate combustor, a 1504 degree K (2250 degree F) uncooled radial turbine rotor, and a multi-purpose reduction gearbox constitute the major elements of the common core. Commonality of these parts across a 197-422 kW (265-565 hp) power range for turboprops and turboshafts was demonstrated.

In Task IV, a 5-year plan was constructed for component development and engine demonstration focusing on the requisite advanced technologies. It was concluded that a successful engine family could result from such a plan; NASA's investment in the program would identify and reduce the risk inherent in the advanced aerodynamic, materials, and structural technologies.

SECTION 2.0

INTRODUCTION

Efforts are underway to improve all types of General Aviation engines (reciprocating, rotating, diesel and gas turbines). The drivers are the expanding market, the need for energy conservation, and the demand for more stringent environmental controls.

Turbine power has been accepted (Figure 1) in larger fixed and rotary wing aircraft (above approximately 9.9 kN (2200 lb thrust) and 418 kW (560 hp) because of its benefits to flight speed, payload and aircraft gross weight, and to general passenger comfort and safety. Time Between Overhauls (TBO) intervals are currently significantly higher than competing reciprocating engines.

It was, therefore, appropriate to examine the requirements and technologies for all sizes of advanced General Aviation turbine engines that might be expected to come into service in the late 1980's. These engines include fixed (connected) and free-shaft turbines, as well as smaller size turbofans.

The specific objective of the General Aviation Turbine Engine (GATE) study was to define the requirements for small engine advanced technology suitable for General Aviation service in the 1987-1988 timeframe. Small engines are defined as being in the 112-746 kW (150-1000 hp) range; 1/2 to 3/4 of the effort was directed to engines in the 112-447 kW (150-600 hp) range. For turbofans, emphasis was on 6.7 kN (1500 lbs) thrust or less. The study included fixed and rotary wing aircraft applications, a component technology assessment effort, and a core demonstrator plan to provide the technology base to enter engineering development in 1988.

The study evaluated the opportunities of turbine power in General Aviation aircraft and generated information necessary for the Government to formulate the most effective technology program for smaller sized turbine engines.

The study was divided into four tasks. Task I focused on a market analysis to identify applications, mission profiles, and environmental requirements. Task II encompassed trade-off studies to identify the optimum engine aircraft technology requirements. A common core concept was evaluated in Task III to assess its benefits and penalties for application across the wide range of propulsion requirements. A conceptual "optimum" core engine design results from this task, and a program plan was developed in Task IV for the follow-on component technology and core engine demonstration.

SECTION 3.0

TASK 1: MARKET ANALYSIS

Task I concentrated on projecting fixed and rotary wing markets through 1988 by functional segments using extrapolated and postulated reciprocating, rotary, and turbine engine characteristics. The projection was iterated to determine the effect of various engine technological possibilities (weight, size, performance, cost) and environmental noise and emissions regulations on market quantity and product distribution. From the market scenario, domains of engine superiority were identified and the distribution of applicable gas turbines (and their requirements or features) were extracted. Figure 2 describes the overall approach taken to project the market potential of small gas turbines in the late 1980's time frame.

3.1 Preliminary Data Base

Because the market analysis plan was being performed prior to the availability of detailed engine or aircraft specifications, it was necessary to stipulate market categories and engine characteristics on the basis of current history and previous studies in the General Aviation field extrapolated to the 1988 time frame. Initiation of the task was, therefore, based primarily on executive or experiential judgment. Senior Beech and Teledyne CAE personnel utilize d their experience and prior studies of a similar nature to define bands of: a) engine potential - weight, SFC, cost and bulk and, b) aircraft features - desirable mission payoffs, comfort features, safety, and marketable price.

Relative to engine potential, prior Teledyne CAE engine design studies were assessed, and preliminary performance analysis were accomplished, using bands of potential pressure ratio, turbine inlet temperature capability, and component efficiencies to define the SFC potential. Special consideration was given to small engine design limitations. Weight estimates were based on current production engines and the potential improvement of new materials of higher strength; cost, weight, and scaling information were assembled.

With respect to the aircraft case, Beech personnel assessed their corporate history and the limitations implicit in the types of aircraft. In the rotorcraft case, Bell personnel identified new markets of opportunity - i.e., new products filling a need anticipated for the 1988 time frame.

3.1.1 Aircraft Categories

Five aircraft categories were selected, as summarized in Table I. These categories were separated by their primary mission requirements, rather than on an arbitrary gross weight basis.

The helicopter category shown on Table I is described in Section 3.3.

The first category consisted of a single engine, two-passenger aircraft designed principally for flight training activities. It is a simple training aircraft and will be flown by inexperienced pilots from a fixed base operation. Therefore, it should not have excessive altitude and speed capabilities or be complex; it should be very conservative as to aerodynamic sophistication.

The second category was composed of single engine aircraft with a four-passenger capability. Category III included single engine aircraft with a four to six passenger configuration. These aircraft are most often identified as the high performance end of the single engine aircraft group. Category IV was composed of twin engine aircraft. At the end of the spectrum, the Category V aircraft was primarily a corporate airplane and could accommodate the best potential advanced aircraft and engine technology. (Category V, historical trend data, was the only one to include twin engine turboprop aircraft.)

Later reassessment of the aircraft missions and marketable features elicited the opinion that single engine, pressurized, high performance Category III aircraft were beginning to appear in several product lines. This observation was included in the study by dividing Category III aircraft into pressurized (IIIP) and unpressurized (IIIU) types.

An agricultural aircraft was added, although it was outside the current Beech market spectrum. In each case, with payload fixed by passengers and baggage, it was necessary to complete the mission definition with cruise altitude, velocity and range assumptions. Upon reviewing Task II, the initial Task I projected increases in these parameters proved to be optimistic.

For clarity of presentation, the final categories, their current price, and their missions (i.e., determined following Task II iteration) are summarized on Table I. The differences between the original judgment and final analytical category definitions represent the iterations undertaken to balance Task I "desired" features and Task II "affordable" features. The final result was a 7.7 to 15.4 m/s (15-30 ktas) increase of cruise velocity, and a 10-25 percent increase of range, depending on category, defined for 1988 GATE-powered aircraft.

3.1.2 Engine Performance

As noted previously, it was necessary to utilize executive judgment to postulate engine technology levels which could be achieved in 1985. Assumptions were therefore made on the basis of preliminary cycle calculations, using extrapolated component technology levels for simple, single-spool turboprops and two-spool turbofans.

A single spool (connected shaft) turboprop was used in all fixed wing studies because it was judged to offer the minimum production price potential.

The mission assumptions and preliminary turboprop engine cycle definitions are summarized in Table II and Table III. Table II shows that cruise SFC varies less than 3 percent with a 55 degree K (100 degree F) change of turbine inlet temperature; however, Table III shows that required component size (flow) changes 10-16 percent. They also show that the engines will be flat-rated, i.e., to match reciprocating engine characteristics, takeoff will occur at power levels considerably below maximum temperature capability. Sufficient information is presented to relate cruise requirements to sea level static capabilities, i.e., "lapse rate" is defined for subsequent aircraft-engine sizing.

For the turbofan, similar core engine characteristics were assumed, and fan pressure ratios were optimized at each flight condition in a preliminary analysis. Initially, a 6:1 bypass ratio turbofan was predicated in order to obtain the earliest possible sizing and scaling information. Table IV summarizes the turbofan data.

Again, the engines are seen to be flat-rated because of the low flight speed (compared to higher performance turbofan aircraft) and the high takeoff thrust available from the 6:1 bypass ratio cycle.

Accessory power requirements were defined as 1.5 kW (2 hp) for Categories I and II, 2.2 kW (3 hp) for Categories III and IV, and 6 kW (8 hp) per engine for Category V. A requirement was also defined for 0.038 kg/S (5 lb/min) bleed airflow for Categories III and IV, and 0.045 kg/S (6 lb/min) for Category V. These power requirements were considered in sizing the engines for each category, i.e., the cruise power was increased by the accessory requirement. Bleed air was assumed to be provided by a separate gear driven compressor. The effect of this approach versus bleed air is discussed in Section 4.2.

This range of performance data was submitted to Beech and Bell for integration with the engine sizing and cost analysis to define aircraft-engine combinations.

3.1.3 Engine Cost, Weight and Scaling Data

Engine scaling and cost data were developed for 1985 engine technology as an input to the marketing analyses. These data were developed for a turboprop and a turbofan engine. The GATE baseline Task I turboprop is a single shaft engine (Figure 3) consisting of a single stage centrifugal compressor, a reverse-flow annular combustor, a radial turbine, and a reduction gear. The turboprop installation is shown in Figure 4, and the baseline scaling data are shown in Table V. Similar data for a single shaft geared turbofan are shown in Figures 5, 6, and Table VI.

The basic scaling equation is expressed as follows:

$$N = N_0 \; (PWR/PWR_0)^x$$

where N = dimension or weight
x = exponent defined for each dimension or weight
PWR = Kilowatts (horsepower) or thrust as applicable

These scaling data were generated from softline sketches. The dimensions and weights, as a function of power, were reduced to exponential functions, thereby providing continuous and consistent scaling data over the power range. The 116 KW turboprop is beyond the scaling range, thus a single tabulation for this size is shown in Table V.

The engine cost was estimated by comparison with current technology engines.

The Task I baseline turboprop is compared with a 1976 technology hypothetical production turboprop in Figure 7: the significant difference in the schematic sections is the reduction in the number of compressor and turbine stages. The engine component cost, relative to the hypothetical production turboprop engine is shown in Table VII.

Detailed component cost data are generally considered to be highly proprietary. The baseline component estimates shown here are based on a combination of both private and published data and do not represent a detailed analysis of a specific engine. These data, however, are considered both appropriate and sufficiently accurate to be useful in the GATE engine cost estimation procedure.

All of the following comparisons are made at a fixed engine weight, irrespective of engine cycle or performance. The latter factors are addressed later.

Comparing GATE advanced technology to the hypothetical production engine, the gearbox and air inlet housing are estimated to be equal. The compressor stages have been reduced from two to one; the relative cost is reduced from 0.16 to 0.08. The combustor features a simplified "vaporizer plate" design to replace an atomizing nozzle, and the cost reduction is estimated to be 33 percent, from 0.06 to 0.04 (based on Teledyne CAE in-house studies). Three turbine stages have been replaced by one; the cost is reduced from 0.20 to 0.07. The cold housings (compressor section) and hot housings (combustor and turbine section) have been reduced due to the reduction in number of compressor and turbine stages. The accessory system cost is primarily the fuel control. GATE envisions using a full authority electronic control to replace the current hydromechanical controls, with an estimated cost reduction from 0.24 to 0.12. The assembly and test (A&T) column has been reduced, due to the fewer components, from 0.06 to 0.04. The resulting cost is 60 percent of the hypothetical production engine.

The third comparison features advanced fabrication technology, such as powder metal gears and turbine rotors, and die cast aluminum housings and squeeze cast compressor rotors for a further cost reduction from 0.6 to 0.5. The estimated OEM (Original Equipment Manufacturer) price of the hypothetical production turboprop engine is $74,000 in 1977 dollars. The Task I GATE advanced technology baseline engine price would be 60 percent of this, or $44,400.

When the engines are scaled to different sizes, there will be a price change as a function of size. The price relationship as a function of engine weight is shown by the CR (cost ratio) curve in Figure 8 (based on Teledyne CAE generated data for scaling a fixed configuration over a size range). The cost formula representing the curve is shown in Figure 9. The $44,400 price previously developed is for a GATE turboprop engine weighing 149.8 kg (330 lb.). Normalizing to a CR of 1.0 and a weight of 227 kg (500 lb.), the OEM price would be $59,870. The single shaft turbofan (Figure 5) is similar to the turboprop (Figure 3); the compressor, combustor, and turbine are the same, the high ratio turboprop reduction gear is replaced by a smaller, low ratio gear and a fan stage. The turbofan cost (for the same weight) is assumed to be equal to the turboprop. The turbofan and turboprop core are the same, the small high speed turbofan reduction gear and fan stage are assumed to equal the price of the heavier low speed reduction gear of the turboprop.

The engine price is based on current technology turboprops produced at the rate of approximately 500 per year. Assuming a substantial market penetration of the GATE engines, these production rates would increase by a factor of 10 to 20, and substantial cost reductions would accrue from the high production rates. The estimated relative price as a function of production rates is shown in Figure 10. The 500 per year starting point is representative of current turbine production rates, and the step change at 2000 per year assumes the new fabrication technology would be implemented at this point. The slope of the curve is based on a 90 percent improvement curve for the number of units produced in one year. As the yearly production rate increases, an additional cost reduction is expected due to increased automation. This improvement curve is estimated to be 80 percent, i.e., doubling the production rate reduces the price to 80 percent of the initial value. The final price equation is expressed as follows:

$$C_x = \frac{C_i\ K_1\ K_2}{(R_x/R_i)^b}$$

Where: C_X = price at X units per year

C_i = price at i units per year

K_1 = ratio of "retail" or "list" price to OEM (Original Equipment Manufacturer) price

K_2 = fabrication technology factor

R_i = rate (units per year) corresponding to the price Ci

R_x = rate (units per year) corresponding to the price Cx

b = exponent based on the slope of the improvement curve

For the dual improvement curves (90 and 80 percent) the exponent b = 0.474. The factor K_1 has been estimated at 1.5. The value of K_2 is 1.0 for R_x less than 2000 units per year and is estimated to be 0.80 for the reduction gear and air inlet, and 0.60 for the compressor and the turbine sections for R_x greater than 2000 units per year. The composite factor for the engine is 0.833.

3.2 Market Research and Analysis - Beech: Fixed Wing Aircraft

Activities in the market research task were divided into four sub-projects as shown on Figure 11:

- Proper identification of aircraft categories. The criterion was that aircraft mission profiles in each category were closely related, e.g., flight training in Category I. (The categories were discussed in Section 3.1.1).

- Engine-aircraft price relationship analysis. The output of this task was a current market cost per kilowatt (horsepower) for today's engines, and engine price-to-aircraft price relationship in the current market.

- An aircraft price-to-demand relationship analysis. From this, equations relating the current market aircraft volume to aircraft price were developed.

- Historical demand trends for the aircraft categories, extrapolated to 1988.

The output of each project is combined to define a perturbed (GATE-influenced) 1988 market.

3.2.1 Aircraft - Engine Price Relationship Analysis.

The turbine engine initially considered for replacement in each of the defined aircraft categories provided power ratings at cruise equal to those currently in production. The engine cost data previously developed was used to calculate engine price. Since the study utilized historical delivery volume trends spanning 14 years, it includes the effect of changing airframe technology and new models. New models which would be developed in the 1977 and later timeframe would have these effects built into the forecast.

In the engine historical price analysis, only those aircraft manufactured by Cessna, Beech, or Piper were studied because of the accessibility of the engine information. Within each category, the individual aircraft engine power and price were identified, and the corresponding cost per kilowatt (horsepower) and engine percent of aircraft price were calculated. The average values for each Category are shown in Figure 12. A relationship between engine and aircraft price for each of the aircraft categories was constructed by comparing the 24 percent value for turboprop powered Category V aircraft to the 14 percent for reciprocating powered aircraft and adding this 10 percent increment to the historically observed percentages for the other categories.

Engine price to aircraft price percentages were used to derive the maximum acceptable engine price for each aircraft price in each category, with the current size engine used in each aircraft. Combining 1) the cost per kilowatt (horsepower) for equivalent turbine engines for each category, 2) the above engine price to aircraft price relationship, and 3) an aircraft volume to price relationship, the resulting 1988 disturbed market forecast was derived through simple iterations of the equation:

$$PCA = PWR \times \$/PWR \div \text{Aircraft Price}$$

Where: PWR = Kilowatts or Horsepower

PCA = Percent Aircraft Price

This equation was iterated until the PCA was equal to the maximum acceptable value shown in Figure 12, thereby defining the market penetration.

As noted in Section 3.1, this modeling technique used executive judgment on the part of Beech staff, because detail aircraft and engine price analysis would not be available until Task II. It, therefore, remained for Task II to validate the apparently simplistic assumptions that a marketable airplane would result - this later proved to be the case, as described in Section 4.5.2.

3.2.2 Aircraft Price - Demand Approach

Because of overlapping price ranges in Categories I, II, and III (Table I) the three categories were grouped. The result is a more realistic price-demand curve that eliminates the influence of small volume airframe manufacturers and other abnormal perturbations in the historical delivery figures.

Within each of the categories (I-III, IV, V) the aircraft were grouped by price. In the case of categories I-III, the aircraft were grouped into five price ranges starting at $16,000 through $91,000 -- in $15,000 increments. The corresponding 1976 delivery volume for each of these price ranges was determined. For example, the first group consisted of those aircraft priced between $16,000 and $31,000 -- with a combined 1976 delivery volume of 5569 airplanes. These groupings were then modeled from scatter plots and replotted on a price -vs- demand graph as shown in Figures 13 through 15.

3.2.3 Historical Trends

The output from the historical demand analysis included a 1988 undisturbed (no GATE turbine influence) market forecast, derived from a straight line extrapolation of the historical trends in delivery volumes for each category of aircraft. Typical values are shown in Figures 16 through 19. In each case, extrapolations were computer-modeled from 5, 10, and 15 year historical data to evaluate the effects of national economy trends. As typical examples, the figures show that the 1966-68 timeframe represented high sales volumes, whereas sales in 1970-72 (a time of recession) were low. Incorporation or exclusion of these cyclic trends resulted in large changes in the 1988 end-point of the projection. The 1988 undisturbed market projections are also shown in Figures 16 through 19. Based on prior GAMA and Beech estimates, the 10 year values were selected as most valid for Categories IV and V. However, the growth in Categories I through III (single engine aircraft is expected to exceed the 10 year extrapolation as shown in Figure 16. The second output from the historical demand trends was a perturbed forecast of 1988 delivery volumes for each category, as influenced by the 1988 introduction of a low cost turbine powerplant suitable for each of the aircraft categories. This perturbed forecast is discussed further in the next section.

3.2.4 Price-Demand Analysis

A simple undisturbed forecast of 1988 deliveries of Category I aircraft is 3100 units (Table VIII). It was deemed that penetration of this market by turbine powered aircraft would be minimal, since most of the activities of these aircraft are flight instruction. This conclusion was drawn on the basis of the low sophistication level of the aircraft, and more so on the expectation that turbine prices in this market (power levels of 74.6 kW 3100 hp) could not result in a sufficiently low aircraft price, relative to current $3-4000 reciprocating engines. Both production rate and power level militate against the turbine. Thus, the forecast for Category I turboprop deliveries in 1988 is zero. Some subjective number could be added to this, based on the assumption that some minimal level of primary flight instruction may be performed in a turbine aircraft.

In the same table, the undisturbed 1988 forecast for Category II is 12,000 units. Given this demand quantity in 1988, the forecast equivalent turbine powerplant cost per kilowatt (horsepower) becomes low enough that all 12,000 units could be theoretically converted to turbine power. It was judged; however, that regardless of the economic feasibility, customer acceptance levels would restrict the demand for a Category II turboprop in the 1988-93 timeframe. Thus only 80 percent of the 12,000 units forecast for 1988 were projected, by marketing judgment, to be turbine powered. The Category II 1988 forecast becomes 2400 piston powered aircraft and 9600 turboprop powered aircraft.

Because of the engine similarities in Categories III and IV, demand iterations for these aircraft were done with combined delivery volumes. As in Category II, the cost per kilowatt becomes low enough, given the combined volumes of Categories III and IV, to allow total conversion of the Category III aircraft to turbine power. As in Category II, it was felt, however, that market conditions would restrict the conversion to only 80 percent turboprop. Thus, the forecast calls for 1100 piston powered aircraft and 4400 turbine powered airplanes. These were later subdivided into Category IIIU and IIIP types, as previously noted, and as shown in Table I.

In Category V, where there are already turbine powered aircraft, total conversion becomes economically and acceptance-wise possible, and demand expands based upon the lower engine prices. Total demand in 1988 for Category V calls for no piston powered aircraft and 3000 turboprops.

The industry growth trends, with and without GATE power influences, are summarized in Table VIII. Overall, General Aviation is projected to grow at a simple annual rate of 4.6 percent. This rate falls into the "conservative, but probable" region of various industry projections.

Summarizing, without any introduction of a low cost turbine, the forecast is for a total of 21,350 piston and 990 turboprops. Given a lower cost GATE turbine, this forecast becomes 7240 piston powered aircraft in 1988 and 19,570 turbines.

3.3 Market Analysis - Bell: Rotary Wing Aircraft

The market analysis for the rotary wing aircraft (helicopters) indicated that gaps in terms of productivity and price exist in the currently available products. These gaps could be effectively filled by new designs using either GATE engines or derivatives featuring GATE technology levels. The engine requirements are summarized in Figure 20; the power requirements of 261 + 56 kW (350 + 75 shp) fits within the GATE band. The engine performance levels such as fuel consumption, weights, and TBO (time between overhaul) can be satisfied by both uncooled and recently developed high technology air cooled turbine engine designs. This technology span is represented by the older T63 and the more recently developed T700 turboshaft engines (Reference, JANE'S ALL THE WORLD'S AIRCRAFT 1977-78). The most challenging requirement for a new generation of small turbine engines (GATE power class) is the initial cost bogie of $20,000 to $35,000. One additional highly desirable feature is that the engine have the torque-stall characteristics of a free turbine powerplant.

Three different light helicopters: a single engine, twin engine and a tri-pac are envisioned, each using the same engine. The projected market is summarized in Table IX; 2750 helicopters requiring a total of 4150 OEM (original equipment manufacturer) engines over a 5 year time span. The potential missions for this line of three helicopters include training, search and rescue, agriculture and others, as summarized in Table X.

The aircraft (helicopter) capabilities and selling prices are summarized in Table XI. The single engine helicopter has 3 seats, a useful load of 545 kg (1200 lbs), gross weight of 1271 kg (2800 lbs), range 334 kM (180 nm) at a cruising speed of 46.3 M/s (90 knots). The selling price is estimated to be $100,000 to 125,000 (1977 dollars).

The twin engine helicopter has 5 seats, a useful load of 976 kg (2150 lbs), gross weight of 1952 kg (4300 lbs), range 834 kM (450 nm) at a cruising speed of 72 M/s (140 knots). The selling price is estimted to be $300,000 to 500,000 (1977 dollars).

The trip-pac (three engine) helicopter has 8 seats, a useful load of 1657 kg (3650 lbs), gross weight of 3337 kg (7350 lbs), range 1019 kM (550 nm) at a cruising speed of 77.2 M/s (150 knots). The selling price is estimated to be $700,000 to 1,000,000 (1977 dollars). The range in selling price for each of the three helicopters reflects the variations in equipment and modification for the different missions summarized in Table X.

3.4 Alternate Cycles - Identifying Domains of Engine Superiority

The objective of this sub-task was to compare 1988 capabilities and requirements for power plants of various types, and to determine the regimes in which each would play a significant role in the marketplace. In order to accomplish the task within the scope of the GATE study, published design data were researched, and various extra sources were contacted (References 1 through 4). Subsequent to completion of the task, reference 5 became available - it quantifies the other opinions on competing powerplants.

The only precise method of comparing the resulting broad range of powerplant capabilities would be to predict the actual performance of the engines installed in GATE-type aircraft in 1988 - this would require detailed engine and aircraft design and performance analysis. Since this depth of analysis is beyond the scope of this study, a relative value comparison, as shown in Table XII, was prepared from the literature research on engine information.

As shown in the table, the reciprocating spark ignition engine was chosen as baseline, and was assumed to be 10 percent improved in fuel consumption, (primarily due to the anticipated emissions-driven pressure for lean burn combustion). Additionally, a very conservative assumption was made that no increment of production price will be necessary to enable the spark ignition engine to meet the EPA emission targets. (Reference 2 indicates that a 15 percent price increase could result).

As can be seen from the table, the gas turbine is superior to all other powerplants in power-to-weight and power-to-frontal area, as well as TBO (Time Between Overhaul) - the diesel is superior in fuel consumption. Comparisons were drawn from the assessment data in Reference 1, and combined with experience-based evaluations.

The literature research, especially References 1, 2, 3, and 4, indicated that there do not appear to be any breakthroughs on the horizon for reduction of cooling or weight for the diesel or rotary engines; consultation with Beech indicated that current cooling losses could be as much as 8-10 percent of aircraft drag. This penalty would have to be levied against the diesel, rotary, or advanced reciprocating engines' test cell fuel consumption for comparison of aircraft performance with a GATE-derived turbine. References 2 and 4 indicate that future reciprocating engine developments will move in the direction of leaner fuel air ratios, hence increased cooling loads on the system; when this trend is combined with expected requirements for reduced weight, the ability to achieve time between overhaul (TBO) greater than the current 1200-2000 hours will be in question. The 373-597 kW (500-800 hp) gas turbine engine has a proven ability for at least 3500 hours TBO as described in the open literature; the Task III engine studies showed that this TBO is also achievable with Advanced Technology GATE engines. The high risk of adapting a diesel for aircraft purposes would appear to indicate that company capital requirements for either development or production tooling raise serious questions about the diesel's ability to penetrate the marketplace; government support could alter this assessment. In the case of the rotary engine in the USA, there is no sales or service base in existence for aircraft, hence substantial funding would be required to support the new, unfamiliar powerplant - this could require a timeframe longer than the 10-12 years predicted for the more familiar turbine, hence would raise serious business questions to the developing company.

It was concluded that the basic competition in the 1988 marketplace will be between the gas turbine and the reciprocating spark ignition engine. Primary reasons are that the risks of application and long term for a return on investment of the other two types of powerplants are expected to be too high to warrant the investment capital; this would appear to be especially true when compared to the current established status and projected improvements of the gas turbine and spark ignition reciprocating engines. Because of the private nature of such business assessments, no public projections of these considerations are known to be available.

Again, subsequent to completion of this task, withdrawal of EPA emissions regulations for the GATE fleet suggest that the costly development for lean burn combustion, or for sophisticated fuel injection and control systems may be delayed or canceled. The expected, but unquantified durability consequences (Refs. 2 and 4) of reduced fuel-air ratio in the reciprocating engine could lead to sustaining the current "burn rich for cooling" flying operations.

3.5 Noise and Emissions Regulations

Projection of noise and emissions regulations was recognized as potentially being both a major propulsion system driver, and a very speculative exercise. United States and international environmental legal restrictions are more subject to political than engineering extrapolations over the ten year period.

To bring some order to the projection of emissions criteria, references 1 through 4 and 6 through 10 were reviewed; the data are summarized in Table XIII which compares the EPA 1979 standards for the LTO (landing/take off) cycle for the three categories of powerplants within the GATE purview. For comparison, the QCGAT objectives are listed. In general, it can be seen the current production engines exceed the standards. Future engines, be they reciprocating spark ignition or gas turbine, are expected to fall within at least the EPA 1979 standards.

As indicated in reference 2, extra componentry and control elements will probably have to be added to the reciprocating engine to account for emissions control. When combined with development requirements to move in the direction of lean burn for emissions reduction, a substantial delay could be incurred in the piston engine fleet meeting the standards. Increases of engine price are also probable. On the other hand, the rapid progress made in the reduction of gas turbine emissions, as exemplified in references 6, 9, and 10, would indicate that a smaller impact on the complexity and sales price of gas turbines could be expected.

This qualitative review can be summarized as:

1. Any of the proposed powerplants can (or could) meet the 1979 standards, given enough capital for development investment and enough time, but with possible consequent operational penalties. (e.g., In the case of the reciprocating spark ignition engine, increased maintenance due to injection and retardation controls, or cylinder overheat.)

2. The GATE Task II engine design studies can incorporate some of the advances made in the larger turbine engine demonstration vehicles funded by NASA and other sources - where "large" engine in this context also includes the QCGAT at 7.12 - 17.79 kN (1600 to 4000 lbs.) thrust.

3. The current reciprocating engine fleet is a mature set of engines, based on large capital investments and production tooling. The GATE gas turbine engine would begin from a clean sheet of paper; it would of necessity include significant new manufacturing methodology to achieve the projected price targets. Therefore, beginning from the research base now available in gas turbines, a speculative opinion is offered that if the standards were tightened for 1988, the GATE gas turbine could more easily meet them, thereby enhancing its market.

In mid-September, 1977, the above analysis became moot, in view of the EPA announcement postponing (indefinitely) the imposition of the 1979 LTO cycle requirements; it was stated that the primary reason was the minuscule benefit-to-cost value of the standards to the national environment.

A similar approach was taken to the comparative analysis of noise requirements. References 7, 8, and 10 were reviewed and the existing General Aviation fleet data summarized as shown in Figure 21. The noise levels presented are for the American General Aviation Fleet, and are based on a 305 M (1000 feet) fly over measurement, corrected for rate of climb, as indicated in FAR 36. Also shown are four levels of regulation - existing FAR 36/ICAO; a projected agreement for 1980, a draft FAA NPRM and an EPA suggestion for the 1980-1985 period.

The data for the current fleet indicate that differences from the 1980 FAR requirement are small, hence it is conceivable that this regulation could be met with straightforward engineering development. However, should the EPA suggestion for 1980 become law, a major crisis would exist in General Aviation.

In summary, the conclusions as to noise regulations show that:

1. Potential rule making varies over a 10 db. range in the area of interest for GATE.

2. This large variation could of itself drive the definition of a propulsion system. The analogy is to congressional mandates on the automobile industry which forced catalytic converters into automobiles, even though better long range solutions might have existed. Specifically, lower noise could, in general, require lower tip speed propellers, which would require higher ratio gear boxes, increased landing gear length, and outboard engine placement in twins. Each of these factors has an impact on the design, cost, stability, and safety of GATE-type aircraft. The smaller nacelle diameter and ease of gear ratio design favor turbine power. In the turbofan propulsion system, high levels of attenuation would be necessary in entrance and exhaust ducts, accompanied by internal design changes for aerodynamic noise reduction; these could have a serious impact on small engine design performance and cost. Nevertheless, the advantage could still be with turbine power, if reciprocating engine performance is seriously degraded by muffling and gearbox weight.

3. Should the lowest limits be imposed, the impact on aircraft and engine design could substantially increase the cost of GATE aircraft, and inhibit sales. A dialogue similar to that between the automobile manufacturers and Congress/EPA could be expected.

4. In the case of the commercial airline fleet, prior NASA studies have utilized a percent Return On Investment (ROI) or Direct Operating Cost (DOC) change versus change of perceived noise; the GATE market does not respond to these factors, as shown in Section 4.7. Most airplanes are not bought as investments (except for the corporate aircraft), and direct operating cost is not a primary sales feature. Therefore, excessive initial purchase price increases could decrease market demand in the non-business portion of the market, e.g., Categories II, IIIU, IIIP and parts of IV.

5. During Task II, engine detail design allows the development of more specific data on the noise issue; the study plan incorporates such potential noise reducing features as the Hamilton Standard Q Fan(tm) and 33.3 rev/s (2000 RPM) turboprop gearboxes.

3.6 Market Forecast - Task I (Summation of Findings)

As previously noted in Section 3.1.1, the missions for each category were iterated in Task II; it was discovered that the initial assumed range and velocity improvements projected for 1988 resulted in both excessive power demands and oversize aircraft in some categories. New information on pressurized aircraft also indicated the need for iteration. Table XIV summarizes the final (post Task II) 1988 market projections. An assumption has been made that the 1988 date represents a mature sales market. This is recognized as being somewhat optimistic; therefore, the data more accurately represent a 1988-1995 time period. It can be seen that a potential exists for upwards of 31,000 engines per year, which represents a $220,000,000 annual turbine engine market. This is OEM value including spares at the OEM value and based on the recommended common core design discussed in Section 5. The helicopter market is a small percentage of the total and the assumption is that one manufacturer (Table XIV) will capture all this market.

Under the assumption of a 50 percent market penetration by a single company, over 16,000 engines would be sold, thus justifying the assumptions made in the engine price predictions.

Two factors arise from the summary forecast. First, no penetration was possible into Category I, the simplest aircraft, due to a 15 percent aircraft cost increase. On the other end of the spectrum, in Category V, the 1081 kW (1450 hp) engine size, i.e., 559 kW (750 hp) flat rated to cruise altitude, is outside the scope of GATE. Therefore, it was concluded that the GATE area of interest covers the 197-422 kW (265-565 hp) range of engines, and that a large market potential exists.

Figure 22 summarizes the desirable engine features or factors which drive the engine design in Task II. These features, especially the SFC (equal to piston engine), high power to weight and zero cooling drag, lead to an expectation of Task II aircraft designs which are substantially improved over 1976 General Aviation aircraft - due to GATE baseline power on its own merits. The multi-fuel capability has both competitive and national energy conservation implications, owing to the ability of the turbine engine to adapt to a variety of fuel types; the reciprocating engine is dependent on high octane aviation gasoline which may be in very restricted supply by 1988.

Figure 23 summarizes the accessories desired for the GATE-type engine, accommodating both helicopter and fixed wing aircraft. Preliminary investigation of the effect of environmental control requirements on turboprop engine performance indicated the desirability of a gearbox which could accept an optional or plug-in auxiliary compressor for pressurization. Other accessory requirements were conventional

Figure 24 describes the GATE interface considerations. In the fixed-wing aircraft, the most important effect on the assumed single shaft (connected) turboprop was the need for a variable pitch propeller, to accommodate negative thrust on approach. In the rotary wing case, the need for free turbine torque characteristics was strongly stated by Bell, and resulted in several Task II design evaluations.

Figure 25 draws together the conclusions from the market analysis. It is recognized that some of the specific modeling techniques used to define the engine price and the market elasticity relationship could be questioned as to absolute validity. The primary challenge for the rest of the study was to address the engine rate/price/market circular argument; to do this, turbine engine designs must be produced in Task II which reflect the engine price "bogies" shown on Figure 26.

SECTION 4.0

TASK II: TRADE-OFF STUDIES

The Task II Study Plan for engine-aircraft trade-offs is shown in Figure 27. The input from Task I, by Market segments, defines the general objectives to be accomplished.

Initially, parametric studies were run for each aircraft category, at varying temperatures and pressure ratios for all engines, and varying bypass ratios for the turbofans, all using the Teledyne CAE assessment of the 1985 component state-of-the-art. The results of these parametric studies defined areas of concentration to be addressed in the conceptual engine layouts.

These layouts incorporated inputs from the TCAE component and configuration data bank, large engine and other recommended technologies, and sub-contractor inputs such as the Hamilton Standard Q-fan(tm), advanced propellers, and fuel controls. These engine layouts were then iterated with cost and performance analyses, using in-house manufacturing and vendor data bank projections as criteria.

In parallel with the engine studies, Beech Aircraft provided conceptual aircraft layouts and their evaluation, as well as parametric performance analyses around the point designs, using baseline engines. Trade-offs were accomplished with the competitive engine layouts using the aircraft sensitivity calculations to assess cost, performance, and take-off gross weight deviations from the baseline.

From the aircraft-engine synthesis information, Life Cycle Cost Analysis was accomplished, and an optimum engine selected for each category of aircraft.

The task output covers power and SFC -vs- cost trades, a description of the optimum engines and their requisite features to meet the challenges laid down by Task I, the aircraft layouts and their performance/cost assessment, an analysis of the benefits of the improved aircraft compared to the current General Aviation fleet, an assessment of the applicability of various technologies and their worth to the GATE concept, and finally the systems cost analysis and environmental impact.

4.1 Parametric Performance Analysis

A parametric cycle analysis of turboprops, turbofans and turboshaft is the starting point to determine the "optimum" engine configuration(s) for the GATE missions. This analysis included the effect of reducing component efficiencies in the small (GATE) flow sizes, turbine cooling, and cycle pressure ratio.

4.1.1 Baseline Analysis

Parametric performance was calculated for turboprop, turboshaft, and turbofan configurations, using projected levels of efficiency capability for the 1988 time frame.

The analysis was accomplished for three mission conditions: helicopter - sea level 56.6 m/sec (110 KTAS): Category II and IIIU (Unpressurized) - 3048 m (10,000 ft) and 92.6 m/sec (180 knots); and Category IIIP and IV - 5486 m (18,000 ft) and 123.5 m/sec (240 KTAS). In the latter two cases, an average mission was used, because there was insufficient spread of the velocity and altitude conditions to make separate analyses worthwhile. Table XV provides the matrix of efficiency assumptions used in this parametric analysis, and in the determination of sensitivity values of, for example, power and SFC to component efficiency levels. The sensitivity values are desirable to allow later iterations of performance with the effect of selected component configurations. These initial calculations are purely parametric, to outline trends.

Conventionally, this type of analysis is done by assuming constant efficiency levels, then varying the major cycle parameters such as pressure ratio and temperature at the critical mission point (assumed to be cruise, in this study). Optima are then deduced from the shape of the curves; sensitivity values are calculated for small changes to the input efficiency assumptions, and priority design drivers are determined from the results.

During the time frame of the parametric analysis, the parallel component evaluations (described in Section 4.3) were producing results which indicated that the efficiency levels of components in the small airflow category of the GATE problem statement would not be constant across the range of pressure ratios indicated in Table XV. Therefore, the analysis was repeated at key conditions with the analytically determined variable efficiencies of Sections 4.3.1 and 4.3.3 using sensitivity values determined from the data output of Table XV. The results are shown in Figure 28 for the Category IIIP and IV mission statement, and in Figure 29 for the helicopter mission statement. They show a trend of decreasing specific power with increasing pressure ratio, and an optimum, or minimum SFC at a specific pressure ratio. SFC is seen to be relatively constant (plus or minus 1 percent over a substantial pressure ratio range). This latter trend leads to the ability to meet low SFC requirements with a number of component arrangements, as discussed in Section 4.4. In each case, it is evident that the analytical or "real" efficiencies tend to reduce the level of optimum pressure ratio from the 15 to 20 range to the 9 to 12 range.

4.1.2 Sensitivity Studies

In order to help determine where priority attention must be paid in the engine component choice and design assessment, sensitivity analyses were run at two different flight conditions, one for Category IV and one for the helicopter, as indicated in Figure 30. The sensitivity coefficients show the percent change of specific fuel consumption per percent change of compressor and turbine efficiencies, versus pressure ratio. The curves show that the turbine overall efficiency has a higher impact on engine performance than does compressor efficiency. However, both are important, in that they are above 1.0, i.e., more than 1 percent change of fuel consumption per percent change of either component efficiency. The figure also shows that both the lower altitude mission (helicopter engine) and the higher pressure ratio cycles are more sensitive to changes in efficiency. These sensitivity coefficients aid in determining priorities for choice of component arrangements in detail engine design

4.1.3 Cooling Effects

It is commonly accepted that increasing turbine inlet temperature is beneficial to most gas turbine cycles; in the case of the turboprop cycle it is especially beneficial. Therefore, considerable attention was paid to methods of achieving higher turbine inlet temperatures than are currently operational. Because of Teledyne CAE's considerable experience in the cooling of very small turbines with blade spans between 6.35 and 12.7 mm (0.25 and 0.5 inches) (Reference 11) and the low efficiency test results of that experience, the input assumptions used for the high temperature analysis were carefully evaluated.

These assumptions are summarized in Figure 31 as an effect on turbine efficiency and the cooling bypass bleed required by increasing turbine inlet temperature. Figure 31 shows that if an all-axial turbine had been assumed for the design, the low aspect ratio and thick blade shape problems (resulting from the difficulty of cooling small blades) would reduce turbine efficiency capability by 6 to 8 percent below design requirements and the parametric data assumptions. This same figure also shows that if the radial portion of a radial-axial configuration were to be cooled, an efficiency loss of between 1 percent at maximum temperature ratings of 1421 degrees K (2100 degrees F) and 5 percent at 1643 degrees K (2500 degrees F) would be incurred. The component analyses showed that the axial element of a radial-axial turbine complement would not have to be cooled, because of the large temperature drop through the radial turbine (see Section 4.3.3). The study baseline rotor is radial, and is uncooled to a takeoff turbine inlet temperature level of 1504 degrees K (2250 degrees F).

The right hand side of Figure 31 indicates the equivalent radial turbine bypass bleed as a function of temperature and cycle pressure ratio. The baseline value for a high tip speed (uncooled rotor) radial inflow turbine, is 2 percent of compressor exit bleed required to cool the turbine inlet nozzle and the shrouds. Most of this flow is recovered for use, in the rotor, hence does not represent a large cycle loss. It is known from design experience that heat flux and Nusselt number both increase as the turbine pressure level is increased; thus, higher levels of cooling bleed are required for the 20:1 cycle than for the 9:1 pressure ratio cycle. It is evident that an important input to a GATE engine design is the ability to attain an uncooled radial inflow turbine rotor at temperature levels as high as possible, providing zero reduction of turbine aerodynamic efficiency, and a requirement for approximately 2 percent bypass bleed (at the 9:1 pressure ratio).

Figure 32 shows the resulting effect of increased turbine inlet temperature on specific horsepower and specific fuel consumption, as temperatue is raised at the Category IIIP/IV flight condition of 123 M/s (240 KTAS) at 5486 m (18000 ft). Preliminary engine and aircraft matching analysis had indicated that an approximate difference of 167 degrees K (300 degrees F) exists between the cruise inlet temperature and the maximum thermodynamic power turbine inlet temperature for this mission (see also Section 4.2).

Performance is shown for the upper and lower limits of cycle pressure ratio 9:1 and 20:1. At the 9:1 cycle pressure ratio, two levels of bleed ("optimistic" and "conservative") loss assumptions are shown, to illustrate the range of consequences of cooling the small 1.19 kg/s (2.6 lb/sec) flow rotor, if required. Table XVI illustrates the losses used for the analysis; the values range above and below those shown on Figure 31; the "conservative" values represent upper limits, based on previous Teledyne CAE design experience and materials. The power (Figure 32) is seen to increase substantially with cruise inlet temperature. Cooling effects are shown to represent a minimum of 3 and a maximum of 10 percent increase in equivalent specific fuel consumption, hence an objective of the GATE engine design is to minimize these losses.

4.1.4 Turbofan Performance Evaluation

The matrix of data assumptions used to do the turbofan parametric analysis is shown in Table XVII. Efficiency assumptions are consistent with advanced technology GATE levels used throughout the study. The calculation was made at Category IV flight conditions because these offer the best specific fuel consumption opportunity within the Category II - IV range for a turbofan application. If the analysis had indicated a turbofan to be superior at these conditions, additional calculations would have been made at the lower flight speeds and altitudes. The performance resulting from these parametric assumptions is summarized in Figure 33 as specific fuel consumption -vs- bypass ratio for a range of core pressure ratio and temperature assumptions. In each case, fan pressure ratio was optimized for the cycle, thus the solid and dashed curves represent a range of turbofan SFC capability for the core technology levels assumed in Table XVII. It is seen that the thrust specific fuel consumption of the turbofan is 20 to 30 percent higher than the previously calculated range of turboprop specific fuel consumption.

In order to offer the most optimistic comparison of the turbofan and the turboprop, the design duct Mach number was reviewed in an attempt to reduce the fan duct loss for the loss-sensitive high bypass ratio cycle. The casing of the assumed typical Category IV turbofan was increased by 43.2 mm (1.7 inches) (approximately 10 percent of baseline engine diameter) and the losses recalculated at a bypass ratio of 8. The duct loss was reduced from 4 to 2 percent; the result was still an 18 percent increase of specific fuel consumption over the turboprop.

It was therefore concluded that on a specific fuel consumption basis alone, the turbofan was not competitive; the configuration is not excluded from further consideration, depending on the final study results and the applicability of GATE power to the market categories. A turbofan could well be considered as a fall-out derivative of a successful GATE turboprop engine, for special markets requiring either higher speed than was assumed in Category IV, or a more attractive aircraft configuration.

4.1.5 Parametric Performance Analysis Conclusions

The parametric cycle analysis led to the following observations:

1. A turbofan is not competitive (on an SFC basis only) in Categories II -

IV. A derivative of a successful turboprop could provide a special market for a high performance airplane.

2. Turbine cooling is high risk in this size of powerplant, and offers a very limited payoff. Teledyne CAE foresees no breakthroughs in the industry ability to achieve a small cooled axial flow turbine under 1.3 kg/s (3 lb/sec.) with a suitable efficiency. Manufacturing techniques, thin-wall materials property degradations, and heat transfer limitations all militate against an effective design. Additionally, the expected production price of a small cooled turbine would run counter to a major requirement of this study - the need to approach reciprocating engine prices. This would be especially true in comparison to the uncooled radial turbine at 1504 degrees K (2250 degrees F) take-off temperature.

3. High pressure ratio cycles are more sensitive to flowpath efficiency and are prone to flange leakage.

4. High temperature cycles are less sensitive to flowpath efficiency.

5. Design-derived (real) efficiencies estimated for GATE-type components decrease optimum pressure ratio for minimum specific fuel consumption.

Therefore, the optimum GATE engine should have a medium pressure ratio (range of 9-12) and the maximum allowable uncooled take-off temperature: 1420-1504 degrees K (2100-2250 degrees F).

4.2 Sample Engine Performance Studies

A computerized turboprop engine performance model was constructed to allow additional evaluation of component design priorities (matching, surge margin, definition of ratings) and better integration with ongoing Beech aircraft design studies.

The model was constructed for a 9:1 pressure ratio cycle (C9 configuration) connected shaft turboprop (Ref. Section 3.1.2). Maps for the compressor and turbine were synthesized from available Teledyne CAE and open literature data.

Prior to calculating wide-range performance, investigations were conducted to evaluate the effect of turbine back pressure on the engine design and performance. It was hypothesized that an increase of back pressure at the turbine exit would have a small effect on ESFC, but could reduce turbine stresses significantly: at a constant flow and radial turbine exit Mach number, the annulus area will reduce with increasing back pressure. This in turn reduces exducer AN2 (annulus area x square of RPM), which is a direct measure of exducer stress.

Figures 34 and 35 summarize the results of the analysis for Category IV flight conditions and sea level static (SLS) respectively. They verify that the turbine back pressure can be increased beyond conventional practice; as an example, increasing it to 1.25 times ambient, increases specific fuel consumption by only 2 percent. This conclusion holds with the three engine speeds shown on the figure, and over most of the applicable operational power spectrum. A tradeoff therefore exists between specific fuel consumption and either turbine durability (lower specific fuel consumption, higher stress) or between specific fuel consumption and a higher cost turbine configuration (radial plus axial, to maintain suitable stress levels). Subsequent preliminary engine designs assumed the 1.25 x ambient value, to maintain the lowest cost turbine configuration.

The figures also indicate that the falloff of efficiencies resulting from the assumed component characteristics actually results in increased cruise specific fuel consumption above design corrected speed.

Figure 34 shows performance for three engine speeds: 100 percent, 95 percent, and 90 percent of design mechanical RPM rating. At the Category IIIP or IV flight condition, compressor face temperature = 262 degrees K (471.2 degrees R), they correspond to corrected speeds of 104.9, 99.7, and 94.7 percent of design respectively. At a typical cruise condition of 1.068 kN (240 lb) thrust, Table XVIII shows the performance at each of these conditions. The best cruise performance, as to required temperature (durability) and specific fuel consumption is obtained at approximatly 100 percent of design corrected speed. Tc maintain best climb and cruise SFC, it was concluded that this particular configuration should be controlled to operate at constant mechanical speed at inlet temperatures over 288.5 degrees K (60 degrees F), and constant corrected speed at inlet temperatures below this value. A 2.3 percent maximum thrust reduction is implied by this rating method - from 1.530 to 1.495 kN (344 to 336 lb) at 1504 degrees K (2710 degrees R) on Figure 34, but the 6 percent specific fuel consumption improvement and 38.8 degrees K (70 degrees R) reduced temperature make the trade-off worthwhile. Additionally, the engine would run at less than 100 percent mechanical design speed at all inlet conditions less than standard day, with a consequent durability improvement relative to a constant RPM engine.

Detail performance calculations were then completed at a jet nozzle area of .01129 m (17.5 square inches), representing a judgement compromise. Subsequent studies should further evaluate this rating method as a means to optimum component design. The rating method also affects engine installation features:

1. Excessive jet velocity due to a high pressure ratio could cause taxi area erosion in a single engine aircraft if the exhaust is under the aircraft nose.

2. The effect of rating method on the match of the connected shaft engine in taxi or acceleration mode might be significant. It is desired to warm up and taxi at minimum propeller speed for noise and erosion attenuation, yet to have the instantaneous prop response of the connected shaft engine. This requires the ability to decrease engine RPM to 60-70 percent of design, without encountering surge - a difficult task for a connected shaft engine.

The engine performance was calculated for a nominal 1.19 kg/s (2.62 lb/sec) corrected design flow (approximate match of anticipated Category IV aircraft point design horsepower) over the range of flight conditions. Typical equivalent specific fuel consumption and thrust data -vs- power level are shown in Figure 36 for the Category IV cruise and maximum altitude conditions (solid and dashed lines respectively). For subsequent scaling of the configuration to a specific aircraft design (Section 4.5), a maximum cruise rating scaling point (circle) was chosen at 1328 degrees K (2390 degrees R) as a balance between weight, durability and SFC.

The analysis also showed that an initial assumption - that cabin pressurization air if bled from compressor discharge pressure (CDP) - resulted in 6-9 percent power and SFC loss, due to the small airflow of the engine. It was therefore decided that all accessory power would be taken from the gearbox, including a mechanically-driven compressor. This reduced the pressurization SFC loss to between 2 to 3 percent.

The studies thus provided background data for the operation of a typical advanced technology GATE engine as an aid to outline both a need and a direction for future, in-depth, evaluations.

4.3 Component Analysis

This section describes the development of candidate component data for input to the trade-off studies to define an optimum engine type for each of the market segments identified in Task I. The rationale for development of the component data is as follows:

1. The maximum performance potential of compressor types know to be applicable to the GATE market was determined. By experience, it is known that centrifugal and axial-centrifugal compressors suit the 0.454-1.361 kg/s (1-3 lb/sec) market place, and that all-axial compressors do not. For this reason, single centrifugal, twin centrifugal, and axial-centrifugal combinations (from one to three axials) were chosen, and their limits and domains of superiority identified.

2. The impact of these compressor configurations on engine aero/mechanical design and structural integrity was assessed to determine best choices for detail engine incorporation.

3. Four configurations were chosen as representing the required trade-off potential. One of each of the configurations was selected: single centrifugal, one axial plus 1 centrifugal, 3 axials plus 1 centrifugal, and 2 centrifugals, covering the pressure ratio range from 9 through 20 (as determined from the parametric cycle analysis above).

4. The turbine requirements, their temperature capability and their performance potential, were evaluated in reference to the speed and pressure ratio determined from the compressor study. Both radial and radial-axial combinations, for connected shaft and free turbine configurations, were evaluated.

5. A short combustor evaluation was conducted to determine whether the combustor was a critical component, or could be drawn from ongoing technology programs.

4.3.1 Compressor Component Studies

A series of nine typical compressors, covering the range of pressure ratio from 9 through 20, all applicable to small engines, was analyzed as summarized in Table XIX.

Each of the configurations was evaluated using standard design techniques, plus efficiency algorithms. For the axial compressor, the model included single and multi-stage aerodynamic and tip speed loading effects, as well as size effects; centrifugal configuration analysis included specific speed, backward curvature, pre-whirl factors and size effects.

The algorithms were then used to extend the parametric analysis to define envelopes of maximum efficiency -vs- pressure ratio for each type of configuration, thereby determining domains of component and configuration superiority. In each case, usable (operating line) efficiency was assessed.

Figure 37 presents the results, in terms of compressor polytropic efficiency -vs- pressure ratio, for various configurations of compressor, to allow comparison with:

- o Existing state-of-the-art of small compressors, compiled from Teledyne CAE and open literature data.
- o The large engine state-of-the-art, compiled from open literature data and recent NASA-sponsored compressor studies on the 198X energy efficient, all-axial transport engine.

This figure verifies the general curvature and level of the assessment derived from the algorithms.

From this matrix of compressor designs, four were chosen for preliminary engine designs as representative of applicable trade-off data. The four compressors are described in Figures 38 through 41. Figure 38 shows a 9:1 pressure ratio single stage centrifugal, the simplest configuration. For maximum flexibility of match (See Section 5.0), variable inlet guide vanes are included. The radial diffuser is configured for maximum diffusion efficiency of the supersonic inlet Mach number. A separable inducer is shown as one method of efficiently handling the transonic tip Mach number resulting from the design.

Figure 39 shows an axial-centrifugal design at 11.3:1 pressure ratio. The stage pressure ratio split was chosen from the design algorithms for each element to maximize overall efficiency. The small size (flow) effect has been taken into account for the axial stage, at 82.2 percent adiabatic efficiency. A transition duct is incorporated, both to eliminate inducer vibratory effects from the stator wake, and to allow a sufficiently low inducer hub-tip radius ratio for maximum centrifugal stage performance.

Figure 40 shows a three-axial, one centrifugal design, at 15.0:1 pressure ratio. The design philosophy is an extension of the approach for the 11.3:1 pressure ratio configuration. Of particular significance is the blade height in the third stage axial, which is only 10.2 mm (0.4 inches) at the 1.19 kg/s (2.62 lb/s) flow size - at the lower level of manufacturing feasibility.

Figure 41 shows the two stage centrifugal design, at 19.9:1 pressure ratio.

Each stage is optimized for efficiency. Significant results evident from the design are the diameter - greatest of all the configurations, the "swan's neck" transition duct, and the very narrow (2.51 mm/0.099 inch) second stage diffuser width.

The compressor study showed that the GATE compressor design challenge is approximately plus 2 points in compressor efficiency. The program plan described in Section 6 addresses this need via:

1. In general, better clearance control, using improved deflected housing design techniques, and improved abradable coatings.

2. Improved design system - a better understanding of secondary and leakage flows in both types of compressors is required.

3. In the axial case, more effort is required to define the efficiency capabilities of low aspect ratio, highly loaded, configurations.

4. In the centrifugal, an intensive effort is required to develop better knowledge of the transonic inducer.

5. Again in the centrifugal unit, backward curvature must be extended to the 9-10 pressure ratio regime (this will not only increase efficiency level, due to reduced Mach number, but also tend to move the efficiency islands away from surge, into the usable match regime).

6. The advanced GATE engine design does not restrict radial diffuser depth, hence limits of diffusion may be relaxed.

To meet GATE performance and stability needs, the compressor effort outlines a research challenge and a path to meeting that challenge.

4.3.2 Combustor

A reverse flow, vaporizer-plate combustor was chosen as baseline, based on the promise shown by the configuration in current TCAE programs for reduced cost and reduced emissions potential, at excellent performance. A typical configuration is illustrated in Figure 42. It is a conventional reverse flow design, with a unique fuel injection scheme. A cylindrical annulus is used as an aid to spreading fuel from discrete injection points. Heat transfer across the vaporizing plate is used to pre-vaporize the fuel, which is then injected into the primary combustion zone via the turning action of the end cup.

A performance analysis was performed for the 11.3, 15, and 20:1 pressure ratio engine designs at a cruise condition. The results were based on preliminary engine layout combustion volumes, and indicated that all intensity, dwell time and loadings factors were within current design practice. This is the expected outcome of the choice of compressor pressure ratio and diffuser depth.

This conservatism is evidenced by the summary performance shown in Figure 43. A conventional plot of efficiency -vs- aerodynamic loading is shown, with successful rig and engine data points superimposed. It is seen that both starting and steady state aerodynamic loadings are lower than previously demonstrated rig and engine data.

It is therefore concluded that the combustor is not a critical research challenge or limit to GATE progress. A well-structured but straightforward development program is expected to provide the required performance, durability, and gradients.

4.3.3 Turbine Component Design

Prior studies have indicated that engine cost, and as an input to it, maximum allowable uncooled temperature, are major drivers in the applicability of GATE turboprop engines. For these reasons, it was assumed that the simplest uncooled turbine configuration would best suit GATE engine design features.

Teledyne CAE has prior experience in high tip speed, high pressure ratio, radial inflow turbines on small engines. This experience was at a 609.6 M/s (2000 feet per second) tip speed and 1227 degrees K (1750 degrees F) maximum turbine inlet temperature, on a 89.5 kW (120 hp) turbogenerator set development for Ft. Belvoir-Mobility Equipment Research & Development Center. This experience, combined with the recent work of two recognized authorities in the field of radial turbomachinery, O.E. Balje and H.J. Wood (references 12 and 13) indicated that considerable advancement in this technology could be predicated, given a suitable research and exploratory development program, and the availability of modern high strength material. The high tip speed of these designs results in turbine rotor tip and wheel relative metal temperatures within acceptable levels for uncooled operation.

This capability, combined with the results of the parametric performance analysis shown in Section 4.1, showed the single stage radial turbine to offer the simplest configuration, with a substantial SFC benefit over an air cooled axial turbine arrangement. Tradeoff studies shown below and in Section 5.0 verify the initial analysis.

A radial inflow turbine, running at tip speeds greater than 701 m/s (2300 ft/sec), and thereby capable of running uncooled at temperature levels up at 1532 degrees K (2300 degrees F) is a prime candidate for baseline engine design studies, Figure 44. The turbine aerodynamic and structural evaluation studies therefore proceed from this assumption as follows.

The turbine design requirements are established by the compressor component study results. These results establish the turbine work load and speed. Available computer programs were used to define the preliminary design of turbine configurations suitable for driving the four candidate compressor designs described in the previous section. Figures 45 through 48 describe the connected shaft turbine configurations.

The analysis showed that the 9:1 pressure ratio centrifugal configuration, C-9 could be driven by a single radial inflow turbine running at 759 m/s (2490 ft/sec) tip speed. At this tip speed, the blade metal relative temperature at the rotor tip was approximately 1258 degrees K (1806 degrees F), hence the rotor could be run at 1504 degrees K (2250 degrees F) uncooled, assuming advanced materials. The other designs required either one or two axial stages in addition to the highly loaded radial stage. Preliminary velocity triangle analysis showed rotor design exit relative velocity to be near transonic (M-0.9) at the mean diameter. This level leads to the assumption that some aerodynamic rig work is required in the follow-on program.

Initially, an arbitrary work distribution was assigned to the radial and axial components; it resulted in an assessment of efficiency potential for all configurations, at the 1.19 kg/s (2.6 lb/sec) size, of 88 ∓ 0.5 percent. However, this arbitrary work distribution resulted in a significant difference in temperature capability of the various designs; it was determined that the lower tip speed of the radial turbines for the AC11.3, AAAC15, and CC20 configurations would result in a reduction of approximately 67-78 degrees K (120-140 degrees F), in maximum rated (thermodynamic) temperature capability. This degrades the performance of these engines, primarily in specific power (hence in size), but only slightly in specific fuel consumption.

In Task III, a re-evaluation was conducted of the turbine aerodynamic testing. The work was redistributed to increase the loading on the radial component, and decrease loading on the axial component. It was found that the efficiency was reduced by only 0.2 points, but the temperature capability <u>increased</u> back to the original 1504 degrees K (2250 degrees F) baseline. Detail calculations showed that as the work load and tip speed were raised on the radial element (to reduce the blade relative temperature at a given turbine gas temperature), the specific speed, which are basic measures of efficiency, remained almost constant. The axial turbine became slightly smaller (i.e., lower wheel speed, hence lower work capacity) than the configurations shown on the preceeding figures, but without efficiency change.

In hindsight, it was concluded that the AC11.3 engine could have been rated at a substantially higher specific power and a slightly reduced specific fuel consumption, thereby providing a smaller, lighter engine at a reduced cost. These results were incorporated into the Task III common core evaluation, but are not included in the engine design and life cycle cost analysis described below.

Parallel studies were performed for a free turbine version of the AC11.3 engine, as summarized in Figure 49. In this case, it was concluded that the reduced work load on the radial turbine component (which now drives only the gas generator compressor), did result in a reduction in temperature capability of over 92 degrees K (165 degrees F). This would provide a free turbine variant of the turboprop concept, but at a lower power capacity and slightly higher SFC level. The temperature-tip speed trade-off study was also conducted for this configuration during Task III. It indicated that at the fixed level of turbine work, a reduced temperature capacity would result as the tip speed was arbitrarily increased in an attempt to reduce blade relative temperature. Efficiency would also fall off due to the bad mismatch of increased turbine Parsons number (U/C_o = tip speed/isentropic "spouting" velocity) and increased specific diameter, Figure 50. The isentropic spouting velocity is defined as:

$$C_o = 2gJ_c \sqrt{H_{is}}$$

Where: g = Gravitational Constant
J_c = Joules Constant
H_{is} = Isentropic Enthalphy Drop

4.4 Engine Configuration Layouts

The component characteristics from Section 4.3 were combined into outline layouts and performance evaluations of each of the types of the engines - at a constant airflow. The resulting power output therefore represented the effect of component efficiency, pressure ratio choice, and temperature capability on the configuration and its ability to produce high specific power or low fuel consumption (SFC).

To establish a common baseline, each of the outline layouts was adjusted to a constant Category IV power for subsequent scaling to each market category. In parallel with the outline layouts, scaling limits and size effects were determined for each of the component configurations. These effects were used to modify power, SFC, weight, and cost for the lower power levels of Categories II and III.

4.4.1 Performance Analysis

The component assessments of Section 4.3 were integrated into a series of computer calculations to determine the cruise and sea level static (SLS) maximum thermodynamic performance of the four engines at a constant 1.19 kg/s (2.62 lb/sec) flow, which was baseline for scaling studies to match anticipated aircraft designs. The element input data is summarized in Table XX. The data represents the results of the component studies of the previous sections; an increase of 1 percent in propeller efficiency was assumed, as a result of discussions with Hamilton Standard on future propeller development trends. The cruise performance is summarized in Table XXI for the four engine configurations being used to illustrate engine design tradeoff potential relative to aircraft performance. The AC11.3 configuration is seen to offer 2-7 percent lower SFC than the other models, and the C9 up to 35 percent higher specific power than the other models. These differences are significant in relation to anticipated effects on the aircraft designs. The performance points were then run at SLS conditions at the turbine inlet temperatures corresponding to maximum rating determined by the initial tradeoff studies. The results are presented in Table XXII. These estimates were compared to lapse rates for existing, larger engines, and found to be representative.

A baseline set of performance data was thus established for each of the four configurations, at a constant design airflow. This allowed scaling of each engine to a constant power - for comparative sizing, and to a match power for each aircraft design (Section 4.6).

The components for each engine were then re-analyzed to establish performance degradation guidelines in scaling from the baseline size to power levels as low as one-half of design.

In the compressor cases, the design algorithm on size effects was utilized, with results as shown on Figure 51 (left panel). Two conditions were evaluated: constant absolute clearance (solid line) and constant percent clearance (clearance/height constant, dash line). The results, as expected, showed a sensitivity of each design to increased clearance and reduced size. Axial elements increase this sensitivity, to the point where manufacturing limits prohibit a scale of the AAAC15 configuration below 1.04 Kg/S or .00116 m (2.3 lb/sec., or 0.4 inch) blade height by judgment.

The right hand panel shows similar effects for the radial turbine, but at slightly lower degradation levels.

The engine performance assessments were modified, using these effects, as the aircraft engine match power levels were determined.

4.4.2 Mechanical Design and Cost Analysis

Schematic layouts were prepared for the four candidate engines discussed in the performance analysis section, as illustrated in Figure 52. They are sized for the same power output - 365.5 kW (490 hp) at sea level static rating. Design numbers 2010, 3010, 4010, and 5010 are assigned to each configuration as an aid in tabulating subsequent data. These numbers are representative of an engine configuration and are retained when the engines are scaled to different sizes.

A complete engine cross section for the 2010 design (Figure 53) was prepared and a detail weight analysis made. The other engine weights were calculated using this for a base, and modified to reflect the effects of the different flow path geometries.

The turboprop installation drawing is shown in Figure 54 and the basic scaling data shown in Table XXIII. Two sets of data are presented, one at equal power and the other at equal airflow. The flowpaths were originally sized for equal air flows, and subsequently scaled to a constant power. The reduction gear sizing was maintained constant for the 365.5 kW (490 hp) size in both cases.

The simple cantilevered rotor suspension of design 2010 is dependent upon being able to achieve adequate critical speed margins. A critical speed analysis was performed and the results summarized in Table XXIV. The estimated shaft support stiffnesses, both front and rear, of 175 mm/m (106 lb/in) uses the combined bearing and housing spring rates, and results in adequate critical speed margins. The second critical speed, 1530 rev/s (91084 RPM) provides 30 percent margin over the maximum rotor speed of 1148 rev/s (68,900 RPM) and the first critical speed, 217 rev/s (13024 RPM) occurs more than 60 percent below the engine idle speed of 804 rev/s (48230 RPM).

The ability of the radial turbine rotor to operate uncooled at high turbine inlet temperatures is an important factor in achieving good performance and low cost. Arnold and Balje (Reference 12) discuss the temperature and expansion ratio potential for uncooled radial turbines in the range of the GATE design 2010. A preliminary analysis of the turbine design was performed to verify that the rotor is a worthy candidate for engine development. The results of the analysis are summarized in Figure 55. Two different blade area taper ratios (ATR) were drawn to confirm that the geometries were attainable. The stress rupture life at the cruise rating was bracketed between 3000 and 10,000 plus hours for the ATR range of 16 to 31. The stress rupture life at the maximum temperature and maximum minus 28 degrees K (50 degrees F) provides a reasonable starting point for a detailed design. Two aspects that can further improve the rotor life are the maximum temperature rating and improved material properties. The aircraft operating characterisitcs result in essentially a flat rated engine and will not require the indicated high temperatures at take-off. Therefore, the desired maximum temperature will be established by a function of maximum altitude capability versus the cruise altitude and the desired maximum to cruise power ratio. A detailed analysis of this was beyond the scope of this study. The life analysis was based on current, well-characterized equiaxed IN-100 to give a high confidence level to the results; improvements such as directional solidification, advanced materials, and fabrication methods will further enhance the material capability, and increase the integrity of the design. Several advanced materials were screened for the application, and reserved for detail evaluation of cost-yield-strength tradeoff in Task I of the follow-on program (Section 5.0).

The relative cost summary for the four basic engine designs is summarized in Table XXV, and OEM (Original Equipment Manufacturer) cost in Table XXVI. Figure 56 summarizes the effect of increasing cycle pressure on engine cost and engine power to weight ratio. The increased cycle pressure ratio provides a modest reduction in fuel consumption when the component efficiencies are adjusted to reflect the small sizes, as discussed in Section 4.4.1. The higher cycle pressure ratios require more components, with a resulting increase in relative cost. The four basic engine designs, shown in Figure 56, require an increase in the number of turbine stages, from one to three, as the CPR (Cycle Pressure Ratio) increases from eight to twenty. The bottom line of the vertical band represents the minimum number of compressor stages to achieve the CPR - one centrifugal for 9:1, and two centrifugals for 20:1. The top line represents a parallel band drawn through the 4010 design which has three axials plus one centrifugal compressor. The decreasing power to weight with increasing CPR is shown for three engine power sizes ranging from 365.5 kW (490 hp) to 186.5 kW (250 hp). This band is based on scaling the engine configurations using the basic size data and scaling exponents from Table XXIII.

4.4.3 Alternate Configurations

Two different propulsion configurations were evaluated to meet the special GATE problems imposed by potential low noise requirements and helicopter applications.

Low Noise Requirements: The Hamilton Standard Division of United Technologies provided preliminary design information on the potential integration of the Q-FAN(tm) with GATE technology. If the installed fuel consumption of the high bypass, variable pitch fan were to prove competitive, the low noise signal of the unit would provide a desirable powerplant. The design is summarized in Table XXVII. The configuration is compact, but the cowl drag results in an unacceptable installed fuel consumption at flight speeds of over 77.2 m/s (150 knots). This information was verified by Beech, who had conducted a more thorough study in 1975, and arrived at the same conclusion. This is further substantiated by the Metzger and Worobel (Reference 14) study of Q-FAN(tm) propulsion systems; they show that a 289 kW (387 hp) core engine is required to meet the cruise thrust of a conventional propeller engine with a 213 kW (285 hp) reciprocating engine.

It was, therefore, concluded that unless noise becomes an overriding consideration, the Q-FAN (tm) is not a GATE candidate. Even then, a more detailed comparison with the quieter GATE fleet using a 33 rev/s (2000 RPM) propeller would be necessary.

Differential Turbine: Bell Helicopter Textron reflected the strong feelings of the United States helicopter industry against any form of connected shaft engine (with a clutch to the main rotor): the torque characteristics are unsuitable, a fixed shaft installation requires a higher power than a free turbine, and even then the engine can surge when high cyclic pitch is demanded.

Different engine configurations were reviewed, using the basic fixed wing GATE simplicity and low cost to respond to this need - even though the helicopter represents only 5% of the total market. A differential turbine engine was chosen as a potential candidate. The power characteristics of this type engine are shown in Figure 57. It operates as a connected shaft engine to the right of the lockup line; to the left of this line the ORC (overrunning clutch) in the output drive train allows the turbine to slow down and run at a differential speed to the compressor. Differential gearing divides the torque between compressor, turbine and output as prescribed by the design ratios. During operation with the engine at part power and initially in the lockup region, when the cyclic pitch is increased, the ORC releases and the engine moves nearly vertically along the output speed line, and crosses the "lockup" line to provide increased power in a regime where a connected shaft engine would surge.

Schematic layout designs for a differential turboprop (Figure 58) and a differential turboshaft (Figure 59) illustrate the basic concept, size, and weight for a power output of 365.5 kW (490 hp). They use the design 2010 (C9) compressor, combustor, and turbine. The turbine drives through the compressor bore to a differential gearset that drives the power output shaft and the centrifugal compressor.

The relative cost (for equal weight) of the differential turboprop and turboshaft compared to the baseline, is summarized in Table XXVIII. The significant parameters; cost, weight, and SFC are compared in Table XXVIX. The differential turbine designs are significantly heavier and more expensive than the single shaft turboprop. The increased fuel consumption is due to the increased gear loss to drive the compressor. The cost and weight penalties of the differential design lead to the conclusion that it is not a GATE fixed wing aircraft turboprop candidate.

The cost and performance applicability of single shaft, differential and free turbines to the fixed and rotary wing missions are again reviewed in Task III. Section 5.2 concludes that a free turbine derivative engine using GATE technology is the recommended approach for the rotary wing application. Section 5.3 presents the engine cost and concludes that the free turbine turboprop is too expensive for the General Aviation fleet.

4.5 Fixed Wing Aircraft Point Design and Parametric Analysis

Beech Aircraft developed airplane concepts that could use GATE-type engines during Task II. The airplane synthesis exercise provided the sizes of engines to concentrate on, and what their benefits would be in terms of airplane design. This was done for three of the airplane categories defined in Task I; Category III was divided into pressurized and unpressurized sub-categories. A pressurized airplane in this class was not in the historical data used in Task I, but it is a type expected to be common by the mid-1980's. Categories used in Task II were:

II - Single engine 4-place non-pressurized utility airplane

IIIU - Single engine 5-6 place non-pressurized utility airplane

IIIP - Single engine 5-6 place pressurized utility airplane

IV - Twin engine 6-place pressurized light executive transport

4.5.1 Computerized Point Design Analysis

The main tool used in synthesizing airplane concepts to fit these categories was a Beech in-house computer program designed to match mission requirements and airplane characteristics.

Data inputs to the program included flight performance requirements (cruise speed, take-off distance, landing distance, payload and range), aerodynamic parameters (drag and lift data), engine characteristics, empirical weight coefficients and empirical landing and take-off factors, as shown in Table XXX. The program iterates the airplane size parameters of power, take-off weight, fuel weight, and wing area (wing loading) until the five above-mentioned performance requirements are met. The final size parameters are the program output.

An allowance is made in the fuel calculations for one hour cruise to cover reserve, take-off, and climb requirements, per prior Beech design experience. An allowance is also made for the installed engine weight. This engine weight includes the engine dry weight, controls, exhaust pipe, oil system with cooler, fuel system, propeller and starter generator. Cruise fuel calculations are made at a weight reduced from the take-off weight by a value based on past experience. To maintain a safe aircraft design, landing weight is taken to be equal to take-off weight in this program. The mission is assumed, in each case, to be takeoff at maximum gross weight, climb to cruise altitude, cruise to maximum range, and land. Tradeoffs between reduced passenger and fuel load -vs- extended range or increased speed would be evaluated in any follow-on program, to illustrate market features of this tradeoff. The calculations, however, were made at maximum takeoff weight to illustrate the substantial payoff of GATE turboprop technology at the most adverse mission profile (some current General Aviation aircraft cannot fly quoted range or cruise speed with both maximum payload and a full fuel load).

Drag calculations include profile drag, induced drag, and propeller slipstream drag. The values of induced (wing efficiency factor) and slipstream drag are inputs: profile drag is calculated in the program, using input values of skin friction coefficients, fuselage equivalent flat plate areas, landing gear equivalent flat plate areas, and other factors.

Lift coefficient values are somewhat higher than most of today's production airplanes, but are consistent with modern airfoils without unusually complex flap systems (a safety concern for the skill of most pilots in Categories II, IIIU and IIIP). Values of lift coefficient were adapted from other Beech proprietary advanced airplane studies.

Baseline engine data were supplied by Teledyne CAE for the C9 engine (Model 2010).

Airplane and engine characterisitcs shown in Table XXX were eventually selected as likely for each category in the mid-1980's for GATE engined airplanes. These data were run in the aircraft synthesis program, with the results shown in Table XXXI. Compared to current aircraft in each category, the point designs fall in the upper range of gross weight, consistent with their advanced performance capabilities. Because each category represents a range of marketable aircraft (consistent with the current scenario), it would be expected that availability of GATE engines would also result in a range of derivative aircraft designs of greater and lesser gross weight.

Table XXXI also validates the observation of Task I, that the GATE engines will be flat-rated. Because the engines are sized for power at cruise, the takeoff power required is seen to vary from 88 percent (Category II) to 55 percent (Category IIIP and IV) of maximum sea level takeoff thermodynamic power available. This will ensure engine design margin for both hot day takeoff and structural integrity and durability, because none of the engines will have to operate at maximum turbine entry temperature for any significant portion of its life.

The weight calculation equation is based on empirical factors and exponents for turboprop airplanes. Weight output from the program was further analyzed to get a more detailed indication of gross weight and installed engine weight.

The program was run a number of times to provide airplane design sensitivity information for Teledyne CAE to use in engine size and characteristic tradeoffs, leading to optimum engine selection. Typical output data for Category IIIP, are shown in Figures 60 through 65.

These results were used by Beech designers as a basis for airplane layouts; the three-views shown in Figures 66 through 69 resulted. The engine's small size is made apparent in the single engine airplanes by the rather narrow, pointed nose. Inlet and exhaust pipe sizes are small and unobtrusive. Small engine size is made more apparent by the very small nacelles in the twin engine airplane front view.

A final synthesis was undertaken to relate the (assumed) conservative aircraft improvements to maximum potential aircraft improvements, and the consequent effect on the engine requirements. In Category IIIP, a 15 percent (additional) cruise drag improvement was assumed, representative of maximum cleanup of the airframe. Payload, range, cruise speed, and takeoff/landing distance were held constant. Results included a 7 percent reduction of takeoff power required, and a 17 percent reduction of cruise horsepower from 214 to 177 kW (287 to 237 hp); TOGW was reduced 7 percent and empty weight 8 percent. Most important, an additional 17 percent reduction of fuel usage was calculated. While these results are deemed achievable, no cost analysis was performed to estimate the manufacturing system changes required to achieve the low-drag airframe.

4.5.2 Aircraft Price Analyses

First order approximations of average equipped airframe retail sales price were made for the final four GATE airplane configurations. They include the total airframe, the engine mounts, and propellers and average avionics equipment (a value which can range widely) but does not include engine price. These prices were based on internal preliminary estimating methods used at Beech, and on the rate results of the Task I market survey. The market survey provided an indication of the number of units over which development costs could be amortized. Pricing policies vary greatly from company to company in the General Aviation industry, hence the methods used in setting prices are highly proprietary. The retail prices shown in Table XXXII are probably conservative by industry standards.

Changes in equipped airframe retail price per pound of gross weight change are also tabulated in Table XXXII, to use with the parametric trend curves plotted from results of the airplane synthesis program. These values are based on airframe and propeller costs only, i.e., without avionics, engines or interior features. This provided a means of changing the price with changes in engine weight or SFC, at a constant mission for comparison of various engine types.

The prices shown are representative of the airplane types shown in the conceptual design sketches. In Category II, the design concept chosen for the illustration and price estimate corresponds to the most complex airplane in that category. A lightweight, fixed gear airplane in this size range would have a lower price.

The market survey of Task I was based on historical data that did not include a pressurized airplane in Category III. The first piston engined airplane of this type has recently appeared on the market. It will probably be a common type by the mid-80's. This type airplane can be expected to absorb some sales from the light twin market, as well as generate new sales. With this in mind, the original projected annual sales figure from the market survey for Category IV was consequently reduced from 4400 to 3500 for price estimating purposes.

4.5.3 Noise Analyses

Noise for the GATE-engined airplanes was estimated using an in-house Beech proprietary program for the criteria from FAR 36, Appendix F. A propeller speed of 33.3 RPS (2000 RPM) was used with the 2.03 m (80 inches) to 2.11 m (83 inches) diameters shown on the aircraft three views. Propeller noise was assumed to be dominant; because of the low jet velocities of the turboprop, and the buried inlet, no special account was taken of the noise increment added by the engine; this calculation would be addressed in a follow-on program. The results, shown on Figure 70, show that the GATE-powered aircraft will improve the General Aviation fleet noise picture, and are within 1.6 db (worst case, Category IIIP) of the most severe EPA 1985 criteria.

4.6 Engine - Aircraft Synthesis

The previous section described the integration of the four point design aircraft with the baseline C9 (Model 2010) turboprop engine. As a further step toward definition of the optimum engine for each of the aircraft categories, it was necessary to evaluate the effect on aircraft design and performance of installing each of the other three candidate engines.

To accomplish this task, the aircraft parametric analyses were reviewed and the data found to be reasonably linear (Reference Figures 60 through 65) in the area of the design point. It was therefore assumed that the relatively minor impact of the engine differences on the overall aircraft design could be addressed in a linearized perturbation analysis. The influence coefficients for this analysis are summarized in Table XXXIII.

It is evident that increasing mission requirements from Category II through Category IV result in increased sensitivity of the aircraft design to the engine characteristics. Increased engine weight was treated in the analysis as if it were an increase of aircraft payload. The baseline estimated engine performance characteristics at the several mission points were presented in

Section 4.4.1. Figure 71 presents the engine weight and price by configuration and production rate respectively, versus sea level maximum thermodynamic power. Sea level maximum thermodynamic power was used as a convenience for comparison to conventional turbine engine technology, since it is a more consistent measure of engine capacity than cruise power at varying altitudes and flight speeds.

An iteration procedure was then used to determine the effect of substituting any of the three alternative engines into the baseline aircraft. Baseline data were perturbed by the increments of engine weight and changes of SFC shown in Figure 71 and Table XXI respectively using the influence coefficients noted above. A net change of takeoff gross weight was calculated from the sum of these two effects, and a revised cruise power determined from the influence coefficients. This led to a revised value of thermodynamic maximum power at sea level, which in turn leads to a new cruise power, and engine weight increment. Engine SFC was adjusted for size effects. The calculation was iterated until it closed upon a final answer of cruise power, from which the other characteristics were determined.

Typical examples of the iterations for the effect of different engines on the Category II, IIIP and IV aircraft are shown in Table XXXIV. Three different engine configurations for each category are shown; the baseline C9 engine is representative of the Task I data furnished to Beech for the baseline aircraft studies. The adjusted C9 data represents an update of the engine performance during Task II, and the AC11.3 perturbations are shown as indicative of the effect of a substantially different engine cycle. The payload, range, cruise speed and cruise altitude were held constant.

The baseline Category II aircraft gross weight was 1313 kg (2894 lbs). With the adjusted C9 engine, the gross weight increased by 2 kg (5 lbs), the fuel weight increased 1 kg (2 lbs) and the aircraft retail price increased $100 from $62,500 to $62,600. These changes were due to an increase in fuel consumption from 82.4 to 82.8 ug/J (0.488 to 0.490 lbs/hr/ehp). Installing the AC11.3 with a lower fuel consumption of 77.7 ug/J (0.460 lb/hr/ehp) reduced the aircraft gross weight by 17 kg (36 lbs), although the engine weight increased by 5 kg (11 lbs), and the fuel weight was reduced by 11 kg (24 lbs). However, the more expensive engine (AC11.3) increased the aircraft cost $2100, or 3.4 percent, from from $62,500 to $64,600.

The calculation was repeated for each of the engines as applicable, and as modified by the scale-down factors previously discussed in Section 4.3.

At the other end of the spectrum, in Category IV, the baseline gross weight was 3127 kg (6894 lbs). The baseline C9 engine required a cruise rating of 215 kW (288 hp); with the AC11.3 configuration, gross weight was reduced by 324 kg (714 lbs) (primarily due to the greater impact of the 9.5 percent SFC improvement over the longer range). In this case, the sales price was reduced, from $233,300 for the baseline C9-powered aircraft to $210,800 for the AC11.3-powered aircraft.

Following completion of the calculations, a survey indicated that the baseline aircraft gross weight was not varied through the iteration procedure by more than 11 percent in any case. Because of engine price changes (Figure

71) and aircraft price changes due to changes in empty weight, a maximum price change of only 15 percent was noted, validating the linearized perturbation analysis. This was accommodated in the life cycle cost analysis described in Section 4.7. The results of the engine-aircraft syntheses are summarized in Table XXXIV for the lowest sales price combinations, in terms of incremental aircraft gross weight, fuel load, and power required at the cruise condition. The calculations were limited to 3 categories because they illustrate all of the principles involved in the synthesis (Category IIIU is sufficiently similar in mission and other characteristics that it would not add any value pertinent to the objectives of the analysis).

The life cycle cost implications of these analyses are described in Section 4.7.

4.7 L^2C^2 Analysis - For Selection of Optimum Engines

A limited life cycle cost (L^2C^2) analysis was performed to develop criteria by which optimum engines could be chosen. In conventional military practice, where the aircraft fleet owner is predetermined, a 20 or 25-year life cycle cost calculation can be made with assurance. In the case of GATE aircraft, however, consultations with Beech Aircraft indicated that the lower gross weight aircraft represented by the GATE market - 907 to 3175 kg (2000 to 7000 lb) TOGW - are normally non-revenue producing aircraft, purchased in a manner very similar to a car, and held for usually not more than five years, followed by resale.

For these reasons, it was determined that the life cycle cost analysis would be limited to 5 years, and the acquisition cost approached as a conventionally financed purchase. Figure 72 summarizes the major features of the L^2C^2 model and the data sources. Table XXXV summarizes the input parameters used for the model, derived for the most part by Beech Market Research.

Figure 73 depicts the parametric variables used to evaluate the effect of variable flight time and TBO on the life cycle cost. Again, consulting Beech Market Research indicated that there is no fixed average mission for any of the aircraft in this category; rather a baseline can be assumed, but it is known that various owners will fly the aircraft at widely varying utilization rates per year. Therefore flying hours were also approached parametrically, as were potential fuel costs during the coming decade.

The results of model calculations for Category II are depicted in Figure 74 for each of the candidate engines (the AAAC-15 engine could not be scaled to the cruise power requirement of Category II as described in Section 4.3.1). It is seen that the nominal 5-year Life Cycle Cost of the aircraft is in the order of $140,000. The CC-20 configuration results in the highest life cycle cost value, but not substantially over the other engine configurations; nevertheless, the basic purchase price of this aircraft would be $10,400 greater than the aircraft powered by the simpler C9 engine, which would mitigate against a market for this design.

The AC11.3 engine is seen to offer a life cycle cost close to the C9 configuration, primarily due to the reduced aircraft price (because of its reduced duced SFC) compensating for the increased engine price. However, when the size effects presented in Section 4.3 are applied to engine performance and included in the life cycle cost analysis, and the effect on SFC and weight calculated, a measurable increase of cost is noted above the C9 configuration

Therefore, the C9 engine, the simplest and lowest cost configuration, is most applicable to the Category II aircraft. Because of some doubt on the validity of the 15 percent resale value assumed in the original model, a separate calculation was performed for a 30 percent resale value; it was later determined to be more realistic. The result reduced the life cycle cost by some 7 percent, but does not change the resulting engine choice.

Figure 75 illustrates a corresponding calculation for the Category IV aircraft. In this case, all four engine configurations are applicable, and a nominal life cycle cost over a 5-year period is $380,000. The AC11.3 configuration is seen to be optimum, with the C9 close behind; the other two configurations are not marketable, especially when acquisition price differences are considered.

Variations in the life cycle cost with fuel price and flying hours were also calculated; Figure 76 presents the information for the Category II aircraft, and indicates a 39 percent increase of cost as the price of fuel increases from the current level of approximately 18.5 cents per liter (70 cents per gal.) to a potential 53 cents per liter ($2 per gal.) level in the late 1980's. Similar data are presented for Category IV aircraft on Figure 77; a 36 percent life cycle cost increase is indicated for the baseline flying hours per year, for the same increase in fuel costs. The percentage change shown for the calculation would not differ significantly for the AC11.3 engine.

The L^2C^2 analysis, therefore, eliminated the AAAC-15 and CC-20 configurations from contention. Figures 74 and 75 also show that acquisition cost is, as expected, a major market driver, consisting of between 60 and 75 percent of Life Cycle Cost for the owner. At current prices, fuel represents only 15 percent of the life cycle cost; however, as fuel prices increase per national expectations, fuel could become as much as a 34 percent factor in General Aviation. This places a large emphasis on the need for development of GATE turboprop technology - both to make available the multi-fuel capability of the engine (to compensate for the expected unavailability of 100 octane aviation gasoline), and to reduce SFC levels below current turboprops, to conserve petroleum.

4.8 GATE Point design Aircraft with Reciprocating Power

To obtain an indication of the GATE engine benefits, and to separate the aircraft improvements from those due solely to the engine, estimates were made for Categories II and IV (lowest and highest TOGW) of the GATE airplanes with typical piston engines. Two comparison studies were made: First, for constant aircraft size but variable performance; second, for constant aircraft performance, but allowing aircraft size to vary for the design with reciprocating engines.

Tables XXXVI and XXXVII show the results when the airplane size is held constant for Categories II and IV, and the mission is allowed to vary, using equal cruise power for both engine types. The numbers in the left column in each chart are the same as in the GATE-derived designs of Tables XXX and XXXI. The right column shows values for a piston engine version of the airplane. Changes and percentage changes are shown in the center.

The following assumptions were made for this comparison:

- The take-off weight was held constant.
- The empty weight was increased by the amount of the increased installed engine weight.
- The fuel plus passenger load was decreased by the amount of the increased installed engine weight.
- One-half the empty weight increase was taken from payload.*
- One-half the empty weight increase was taken from fuel.*
- Cooling drag was added. This was 10 percent as a representative value.
- For the twin, drag was also increased by 7 percent to allow for larger nacelles. No drag addition was made for the single, because of the nose location - this is an assumption which decreases the advantages apparent to the GATE turboprop.
- Reciprocating engine SFC and weight characteristics were taken from 1977 manufacturer's data, due to the uncertainty of projecting potential advances in SFC, power/weight and the consequent engine price increases. Reference 5 offers an opinion on these factors.
- Takeoff distance of 2,000 feet or less is judged adequate.

* These values were judged worthy of comparison by Beech, since there is no clear figure of merit for the aircraft types under consideration. Other assumptions could have been used, but would not have changed the main thrust of the conclusion as to superiority of GATE engines.

The added weight of the reciprocating engine is seen to reduce range substantially (26-34 percent), and cruise speed only slightly (3-6 percent). Takeoff and landing distances were found to be equivalent.

Another way of comparing GATE and piston-engined airplanes is to hold the mission requirements of speed, range and payload, and let the airplane grow as a result of using an assumed piston engine. The results of this estimate for Categories II and IV are shown in Tables XXXVIII and XXXIX. Take-off distance was allowed to change in this simplified calculation. The engine power requirement increased because of: higher weight and increased drag caused by engine cooling, the larger wing and, for the twin, larger nacelles. Fuel required goes up in proportion to the power increase. For the Category II single engine airplane, the cooling drag was estimated to require 8 percent more power, and the larger wing, an additional 4 percent power. Corresponding figures for the Category IV twin are 9 percent and 6 percent. Additionally, the twin required 5 percent more power because of the increased nacelle profile drag. Each of these factors is compounded from the assumption of equal mission requirements - the added weight and drag of the reciprocating engine results in considerably higher power requirements, which drive the results of the design.

Therefore, with a constant size airplane, the GATE powered versions show 26-34 percent more range, 3-6 percent more speed, and 14-22 percent more payload. When the airplanes are compared on the basis of a constant mission (Table XL) the GATE powered versions show a reduction in takeoff gross weight (TOGW) of 12 to 20 percent, a reduction of empty weight (which is proportional to airframe price) of 18 to 25 percent, a reduction of cruise power from 12 to 20 percent and a reduction of fuel required of 12 to 20 percent. The takeoff distance for Category II shows a reduction of 13 percent, however, in Category IV, the takeoff distance is increased 22 percent which is considered quite acceptable. The method is a simplified approach, using one set of assumptions for a complex comparison problem. This type of comparison could be done with other, more comprehensive methods; the approach indicates definite and large advantages for the GATE type engine. These values were converted to dollar increments using the same model, as shown on Figure 78. The increment is seen to be a 13 percent improvement for Category II aircraft, and a 20 percent improvement of life cycle cost for the Category IV aircraft.

4.9 Technology Applicability and Worth

The objective of this sub-task was to identify large engine and other technologies applicable to GATE powerplants, and to assess their value to the program. Throughout this study, minimum price has been demonstrated as a major output need of the study. Three sources of price reduction in the 1988 timeframe have been identified:

- o advanced performance technology (more performance per pound of simplified components)
- o substantially increased production rates
- o improved manufacturing techniques on specific components

This section focuses primarily on materials and manufacturing techniques which support the feasibility of achieving low cost on advanced aerodynamic and high temperature, i.e., high performance components. The technology advancements required in the latter areas was described in Section 4, and is amplified in Section 6.

4.9.1 Technology Identification

Figure 79 summarizes several technologies identified from ongoing NASA or DOD-sponsored efforts, most of which involve engines much larger than the proposed GATE engines. Many are nonetheless applicable, if suitably adapted, to such small sized engines. Other technologies incorporated into this section derive from ongoing proprietary work at Teledyne CAE and in the component fabrication industry. The timeframe of the GATE projections - a readiness to go into full scale engineering development in 1988, i.e., a 6- year lead time, and a 2-4 year lead time on availability of materials for feasibility demonstration, forces a degree of pragmatisim into the projections.

The NASA MATE program is providing substantiation data for new materials techniques, but in a radically different environment and shape than GATE. Therefore, MATE references in the figure imply a similar type of program, rather than a direct technology transfer. From a qualitative point of view, the technologies are described for the C9 engine, but are equally applicable to the AC11.3. They are summarized below:

Turbine Nozzles: High temperature materials, possibly coated with the NASA Yttria-stabilized thermal barrier coating. A slight probability exists for the application of ceramics, either in the total nozzle unit, or as a composite, e.g., trailing edge. In any case, the objective is to provide a high integrity component (including backface shroud) with minimum parasitic cooling, at a low cost. The ceramic rotor blade shroud and thermal barrier coatings effort of MATE could apply directly to the turbine inlet nozzle design for GATE, as a static part. Substantial basic data transfer would be expected.

Rotor: As shown in Section 4.4, an integrally cast wheel appears feasible in a conventional alloy; it could be much enhanced as to thermal fatigue by local (tip) directional solidification. Alternately, new developments in rapid solidification, ultra-fine powder metallurgy manufacture also show promise for increased temperature resistance.

The powder metal disk work under MATE addresses axial flow compressor turbine rotors only. Thus, the integral radial turbine GATE rotor represents a different shape, with varying material strength requirements between the disk portion and the blade tips. Directional solidification techniques which are being developed at Teledyne CAE and throughout the industry for separate axial flow blades would probably be adaptable to the integral blade tips on GATE, but represent a significantly different problem statement and research risk as to represent a new, unproven technology.

Abradable Coatings: The abradable centrifugal compressor shroud coatings on MATE do address an applicable temperature range: 700 degrees K (800 degrees F) - but at far lower tip speeds than the specified 670 m/s (2200 ft/sec); since the abrasion forces are proportional to a power of tip speed, a considerably different environment is imposed by the GATE conditions. A similar comparison could be offered for turbine shroud coatings, where GATE requires a 1365 degree K (2000 degree F) plus capability, and more important, a compatibility with 747 m/s (2450 ft/sec) tip speeds, thus a completely different shape and thermal distortion environment. GATE research effort could thus draw from MATE, but would have to proceed along lines of different coating composition and application technique.

Emissions: It is expected that all of the information generated on emissions reduction research will be applicable.

Noise: Analysis and treatment of noise will parallel the technology transfer for emissions - it is expected to be eminently applicable, from many sources.

Electronic Fuel Control: The full authority electronic fuel control system (i.e., including sensors) will draw heavily from Teledyne CAE's excellent experience on the J402 (HARPOON/VSTT) and Cruise Missile engines, as well as ongoing development for large engines. A major source of the cost technology will be derived from the automotive field, where mass production - at a cost - is known to be committed before 1983. The automobile fuel control will sense and activate engine emissions, fuel-air, temperature, valve and injection modulation mechanisms, as well as other monitor and display functions. The sensors and computational needs are of comparable complexity to an aircraft engine control, hence should form a technology base. Environmental, redundancy and FAA certification requirements will probably result in design changes, but the capability and worth will be proven by analogy.

Gears: The baseline approach to gearbox cost reduction is selective die casting of housings, with new and novel application of powder metallurgy, near-shape gears. The necessary research proof will be to demonstrate the structural integrity of the gears under turboprop and helicopter loads and environments, which are more highly loaded than currently proven similar powder parts.

Shaft: Pitch and yaw rates on General Aviation engines are not excessive, but could result in a requirement for either very stiff (large diameter) shafts or increased rotor clearances to accommodate gyroscopic forces. This would drive the design toward advanced technology bearings or lube systems. An alternative is the high stiffness-low density TiBorSic composite shaft shown on Figure 4.9-1, which allows bearing DN reduction without compromising the set-up rotor clearances. The high modulus-to-density value of the material will allow the simple, minimum heat rejection shaft system (Figure 79) and offer weight benefits as well.

Other material technologies were assessed, and judged not to be in the stipulated timeframe for a commercial engine. For example, titanium aluminide, carbon/carbon composites, ceramic (turbine) rotors and unlubricated bearing systems are known to represent benefits to gas turbine engines; Teledyne CAE has been involved with each in military engine research, and foresees a long-term applicability to GATE-type engines, if they are rigorously pursued.

Therefore, the recommended adaptations and innovations from the quoted currently active technology baselines were chosen to establish a credible and time-of-arrival consistent input to the Task IV technology plan.

4.9.2 Technology Worth - Evaluation

Section 3.6 showed that, unless GATE engines could be produced for a price competitive with current reciprocating engines, there would be very limited, if any, market penetration. Section 4.6 presented the engine price data, and validated the Task I market scenario. The technology advancements (as differentiated from production rate-derived price improvements) were identified in Sections 3 and 4.4.1.

To place a value on these technologies, the L C model was exercised with results as shown in Figure 80. Perturbing the model plus or minus 5 percent in SFC and plus or minus 4.55 kg (10 lb) in weight from the baselines of Section 4.7 resulted in an influence coefficient of each parameter on the life cycle cost. In a Category IV aircraft, it was found that 1 percent in SFC was worth $4890 over 5 years, and 0.907 kg (2 lb.) in engine weight was worth $895. The key GATE technology advances were identified in Section 4 (compressor efficiency), Section 4.3.1 (turbine inlet temperature) and Section 4.4.1. Their worth to a Category IV aircraft was assessed relative to a baseline 1977 engine - a hypothetical, same-configuration engine of 9:1 pressure ratio and 1311 degree K (1900 degree F) maximum rated turbine inlet temperature. A $72,510 benefit accures over the 5-year period, compared to using typical 1977 production engine technology.

Similar values were computed for Category II aircraft, with the results summarized on Figure 81 for the average annual savings for the first five mature fleet years. A fleet-wide savings of $342 million per year is estimated by combining the calculations for Categories II and IV and extending them to include Categories IIIU, IIIP, IV and the helicopter fleets. The L C savings, compared to reciprocating engine-powered aircraft, were shown in Figure 78. Thus a successful GATE program would create a market for new products with inherent economy to the owner.

4.10 Task II Conclusions

The preceeding sections lead to the following conclusions:

1. The optimum engines for each aircraft category are:

CATEGORY	CONFIGURATION	SEA LEVEL THERMODYNAMIC MAX. POWER kW (hp)	SFC CRUISE μg/s-lb/hr/lb
II	C9	129.8 (174)	82.8 (0.49)
IIIU	C9 or AC11.3	283.4 (380)	77.7-81.1 (0.46-0.48)
IIIP	AC11.3	417.6 (560)	72.7 (0.43)
IV	AC11.3	395.2 (530)	74.4 (0.44)

2. Market penetration down to Category IIIU is assured. Sales in Category II are highly probable; the point design aircraft (Figure 66) represents the high-priced end of the broad Category II spectrum (Task I market analysis). To expand upon the exact degree of Task II penetration would require additional aircraft designs similar to the types currently being sold in Category II, i.e., of lower sophistication level. Engine price bogies (reference Figure 3.6-6) have been approached, but the wide aircraft price and performance spread in this category do not justify a complete penetration at this level of analysis.

3. The challenge presented to Task III is to define a common core to cover a 2:1 horsepower ratio without excessive performance sacrifice, and with sufficient commonality to the helicopter powerplant to bring its price into an acceptable range (defined by Bell as significantly greater than for the fix-

ed-wing aircraft).

4. The key technologies to be addressed in Task IV are:

- o High temperature - 1504 ± 55 degrees K (2250 ± 100 degrees F) uncooled radial turbine and associated abradable housing coatings.
- o High pressure ratio (6.6-9:1) backward curved centrifugal compressor and associated shroud abradable coatings.
- o A low cost gearbox.
- o A low cost, full authority electronic control system.

5. The benefits of the application of these technologies have been quantified in terms of:

- o More passenger-miles per gallon of fuel.
- o More passenger comfort.
- o Higher flight speed.
- o More useful load per pound of aircraft structure.
- o Lower environmental noise than the current fleet, and, if necessary, reduced emissions levels.

The overall results - more aircraft productivity per dollar, at a lower energy consumption level and with a better environmental compatibility.

SECTION 5.0

TASK III: COMMON CORE CONCEPT EVALUATION

The individual optimum engines are assessed to define the possibility and utility of a common core across the fleet. The performance, cost, benefits, penalties, and an outline of the methodology of up- and down-rating are described.

5.1 Common Core Candidates

The approaches to the common core are a logical fallout from the Task II optimum engine investigation. The C9 and AC11.3 exhibit the lowest cost and good performance levels. The higher pressure ratio configurations, AAAC15 and CC20, did not show a measurable advantage over the two lower pressure ratio configurations, and are not considered viable candidates as a common core. Three basic approaches were evaluated to cover the wide power range (greater than 2:1) required for the general aviation fleet: one frame size plus shaving, two frame sizes plus shaving and a two-frame family, as summarized in Table XL.

<u>One Frame Size plus Shaving</u>: This engine, (Table XL and Figure 82a) has a thermodynamic design and gearbox rating of 365.5 kW (490 hp) and envisions shaving the flowpath to cover the thermodynamic power range from 198 kW (265 hp) to 422 kW (565 hp). The shaving would both increase and decrease the flow channel to cover the full power range. The major penalty of this approach is that the engine weight would remain essentially constant at 93.5 kg (206 lb). This engine weight would disadvantage the smaller aircraft by increasing the gross weight over what would be realized by a lighter engine.

<u>Two Frame Sizes plus Shaving</u>: This approach would add a smaller (down-scaled) engine to complement the larger 93.5 kg (206 lb) frame. This engine would have a thermodynamic design and gearbox rating of 224 kW (300 hp) and would modify the flow channel to span the thermodynamic power range from 198 kW (265 hp) to 280 kW (375 hp). The smaller engine size (Figure 82b) and lower weight of 65.8 kg (145 lb) would provide a more desirable powerplant for the smaller category II and III aircraft. The down-scaled engine would utilize the larger engine technology, however, parts commonality would be insignificant, thereby reducing the cost reduction benefits of high production rates.

<u>Two Frame Family</u>: This approach has the AC11.3 flowpath with a thermodynamic design point of 422 kW (565 hp) and a gearbox rating of 410 kW (550 hp). The basic C9 flowpath engine is derived from the AC11.3 by omitting the axial compressor and turbine, and part of the reduction gearing, to provide a smaller, lighter engine with a thermodynamic rating of 250 kW (335 hp) and a gearbox rating of 205 kW (275 hp). The size and weight of these two engines are shown in Figures 82c and 82d. The differences in the mechanical configurations are illustrated more clearly in Figure 83. The AC11.3 configuration consists of a two stage compressor (axial plus centrifugal), a reverse flow annular combustor and a two stage turbine (radial plus axial). The reduction gear consists of a single stage herringbone mesh followed by a planetary

gearset with two compound idlers. The C9 configuration is achieved by removing the axial compressor and static structure sandwich, the axial flow turbine, one half of the herringbone gearset (resulting in a single stage helical mesh) and one of the compound idlers, providing a smaller lighter engine. The gearbox sizing criterion was established by the Category IIIU take-off power requirement of 205 kW (275 hp), thus the AC11.3 rating was a fallout.

The performance of the two-frame family is summarizad in Table XLI. The baseline AC11.3 configuration has a thermodynamic rating of 422 kW (565 hp) with a specific fuel consumption (SFC) of 78.2 μg/J (0.463 lb/hr-hp). This is a refinement from prior estimates due to the Task III discovery that the turbine inlet temperature could be raised to 1504 degrees K (2250 degrees F).

It was estimated that this engine's centrifugal compressor could be designed to match over a 6.6 to 9:1 pressure ratio range with only a minor (perhaps not any) diffuser change. The estimated performance with the axial compressor and axial turbine removed was 250 kW (335 hp) and an SFC of 87.5 μg/J (0.518 lb/hr-hp) at 1389 degrees K (2040 degrees F) turbine inlet temperature. The temperature resulted from an assumption of no nozzle area change between the two engines. The resulting SFC is only 1.8 percent above the baseline C9 (Reference Section 4.4.1).

A further reduction in power can be achieved without changing the design for production by using inlet guide vanes (IGV) to reduce the airflow and rematch (closed down turbine inlet nozzle area) to a turbine inlet temperature of 1394 degrees K (2050 degrees F) (Table XLI). This power reduction of 20 percent, to 197.7 kW (265 hp) is achieved with only a 5 percent sacrifice in SFC.

5.2 Free Turbine Design

For the rotary wing (helicopter) application, the torque/stall characteristics of the free turbine are highly desirable. Two free turbine designs were evaluated (Figure 84), a turboprop for fixed wing aircraft, and a direct drive turboshaft for helicopter applications. These designs use the AC11.3 compressor configuration driven by a single stage radial turbine followed by a two-stage axial flow turbine with power extraction from the rear (exhaust) end of the engine. The accessory drive is located at the front. The differential turbine engine was investigated earlier (Reference Section 4.4.3) as an alternate approach for both fixed wing and rotary wing applications, however, the increased cost and weight relative to the fixed shaft engine ruled it out from further considerations. The result is the free turbine turboshaft derivative which is the most acceptable approach to the rotary wing application.

5.3 Cost Analysis

The relative cost of design 3013, the AC11.3 common core approach; design 3011, a free turbine turboprop and design 3012, a free turbine turboshaft is shown in Table XLIII. The OEM (Original Equipment Manufacturer) costs are summarized in Table XLIV. The methodology used is the same as discussed in Section 3.1.3. The cost distribution and summary for the AC11.3/C9 common core is presented in Table XLV. Seven of the eight components have been divided into A and B cost units and their engine cost ratio estimated. The A units are common to both the AC11.3 and the C9 derivative, the B units are used only on the AC11.3 design. The combustor is common to both the AC11.3 and the C9 and is therefore only an A unit. The K2 column is the fabrication technology factor that is applied for production rates greater than 2000 per year. The production rates for the A units is 15165 per year, which is the fixed wing aircraft turbine engine market estimated for one engine manufacturer (Reference Table XIV) plus 35 percent spares. The production rate for the B units is 7525 per year, these are the parts unique to the AC11.3 design that power the Category IIIP, IV and the AG (agricultural) fixed wing market. The engine prices and their relation to the projected fixed wing (by category) and helicopter market is summarized in Table XLVI. The number of engines quoted for the fixed wing categories assumes one engine manufacturer will capture only half the aircraft market plus 35 percent equivalent engines worth of spare parts.

The helicopter market is a small percentage of the total, and assumes that one engine manufacturer will capture the total, plus 35 percent spares. The AC11.3 prices were estimated based on using only a compressor and combustor in common with the AC11.3/C9 engine family.

The C9 derivative of the AC11.3 offers the lowest price (7 percent less) for the Category II and IIIU aircraft and is 16 percent lighter than the C9 one frame engine - the next higher up on the cost scale. The category II and IIIU engines represent slightly over 50 percent of the fixed wing market and are more sensitive than the other categories to small increases in engine price, therefore, the AC11.3/C9 two-frame family appears to be the promising approach to the common core. The maximum engine price for market penetration is shown in Figure 85 (based on the ratio of engine price to aircraft price used in Section 3.2.1). The AC11.3/C9 prices (using this ratio) shows a potential market penetration of turbine powered aircraft with a selling price as low as $27,000. The engine price analysis is based on the projected quantities shown in Table VIII.

The low cost features of the C9 core engine relative to current technology are summarized in Table XLVII. Reducing the number of compressor and turbine components reduces the engine cost by 26 percent. New design concepts for the combustor and control provide another 14 percent, and the improved cycle results in a smaller engine for a further 9.1 percent cost reduction. To be competitive in the general aviation market requires a combination of a low cost design and high production rates. The common core approach to achieving these objectives starts with a simple engine (for minimum cost), then adds parts to increase the power output. The resulting high production rates for the common parts further reduces the engine cost.

SECTION 6.0

TECHNOLOGY PROGRAM PLAN

The previous tasks have identified the high priority follow-on exploratory programs requisite to achievement of GATE turbine engine quality, and the resulting payoff to the General Aviation and helicopter fleets.

The primary objective of this section is to present the overall Technology Development plan which converts the study results into representative hardware and addresses the associated risk. Another objective is to provide a sufficient number of management decision milestones to ensure logical cut-off points or alternative directions should the technology achievement be below the level required for the investment strategy.

Figure 86 presents the major milestone schedule and the key decision points for a 5-year plan, culminating in the delivery of a demonstrator baseline engine for NASA testing. This engine would have a test-defined measure of reliability, making it worthy as a demonstrator of what can be achieved in full-scale engineering development of the GATE technology. In each task, the dashed lines represent the estimated number of design and/or test modifications required to achieve program objectives for the subject component.

The program is divided into seven major line items. It builds from a design definition of the engine through critical component demonstration of the turbine, compressor, and gearbox to their integration in a demonstrator engine design.

Because of the breadth of this initial GATE study, and its lack of single-engine design detail, the program begins with a series of visits to potential airframer users of GATE technology. These visits will result in an accumulation of mission and power definition data, general information on accessory and installation features, and on flexibilities required of the engine series. These requirements will be integrated into a mission definition for the baseline engines, against which a specification, sizing, flowpath, structural design, and manufacturing cost analysis may be accomplished.

The major decision milestones are also shown on Figure 86. Near the end of the first year, sufficient engine detail design, cost analysis, and manufacturing methodology definition will have been achieved to allow the design to pass through its first gate - is the price of the engine low enough to assure penetration into sufficient new markets to warrant proceeding with hardware demonstration?

In the middle of the third year, sufficient test information will have been collected in radial turbine component development to define its turbine inlet temperature capability. The decision is whether that temperature is sufficiently high to warrant proceeding with the program. (At this point in the study, it is estimated that a reduction from 1504 degrees K to 1449 degrees K (2250 degrees F to 2150 degrees F) would not prejudice the results of the program; i.e., even a 56 degrees K (100 degrees F) reduction would not be deleterious enough to engine size, weight, cost, or performance to lead to cancellation of the program).

Also in the middle of the third year, sufficient compressor testing will have been undertaken to allow assessment of the worthiness of the compressor, as measured against the original objectives and the requirements of the demonstrator engine.

By the fourth quarter of the second year, the gearbox component development will be sufficiently far along to answer whether the powder metallurgy gear approach is sound. Critical here are the achievement of cost reduction and demonstration of a measure of durability of the process relative to strength requirements for a main engine gearbox. In Task I of the technology plan (Program Control) - alternate concepts will be made available for substitution should the power metallurgy technique not prove feasible.

At the beginning of year 4, the milestone question is - should the demonstrator engine be built? The answers will be determined from the accumulation of design and component test data, relative to targets established for a worthy demonstrator engine.

It should be noted that in the first year, for each of Tasks 2 through 5, design effort has been overlapped into earlier task time frames to maintain both program momentum and a reasonable capacity for achieving timely milestones. In no case is there any hardware commitment, only design labor. This approach is recommended so that the total program can be sustained at a reasonable momentum, achieve a rational end point within five years, and continuity can be maintained by tapping off task results as they can most effectively be utilized.

The 30-month engine demonstrator task is key to the proof of the engine concept. Initial efforts are addressed to incorporation of the compressor, turbine, combustor, shaft and gearbox component test results into an integrated engine design.

Two serial number engines and the equivalent of 1-1/2 engines in spares will be procured during the fourth year. The first engine will be assembled and instrumented for check run in the first quarter of year 5.

The next three months of engine testing will focus on matching and performance improvement, using minor modifications to the initial design hardware for increase of power and improvement of SFC levels.

In parallel with Serial Number 1, engine Serial Number 2 will be instrumented for structural evaluation, using high speed slip rings and non-contact techniques to measure temperatures and strains. Serial Number 2 will be run during the disassembly period of Serial Number 1, so that both performance and structural data can be integrated into parts modification at suitable times.

Additional testing will be performed during the first three quarters of year 5 to probe the performance potential and structural adequacy of the engine design. This test period will culminate in the running of a 25 hour accelerated mission durability test, patterned from current test technique research being done for the USAF and USN ATEGG and JTDE programs. In this type of simulated mission environmental test, the primary damaging events anticipated from assessment and correlation of expected flying data will be used. A rigorous test will be constructed to assess the structural integrity of the engine design.

Given success in the 25-hour accelerated endurance, Serial Number 1 can be refurbished with best available hardware for delivery to NASA at the end of year 5. This engine is expected to be somewhat over the production target on SFC, but probably will achieve design horsepower targets. Its integrity and adequacy for NASA experimental testing will have been demonstrated by the 25-hour test, hence it will represent a reasonable achievement for the NASA investment in the advanced technology.

This one year test program is a judged value; the program could easily be extended to incorporate two years of testing, with higher end result performance and durability objectives. It is recognized that at some extended length of the program, it is no longer a NASA technology investment; rather it is a full-scale engineering development program.

SECTION 7.0

CONCLUSIONS AND RECOMMENDATIONS

A General Aviation market can exist in the late 1980's for up to 31,500 gas turbine engines per year. Approximately 95 percent of that market will be in fixed wing aircraft of 1040-3040 kg (2300-6700 lb) gross weight, requiring engines of 260-560 horsepower. Five percent will be in helicopters requiring engines of 205-317 kW (275-425 hp). Gas turbine power is not competitive on a price basis below about 1040 kg (2300 lb) TOGW 194 kW (260 hp); larger aircraft requires power levels greater than 746 kW (1000 hp) and therefore beyond the study scope.

The applicable gas turbine engines will provide nationally significant productivity benefits to the General Aviation fleet - more seat-miles per gallon of fuel, lighter aircraft, and greater passenger comfort and safety. They will also meet or exceed anticipated Federal environmental regulations.

To be salable, the engines must approach the current price ranges of equivalent reciprocating engines; benefits to the aircraft design will allow some deviation, but initial purchase price (for the fixed wing aircraft) was verified as a primary objective of any development. The helicopter market can tolerate substantially higher engine prices than fixed wing aircraft.

An approach has been defined to a shaft power engine family which will meet the marketplace needs. It combines advanced technology components with new manufacturing techniques in a high-volume production concept.

The only forseeable competition will be the improved reciprocating engine, based on its current dominance of this market. Key factors in this competition will be the ability to improve reciprocating engine power/weight at the same time as SFC, durability, emissions, and noise are improved - without excessive cost increase. The projected GATE turbine engines will have better power/weight and equal or better installed cruise fuel consumption.

The connected shaft turboprop was found to best address the turbine engine requirements; a free turbine or differentially geared derivative of similar components will suit the torque requirements of helicopters. A turbofan derivative from the baseline turboprop engine would answer the needs of a specialized, high performance market segment.

A family of engines covering the 198-422 kW (265-565 hp) spectrum, with considerable cost-saving component commonality, was defined. The core engine, applicable to the 198-250 kW (265-335 hp) range, consists of a gearbox, 9:1 pressure ratio, backward curved, single-stage centrifugal compressor; a reverse-flow vaporizer plate combustor; and a 2250 degree F maximum rating, uncooled rotor, radial inflow turbine.

By adding a transonic axial supercharging compressor and an uncooled axial flow turbine stage, power levels up to 422 kW (565 hp) may be achieved. All core components are identical, as are many static housings and most of the gearbox. The resulting engine will have an 11.3:1 pressure ratio at the same

2250 degrees F maximum temperature rating, and 10 percent better SFC. Component technology levels are significantly beyond current capability.

Achievement of the component targets requires research to define and attenuate the risk of development. The results of a successful program will also be applicable to cruise missile powerplants and turbogenerator systems. These combine to make the results of such a program applicable to small engines across the board, and thus will be worthy of follow-on NASA investment.

The study showed a high payoff national, industrial, and environmental impact on General Aviation, and a multi-mission applicability of the advanced component technology. It is therefore recommended that NASA develop and implement a five-year GATE component and demonstrator engine program.

This study phase reduced the world of possible gas turbine configurations to a bounded, focused, multi-purpose family of engines. Because of the study breadth, it might be deemed desirable to interpolate a more in-depth design concept validation phase prior to initiation of the total program. This phase would be a portion of the Task 1 described in Section 6.0.

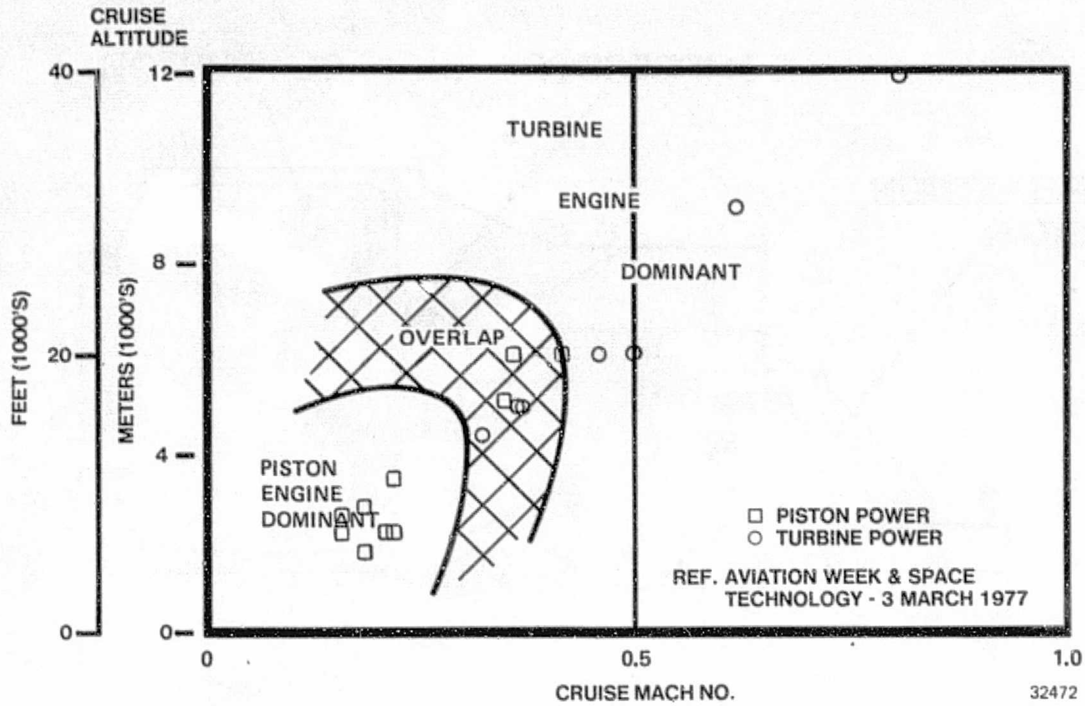

Figure 1. Areas of Power Plant Dominance.

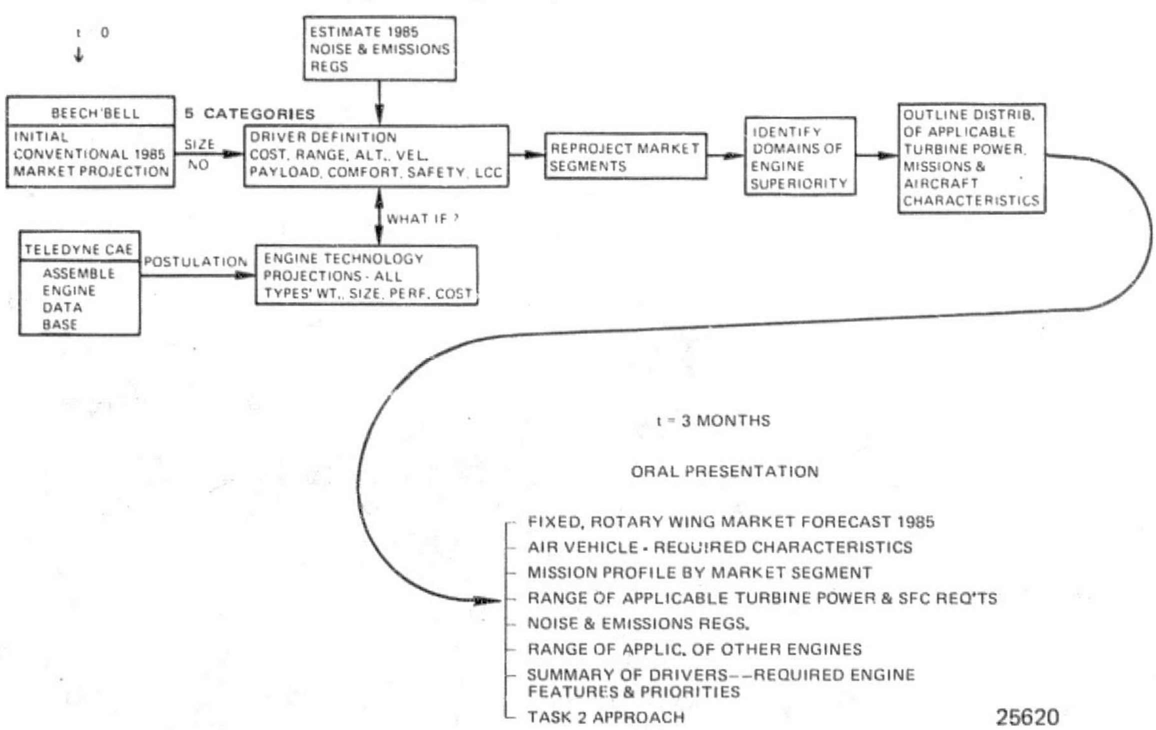

Figure 2. GATE Task I, Market Analysis Study Plan.

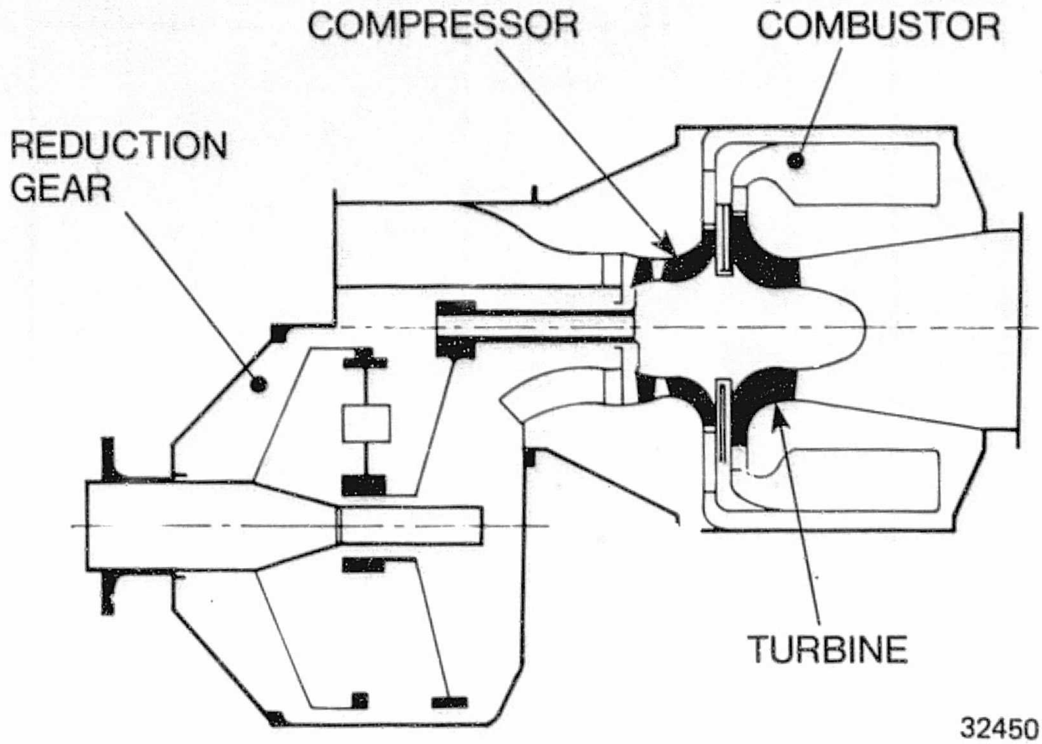

Figure 3. GATE Turboprop.

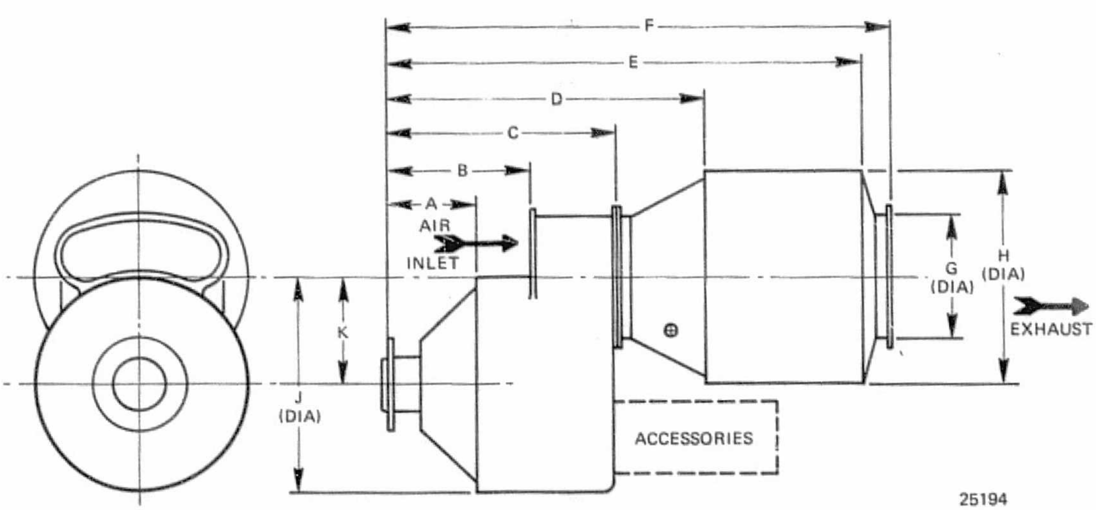

Figure 4. Installation - GATE Turboprop.

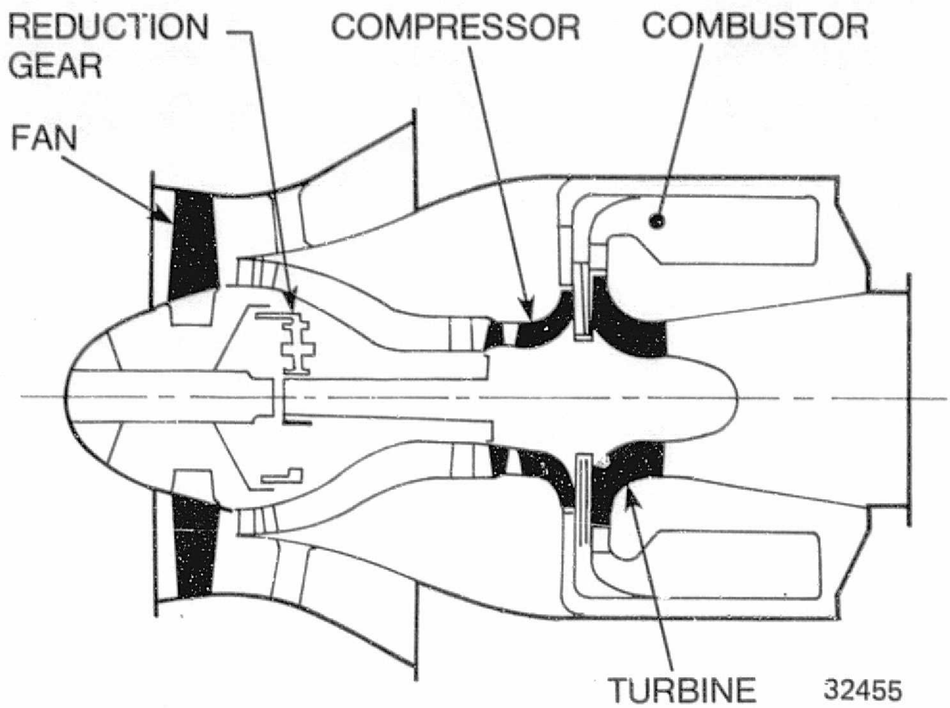

Figure 5. GATE Turbofan.

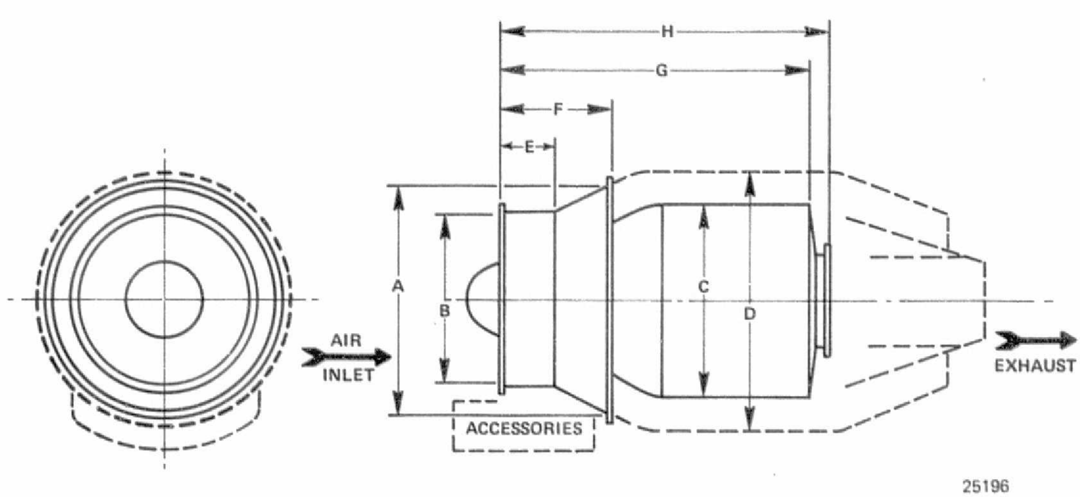

Figure 6. Installation - GATE Turbofan.

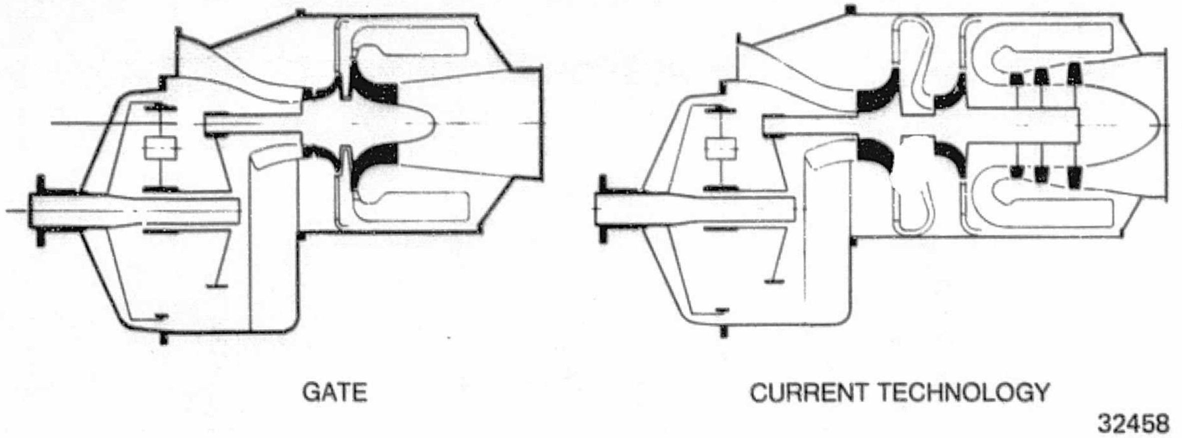

Figure 7. Comparison of Task I Baseline GATE Turboprop With Current Technology.

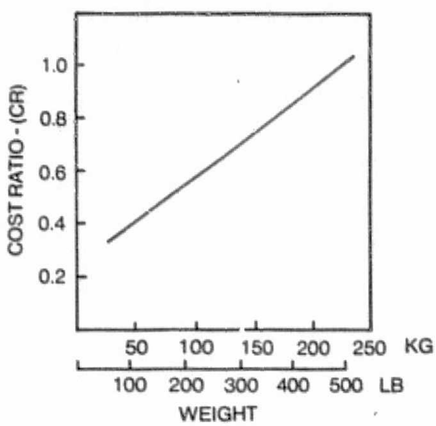

Figure 8. CR (Cost Ratio) Relationship.

CR = 1.0
WT = 227 KG (500 LB)
OEM PRICE = $59,870

$$CR = 0.335\left(\frac{WT}{100}\right) + 0.24$$
WEIGHT IN KG

$$CR = 0.152\left(\frac{WT}{100}\right) + 0.24$$
WEIGHT IN LB

Figure 9. CR Formula and Base OEM Price.

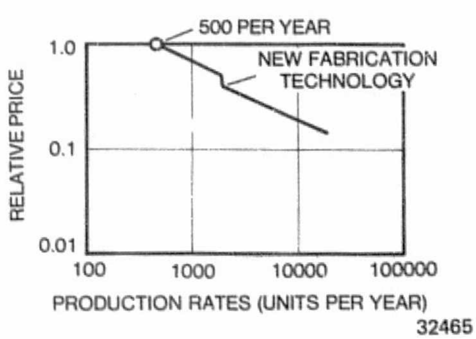

Figure 10. Relative Price Vs. Production Rates.

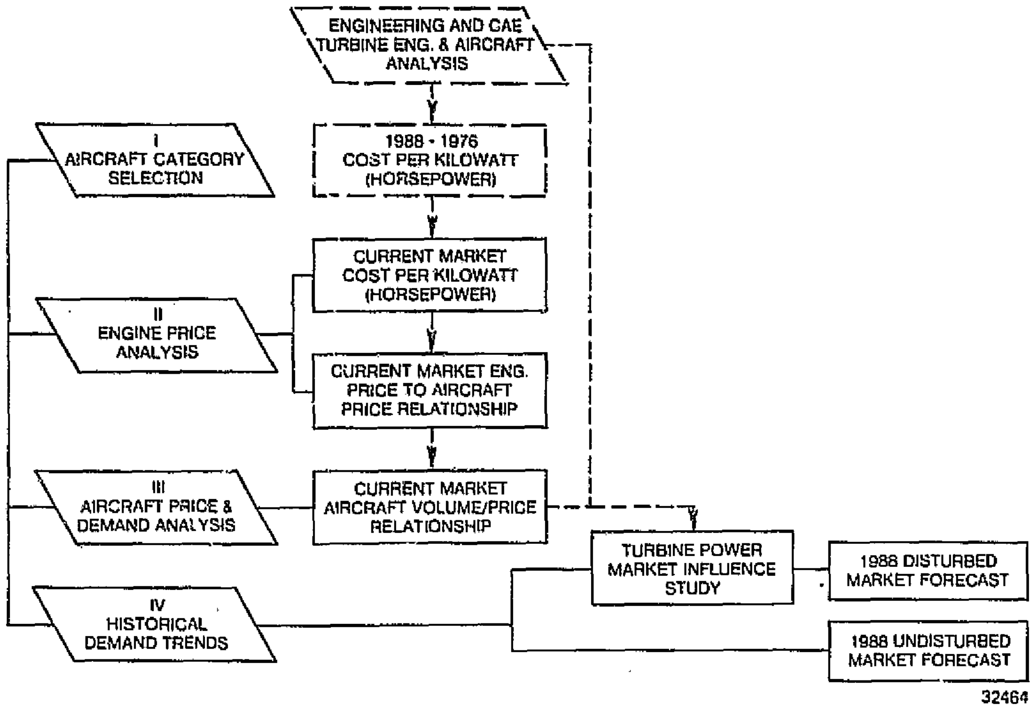

Figure 11. Market Analysis Flow Chart.

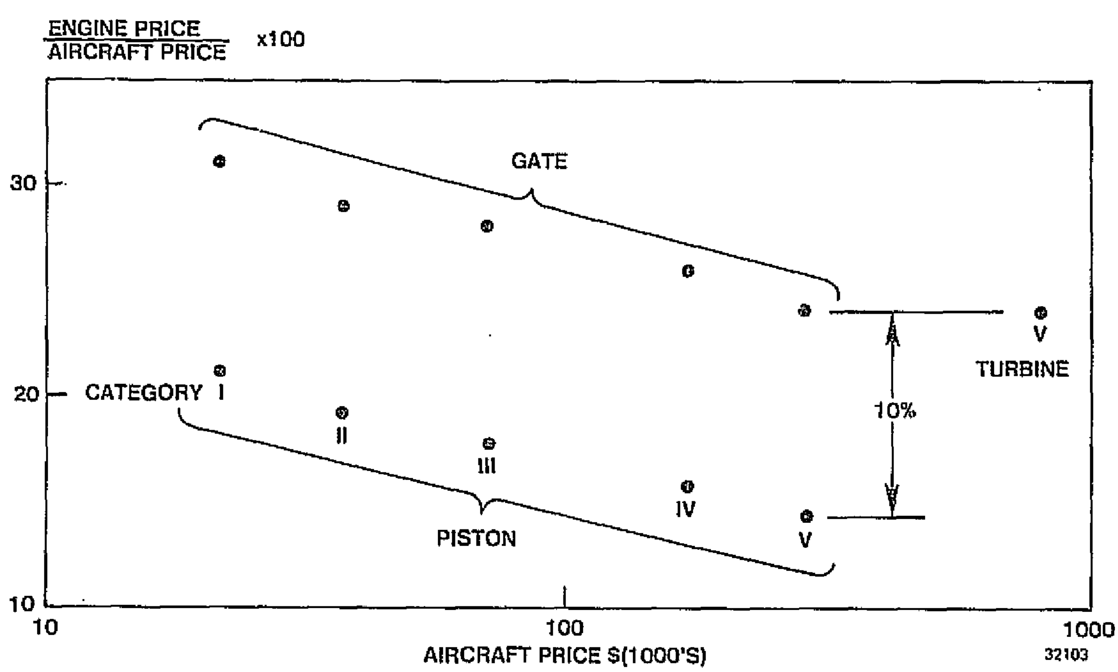

Figure 12. Percent Engine Price Vs. Aircraft Price: Average for Each Category.

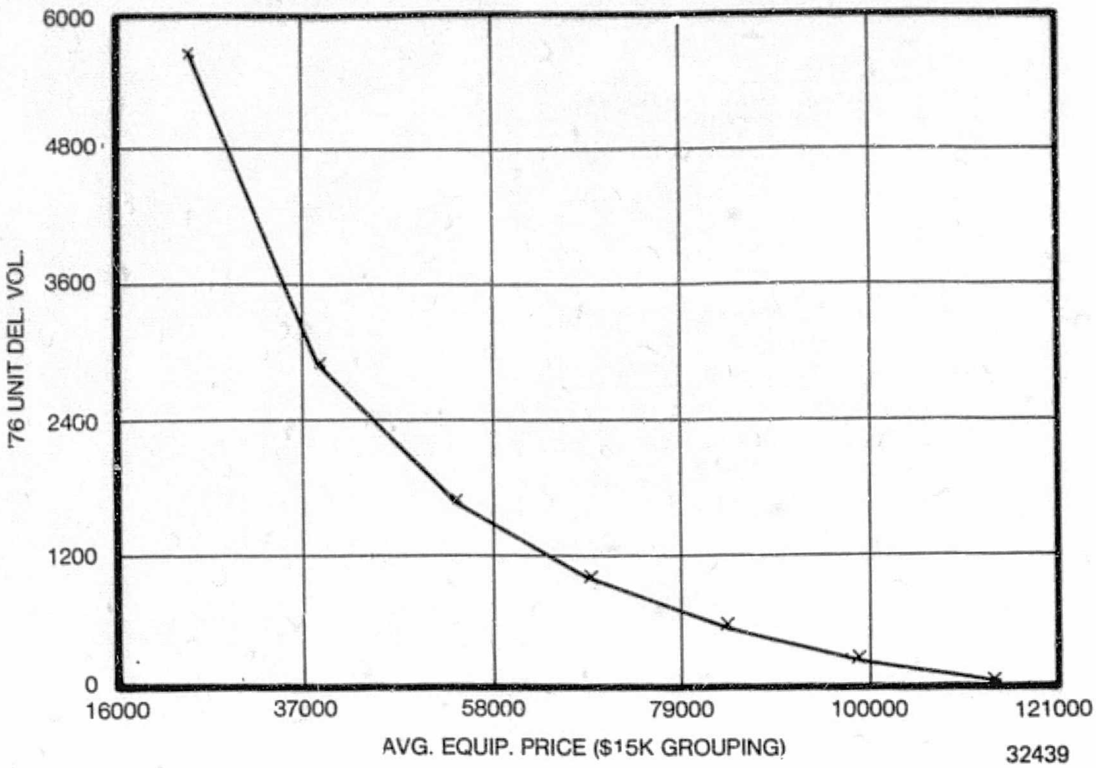

Figure 13. Category I Through III Delivery Volume Vs. Price ($15,000 Grouping).

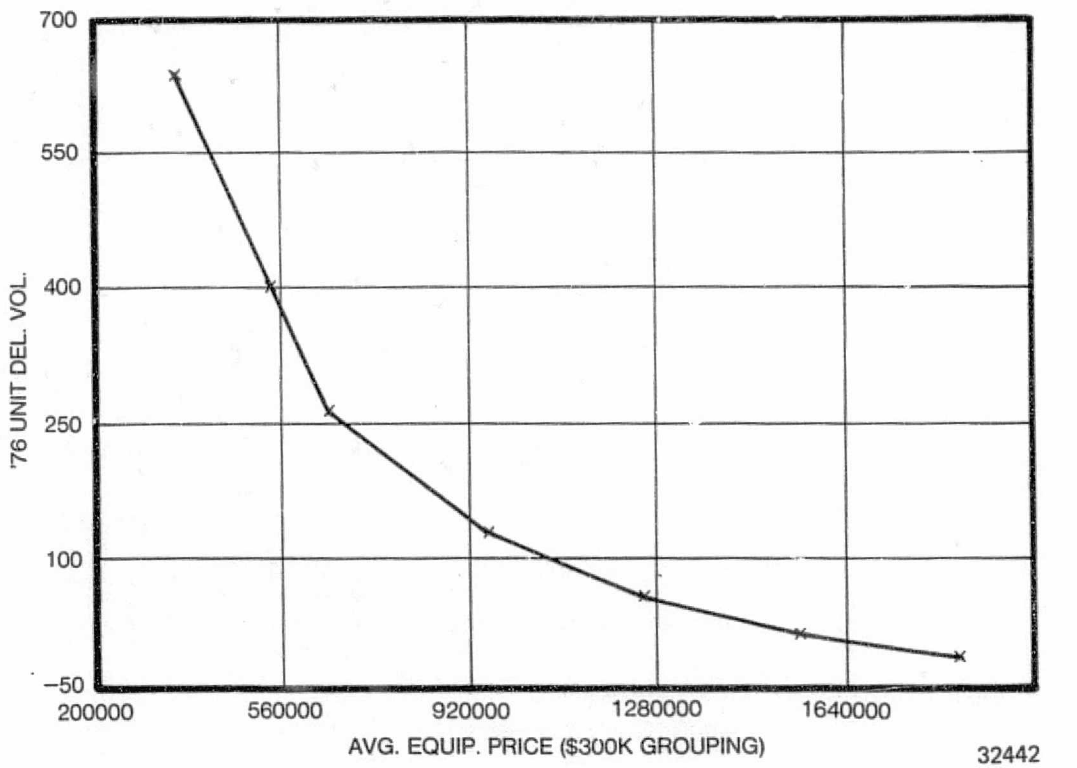

Figure 14. Category IV Delivery Volume Vs. Price ($300,000 Grouping).

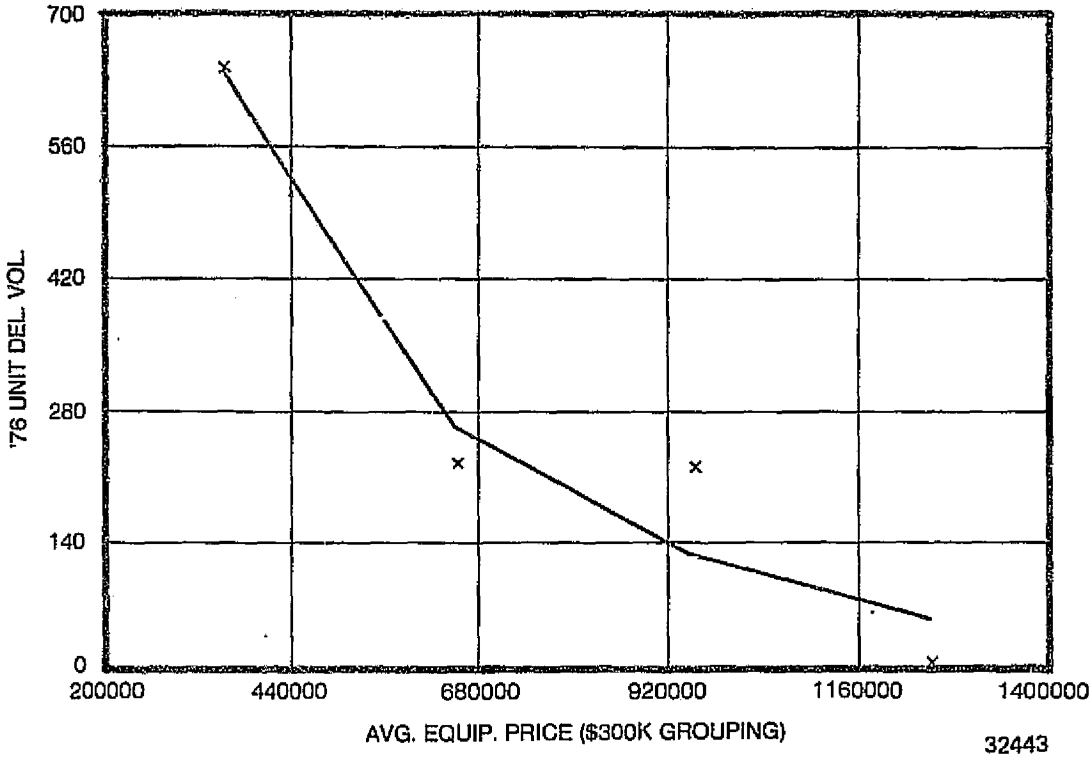

Figure 15. Category V Delivery Volume Vs. Price ($300,000 Grouping).

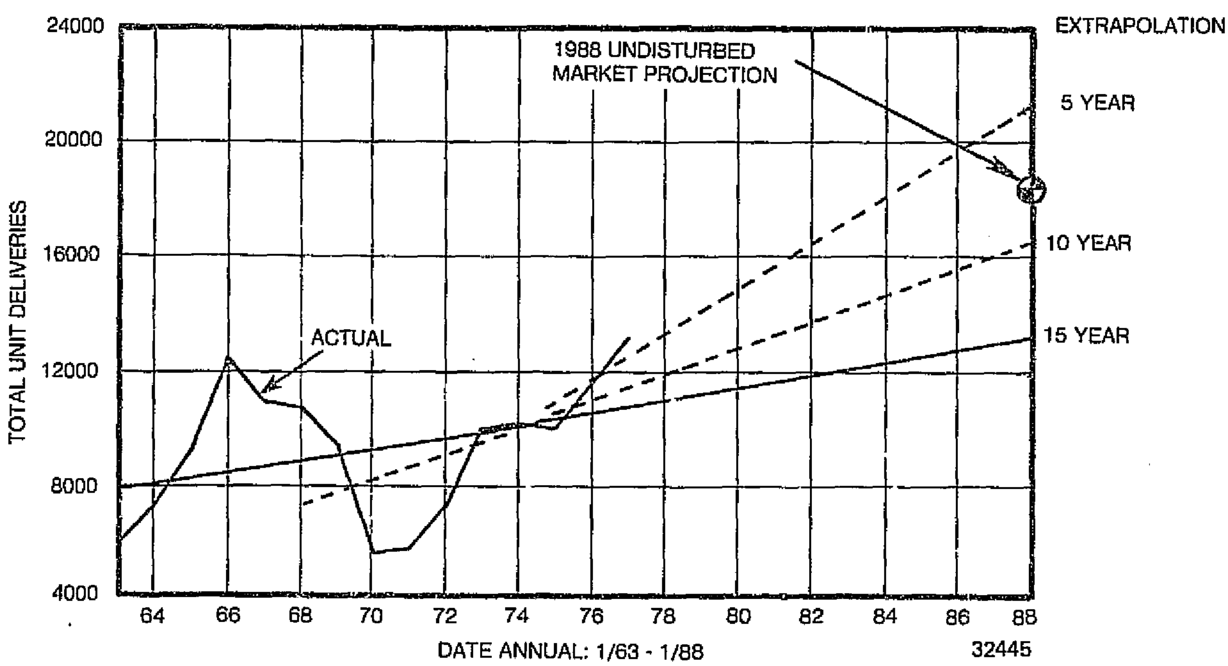

Figure 16. Delivery Trend and Historical Projection, Categories I Through III.

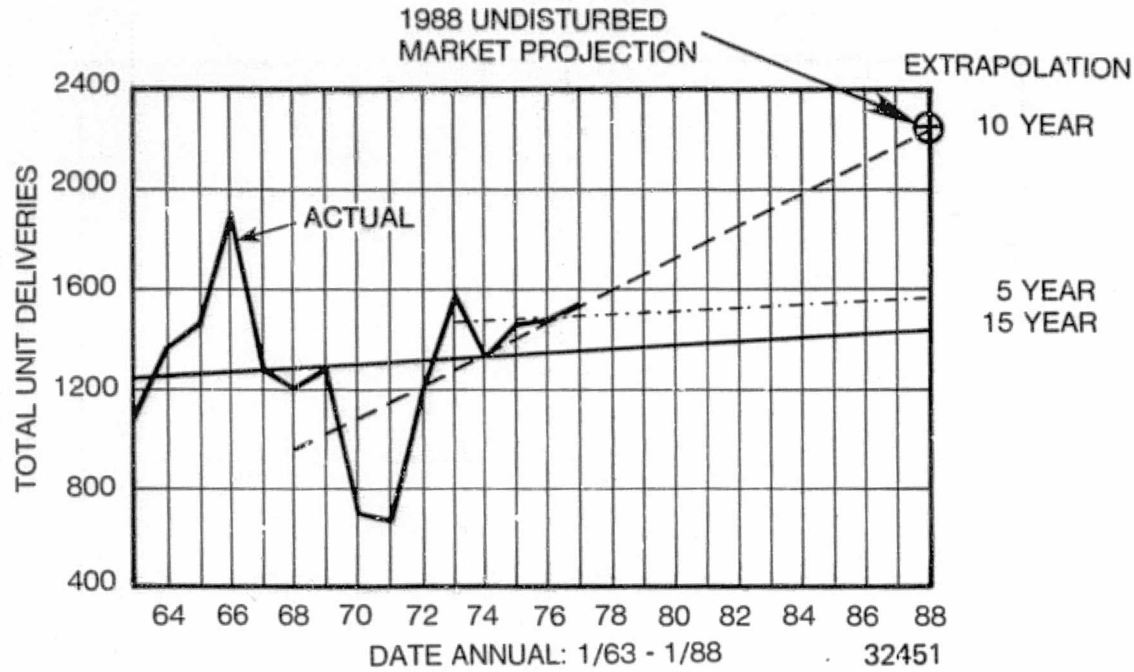

Figure 17. Delivery Trend and Historical Projection, Category IV.

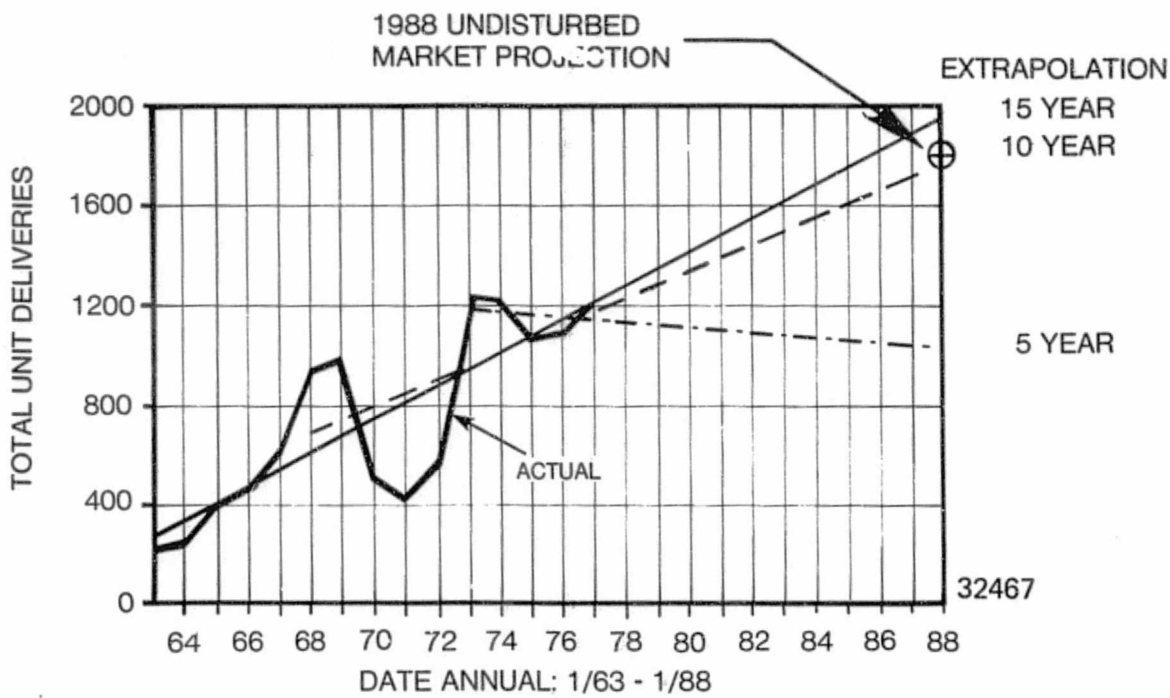

Figure 18. Delivery Trend and Historical Projections, Category V.

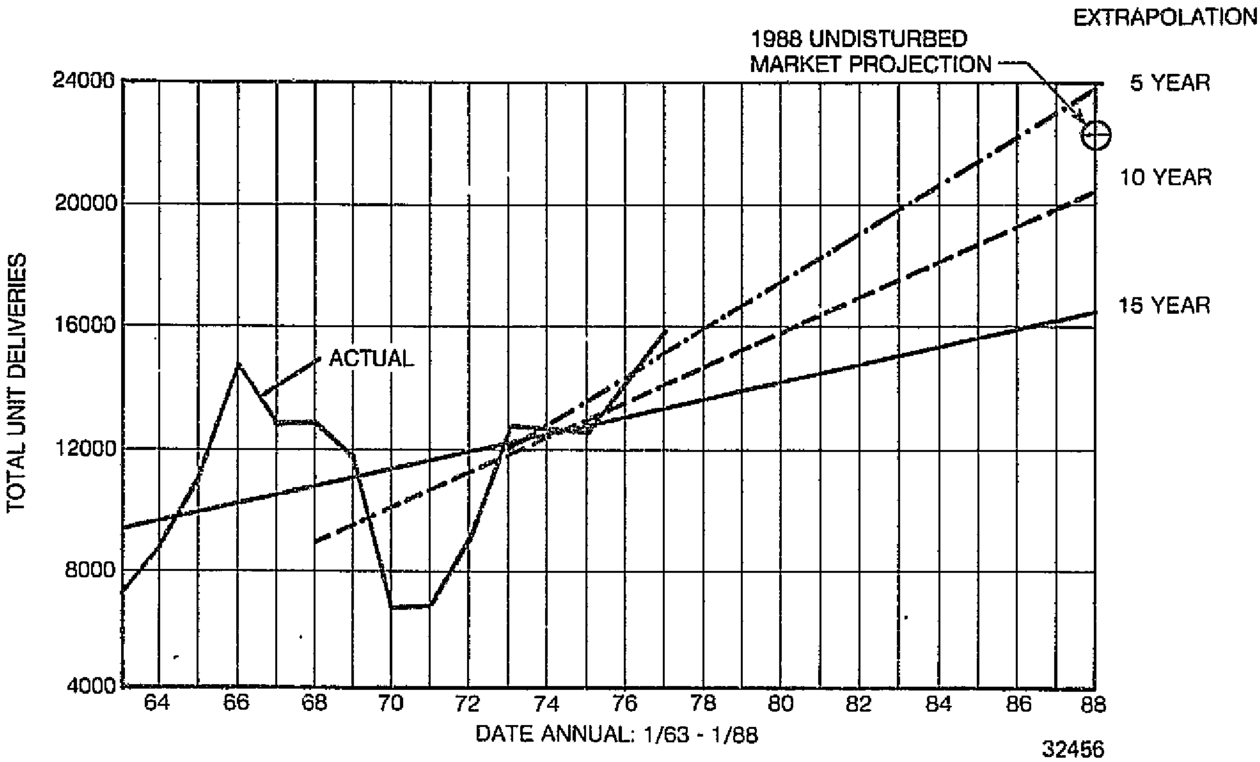

Figure 19. Delivery Trend and Historical Projection, Categories I Through V.

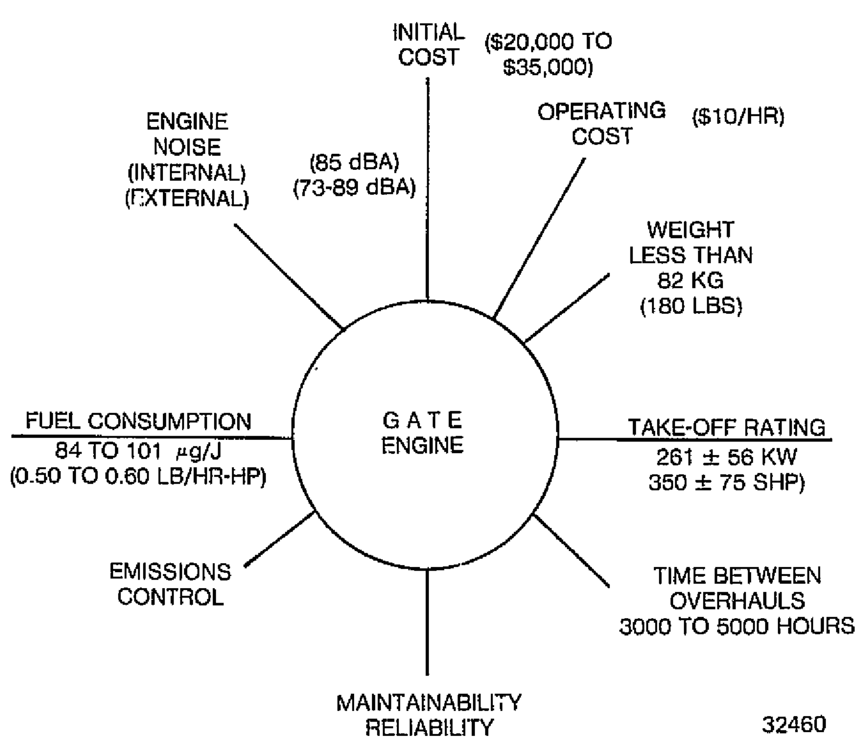

Figure 20. GATE Requirements for the Light Helicopter Market.

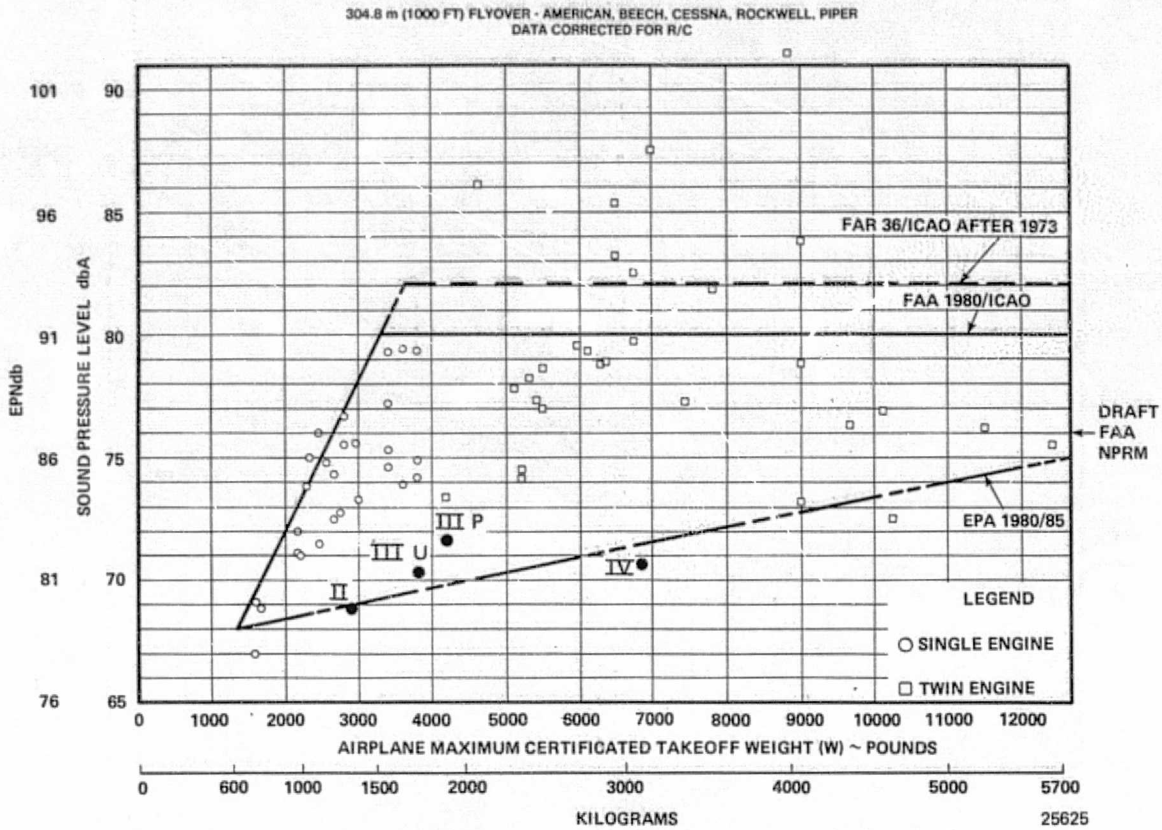

Figure 21. GATE Noise Levels - 1976 GAMA Data.

- **PERFORMANCE**
  - LOW SFC: 76.1-93.0 μg/J (0.45-0.55 LB/HP-HR) EQUAL TO PISTON ENGINE
  - HIGH POWER TO WEIGHT - 2 —3.5 X PISTON ENGINE
- **INSTALLATION**
  - REDUCED FRONTAL AREA - ½ PISTON ENGINE
  - COOLING DRAG - ZERO
  - DIRECT MOUNTING TO HELICOPTER GEARBOX
- **COMFORT**
  - SMOOTH RUNNING - LOW VIBRATION LEVEL
  - QUIET - SUBMERGED INLET/LOW EXHAUST VELOCITY
- **CONTROLS**
  - SINGLE LEVER ELECTRONIC CONTROL
- **MULTI-FUEL CAPABILITY**

32435

Figure 22. 1988 Desirable Turbine Engine Features.

- ELECTRIC STARTER
- OPTIONS
    - GENERATOR
    - HYDRAULIC PUMP
    - BLEED AIR – PLUG IN AUXILIARY COMPRESSOR
    - ENVIRONMENTAL CONTROL – INTEGRATE BLEED AIR COMPRESSOR/HEAT EXCHANGER/ EXPANSION TURBINE

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Figure 23. 1988 GATE Accessories.

- <u>FIXED WING</u>
    - NEGATIVE THRUST ON APPROACH
        - DECLUTCH/BRAKE
        - VARIABLE PITCH PROP
    - HIGH INLET - CLEAN AIR/MIN F.O.D.
- <u>ROTARY WING</u>
    - FREE TURBINE OR EQUIVALENT ENGINE TO ROTOR SYSTEM
    - CLOSE COUPLE ENGINE/HELICOPTER GEARBOX INTEGRATED TRANSMISSION/ ELIMATE DRIVE SHAFT/SEPARATE MOUNTING
    - AIR CLEANERS

25739

Figure 24. GATE Interface Considerations.

- SUFFICIENTLY LARGE MARKET DEFINED TO WARRANT NASA INVESTMENT
- TECHNOLOGIES REQUIRED TO ENSURE MARKET ARE SIGNIFICANTLY ADVANCED, COMPARED TO 1977
- NOISE & EMISSIONS ARE VOLATILE LEVERS – EXCESSIVE REGULATION CAN INHIBIT GENERAL AVIATION
- MAXIMUM ENGINE COMPONENT/MODULE COMMONALITY IN 198-422 KW (265-565 HP) ENGINES IS ESSENTIAL TO RATE/PRICE/MARKET
- EXPECT TO SHOW SUBSTANTIAL GENERAL AVIATION FUEL CONSERVATION

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Figure 25. Task I Market Analysis Conclusions.

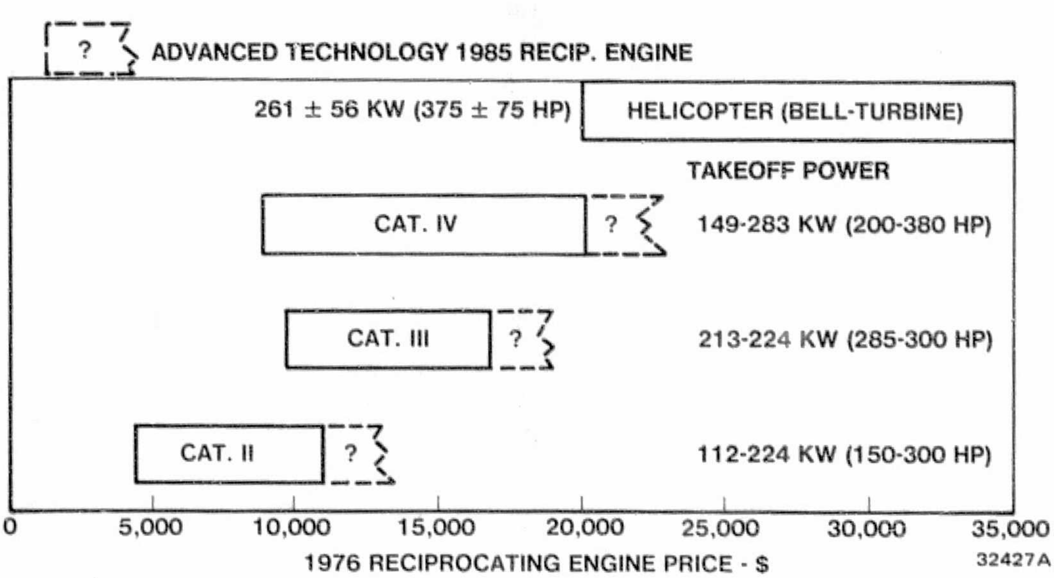


Figure 26. Engine Price Bogies - To Ensure a Marketable GATE Aircraft, Turbine Engines Must Approach Prices Competitive With Reciprocating Engines.

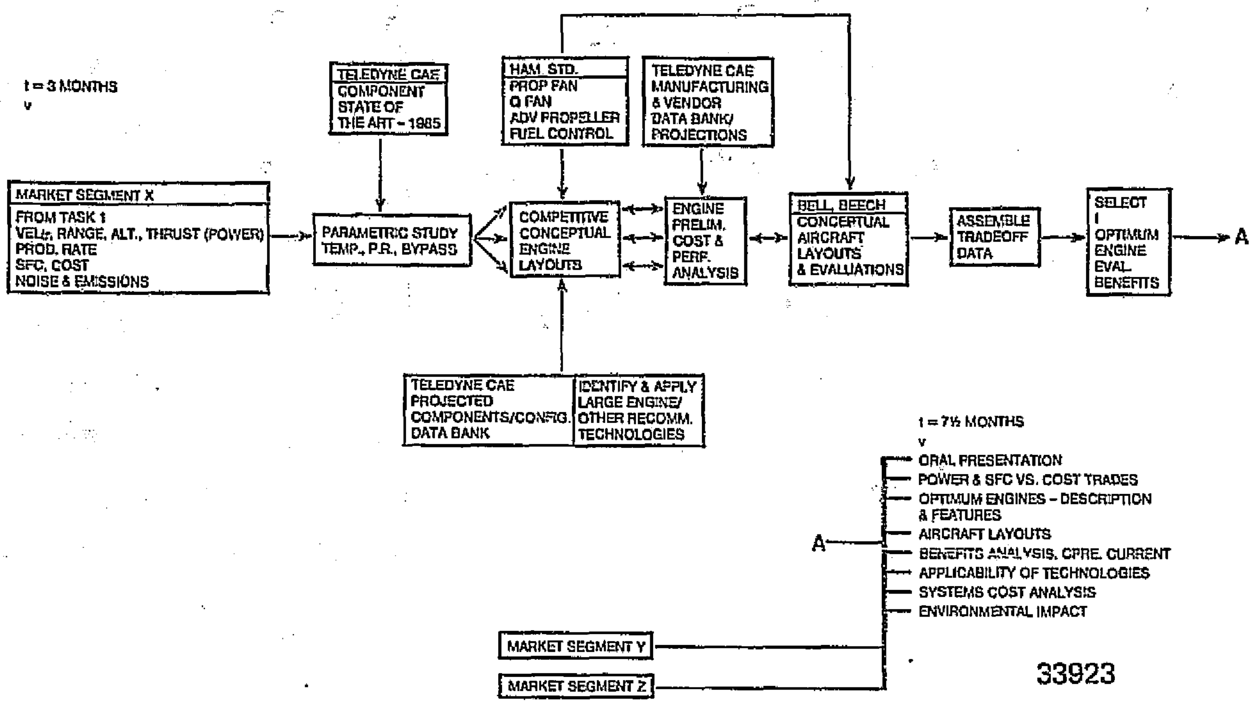


Figure 27. GATE Task II, Trade-off Study Plan.

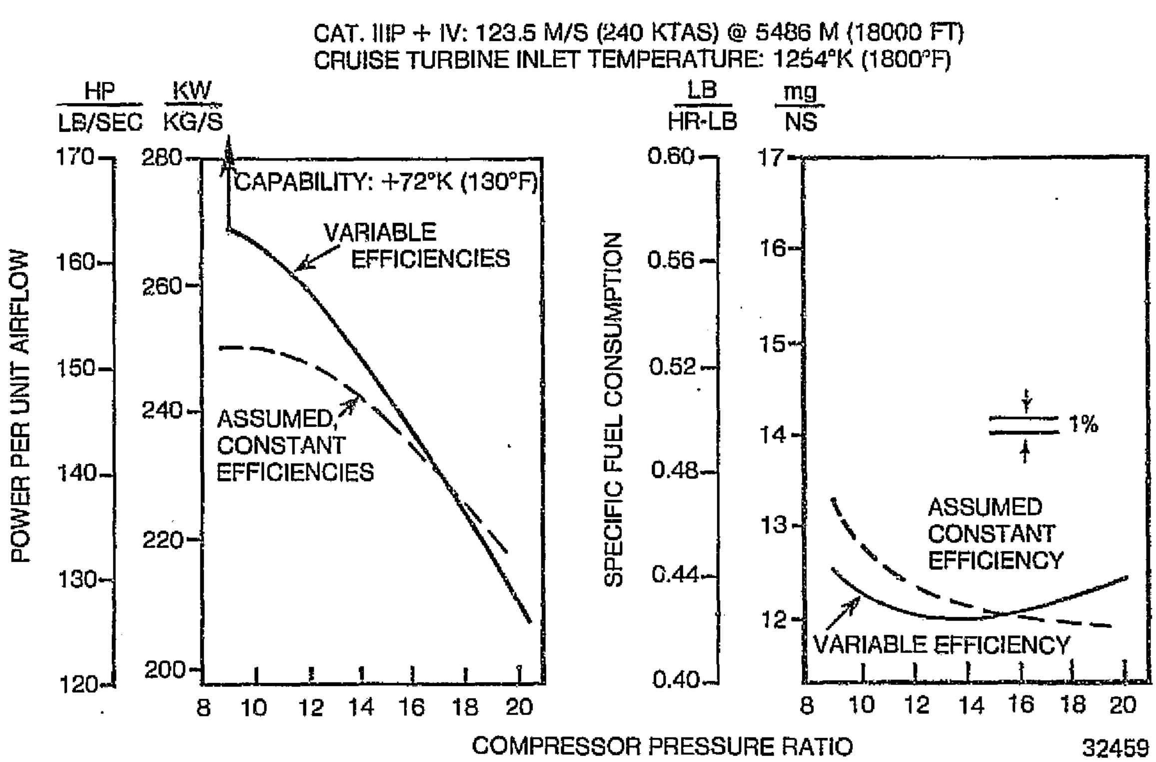


Figure 28. GATE Category IIIp and IV: Effect of Variable Efficiencies on Specific Power, and Specific Fuel Consumption Vs. Pressure Ratio.

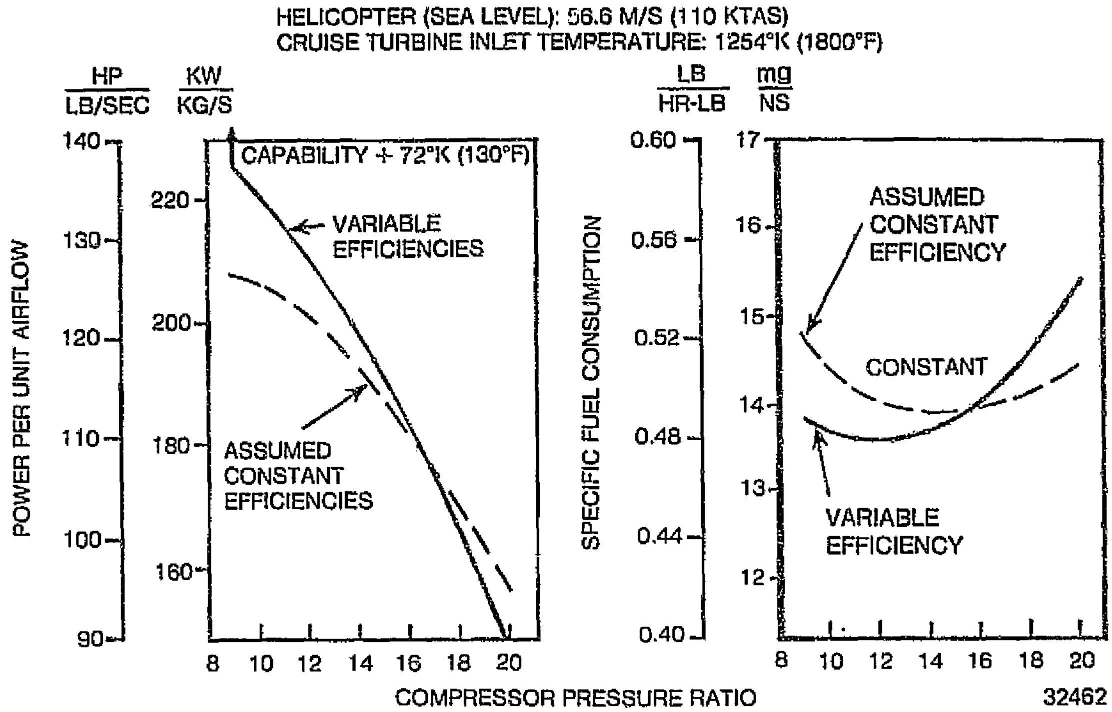


Figure 29. GATE Helicopter: Effect of Variable Efficiencies on Specific Power and Specific Fuel Consumption Vs. Pressure Ratio.

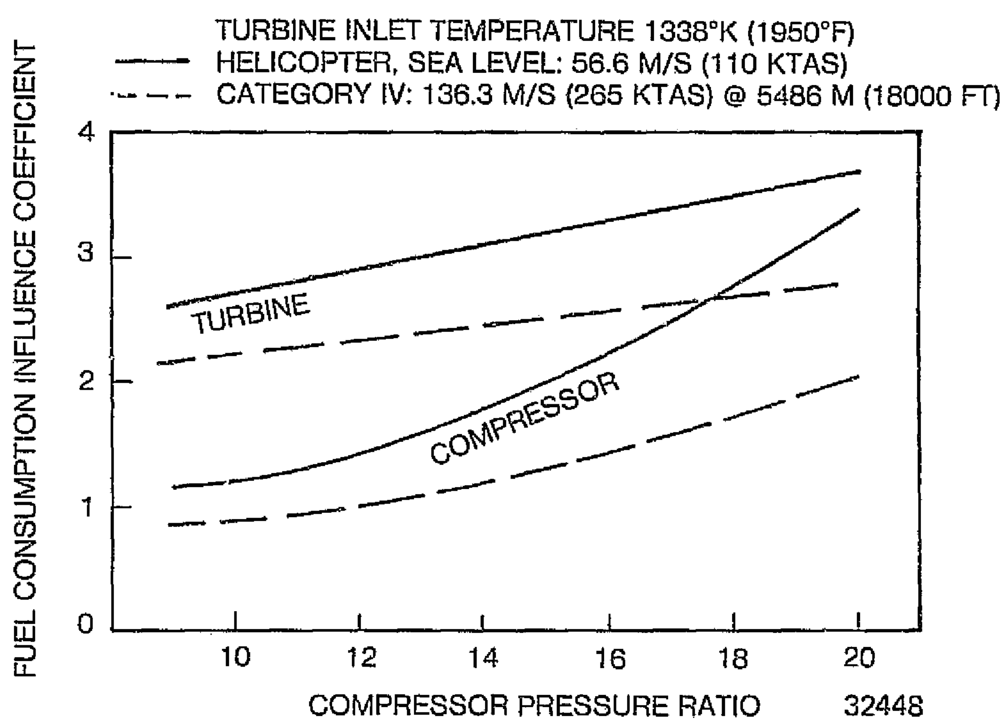


Figure 30. GATE Typical Cycle Sensitivity Analysis; Fuel Consumption Sensitivity Vs. Pressure Ratio.

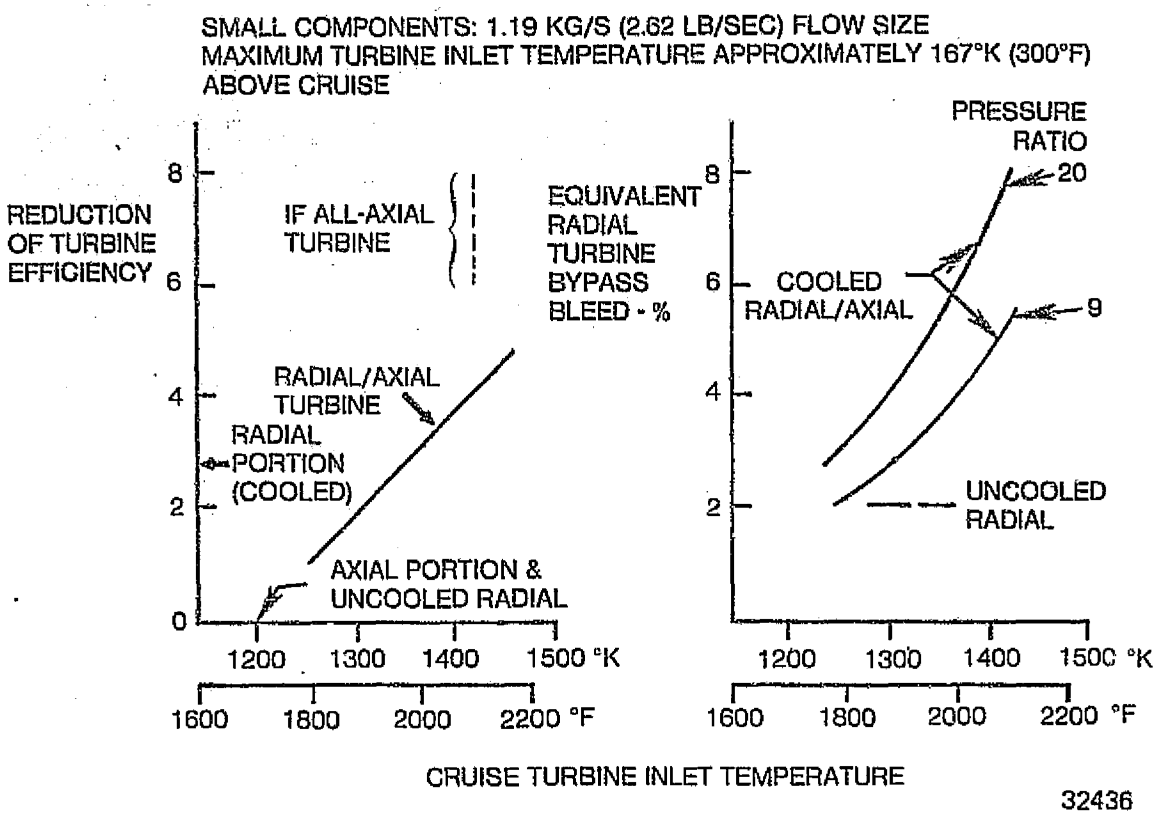


Figure 31. Parametric Analysis.

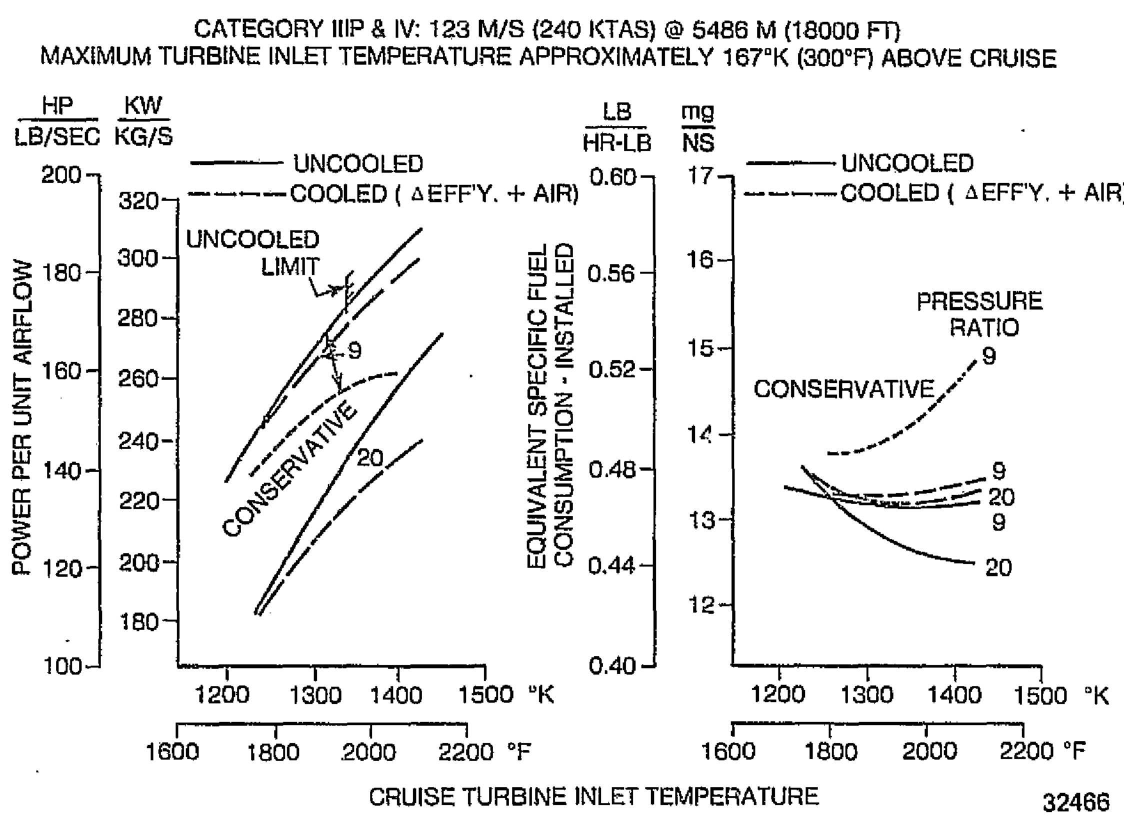


Figure 32. Parametric Analysis.

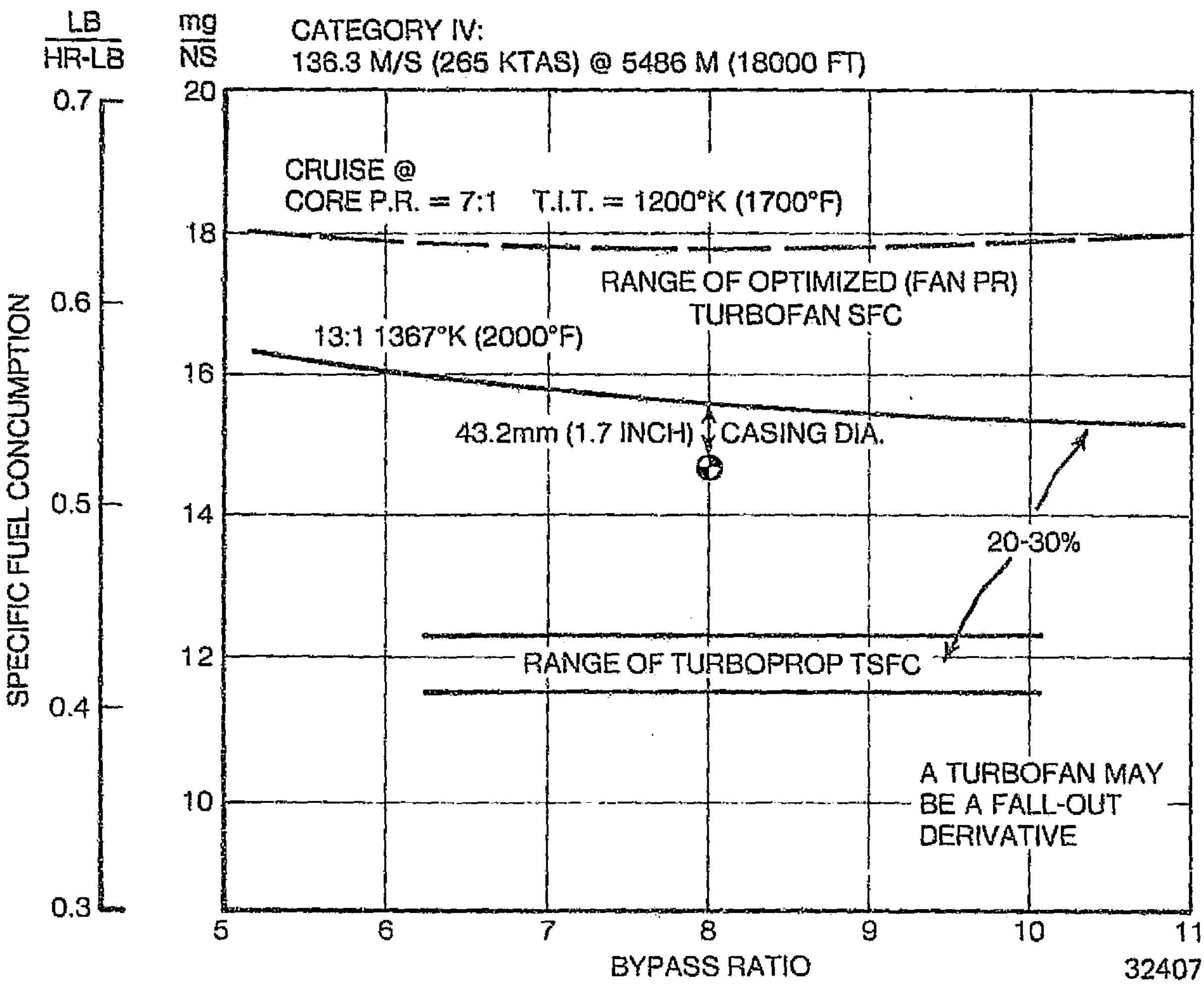
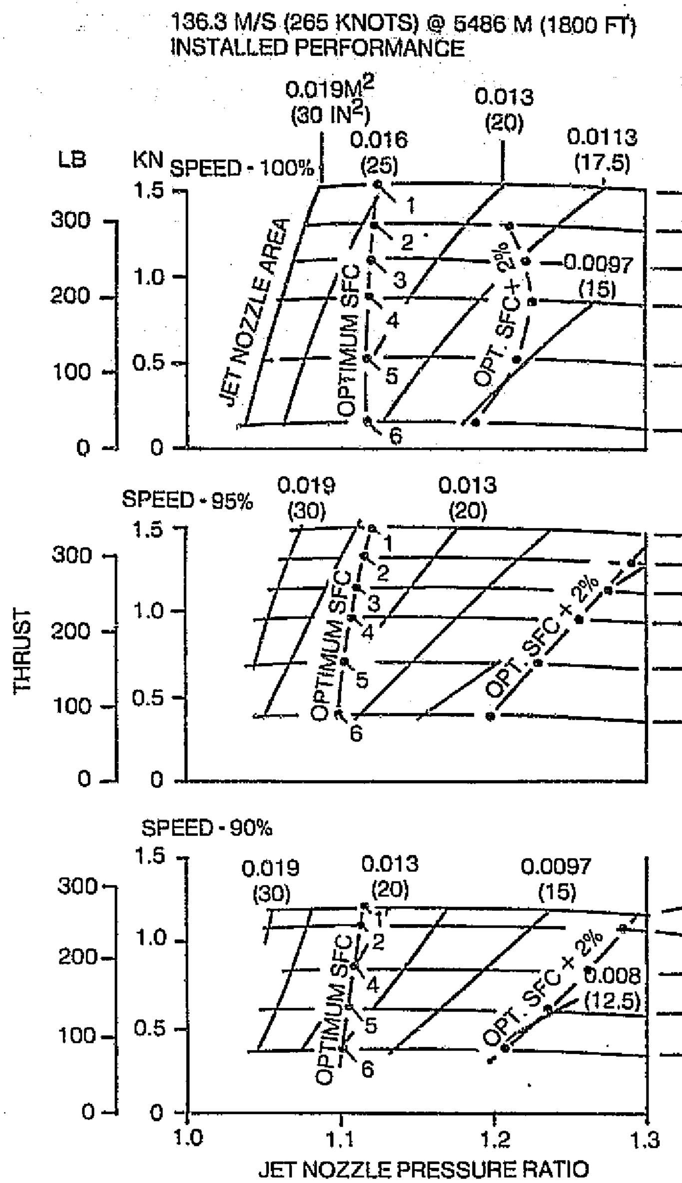


Figure 33. Turbofan Fuel Consumption Compared with Turboprop.



Turbine Inlet Temperature

Speed	°K	°R
100%	1506	2710
	1389	2500
	1278	2300
	1167	2100
	1000	1800
	833	1500
95%	1506	2710
	1389	2500
	1278	2300
	1167	2100
	1000	1800
	833	1500
90%	1506	2710
	1389	2500
	1167	2100
	1000	1800
	833	1500

Specific Fuel Consumption

Speed	Station Number	mg/NS	LB/HR-LB
100%	1	---	---
	2	12.92	0.456
	3	13.12	0.463
	4	13.71	0.484
	5	16.35	0.577
	6	36.29	1.281
95%	1	12.78	0.451
	2	12.64	0.446
	3	12.55	0.443
	4	12.49	0.441
	5	12.95	0.457
	6	14.87	0.525
90%	1	13.63	0.481
	2	13.37	0.472
	3	---	---
	4	13.29	0.469
	5	13.57	0.479
	6	15.27	0.539

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Figure 34. Engine Match Trade-Offs at Cruise: Thrust and SFC Vs. Turbine Inlet Temperature, Speed and Jet Nozzle Pressure Ratio for a 9:1 Pressure Ratio Engine Computer Model.

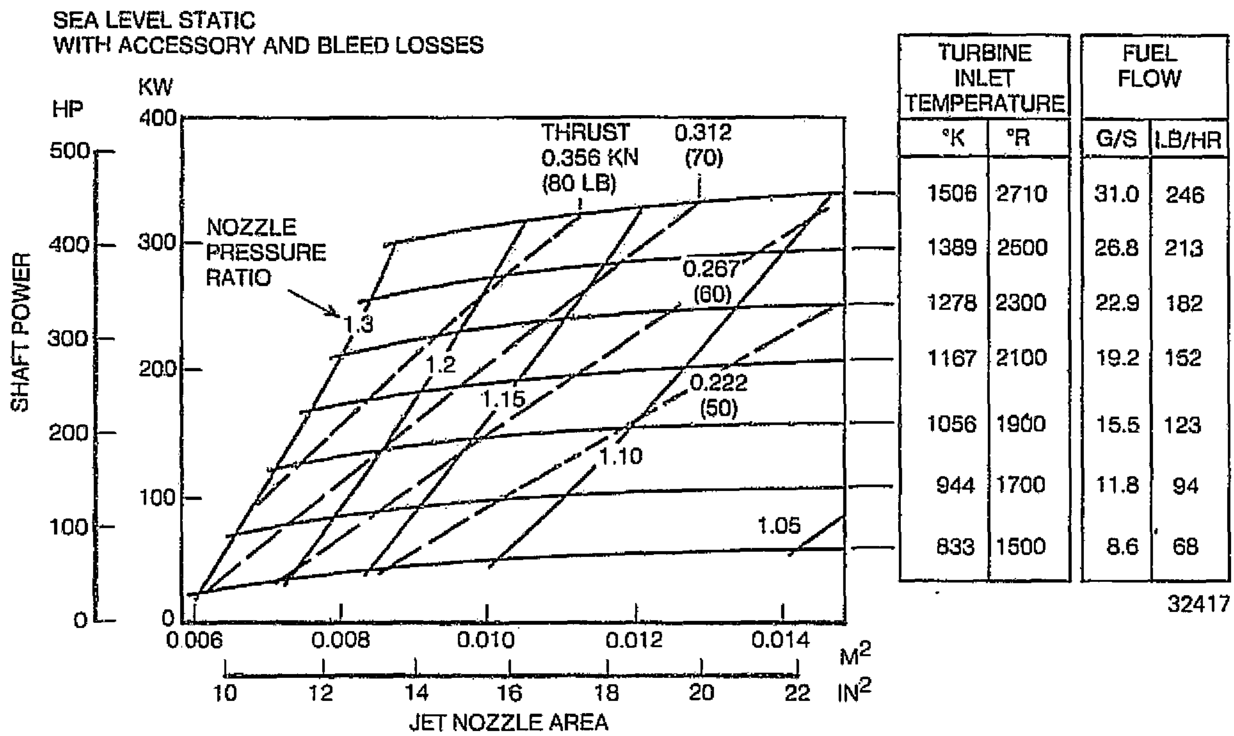


Figure 35. Engine Shaft Power and Thrust Vs. Jet Nozzle Area and Turbine Inlet Temperature at Sea Level Static, 9:1 Pressure Ratio Engine Computer Model.

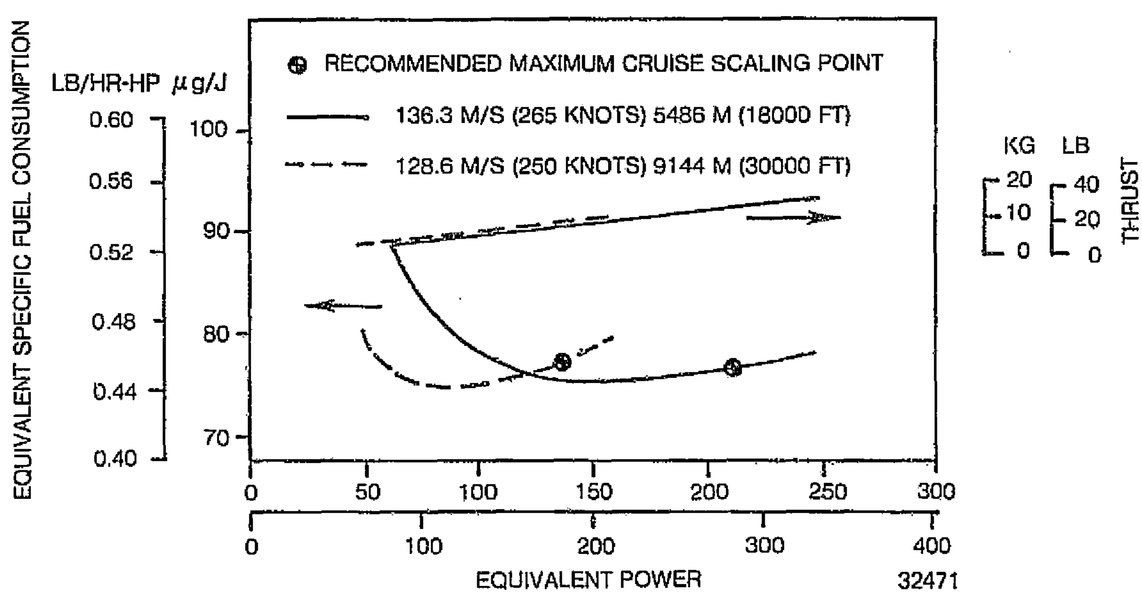


Figure 36. C9 Engine Performance: Category IV Baseline.

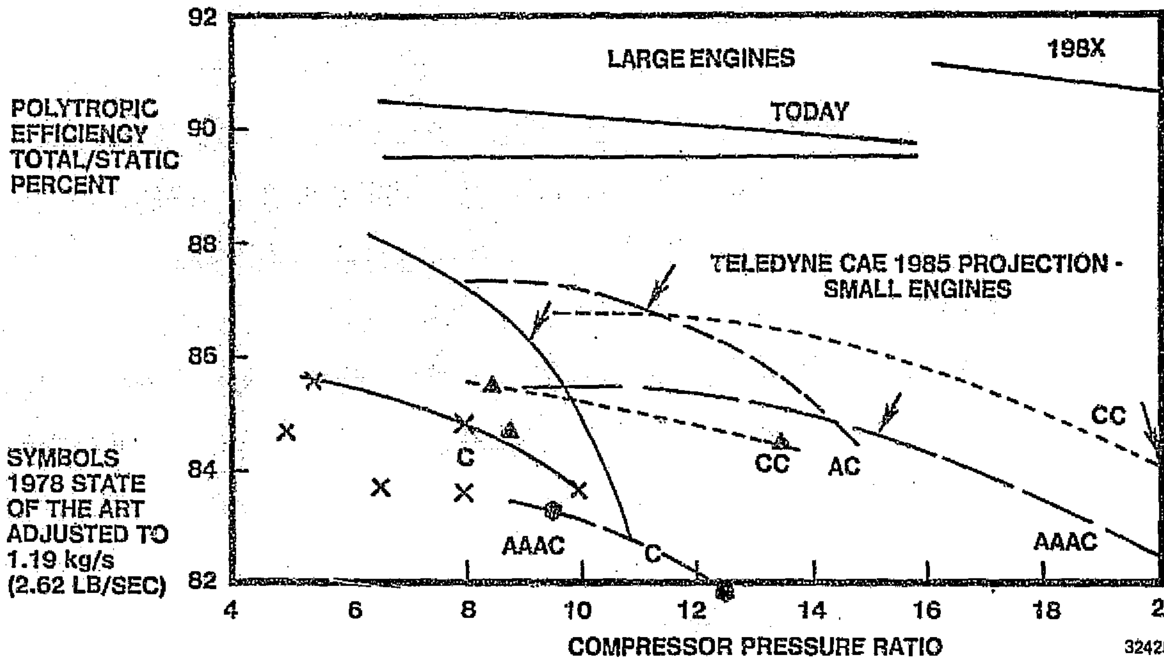
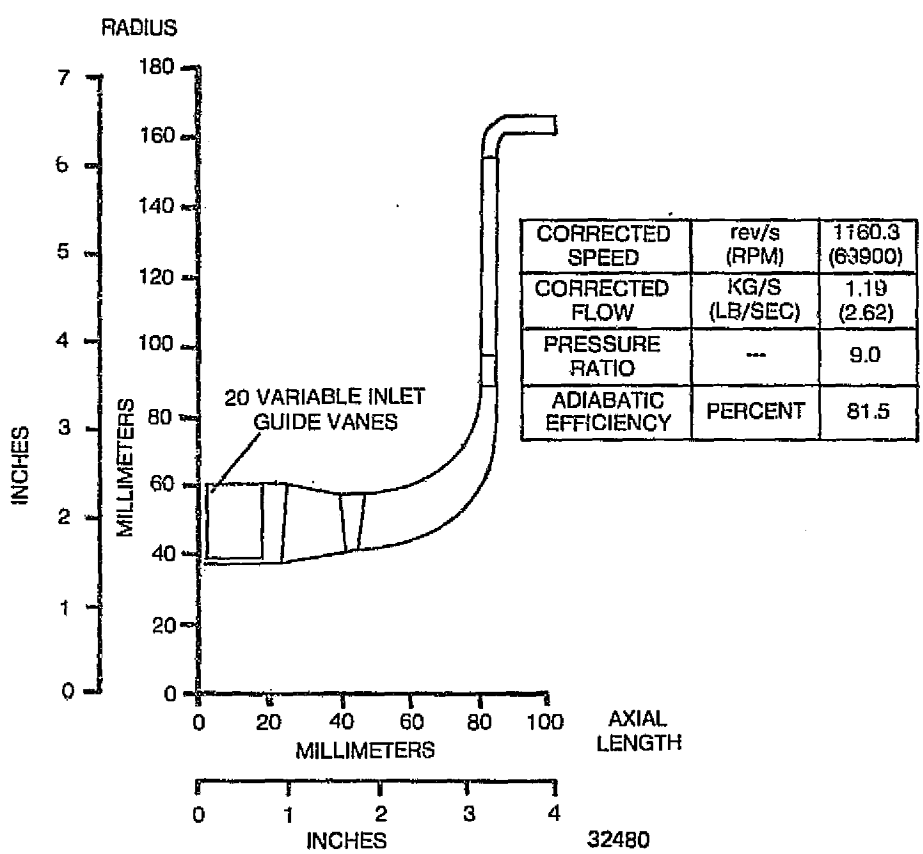


Figure 37. 1985 Compressor Component State-of-the-Art Useable Efficiency.



CORRECTED SPEED	rev/s (RPM)	1160.3 (63900)
CORRECTED FLOW	KG/S (LB/SEC)	1.19 (2.62)
PRESSURE RATIO	---	9.0
ADIABATIC EFFICIENCY	PERCENT	81.5

Figure 38. GATE C9 Compressor Design Study.

STAGE		1	2	OVERALL
CORRECTED SPEED	rev/s (RPM)	1367.0 (82350)	1346.2 (75070)	1367.0 (83250)
CORRECTED FLOW	KG/S (LB/SEC)	1.19 (2.62)	0.77 (1.698)	1.19 (2.62)
PRESSURE RATIO	---	1.70	6.65	11.3
ADIABATIC EFFICIENCY	PERCENT	82.2	84.4	81.7

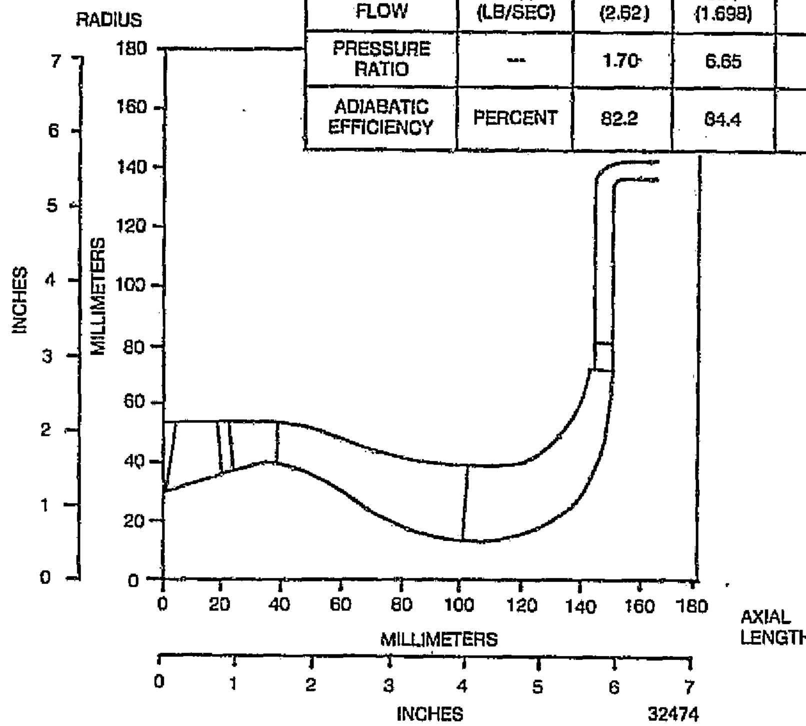


Figure 39. GATE AC 11.3 Compressor Design Study.

STAGE		1 THRU 3	4	OVERALL
CORRECTED SPEED	rev/s (RPM)	1367.0 (82350)	1005.6 (63590)	1367.0 (82350)
CORRECTED FLOW	KG/S (LB/SEC)	1.19 (2.62)	0.334 (0.736)	1.19 (2.62)
PRESSURE RATIO	---	4.66	3.24	15.0
ADIABATIC EFFICIENCY	PERCENT	80.5	83.8	78.2

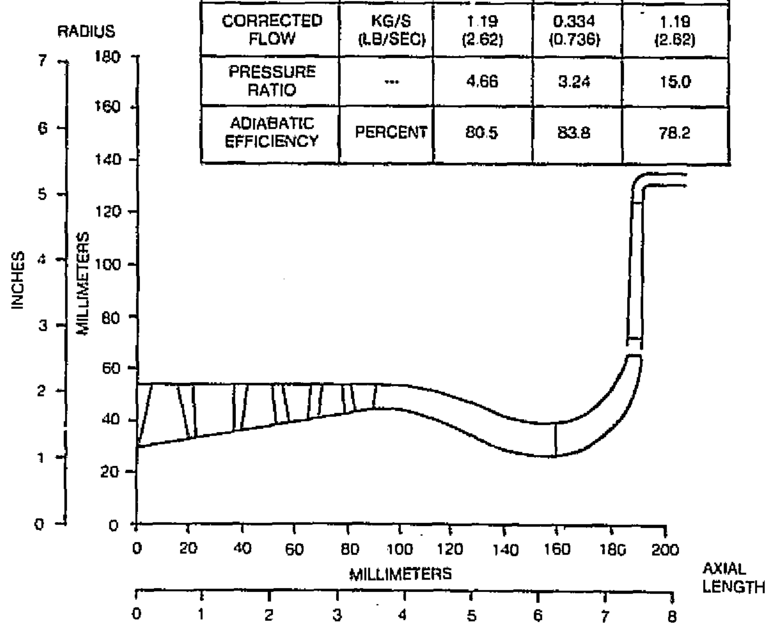


Figure 40. GATE AAAC 15 Compressor Design Study.

STAGE		1	2	OVERALL
CORRECTED SPEED	rev/s (RPM)	1246.3 (75080)	869.0 (52350)	1246.3 (75080)
CORRECTED FLOW	KG/S (LB/S)	1.19 (2.62)	0.19 (0.42)	1.19 (2.62)
PRESSURE RATIO	—	9.0	2.222	19.69
ADIABATIC EFFICIENCY	PERCENT	79.8	80.9	76.6

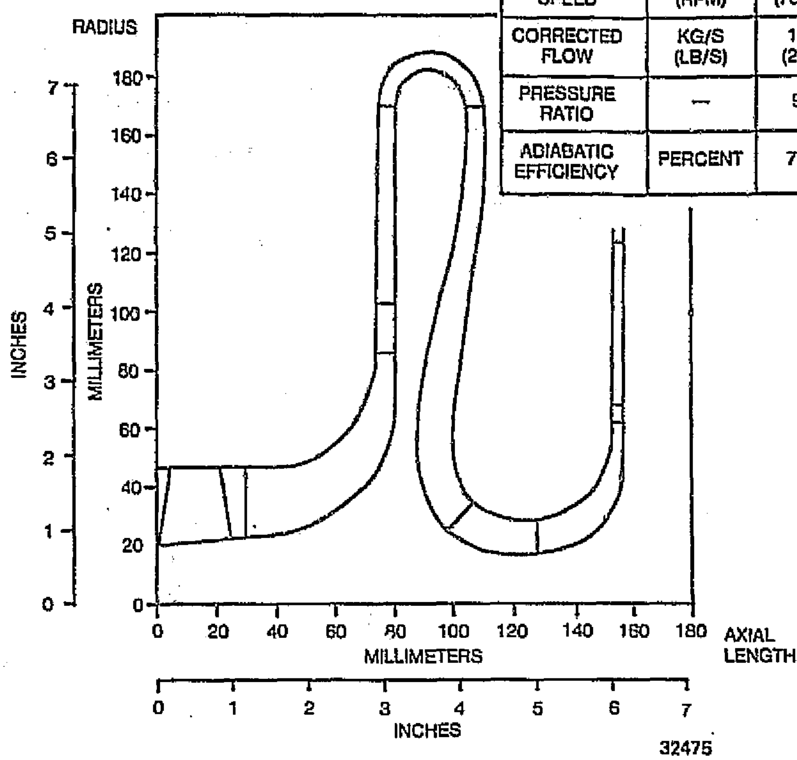


Figure 41. GATE CC 20 Compressor Design Study.

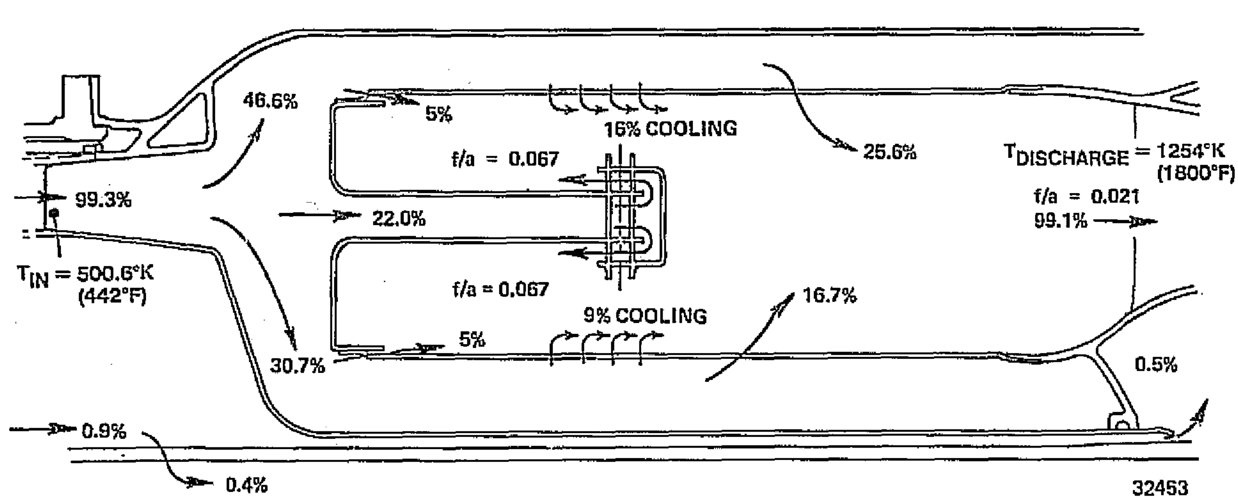


Figure 42. Combustor Flowpath and Flow Distribution.

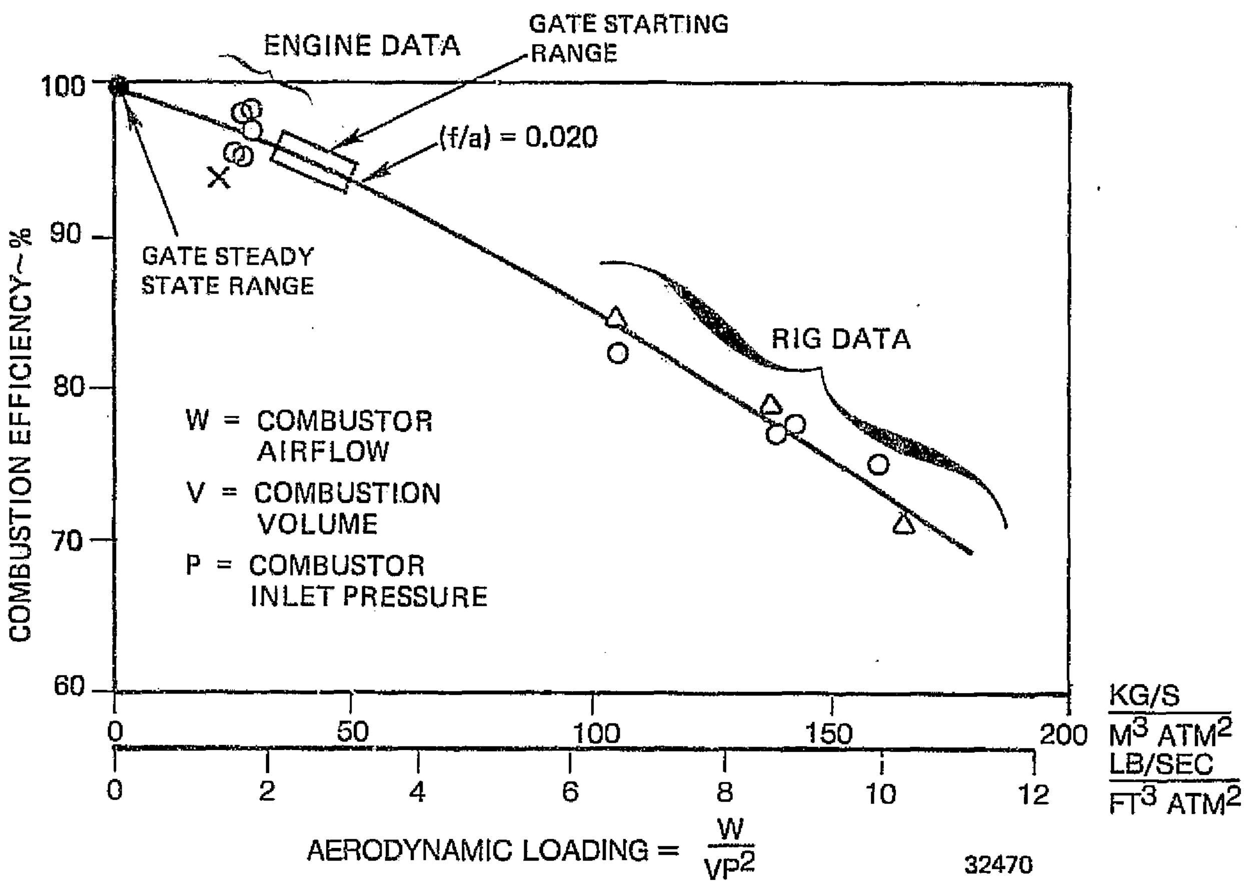


Figure 43. Combustor Feasibility Analysis.

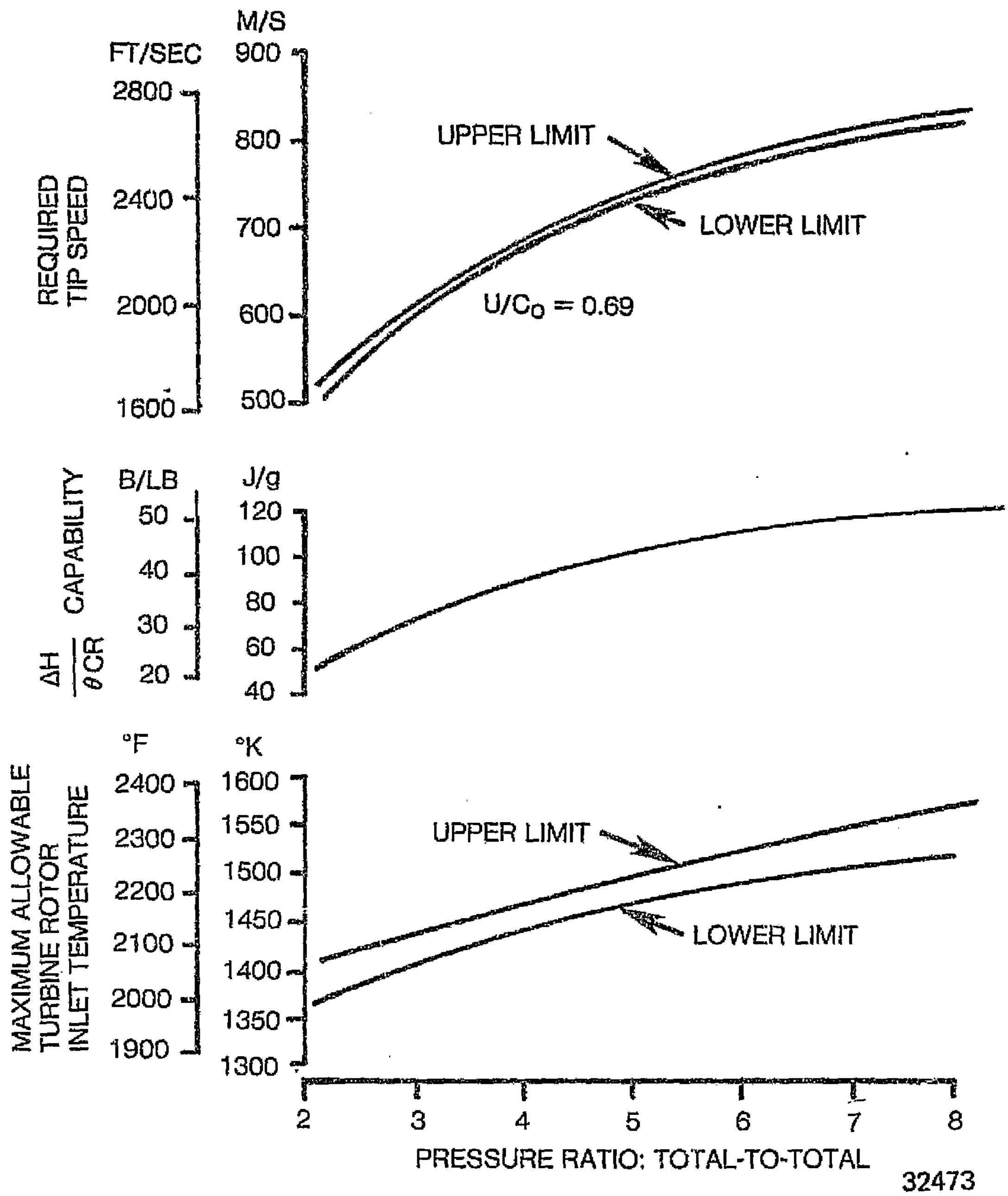


Figure 44. Maximum Temperature Capabilities of Uncooled Radial Turbine Rotors.

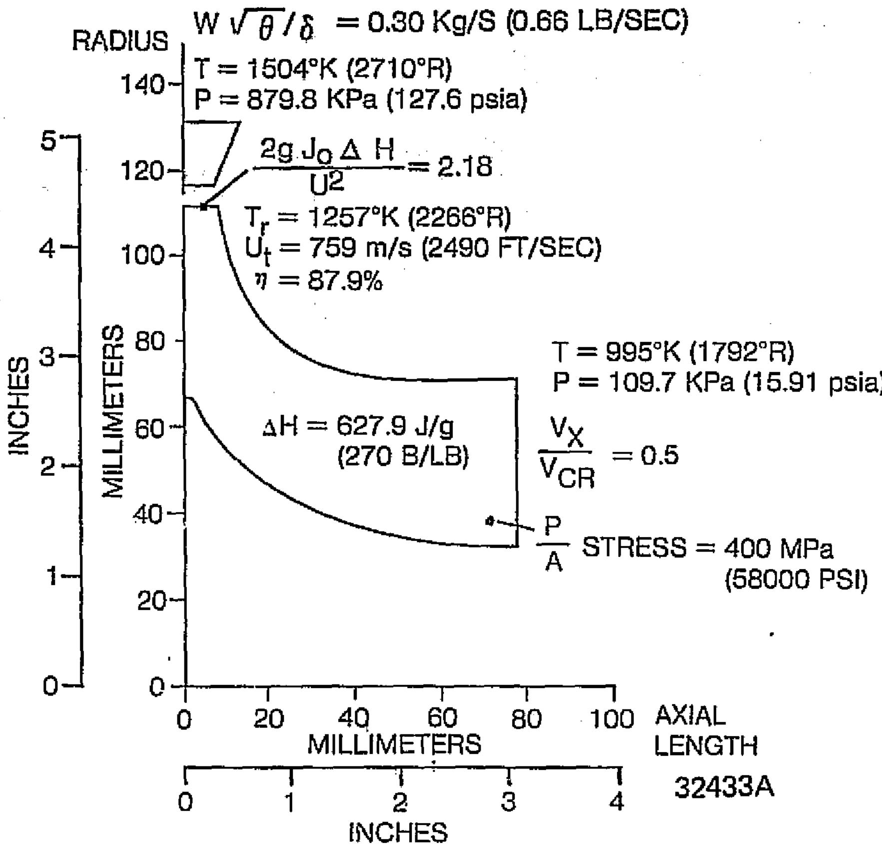


Figure 45. C9 Turbine Design Study.

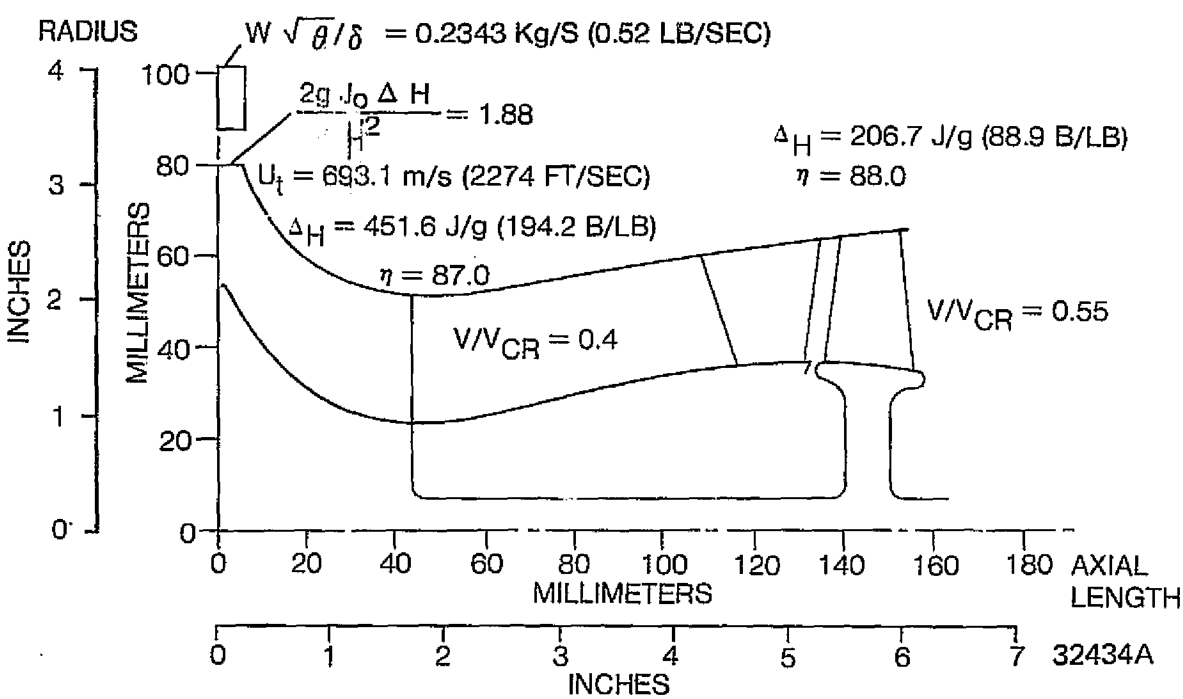


Figure 46. AC11.3 Turbine Design Study

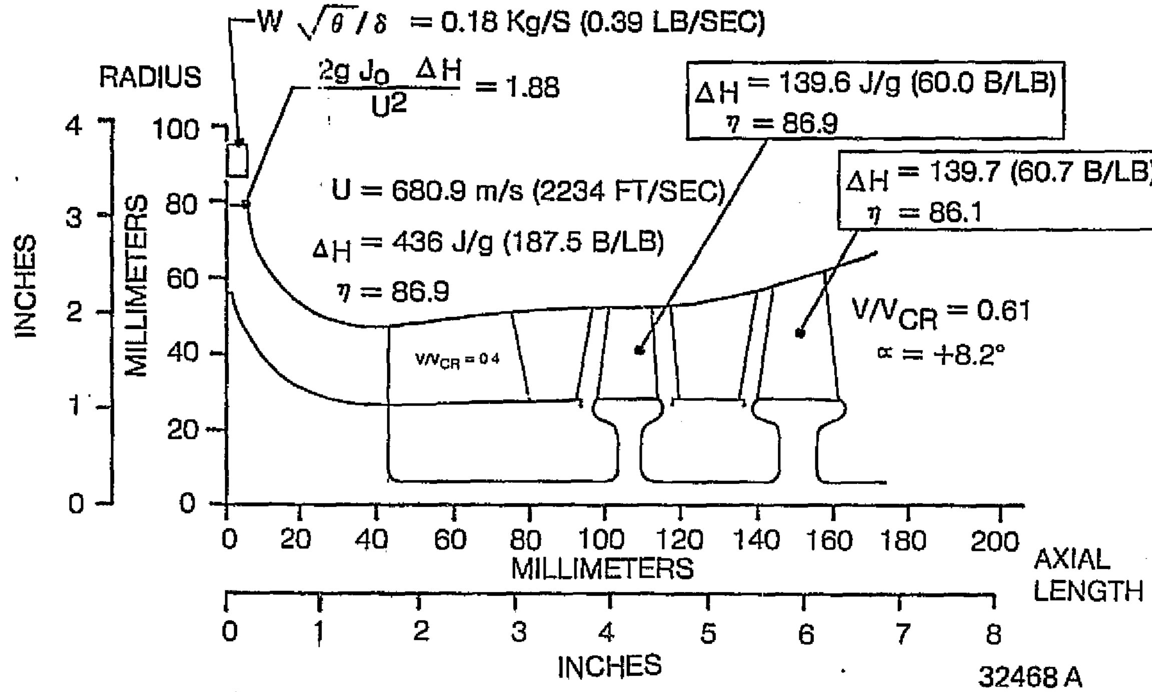


Figure 47. AAAC 15 Turbine Design Study.

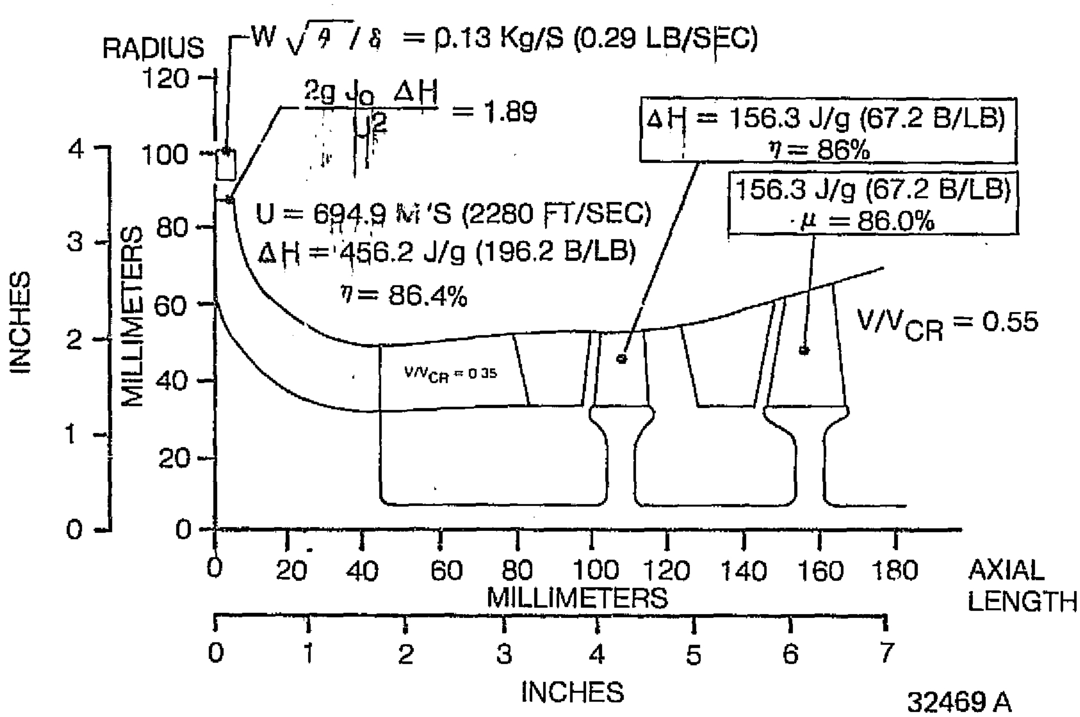


Figure 48. CC 20 Turbine Design Study.

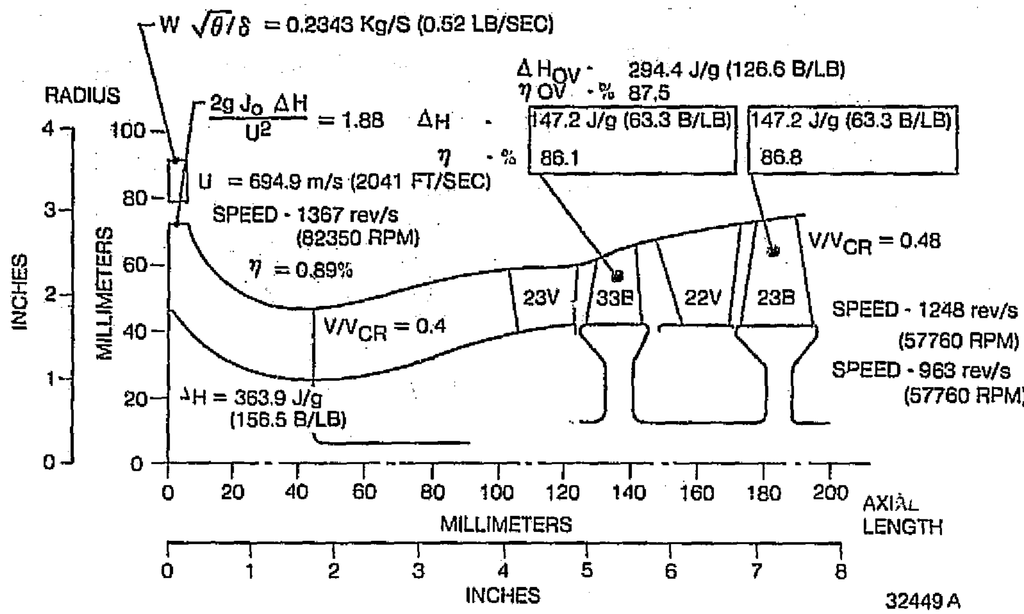


Figure 49. AC11.3 Free Turbine Design Study.

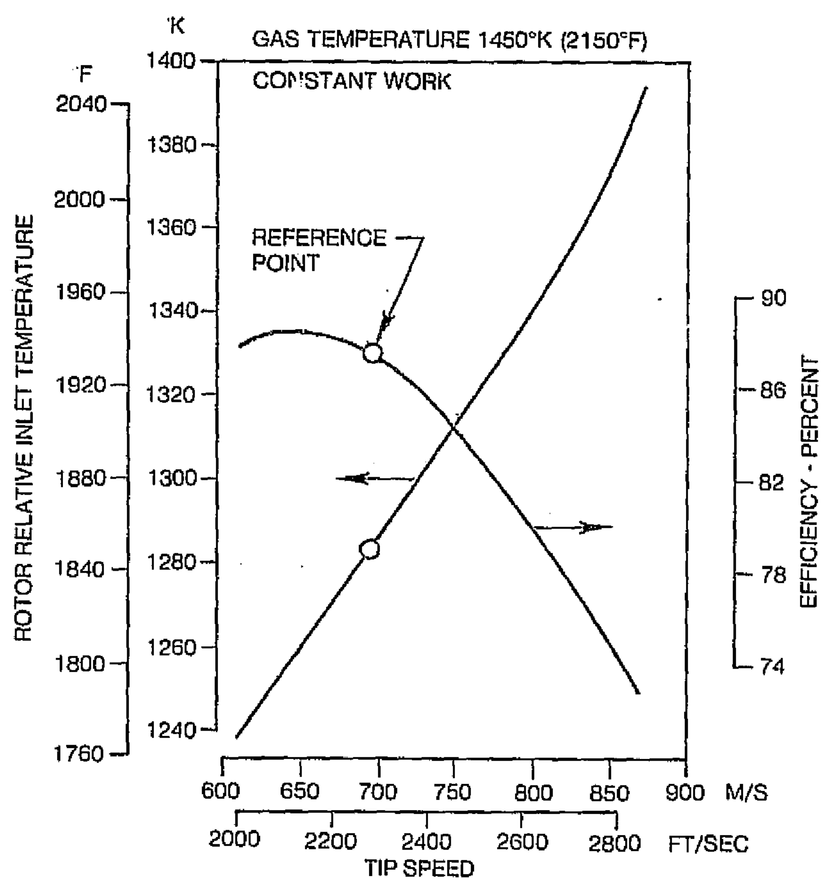


Figure 50. Rotor Relative Temperature and Efficiency Vs. Wheel Speed.

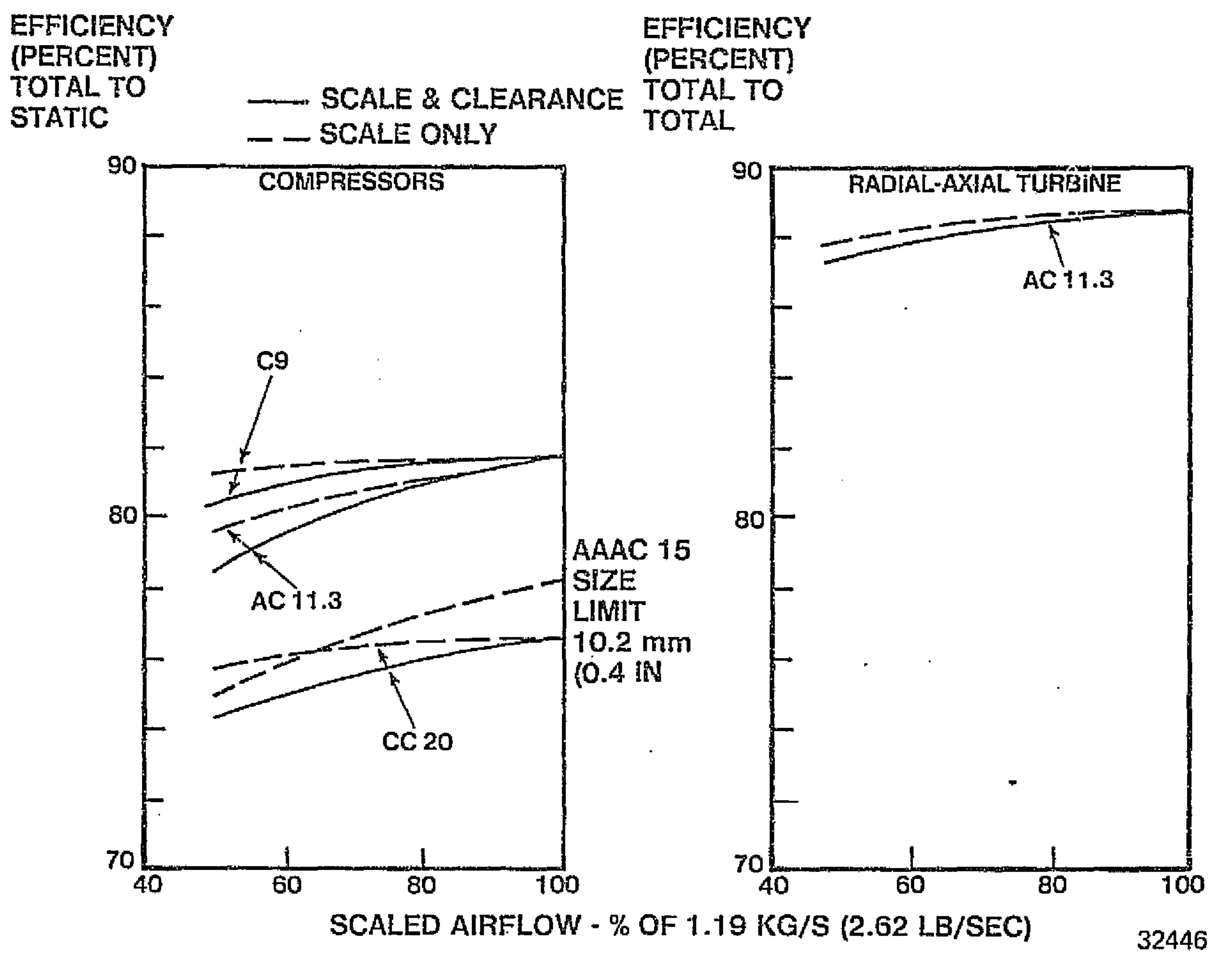


Figure 51. GATE Component Efficiencies Vs. Airflow.

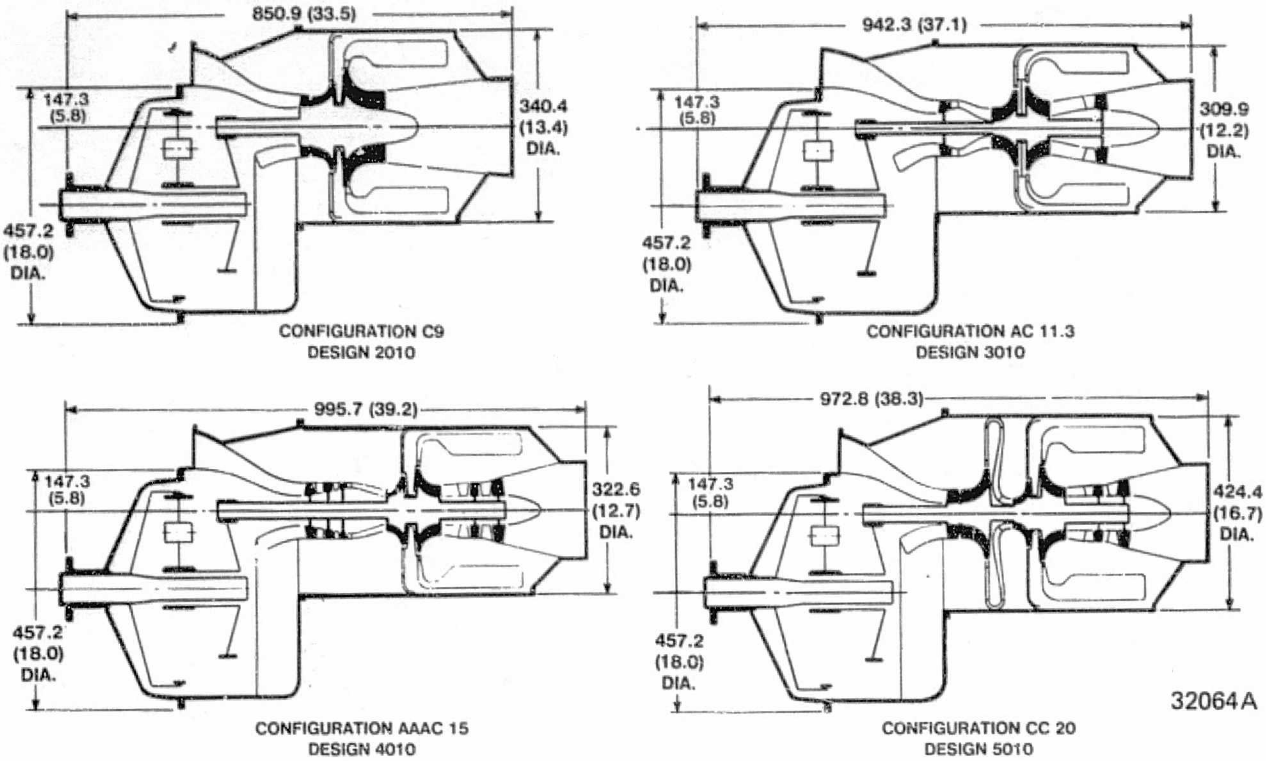


Figure 52. Basic Engine Configurations: Equal Power - 365.5 KW (490 HP) at Sea Level Static Conditions: Dimensions - mm (In.)

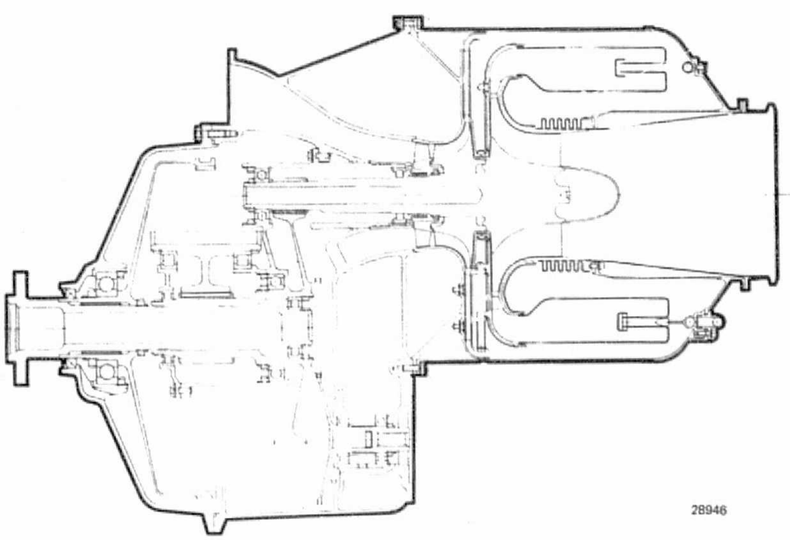


Figure 53. Design 2010 Engine Layout.

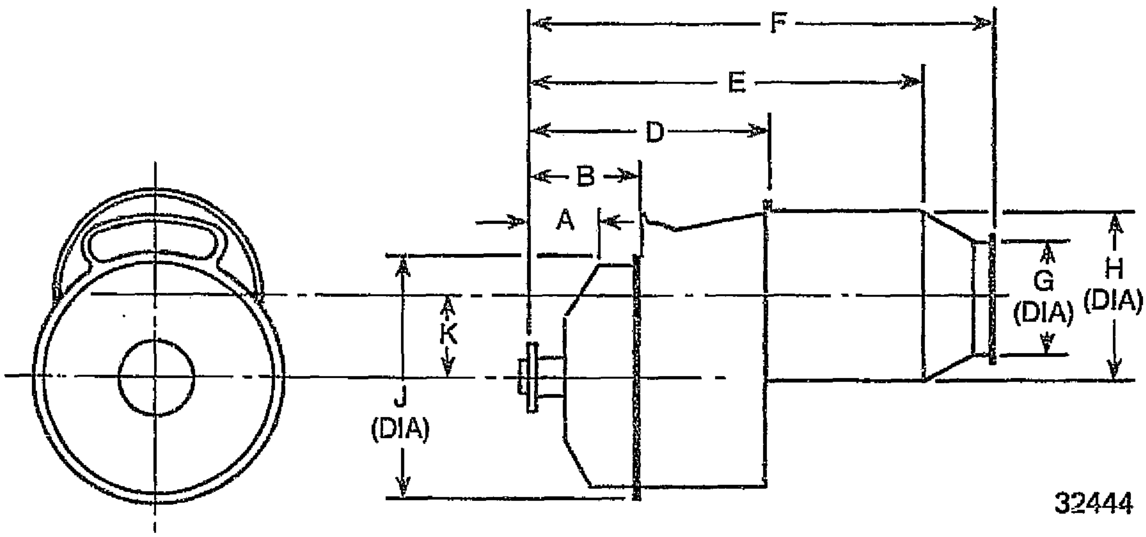
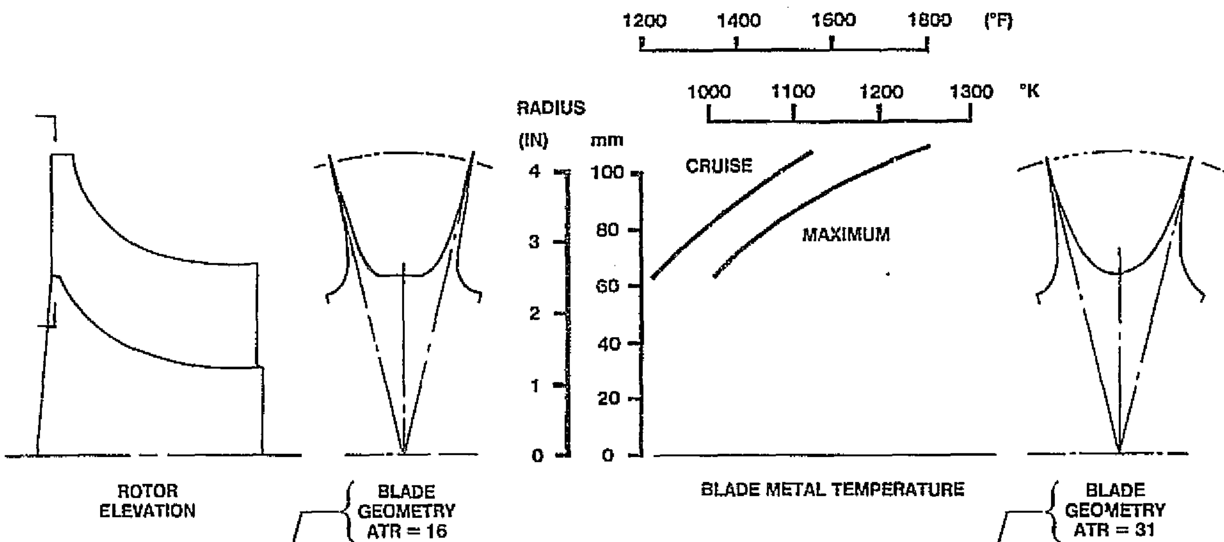


Figure 54. Installation - GATE Turboprop.



STRESS RUPTURE LIFE (HOURS)		
ATR = 16		ATR = 31
3000	CRUISE	10,000 PLUS
20	MAXIMUM TURBINE INLET TEMPERATURE : 1504°K (2250°F)	100
70	MAXIMUM MINUS 28°K (50°F)	300
MATERIAL: 1978 EQUIAXED IN-100		

32432A

Figure 55. Turbine Rotor Design Summary.

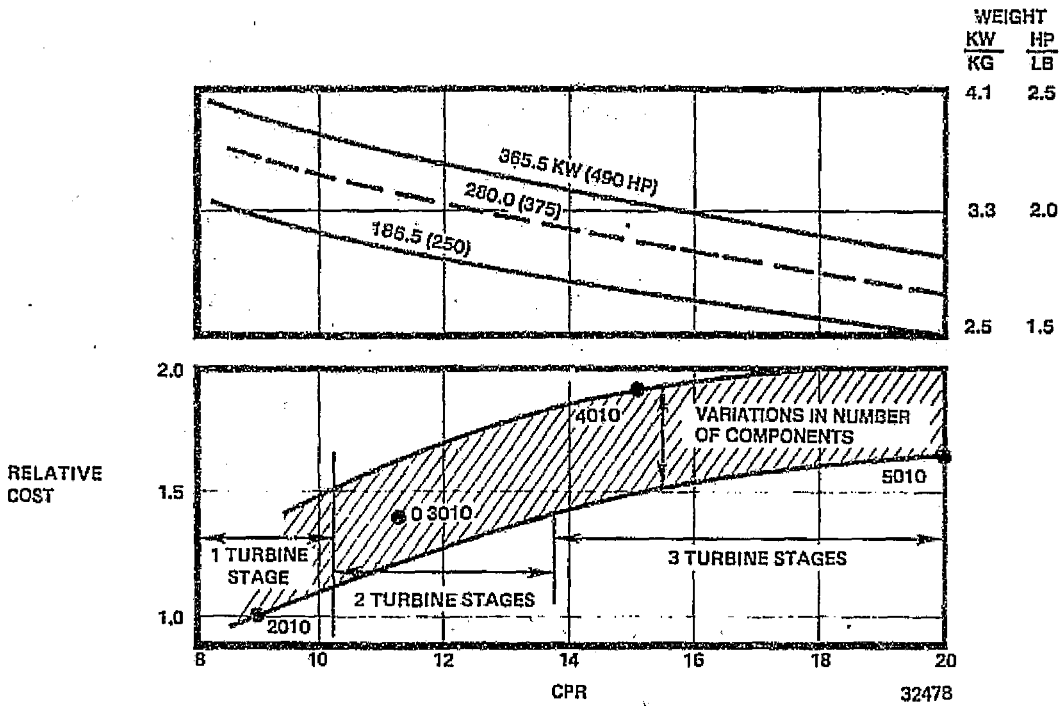


Figure 56. Relative Cost and Power to Weight Ratio With Increasing Cycle Pressure Ratio (CPR).

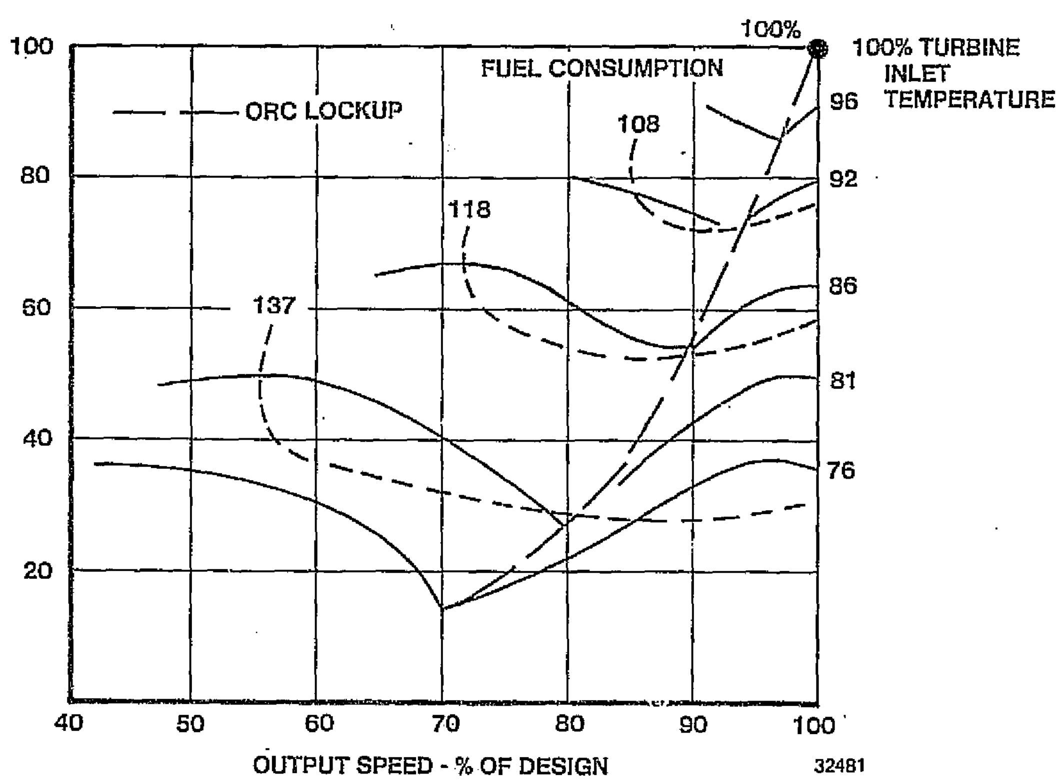
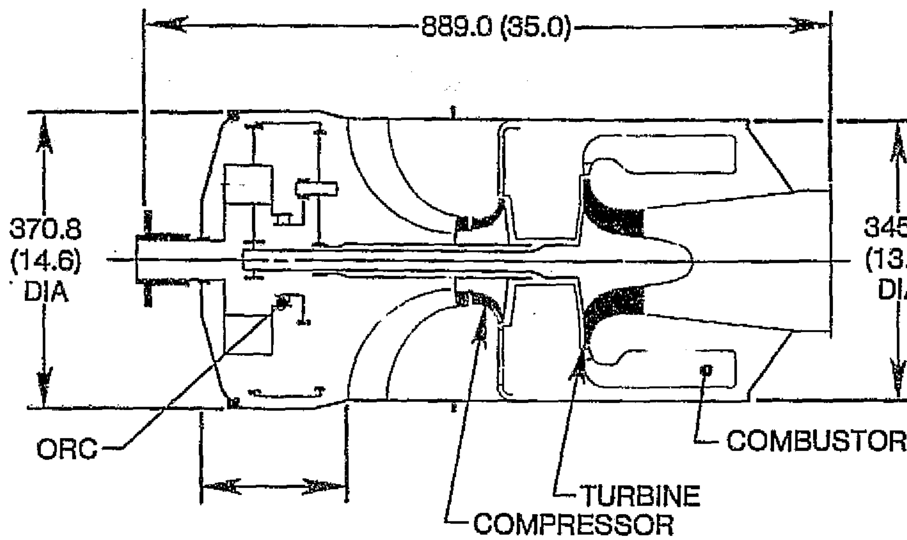


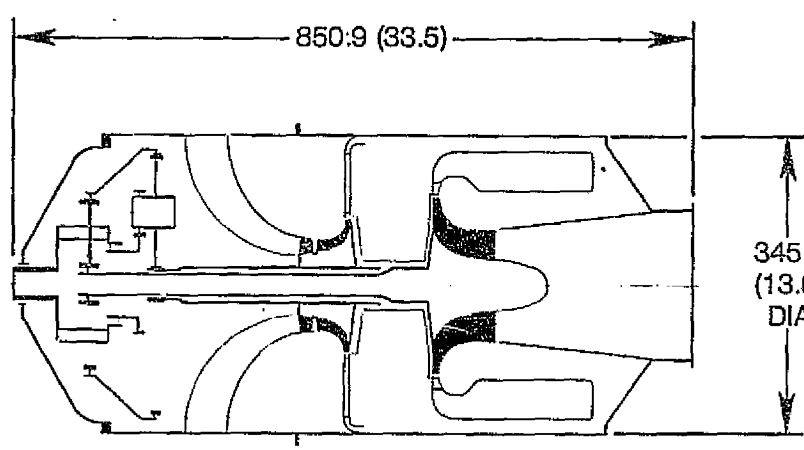
Figure 57. Power Characteristics of a Differential Turbine Engine.



POWER OUTPUT .... 365.5 KW (490 HP)
FUEL CONSUMPTION .... 89.6 μg/J (0.53 LB/HP-HR)
WEIGHT .... 118 KG (260 LB)
DIMENSIONS mm (IN)

32425

Figure 58. Differential Turboprop Design 2011.



POWER OUTPUT .... 365.5 KW (490 HP)
FUEL CONSUMPTION .... 89.6 μg/J (0.53 LB/HP-HR)
WEIGHT .... 111.2 KG (245 LB)
DIMENSIONS mm (IN)

32426

Figure 59. Differential Turboshaft Design 2012.

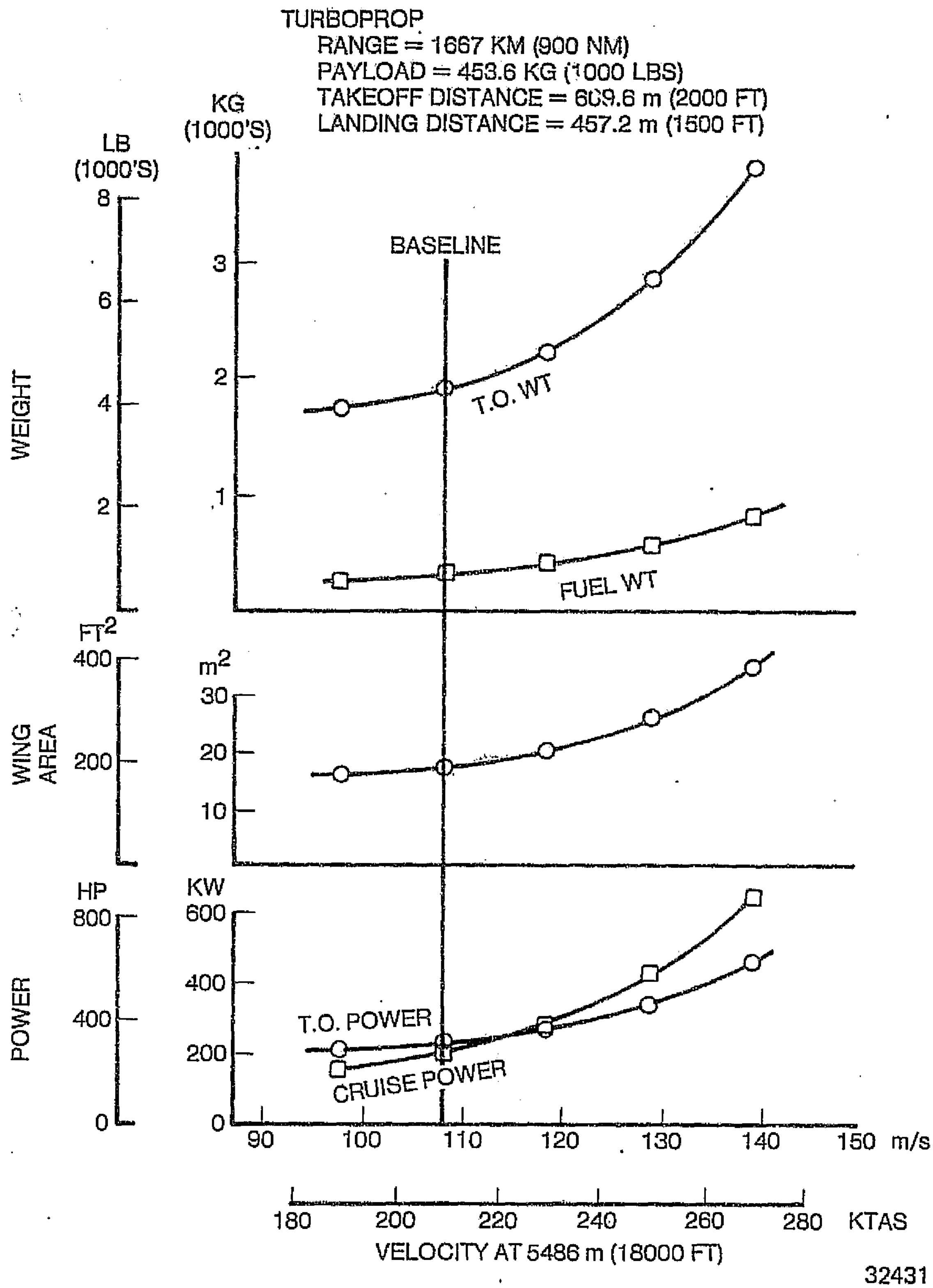


Figure 60. Airplane Size Vs. Cruise Velocity - Category IIIP.

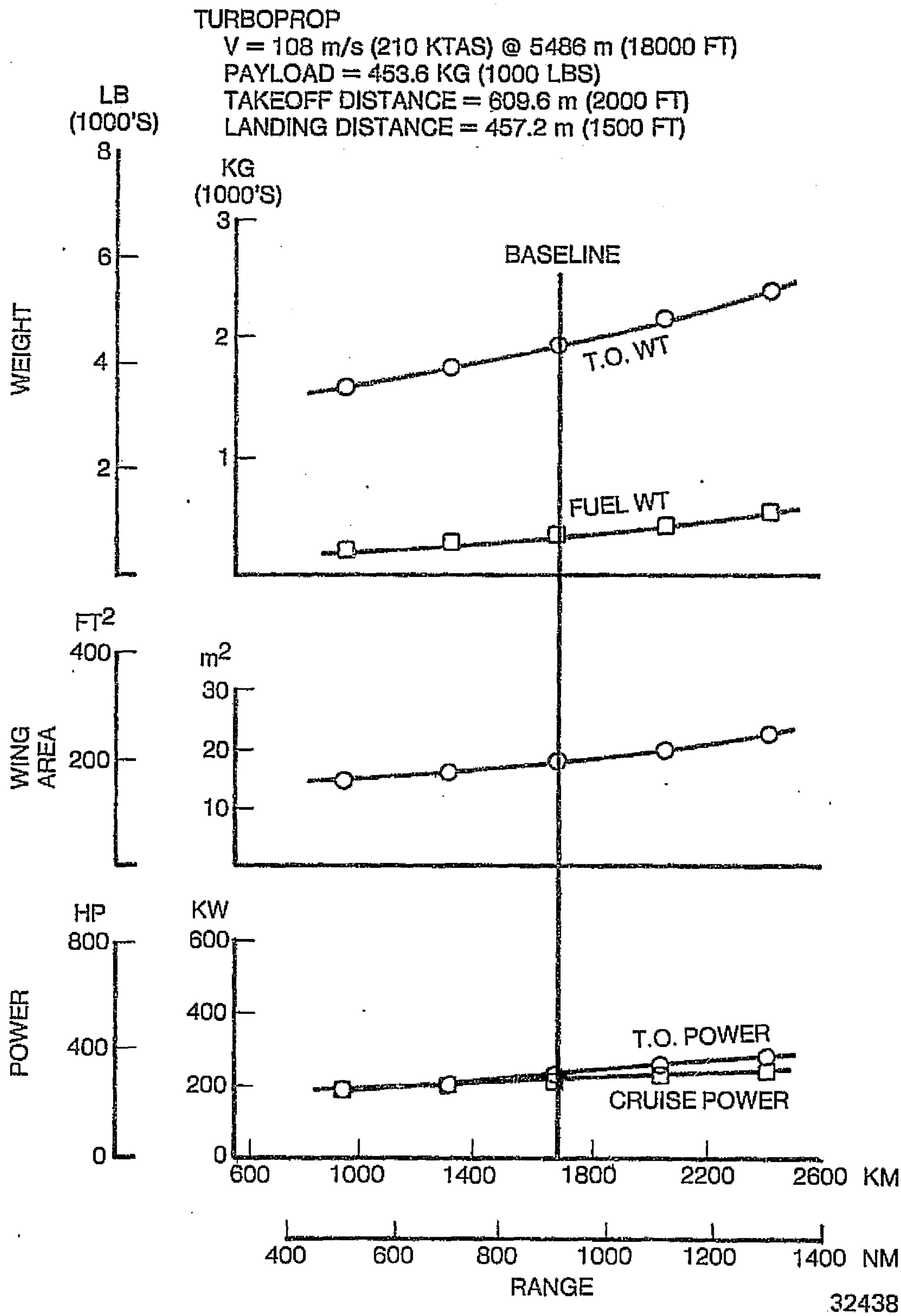


Figure 61. Airplane Size Vs. Range - Category IIIP.

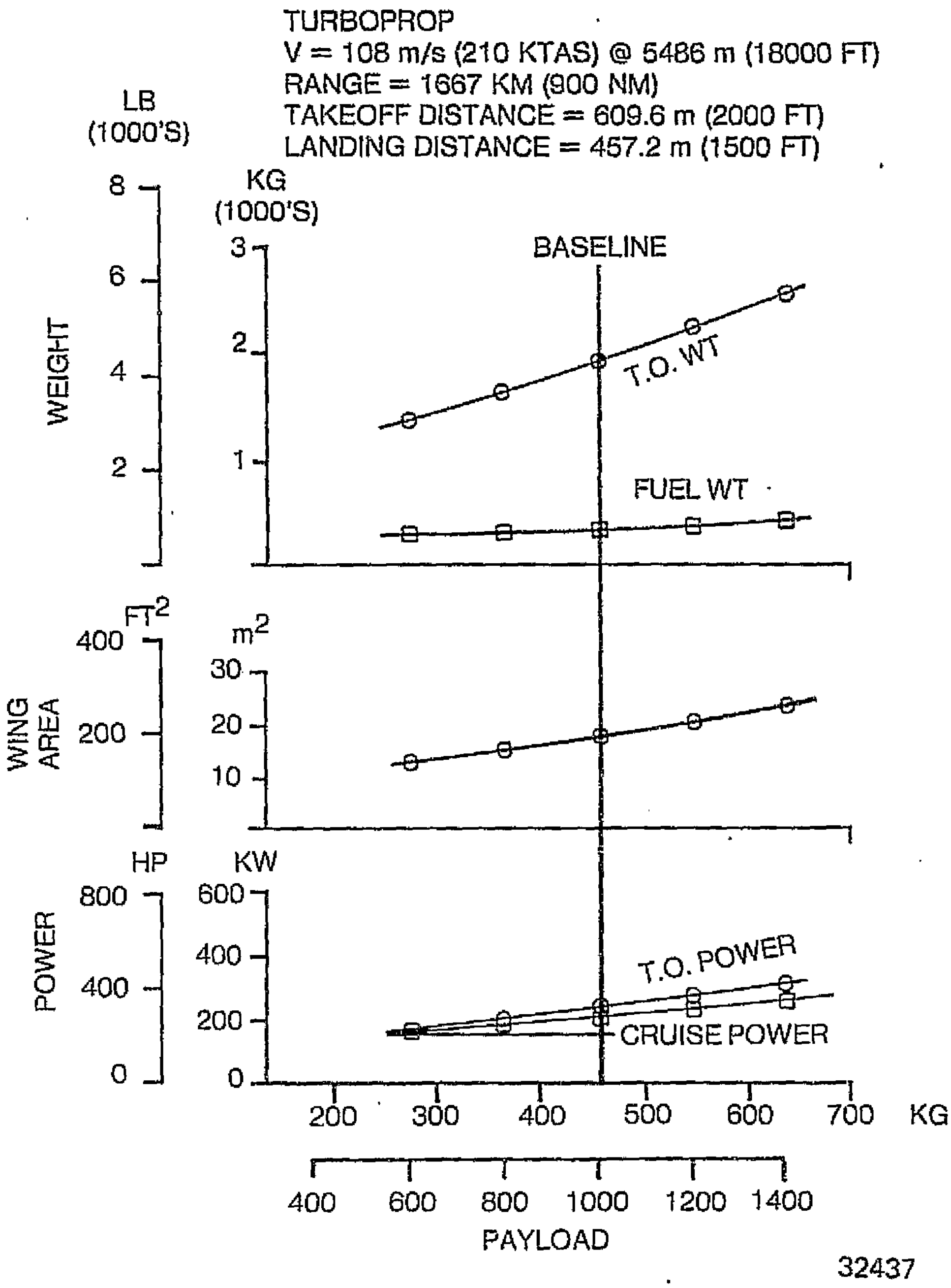


Figure 62. Airplane Size Vs. Payload - Category IIIP.

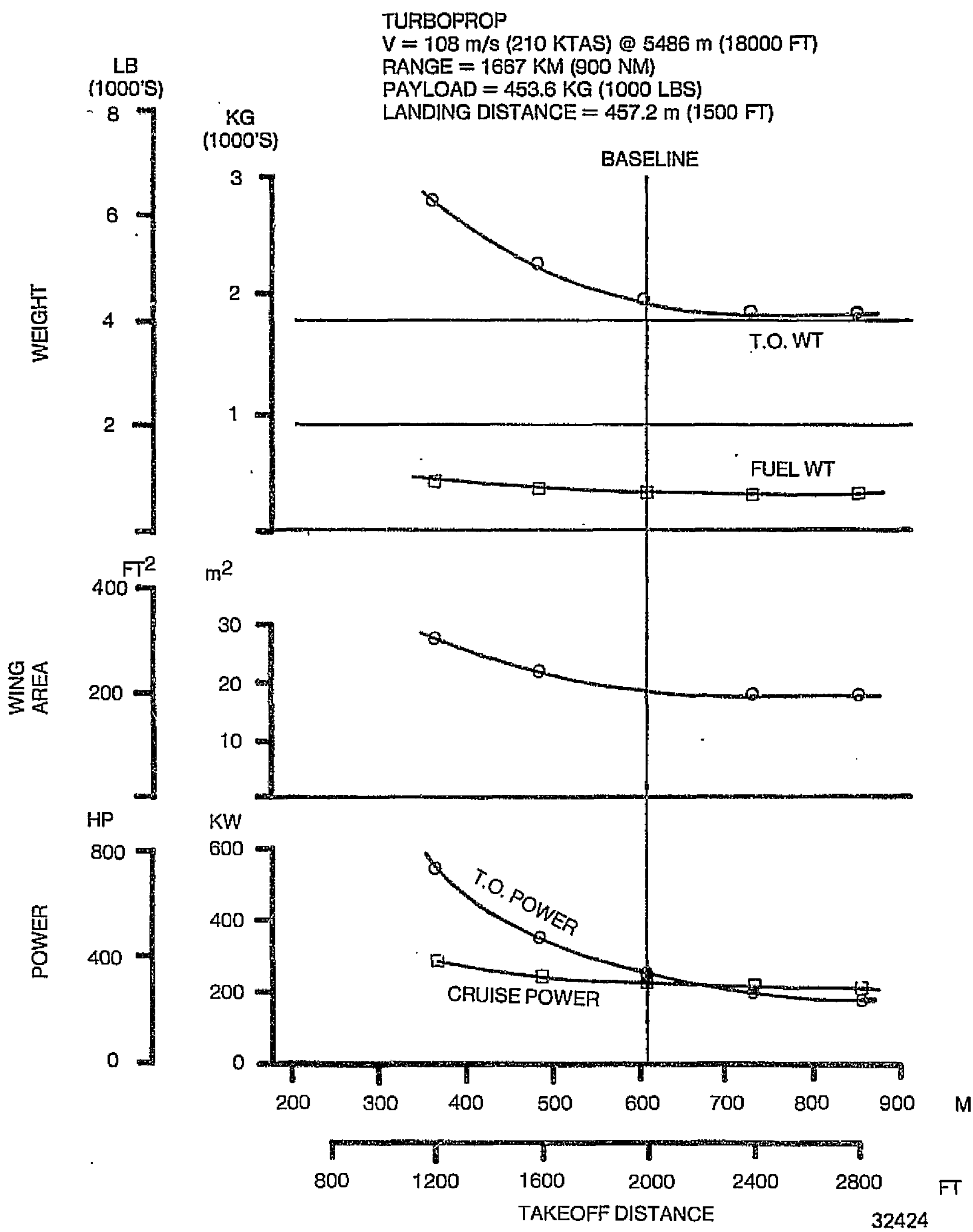


Figure 63. Airplane Size Vs. Take-Off Distance Category IIIP.

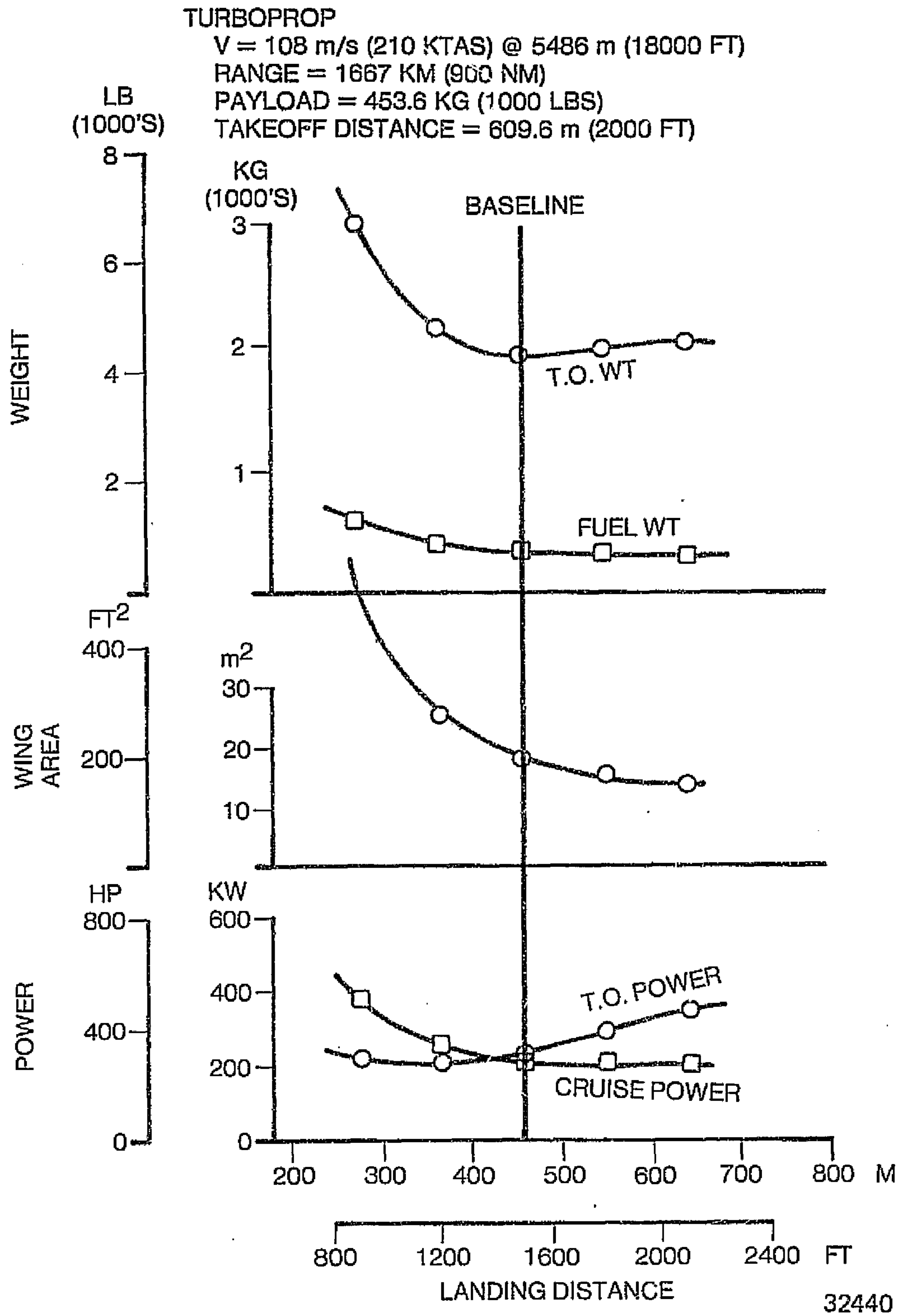


Figure 64. Airplane Size Vs. Landing Distance - Category IIIP.

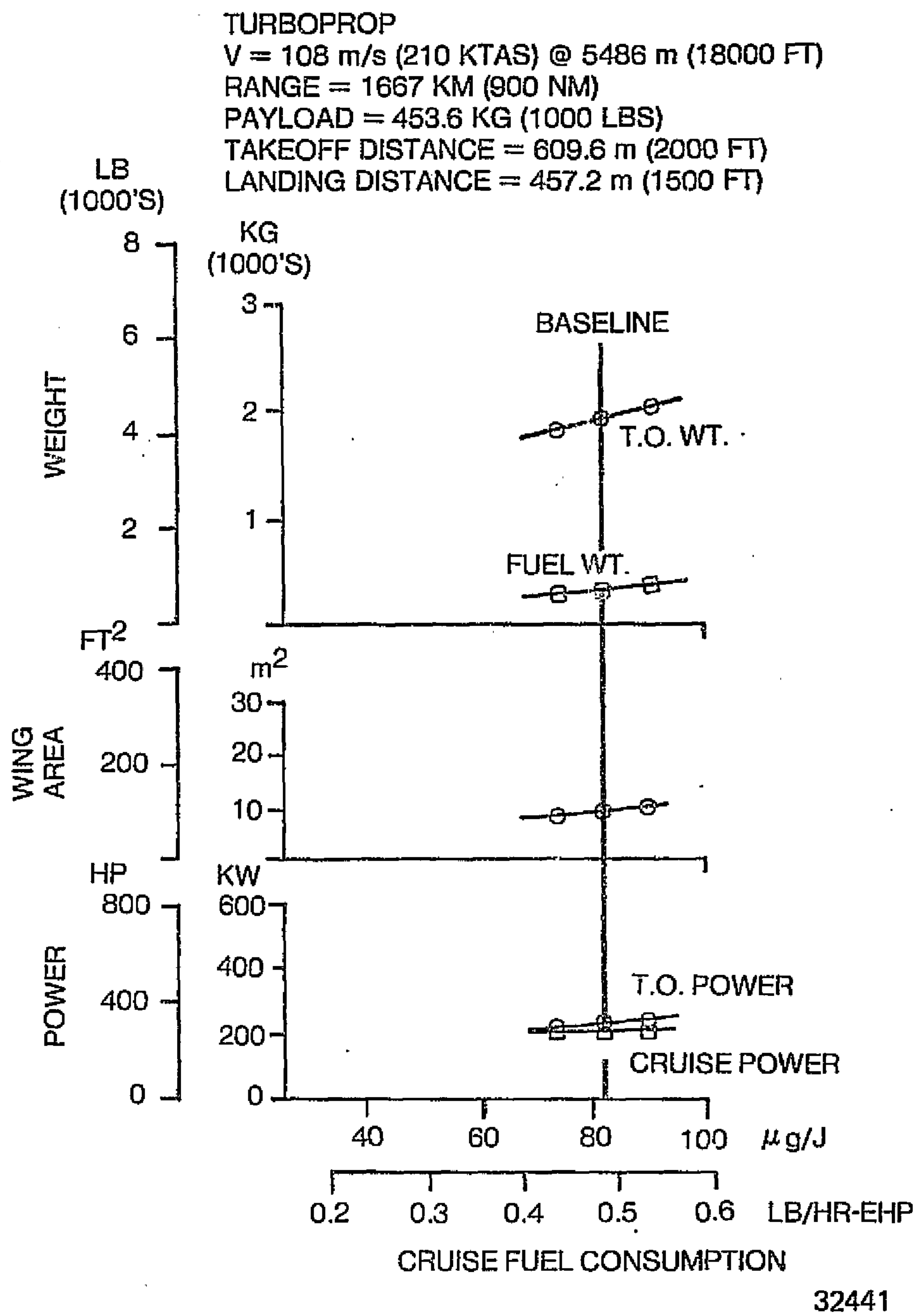


Figure 65. Airplane Size Vs. Cruise Fuel Consumption - Category IIIP.

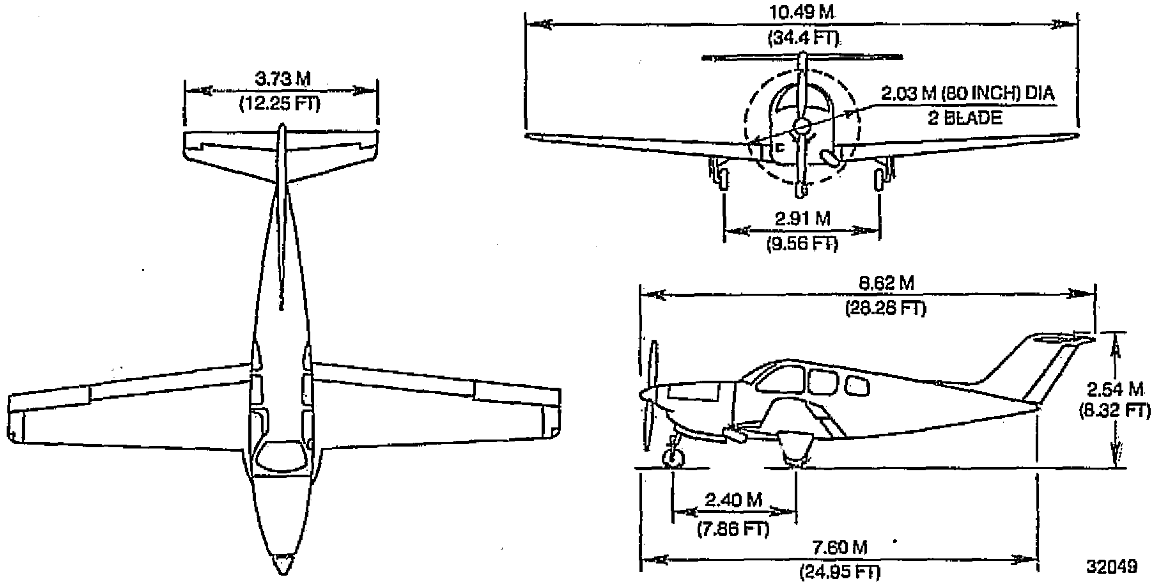


Figure 66. GATE Turboprop Powered Aircraft Three Views - Category II.

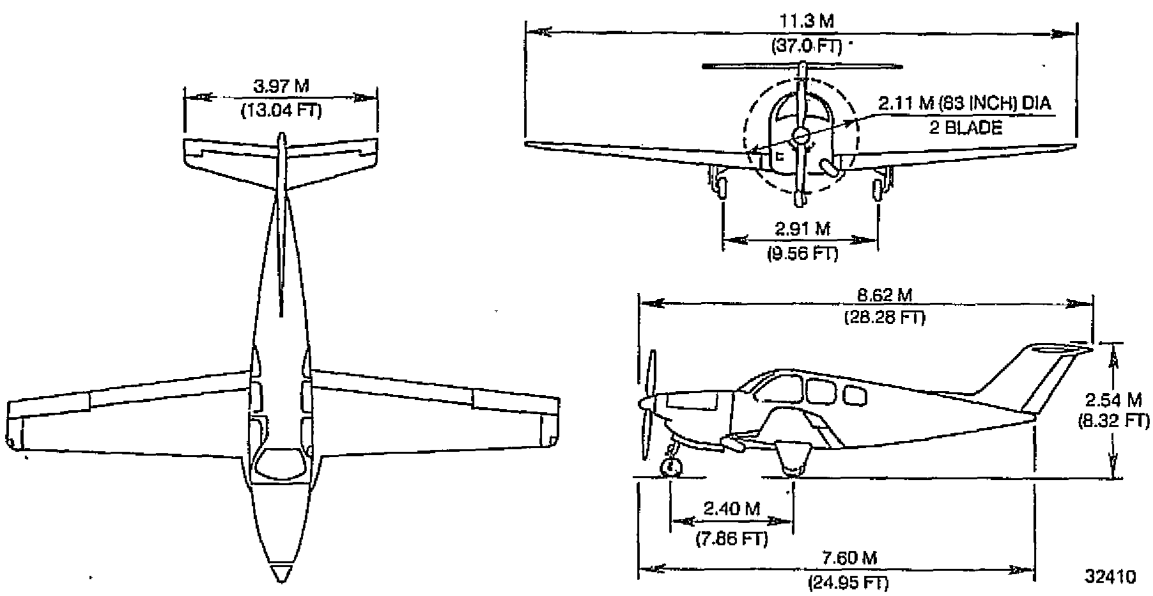


Figure 67. GATE Turboprop Powered Aircraft Three Views - Category IIIU.

C-2

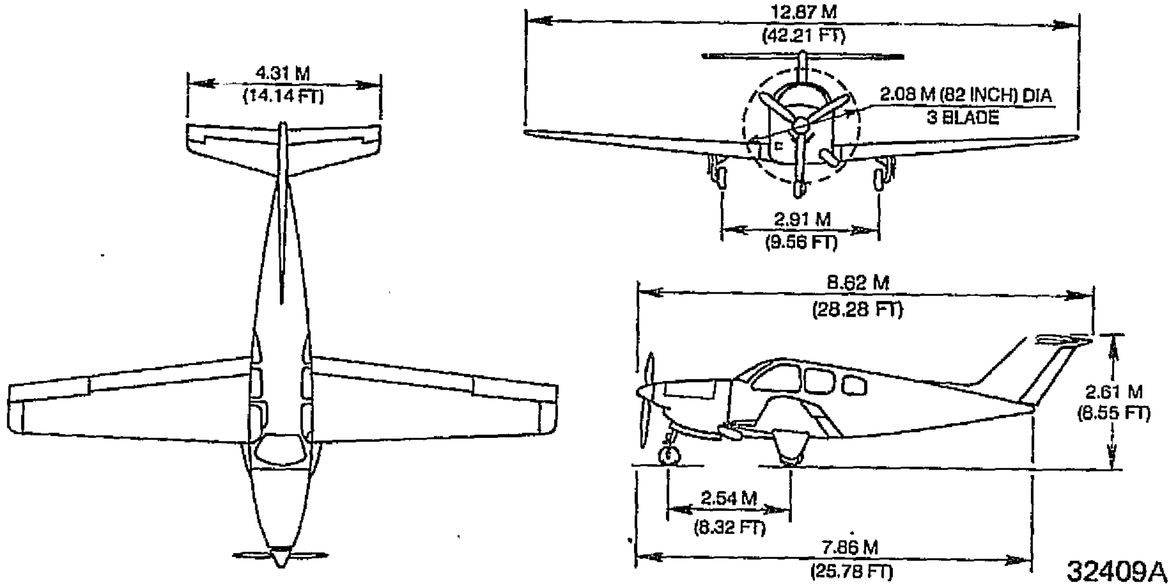


Figure 68. GATE Turboprop Powered Aircraft Three Views - Category IIIP.

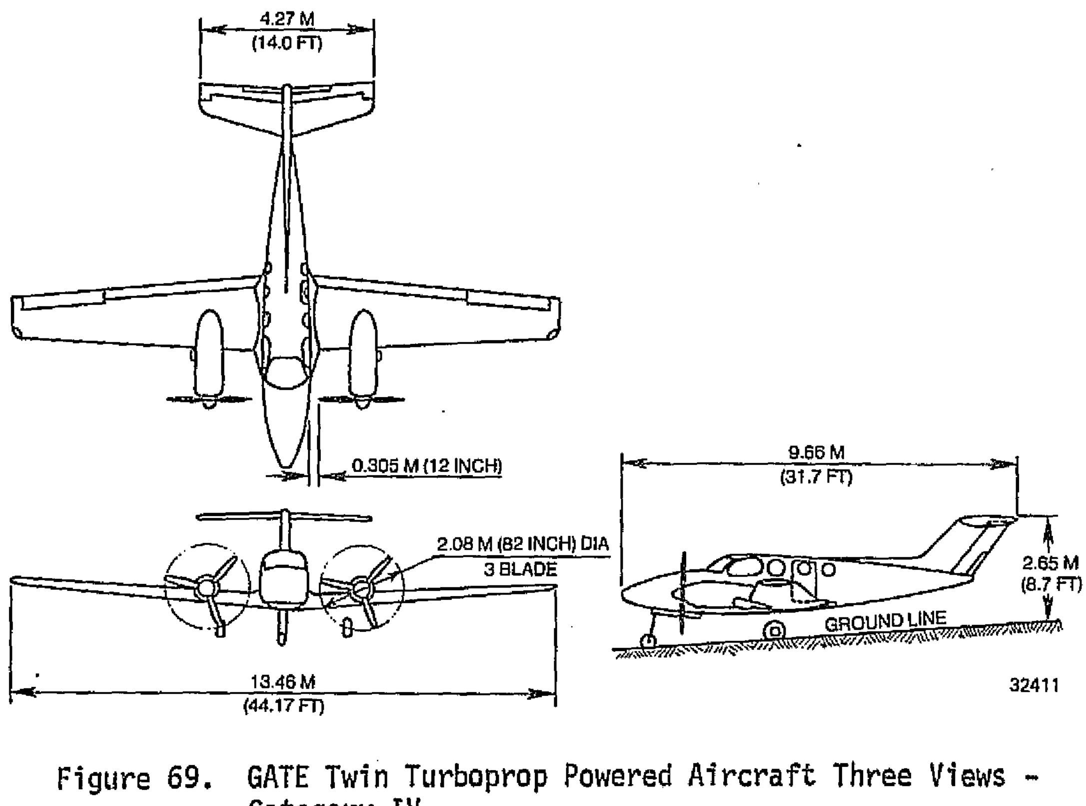


Figure 69. GATE Twin Turboprop Powered Aircraft Three Views - Category IV.

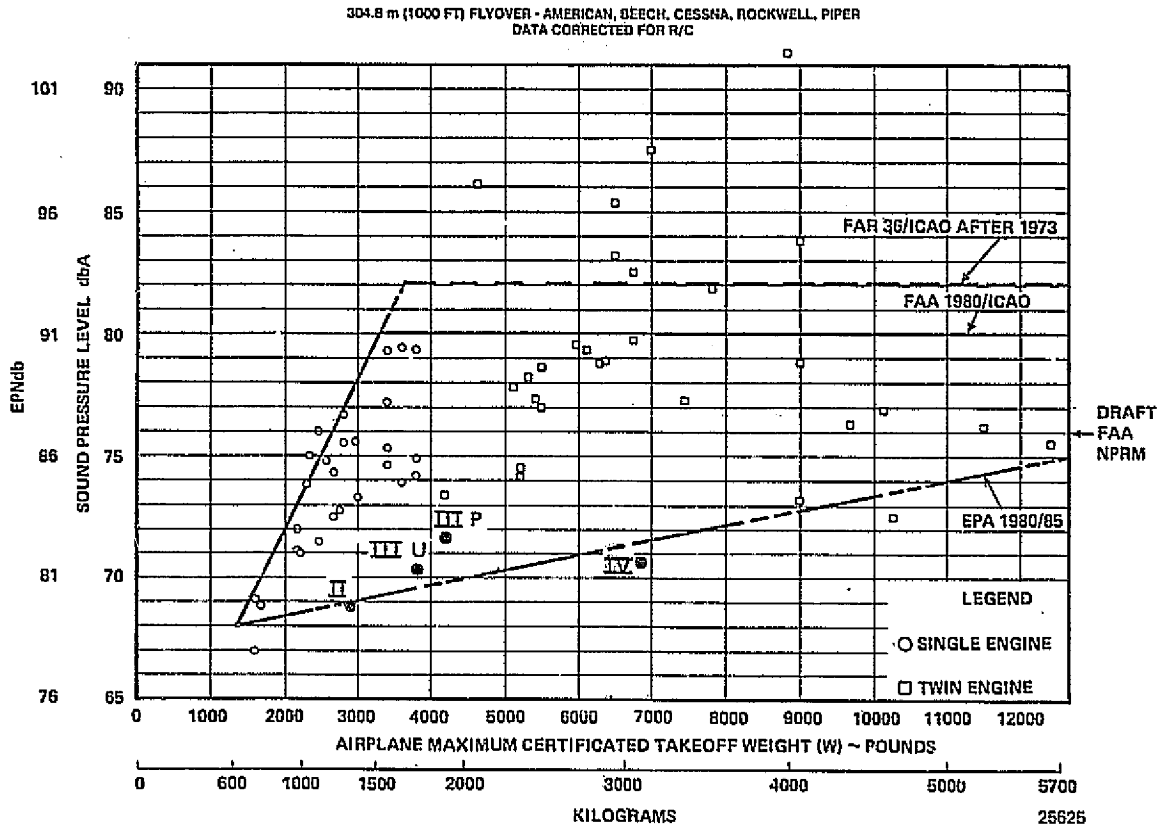


Figure 70. Projected GATE Powered Aircraft Noise Levels Compared With 1976 GAMA Data.

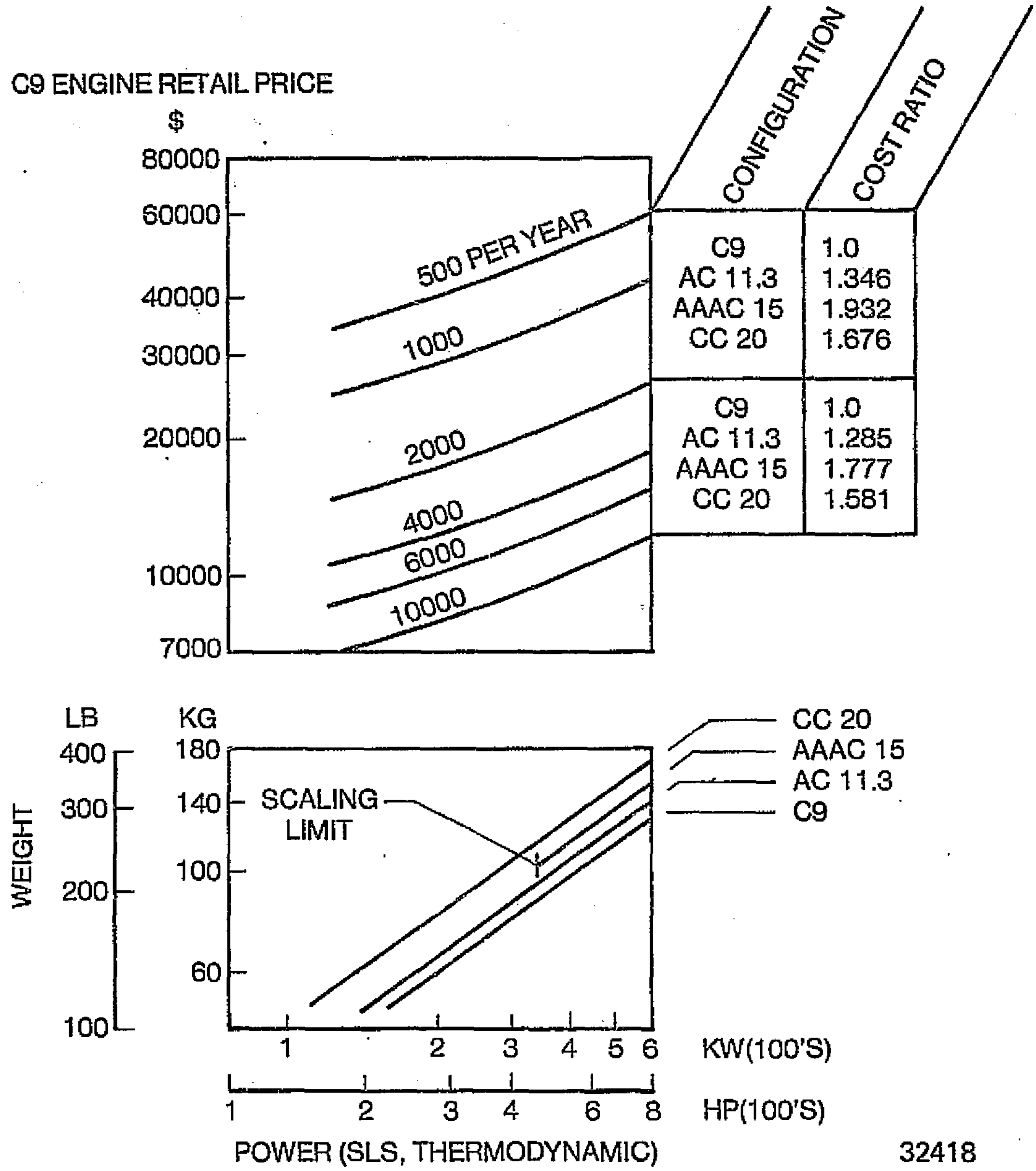


Figure 71. Engine Weight and Retail Price Vs. Power for Different Production Rates.

- NON-REVENUE AIRCRAFT: 5-YEAR OWNERSHIP, 30% RESALE
- L^2C^2 = {FIXED + DIRECT (VARIABLE)} COST OF OWNERSHIP - FY 77 DOLLARS
- MISSION: PAYLOAD & RANGE AS IN AIRCRAFT SYNTHESIS + PARAMETRIC HRS/YR

FIXED		VARIABLE	
AIRCRAFT	ENGINE	AIRCRAFT + PROP	ENGINE
ACQUISITION(1)	ACQUISITION(2)	---	FUEL(2)
DEPRECIATION/ INTEREST(3)	DEPRECIATION/ INTEREST(3)	SERVICING/PREFLIGHT MTCE & REPAIR(3)	SERVICING/PREFLIGHT MTCE & REPAIR(2)
INSURANCE(3)	INSURANCE(3)	OVERHAUL(3)	OVERHAUL(3)
HANGAR & MISC.(3)	---	MISC.(3)	---

(1) BEECH ANALYSIS-AIRCRAFT SYNTHESIS RESULTS

(2) TELEDYNE CAE ANALYSIS-ENGINE STUDY RESULTS

(3) STANDARD FORMULATION

32447

Figure 72. Limited Life Cycle (L^2C^2) Features and Data Sources.

FUEL COST: 18.5¢ TO 53¢ PER LITER (70¢ TO $2.00 PER GALLON)

MISSION USAGE:

CATEGORY	"AVERAGE" HRS/YEAR	RANGE
II & IIIU	500	100 - 1000
IIIP & IV	400	100 - 800

32457

T.B.O.: TURBINE - 3500 HRS.
RECIP. - 1250 HRS.

Figure 73. Parametrics for L^2C^2 Analysis.

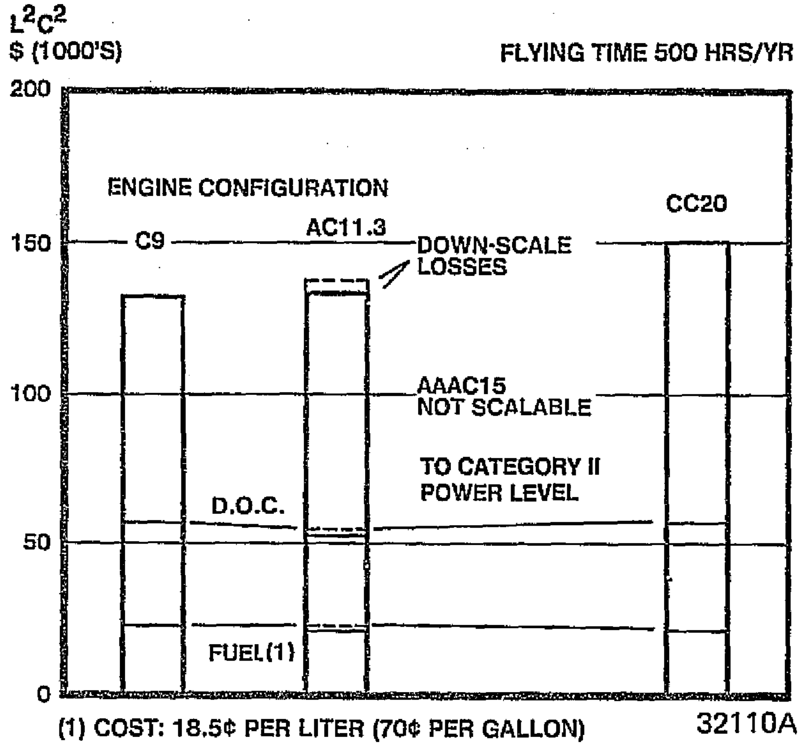


Figure 74. Category II, 5 Year L^2C^2 Summary. The Simplest Engine (C9) is Best.

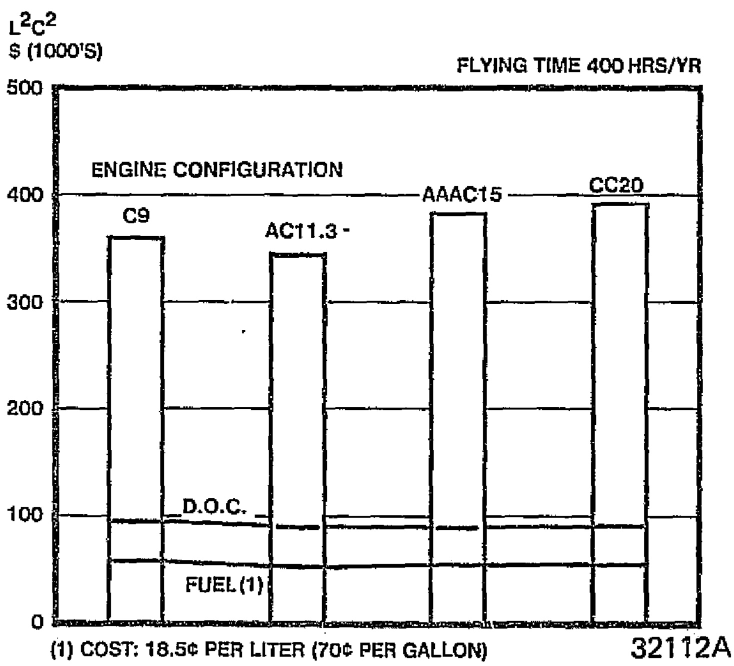


Figure 75. Category IV, 5 Year L^2C^2 Summary. The Simplest Engine (AC 11.3) is Best.

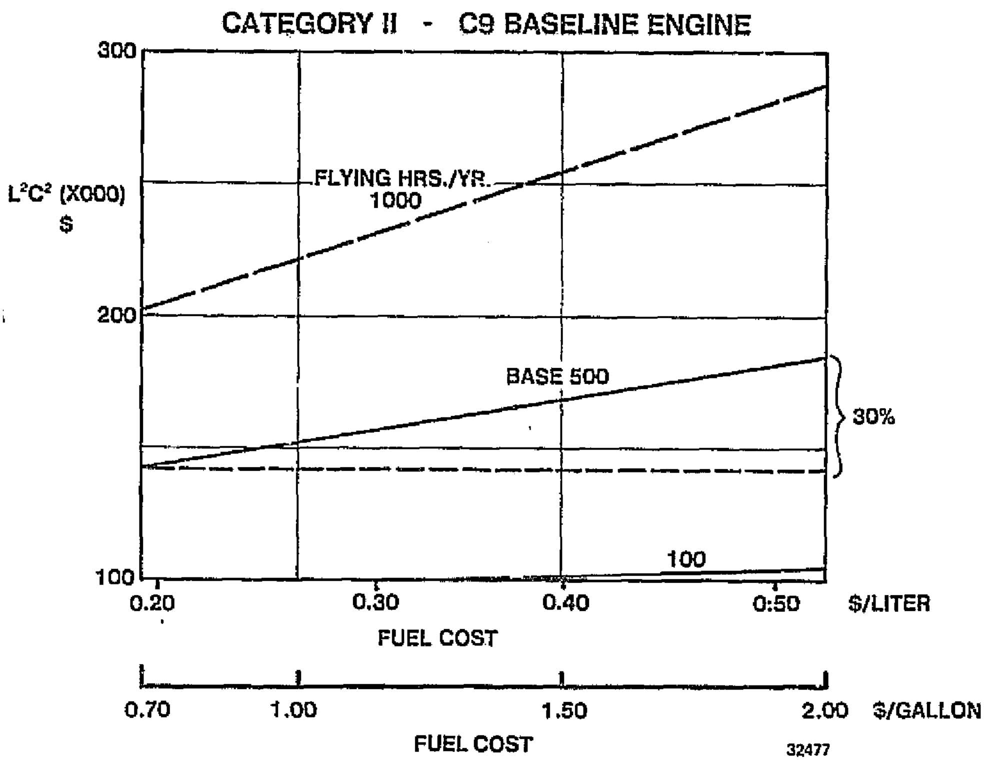


Figure 76. L^2C^2 Vs. Fuel Cost - Category II.

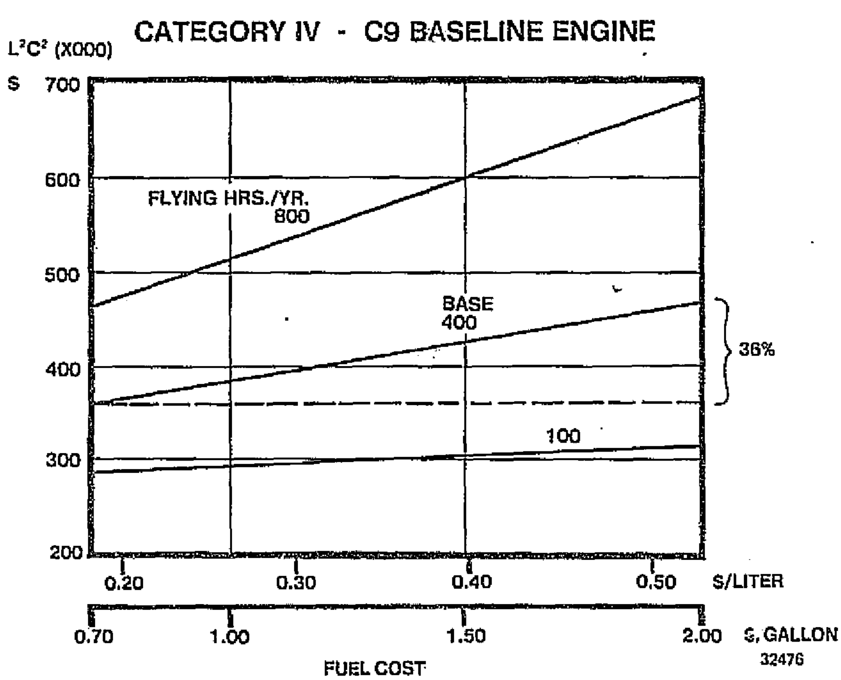


Figure 77. L^2C^2 Vs. Fuel Cost - Category IV.

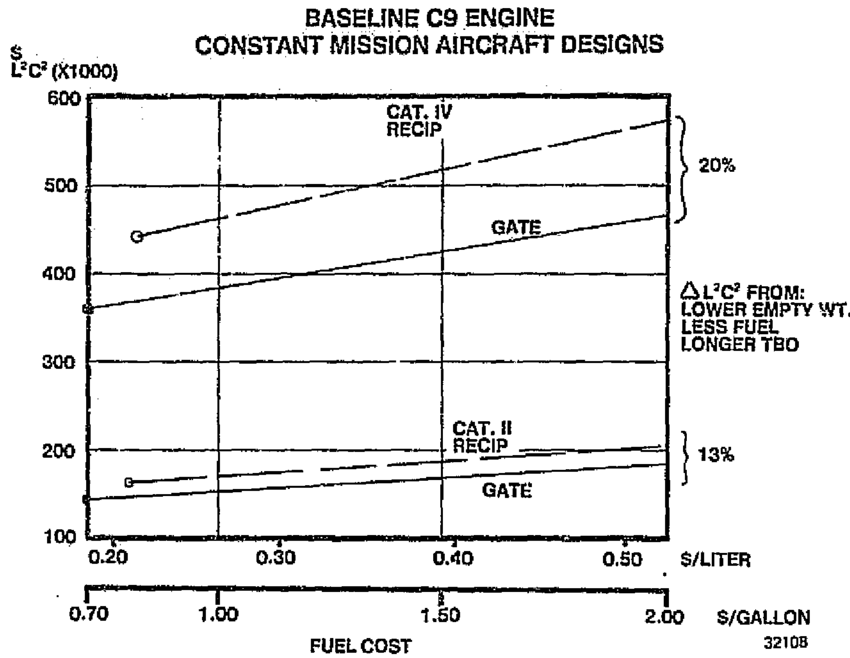


Figure 78. L^2C^2 Vs. Fuel Cost for GATE and Recip. Engines.

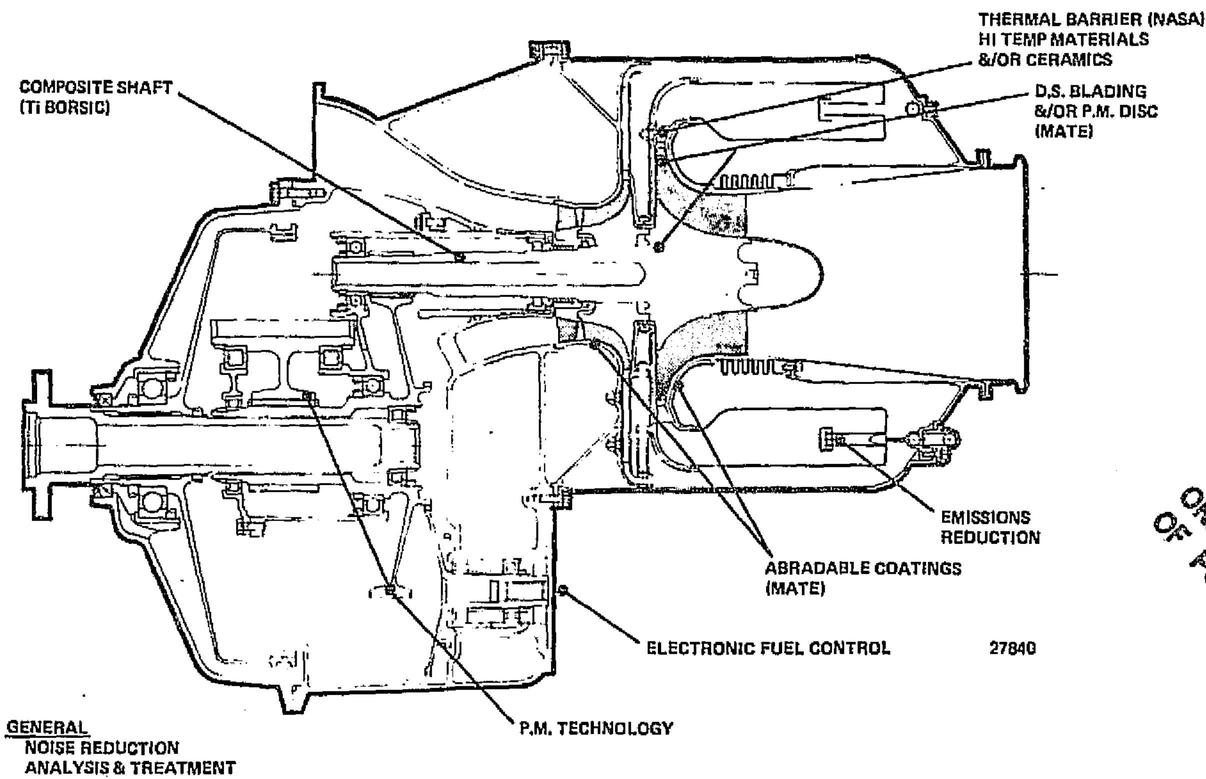


Figure 79. Applicability of Large and Other Engine Technologies to GATE.

5-YEAR L^2C^2 VALUE OF	1% SFC	0.91 KG/s LB) ENG. WT. (a)
CAT. IV (b)	$4890	$895

TECHNOLOGY ADVANCE	EFFECT	ΔSFC-%	ΔWEIGHT KG (LB)	$ L^2C^2 SAVINGS PER A/C
9:1 P.R. COMPRESSOR	+2% $\Delta\eta_c$	−2	−2.7 (−6)	15,150
UNCOOLED RADIAL TURBINE	+167°K T.I.T. (+300°F T.I.T.)	−2	−12.9 (−28.5)	35,300
ABRADABLE COATINGS	+1% $\Delta\eta_c$	−0.9	−1.1 (−2.5)	6,640
	+1% $\Delta\eta_T$	−2.1	−2.0 (−4.5)	14,300
TIBORSIC SHAFT	−0.61 KG (−1.4 LB)	0	−0.6 (−1.4)	1,250
GEARBOX COST	−10%	-	-	435
ELECTRONIC FUEL CONTROL	-	-	-	3,200
			TOTAL	76,275

(a) PER ENGINE
(b) TWIN ENGINE

28888A

Figure 80. Typical Worth of Technology Over a Five Year Period.

AVERAGE OF FIRST 5 MATURE YEARS

			$SAVINGS-MILLIONS
CAT. II:	9600 AIRCRAFT/YR.	=	72.2
CAT. IV:	4400 AIRCRAFT/YR.	=	191.4
			263.6

ADDING CAT. IIIU + IIIP + VI(AG) + HELICOPTER WOULD INCREASE THE SAVINGS BY 30%

CONCLUSION:

PAYOFF IS WELL WORTH NASA INVESTMENT

28889

Figure 81. GATE Fleet Yearly Cost Savings From Turbine Engine Technology Advances.

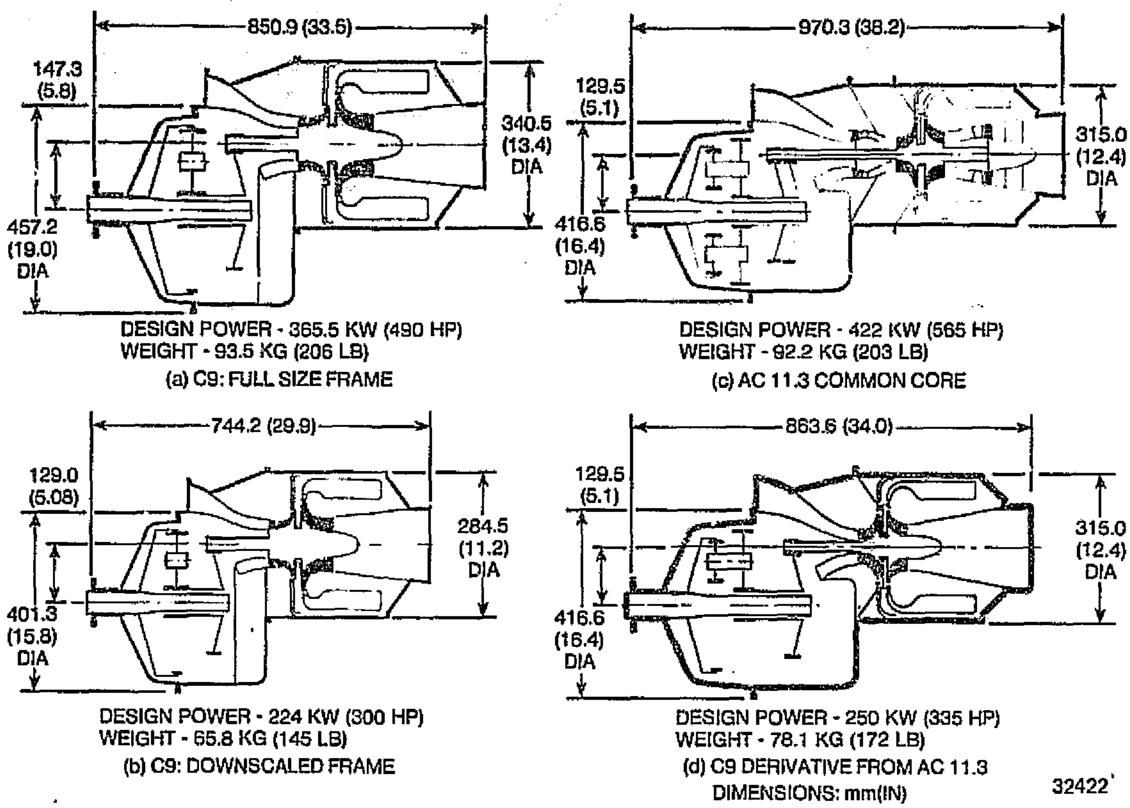


Figure 82. Common Core Layouts.

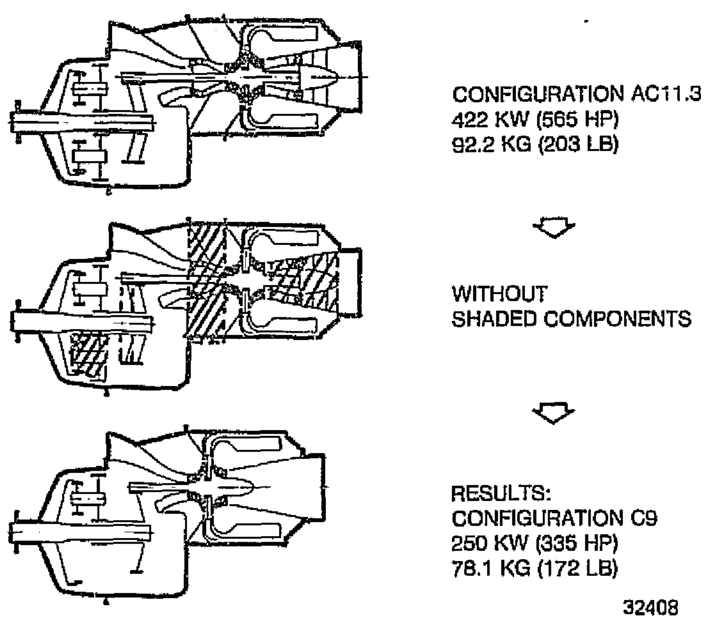


Figure 83. Two Frame Famility Approach to a Common Core.

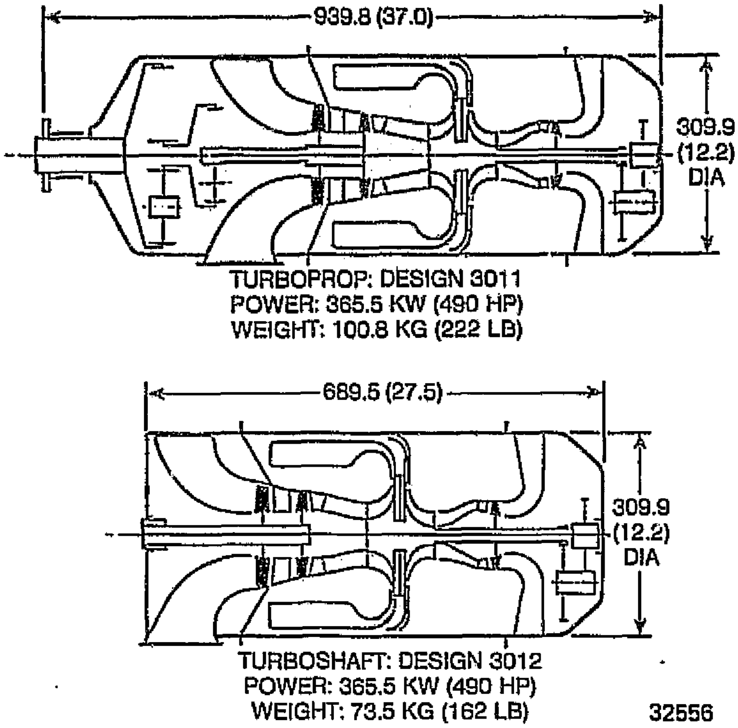


Figure 84. Free Turbine Designs.

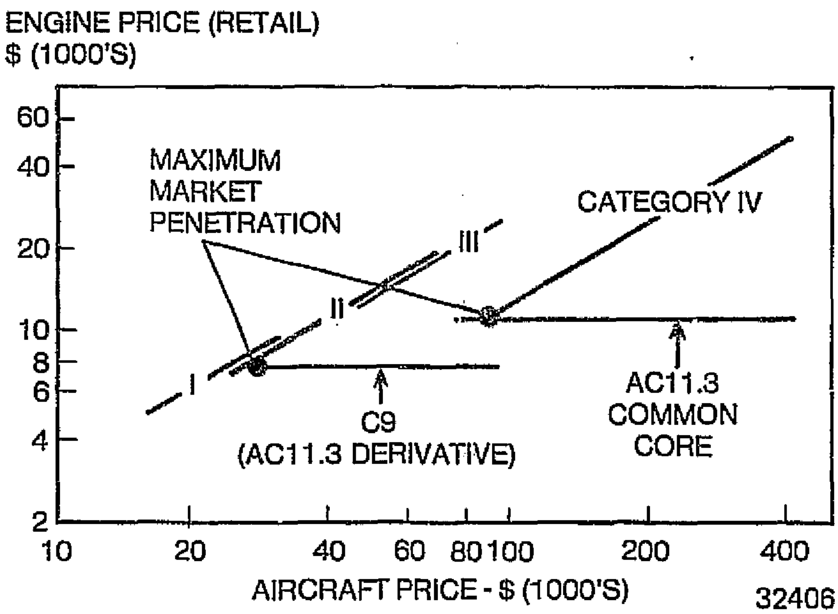


Figure 85. Maximum Engine Price for Market Penetration.

TASK	TITLE	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
1	PROGRAM CONTROL - DESIGN & COST MGT. - ENGINE SPEC. & LAYOUT -MANUFACTURING STUDY & DTC		IS PRICE COMPETITIVE?			
2	RADIAL TURBINE COMPONENT DEVEL. - DES. & FAB. - MATERIAL, COATING, FAB.METHODS RESEARCH - AEROMECH. TESTS: SPIN, PRESS., TEMP.				WHAT IS T.I.T. CAPABILITY IS IT HIGH ENOUGH?	
3	COMPRESSOR COMPON. DEVEL. - DESIGN & PROCURE - RIG AEROMECH TESTS				IS COMP WORTHY?	
4	GEARBOX COMPON. DEVEL. - DES. & FAB. - FABRICATION METHODS RESEARCH - RIG TESTING			IS P. M APPROACH SOUND?		
5	Ti BORSIC SHAFT - DESIGN & FAB. RESEARCH -RIG TEST					
6	PACKAGED PROTOTYPE FUEL CONTROL - DES. & BENCH - 1ST ENGINE RUN				IS PRICE COMPETITIVE?	
7	DEMO ENGINE DESIGN INTEGRATION & PROCURE -ASS'Y. & INSTRUM.; 1ST RUN - DEMO ENGINE IMPROVEMENT - DEL. TO NASA				SHOULD ENGINE BE BUILT?	

32454

Figure 86. Five Year Demonstrator Plan: Major Milestone Schedule.

TABLE I. TASK I AIRCRAFT TYPES

CAT.	NO. ENG.	1976 DATA: PRICE RANGE (1000's)	SALES	TYPICAL PRODUCT	PAX PAYLOAD	POWER RANGE: CRUISE KW (HP)	POWER RANGE: TAKEOFF KW (HP)	GROSS WEIGHT RANGE KG (LBS)	1988 MISSION: RANGE KM (N MI)	CRUISE M/S (KTAS)	CRUISE M (FT)
1 (a)	1	16-31	2387	150, PA 18 SPORT 19	2	56-67 (75-90)	74.6-89.5 (100-120)	697-719 (1600-1650)	926 (500)	61.7 (120)	2440 (8000)
II	1	24-66	7246	172, BEECH C23 SIERRA B24R	4	100.7-111.9 (135-150)	134-149 (180-200)	1089-1198 (2500-2750)	1297 (700)	87.4 (170)	3048 (10000)
IIIU	1	46-91	2171	CESSNA 206 PA32R LANCE 210 TC A36	4-6	159.6-168 (214-225)	212.3-224 (285-300)	1568-1655 (3600-3800)	1575 (850)	97.7 (190)	3048 (10000)
IIIP	1				4-6	---	---	---	1668 (900)	108 (210)	5465 (18000)
IV	2	90-330	1484	SENECA, BARON B60	6-8	303-380 (406-510)	425-462 (570-620)	2396-2675 (5500-6140)	2224 (1200)	136 (265)	5486 (18000)
V (b)	2	200-1,400	1083	SHRIKE, 421 CITATION	6-12	820-1044 (1100-1400)	820-1044 (1100-1400)	4138-4487 (9500-10300)	3335 (1800)	134 (270)	6096 (20000)
VI AG	1	40-80	1111	THRUSH CESSNA A188B	907 KG 2000 LB	168-417.6 (225-560)	224-596.5 (300-800)	1496-2721 (3300-6000)	16.2 KS (4.5 HRS)	56.6 (110)	0
HELIC	1-3	100-900	1030	NEW PRODUCT OPPORTUNITY	2-5	---	---	---	6115 (330)	56.6 (110)	0

32508

(a) Eliminated By Cost, Turbine Power Increased Aircraft Price 15-30%

(b) Eliminated - Power Requirement Beyond Scope of Study

TABLE II. INITIAL TURBOPROP ENGINE PERFORMANCE POSTULATIONS AT CRUISE

CATEGORY	CRUISE CONDITIONS			TURBINE INLET TEMPERATURE AT CRUISE[a]			
				1367 °K (2000° F)		1422 °K (2100° F)	
	SPEED M/S (KTAS)	ALTITUDE M (FT)	POWER REQUIRED KW (HP)	PRESSURE RATIO	FUEL CONSTUMPTION m /J LB/HR-HP	PRESSURE RATIO	FUEL CONSUMPTION mg/J LB/HR-HP
I	56.6 (110)	2440 (8000)	67 (90)	8.8	81.8 (0.485)	9.6	79.4 (0.467)
II	74.6 (145)	2440 (8000)	111.9 (150)	8.7	82.0 (0.486)	9.4	79.9 (0.473)
III	103 (200)	6096 (20000)	167.8 (225)	10.0	74.4 (0.440)	10.8	72.2 (0.427)
IV	134 (260)	6096 (20000)	179.0 (240)	9.8	73.4 (0.434)	10.6	71.3 (0.422)
V	157 (305)	6096 (20000)	559.5 (750)	9.6	73.0 (0.429)	10.4	70.8 (0.491)

32509

(a) Maximum Temperature rating - 1533° K (2300° F)

TABLE III. INITIAL TURBOPROP ENGINE POWER AND AIRFLOW AT SEA LEVEL STATIC

CATEGORY	REQUIRED POWER		TURBINE INLET TEMPERATURE RATING AT CRUISE			
			1367° K (2000° F)		1422° K (2100° F) (a)	
	CRUISE	TAKEOFF	SEA LEVEL STATIC PARAMETERS			
			AVAILABLE POWER KW (HP)	AIRFLOW KG/S (LB/SEC)	AVAILABLE POWER KW (HP)	AIRFLOW KG/S (LB/SEC)
I	67.1 (90)	89.5 (120)	116.3 (156)	0.34 (0.74)	100.7 (135)	0.29 (0.64)
II	111.9 (150)	149.2 (200)	194.0 (260)	0.56 (1.23)	167.1 (224)	0.48 (1.08)
III	167.8 (225)	223.8 (300)	350.6 (470)	1.01 (2.22)	305.9 (410)	0.88 (1.94)
IV	179.0 (240)	223.8 (300)	361.1 (484)	1.04 (2.29)	314.8 (422)	0.91 (2.00)
V	559.5 (750)	559.5 (750)	1081.7 (1450)	3.12 (6.88)	947.4 (1270)	2.73 (6.02)

(a) MAXIMUM TEMPERATURE RATING - 1533° K (2300° F)

32510

TABLE IV. INITIAL TURBOFAN ENGINE PERFORMANCE POSTULATIONS

CATEGORY	BYPASS RATIO 6:1						
	CRUISE CONDITIONS				SEA LEVEL STATIC		
	SPEED M/S (KTAS)	ALTITUDE M (FT)	REQUIRED THRUST KN (LB)	FUEL CONSUMPTION mg/NS (LB/HR-LB)	AVAILABLE THRUST KN (LB)	FUEL CONSUMPTION mg/NS (LB/HR-LB)	AIRFLOW KG/s (LB/SEC)
I	56.6 (110)	2440 (8000)	1.04 (234)	14.5 (0.512)	1.62 (363)	11.9 (0.42)	6.4 (14.0)
II	74.6 (145)	2440 (8000)	1.31 (295)	15.0 (0.530)	2.12 (4.76)	11.9 (0.42)	8.0 (17.7)
III	103 (200)	6096 (20000)	1.39 (313)	15.7 (0.553)	3.45 (776)	11.9 (0.42)	12.5 (27.5)
IV	134 (260)	6096 (20000)	1.16 (261)	17.2 (0.607)	3.02 (679)	11.9 (0.42)	10.9 (24.0)
V	157 (305)	6096 (20000)	3.11 (700)	18.3 (0.647)	8.41 (1890)	11.9 (0.42)	30.2 (66.5)

32511

TABLE V. BASELINE TURBOPROP SCALING DATA

POWER (a) KW (HP)	DIMENSIONS MM (IN)										WEIGHT KG (LBS)
	A	B	C	D	E	F	G	H	J	K	
361	110	230.4	346.2	440.2	713.5	743.7	176.8	322.6	J = H	$K = \frac{H}{2}$	80.4
(484)	(4.33)	(7.89)	(13.63)	(17.33)	(28.09)	(29.28)	(6.96)	(12.7)	↓	↓	(177.0)
---	EXP 0.12	EXP 0.27	EXP 0.27	EXP 0.27	EXP 0.27	EXP 0.27	EXP 0.50	EXP 0.36	---	---	EXP 0.72
SCALING RANGE 186 KW (250 HP) TO 119 KW (1500 HP)											
116	91.4	157.5	279.4	330.2	561.3	584.2	100.3	254.0	↓	↓	49.0
(156)	(3.6)	(6.2)	(11.0)	(13.0)	(22.1)	(23.0)	(3.95)	(10.0)			(108)

32512

(a) Power Available: Sea Level Static

TABLE VI. BASELINE TURBOFAN SCALING DATA

THRUST(a) KN (LB)	DIMENSIONS MM (IN)								WEIGHT KG (LB)
	A	B	C	D	E	F	G	H	
3.45	446.8	327.7	361.7	493.5	129.8	216.4	586.7	620.5	87.9
(776)	(17.59)	(12.90)	(14.24)	(19.43)	(5.11)	(8.52)	(23.1)	(24.43)	(193.6)
---	EXP 0.50	EXP 0.50	EXP 0.36	EXP 0.42	EXP 0.40	EXP 0.40	EXP 0.33	EXP 0.33	EXP 0.80

32513

(a) Thrust Available: Sea Level Static

TABLE VII. COMPONENT RELATIVE COST

COMPONENT RELATIVE COST: BASELINE								TOTAL
GEARBOX & AIR INLET	COMPRESSOR	COMBUSTOR	TURBINE	COLD HSG	HOT HSG	ACCY SYSTEM	A & T	
0.20	0.16	0.06	0.20	0.02	0.08	0.24	0.08	1.0
GATE: ADVANCED TECHNOLOGY								
0.20	0.08	0.04	0.07	0.01	0.04	0.12	0.04	0.6
FABRICATION TECHNOLOGY								
0.16	0.048	0.04	0.042	0.01	0.04	0.12	0.04	0.5

32514

TABLE VIII. GENERAL AVIATION MARKET AND GROWTH TREND SUMMARY

CATEGORY	ACTUAL 1976 DELIVERIES		1988 MARKET				
			UNDISTURBED		DISTURBED		SIMPLE ANNUAL GROWTH RATE - % UNDISTURBED
	PISTON	TURBOPROP	PISTON	TURBOPROP	PISTON	TURBOPROP	
I	2,387	0	3,100	0	3100	0	2.5
II	7,246	0	12,000	0	2400	9,600	5.5
III	2,171	0	3,210	0	640	2,570	4.0
I-III	11,804	0	18,310	0	6140	12,170	4.6
IV	1,484	0	2,230	0	1100	4,400	4.2
V	638	473	810	990	0	3,000	5.2
I-V	13,926	473	21,350	990	7240	19,570	4.6
TOTAL	14,399		22,340		26,810		
AG	980	0	1,500		1,500		4.4

32515

TABLE IX. PROJECTED LIGHT HELICOPTER MARKET WITH GATE ENGINES FOR THE 5 YEAR TIME FRAME FROM 1988 TO 1993

HELICOPTER DESIGNATION	NUMBER HELICOPTERS	NUMBER OEM ENGINES
SINGLE	1700	1700
TWIN	700	1400
TRI-PAC	350	1050
TOTAL	2750	4150

32516

TABLE X. MISSIONS FOR GATE POWERED LIGHT HELICOPTERS

SINGLE	TWIN	TRI-PAC
• AGRICULTURAL • SEARCH AND RESCUE • POLICE • TRAINING • PHOTOGRAPHY	• CORPORATE EXECUTIVE • SEARCH AND RESCUE • POLICE • AMBULANCE • OFFSHORE • AGRICULTURAL	• CORPORATE EXECUTIVE • SHUTTLE SERVICE • AMBULANCE • OFFSHORE

32517

TYPE XI. HELICOPTER AIRCRAFT CAPABILITY WITH GATE ENGINE

	SINGLE	TWIN	TRI-PAC
	261 KW (350 HP)	522 KW (700 HP)	783 KW (1050 HP)
GROSS WEIGHT KG (LBS)	1271 (2800)	1952 (4300)	3337 (7350)
EMPTY WEIGHT KG (LBS)	726 (1600)	976 (2150)	1680 (3700)
USEFUL LOAD KG (LBS) NUMBER SEATS	545 (1200) 3	976 (2150) 5	1657 (3650) 8
FUEL KG (LBS)	182 (400)	431 (950)	704 (1550)
SFC µg/J (LB/HP-HR) @POWER RATING	101 (0.60) 75%	93 (0.55) 60%	93 (0.55) 60%
RANGE KM (nm) RESERVE MIN	334 (180) 30	834 (450) 45	1019 (550) 45
CRUISE SPEED M/S (KNOTS) (MPH)	46.3 (90) (104)	72.0 (140) (161)	77.2 (150) (173)
SERVICE CEILING M FT	3658 (12000)	3,658/1,524 (12,000/5000) (a)	4267/2438/1219 (14,000/8,000/4,000) (b)
HOVER, OUT OF GROUND EFFECT M FT	1829 (6000)	2438 (8000)	1219 (4000)
CABIN VIBRATION g	0.10	0.05/0.08	0.05/0.08
CABIN NOISE dB2	90	75/80	75/80
SELLING PRICE $	100,000 to 125,000	300,000 to 500,000	700,000 to 1,000,000

32518

(a) Twin & Single Engine

(b) Three, Twin and Single Engine

TABLE XII. 1988 GATE POWERPLANT CAPABILITIES AND REQUIREMENTS

ENGINE TYPE	REL. POWER/WT.	REL. POWER/ FRONT AREA	REL. INSTALLED CRUISE SFC	COST		MULTI FUEL ?	AVG. TBO	SALES/ SERVICE IN PLACE?
				DEVELOP. CAPITAL	PRODUC TION			
RECIP. - SPARK	100	100	100 (a) (1976=110)	LOWEST	LOW	NO	<2000	YES
GAS TURBINE	200-320	280-450	110-130	MED.	MED.	YES	>4000	YES
DIESEL (POTENTIAL)	100	100	80-90 (b)	HIGHEST	MED.	YES	?	PART
ROTARY	180-220	200-300	96-120	HIGH	?	YES	? (b)	NO

32519

(a) COOLING CAPABILITIES UNKNOWN
(b) CURRENT EXPERIENCE IS LIMITED

TABLE XIII. GATE EMISSIONS, EPA 1979 STANDARDS LTO CYCLE

ENG. CLASS	CO (a)		THC (a)		NOx (a)		SMOKE (b)	
	PROD.	STD.	PROD.	STD.	PROD.	STD.	PROD.	STD.
P1-PISTON (c)	50-120	42	3.0-4.5	1.9	0.2-1.3	1.5	—	—
P2-TURBOPROP	20-30	26.8	6-12	4.9	6-10	12.9	—	<50
T1-THRUST <3629 KG (8000 LB)	15-60	9.4	4-16	1.6	2.5-4.5	3.7	—	<32
QCGAT (OBJ.)	6.9-7.2		0.9-1.2		3.3-3.4		INVISIBLE	

32520A

(a) KG/1645 KW-HRS/CYCLE (LB/1000 HP-HRS/CYCLE) FOR PISTON ENGINES AND TURBOPROPS, KG/9.81 KN THRUST-HRS/CYCLE (LB/1000 LBS THRUST-HRS/CYCLE) FOR THRUST ENGINES

(b) RELATIVE REFLECTIVITY (REFERENCE 15)

(c) P1 CLASS EXCLUDES RADIALS (REFERENCE 15)

TABLE XIV. 1988 TURBINE POWER MARKET FORECAST SUMMARY

CATEGORY	POWER-SLS TAKE-OFF TURBINES KW (HP)	RECIP'S AND TURBINES AIRCRAFT SALES	TURBINES	
			OEM ENGINE SALES – 1 COMPANY (50% OF MARKET)	TOTAL GATE ENGINE SALES (a)
II	175/198 (235/265)	12000	4800	9600
IIIU	205/283 (273/380)	3210	1285	2570
IIIP	238/421 (320/565)			
IV	220/395 (295/530)	5500	4400	8800
VI (AGRICULTURAL)	298/358 (400/480)	1500	750	1500
HELICOPTER	261 ± 56 (350 ± 75) SAME	550	830	830
	TOTAL		12055	23300
	SPARES		4220	8150
	GRAND TOTAL		16285	31450
	MARKET VALUE, (1977 DOLLARS)		$120 (b)	$220 (b)

32523A

(a) REMAINDER ARE RECIPS.

(b) THIS IS OEM VALUE INCLUDING SPARES AT THE OEM VALUE AND BASED ON THE RECOMMENDED COMMON CORE DESIGN DISCUSSED IN SECTION 5.

TABLE XV. MATRIX OF ADVANCED TECHNOLOGY EFFICIENCY ASSUMPTIONS: TURBOPROP AND TURBOSHAFT PARAMETRIC ANALYSIS

CATEGORY	HELICOPTER	II& IIIU	III P & IV
SPEED M/S (KTAS)	56.6 (110)	92.6 (180)	123.5 (240)
ALTITUDE M (FT)	SEA LEVEL	3048 (10000)	5486 (18000)

COMPRESSOR			
PRESSURE RATIO	9	14	20
EFFICIENCY - PERCENT	82	82	82
PARAMETRIC RANGE OF EFFICIENCIES EVALUATED FOR SENSITIVITY-PERCENT	82/80	79.5/77	75/72

COMBUSTOR		
PRESSURE LOSS 3.5 PERCENT	FUEL HEATING VALUE 42 798 J/g (18400 B/LB)	EFFICIENCY 99.5 PERCENT

TURBINE: T CRUISE = T MAX - 167° K (300° F)			
T CRUISE °K (°F)	TYPE	ROTOR EFFICIENCY PERCENT	NOZZLE, ROTOR, SHROUD AND SEAL COOLING PERCENT
1256	COOLED	85	3.0
(1800)	UNCOOLED	87	1.0
1339	COOLED	84	5.0
(1950)	UNCOOLED	87	2.0
1422	COOLED	82	8.0
(2100)	UNCOOLED	87	4.0
SENSITIVITY RANGE: EFFICIENCIES VARIED ±2%			

OUTPUT
MECHANICAL EFFICIENCY = 98.5 PERCENT
PROPELLER EFFICIENCY = 85 PERCENT
TURBINE BACK PRESSURE: TURBOPROP = 1.20 x AMBIENT HELICOPTER = 1.06 x AMBIENT

32524

TABLE XVI. RANGE OF COOLING BLEED LOSS ASSUMPTIONS USED IN PARAMETRIC ANALYSIS (9:1 PRESSURE RATIO DESIGN)

CRUISE TURBINE (a) INLET TEMPERATURE °K (°F)	ASSUMPTION	EQUIVALENT BYPASS COOLING BLEED AIRFLOW (NOZZLE, ROTOR AND SHROUDS) PERCENT
1256	OPTIMISTIC	1.0
(1800)	CONSERVATIVE	3.0
1339	OPTIMISTIC	2.0
(1950)	CONSERVATIVE	5.0
1422	OPTIMISTIC	4.0
(2100)	CONSERVATIVE	8.0

32525

(a) Maximum Rated Temperature is 167° K (300°F) Greater Than Cruise

TABLE XVII. DATA MATRIX FOR THE TURBOFAN PARAMETRIC ANALYSIS

BYPASS RATIO	:	5 TO 11.1
FAN P.R.	:	1.20 TO 1.60 @ 89.5% EFFICIENCY
CORE P.R.	:	7 TO 13.1 @ 83 TO 80% EFFICIENCY
CRUISE T.I.T.	:	1037 TO 1365°K (1400 TO 2000°F)
CORE TURBINE EFFICIENCY	:	88%
FAN TURBINE EFFICIENCY	:	89%
SERVICES	:	1% PRESSURIZATION BLEED PLUS 2.24 KW (3 HP) POWER EXTRACTION
OTHER CYCLE VARIABLES	:	CONSISTENT WITH 1985 TECHNOLOGY — COMBUSTOR EFFICIENCY = 99.5% @ 3.5% PRESS. LOSS CORE TURBINE EFFICIENCY = 88% FAN TURBINE EFFICIENCY = 89% SHAFT MECH. EFFICIENCY = 99% (BOTH) PRIMARY DUCT P = 3.0% DUCT MACH NO. = 0.33 FAN DUCT P = 4.0% (SEE TEXT) NOZZLES C_f = 98.5%

32420

TABLE XVIII. TYPICAL PERFORMANCE AT 107 KN (240 LB) THRUST - OPTIMIUM SFC LINE

SPEED % OF MAX	CORRECTED SPEED % OF DESIGN	TURBINE INLET TEMPERATURE °K (°R)	SPECIFIC FUEL CONSUMPTION $\frac{mg}{NS}$ $\left(\frac{LB}{HR\text{-}LB}\right)$
100	104.9	1265 (2280)	13.17 (0.465)
95	99.7	1226 (2210)	12.52 (0.442)
90	94.7	1376 (2480)	13.34 (0.471)

32526

TABLE XIX. 1985 STATE-OF-THE-ART COMPRESSOR SUMMARY AT A CONSTANT AIRFLOW OF 1.19 KG/S (2.62 LB/SEC)

PRESSURE RATIO	FLOWPATH NO.	FLOWPATH CONFIGURATION	ADIABATIC EFFICIENCY PERCENT	SPEED REV/s (RPM)	CENTRIFUGAL TIP SPEED M/S (FT/SEC)	CENTRIFUGAL TIP WIDTH MM (IN)	LENGTH MM (IN)	RADIUS MM (IN)
9:1	2010	C	81.5	1160.3 (69 900)	640.1 (2100)	5.72 (0.225)	82.6 (3.25)	165.1 (6.50)
	--	C	80.4	780.9 (47 040)	487.4/457.2 (1599/1500)	8.79/5.33 (0.346/0.210)	144.8 (5.70)	190.5 (7.50)
	--	AC	81.8	1143.7 (68 900)	587.0 (1926)	4.72 (0.186)	129.5 (5.10)	154.9 (6.10)
	--	AAAC	80.4	1143.7 (68 900)	472.7 (1551)	6.65 (0.262)	205.7 (8.10)	127.0 (5.00)
11.3:1	3010	AC	81.7	1367.0 (82 350)	624.2 (2048)	5.23 (0.206)	154.9 (6.10)	142.2 (5.60)
14:1	--	AC	79.2	1367.0 (82 350)	670.6 (2200)	5.23 (0.206)	165.1 (6.50)	147.3 (5.80)
15:1	4010	AAAC	78.2	1367.0 (82 350)	563.9 (1850)	3.99 (0.157)	208.3 (8.20)	134.6 (5.30)
20:1	--	AAAC	74.3	1367.0 (82 350)	640.1 (2100)	2.84 (0.112)	208.3 (8.20)	137.2 (5.40)
	5010	CC	76.6	1246.3 (75 082)	670.6/487.7 (2200/1600)	5.92/2.51 (0.233/0.099)	177.8 (7.00)	190.5 (7.50)

32529

TABLE XX. CANDIDATE ENGINE COMPONENT DATA AT CRUISE

CONFIGURATION	C 9	AC11.3	AAAC 15	CC 20
COMPRESSOR PRESSURE RATIO	9.0	11.3	15.0	19.8
COMPRESSOR EFFICIENCY PERCENT	81.5	81.7	78.2	76.6
TURBINE INLET °K TEMPERATURE (°F)	1327 (1930)	1254 (1800)	1249 (1790)	1257 (1805)
BYPASS COOLING PERCENT	2.0	1.0	1.0	1.0
TURBINE EFFICIENCY PERCENT	87.9	88.6	88.0	88.0
SPEED REV/S (RPM)	1167 (69900)	1375 (82500)	1375 (82500)	1381 (82900)
CORRECTED KG/s AIRFLOW (LB/SEC)	1.19 (2.62)	1.19 (2.62)	1.19 (2.62)	1.19 (2.62)

COMBUSTOR PERSSURE DROP = 3.5%	JET NOZZLE PRESSURE RATIO = 1.17
FUEL: LOWER HEATING VALUE = 42 798 J/g (18 400 B/LB)	PROPELLER EFFICIENCY = 86%
COMBUSTOR EFFICIENCY = 99.5%	EXHAUST DUCT PRESSURE LOSS = 3%
MECHANICAL EFFICIENCY = 98.5%	

32530A

TABLE XXI. CANDIDATE ENGINE CRUISE PERFORMANCE: CORRECTED AIRFLOW AT SEA LEVEL STATIC, 1.19 KG/S (2.62 LB/SEC)

CONFIGURATION	CATEGORY IV 128.6 M/S (250 KTAS) @ 5486 M (18000 FT)			CATEGORY III P 108.0 M/S (210 KTAS) @ 5486 M (18000 FT)			CATEGORY III U 97.7 M/S (190 KTAS) @ 3048 M (10000 FT)			CATEGORY II 87.4 M/S (170 KTAS) @ 3048 M (10000 FT)		
	POWER KW (HP)	POWER/AIRFLOW KW/(KG/S) (HP/(LB/SEC))	FUEL CONSUMPTION µg/J (LB/(HR-EHP))	POWER KW (HP)	POWER/AIRFLOW KW/(KG/S) (HP/(LB/SEC))	FUEL CONSUMPTION µg/J (LB/(HR-EHP))	POWER KW (HP)	POWER/AIRFLOW KW/(KG/s) (HP/(LB/SEC))	FUEL CONSUMPTION µg/J (LB/(HR-EHP))	POWER KW (HP)	POWER/AIRFLOW KW/(KG/S) (HP/(LB/SEC))	FUEL CONSUMPTION µg/J (LB/(HR-EHP))
C9	200 (268)	286 (174)	76.8 (0.455)	191 (256)	281 (171)	78.5 (0.465)	233 (312)	260 (158)	81.7 (0.484)	228 (305)	258 (157)	82.8 (0.490)
AC 11.3	183 (246)	271 (163)	71.9 (0.426)	176 (236)	260 (158)	73.5 (0.435)	213 (285)	238 (145)	76.8 (0.455)	208 (279)	235 (143)	77.5 (0.459)
AAAC 15	163 (219)	234 (142)	73.1 (0.433)	157 (211)	232 (141)	74.3 (0.440)	184 (246)	206 (125)	79.2 (0.469)	180 (242)	204 (124)	80.0 (0.474)
CC 20	149 (200)	212 (129)	73.6 (0.436)	144 (193)	212 (129)	74.8 (0.443)	163 (219)	182 (111)	81.2 (0.481)	160 (215)	182 (111)	81.9 (0.485)

32531A

TABLE XXII. MAXIMUM THERMODYNAMIC HORSEPOWER AT SEA LEVEL STATIC

CONFIGURATION	TEMPERATURE °K (°F)	POWER KW (EHP)	POWER/AIRFLOW KW/(KG/S) (EHP/(LB/SEC))	FUEL CONSUMPTION μg/J (LB/HR-EHP)
C 9	1504 (2250)	362.4 (486)	304.1 (185)	86.0 (0.509)
AC 11.3	1432 (2120)	344.5 (462)	289.3 (176)	79.4 (0.470)
AAAC 15	1426 (2110)	312.4 (419)	261.4 (159)	79.8 (0.472)
CC 20	1435 (2125)	290.1 (389)	243.3 (148)	79.4 (0.470)

32532

TABLE XXIII. TURBOPROP SCALING DATA

GATE DESIGN	DIMENSION - mm (IN)										WEIGHT KG (LB)
	A	B	C(a)	D	E	F	G	H	J	K	
	EQUAL POWER : 365.5 KW (490 HP)										
2010	110 (4.33)	200.7 (7.89)	----	440.2 (17.33)	713.5 (28.09)	850.9 (33.5)	182.9 (7.2)	340.4 (13.4)	457.2 (18.0)	147.3 (5.8)	93.5 (206)
3010	↓	↓	↓	↓	840.7 (33.1)	942.2 (37.1)	188 (7.4)	309.9 (12.2)	↓	↓	99.4 (219)
4010	↓	↓	↓	↓	894.1 (35.2)	995.7 (39.2)	198.1 (7.8)	322.6 (12.7)	↓	↓	109 (240)
5010	↓	↓	↓	↓	871.2 (34.3)	972.8 (38.3)	205.7 (8.1)	424.2 (16.7)	↓	↓	122 (268)
	EQUAL AIRFLOW: 1.19 KG/SEC (2.62 LB/SEC)										
2010	↓	↓	↓	↓	713.5 (28.09)	850.9 (33.5)	182.9 (7.2)	340.4 (13.4)	↓	↓	93.5 (206)
3010	↓	↓	↓	↓	833.1 (32.8)	934.7 (36.8)	182.5 (7.2)	304.8 (12.0)	↓	↓	97.6 (215)
4010	↓	↓	↓	↓	871.2 (34.3)	972.8 (38.3)	182.9 (7.2)	304.8 (12.0)	↓	↓	102.6 (226)
5010	↓	↓	↓	↓	838.2 (33.0)	939.8 (37.0)	182.9 (7.2)	391.2 (15.4)	↓	↓	109.9 (242)
	SCALING EXPONENT										
	0.12	0.27	----	0.27	0.27	0.27	0.50	0.36	0.36	0.36	0.72

(a) NOT USED

32533

TABLE XXIV. DESIGN 2010 CRITICAL SPEED SUMMARY

SHAFT SUPPORT STIFFNESS		CRITICAL SPEEDS		
FRONT MN/m (LB/IN)	REAR MN/m (LB/IN)	FIRST rev/s (RPM)	SECOND rev/s (RPM	THIRD rev/s (RPM)
175 (10^6)	175 (10^6)	217 (13024)	1530 (91804)	2770 (166230)

32534

TABLE XXV. RELATIVE COST SUMMARY FOR FOUR BASIC ENGINE CONFIGURATIONS

COMPONENT RELATIVE COST: BASELINE								TOTAL
GEARBOX & AIR INLET	COMPRESSOR	COMBUSTOR	TURBINE	COLD HSG	HOT HSG	ACCY SYSTEM	A & T	
0.20	0.16	0.06	0.20	0.02	0.06	0.24	0.06	1.0
GATE 2010								
0.20	0.08	0.04	0.07	0.01	0.04	0.12	0.04	0.6
GATE 2010 WITH FABRICATION TECHNOLOGY								
0.16	0.048	0.04	0.042	0.01	0.04	0.12	0.04	0.5
GATE 3010								
0.20	0.16	0.04	0.14	0.02	0.05	0.12	0.05	0.78
GATE 3010 WITH FABRICATION TECHNOLOGY								
0.16	0.096	0.04	0.084	0.02	0.05	0.12	0.05	0.62
GATE 4010								
0.20	0.32	0.04	0.20	0.04	0.06	0.12	0.08	1.06
GATE 4010 WITH FARBICATION TECHNOLOGY								
0.16	0.192	0.04	0.12	0.04	0.06	0.12	0.08	0.812
GATE 5010								
0.20	0.16	0.04	0.20	0.02	0.06	0.12	0.06	0.86
GATE 5010 WITH FABRICATION TECHNOLOGY								
0.16	0.096	0.04	0.12	0.02	0.06	0.12	0.06	0.676

32535

TABLE XXVI. OEM COST FOR THE FOUR BASIC ENGINE DESIGNS: EXPRESSED IN DOLLARS FOR A PRODUCTION RATE OF 500 PER YEAR

DESIGN NUMBER	CONSTANT WEIGHT 227 KG (500 LB)	CONSTANT POWER 365.5 KW (490 HP)
2010	59870	33115
3010	77831	44588
4010	105770	63970
5010	85814	55552

32536

TABLE XXVII. Q-FAN(TM) DESIGN PARAMETERS

FAN DIAMETER	311.2 mm (12.25 IN)
BYPASS DUCT DIAMETER	386.1 mm (15.2)
FAN PRESSURE RATIO	1.25
FAN SPEED	311.7 rev/s (18700 RPM)
POWER	197.7 KW (265 HP)
THRUST	1.73 KN (388 LB)

32537

TABLE XXVIII. RELATIVE COST SUMMARY (FOR EQUAL WEIGHT) FOR DESIGN 2011 - DIFFERENTIAL TURBOPROP AND DESIGN 2012 - DIFFERENTIAL TURBOSHAFT

COMPONENT RELATIVE COST: BASELINE								TOTAL
GEARBOX & AIR INLET	COMPRESSOR	COMBUSTOR	TURBINE	COLD HSG	HOT HSG	ACCY SYSTEM	A & T	
0.20	0.16	0.06	0.20	0.02	0.06	0.24	0.06	1.0
GATE 2011								
0.34	0.08	0.04	0.07	0.02	0.04	0.12	0.04	0.75
GATE 2011 WITH FABRICATION TECHNOLOGY								
0.27	0.048	0.04	0.042	0.02	0.04	0.12	0.04	0.62
GATE 2012								
0.30	0.08	0.04	0.07	0.02	0.04	0.12	0.04	0.71
GATE 2012 WITH FABRICATION TECHNOLOGY								
0.24	0.048	0.04	0.042	0.02	0.04	0.12	0.04	0.59

32538

TABLE XXIX. COMPARISON OF A DIFFERENTIAL TURBINE DESIGN TO A SINGLE SHAFT DESIGN

	SINGLE SHAFT	DIFFERENTIAL TURBINE	
DESIGN NO.	2010	2011	2012
APPLICATION	TURBOPROP	TURBOPROP	TURBOSHAFT
OUTPUT SHAFT	FLANGED 33 rev/s (2000 RPM)	FLANGED 33 rev/s (2000 RPM)	SPLINTED 100 rev/s (6000 RPM)
COST %	100	144	131
WEIGHT %	100	126	119
SFC %	100	104	104

32539

TABLE XXX. BASELINE AIRCRAFT/ENGINE CHARACTERISTIC FOR POINT DESIGNS

CATEGORY	II	III U	III P	IV
PAYLOAD KG (LB)	363 (800)	454 (1000)	454 (1000)	544 (1200)
CRUISE SPEED M/S (KTAS)	87.4 (170)	97.7 (190)	108.0 (210)	128.6 (250)
CRUISE ALTITUDE M (FT)	3048 (10000)	3048 (10000)	5486 (18000)	5486 (18000)
RANGE KM (NM)	1296 (700)	1574 (850)	1667 (900)	2222 (1200)
T. O. DISTANCE M SL: ISA (FT)	488 (1600)	610 (2000)	610 (2000)	671 (2200)
LANDING DISTANCE M SL: ISA (FT)	427 (1400)	457 (1500)	457 (1500)	549 (1800)
ASPECT RATIO	8	8	9	9
$C_{L_{MAX}}$ TAKEOFF	1.6	1.6	1.6	1.8
$C_{L_{MAX}}$ LANDING	2.1	2.2	2.2	2.3
PROPELLER EFFICIENCY @ CRUISE - PERCENT	85	85	85	85
POWER LAPSE RATE $\frac{\text{CRUISE}}{\text{SLTO}}$ (a)	0.641	0.656	0.508	0.535
CRUISE SFC $\mu g/J \left(\frac{LB}{HR\text{-}EHP}\right)$	82.4 (0.488)	81.2 (0.481)	81.7 (0.484)	79.6 (0.471)
RESERVE FUEL (b) S @CRUISE POWER (HR)	60 (1)	60 (1)	60 (1)	60 (1)

32540

(a) SLTO: Sea Level Takeoff Thermodynamic Power. Gearbox Torque Limited to Lower Rating

(b) Reserves Include Takeoff and Climb Allocations per Beech Experience in Similar Designs

TABLE XXXI. BASELINE AIRCRAFT POINT DESIGN CHARACTERISTICS

CATEGORY		II	III U	III P	IV
TAKEOFF WEIGHT	KG (LB)	1313 (2894)	1607 (3543)	1837 (4049)	3127 (6894)
FUEL WEIGHT	KG (LB)	192 (424)	298 (658)	333 (734)	703 (1549)
WING AREA	M^2 (FT^2)	13.7 (148)	15.9 (171)	18.4 (198)	20.2 (217)
WING SPAN	M (FT)	10.5 (34.4)	11.3 (37.0)	12.9 (42.2)	13.5 (44.2)
C_L CRUISE		0.26	0.23	0.25	0.23
USEFUL LOAD (a)	KG (LB)	555 (1224)	752 (1658)	787 (1734)	1247 (2749)
SLTO (b)	KW (HP)	198 (265)	284 (381)	421 (565)	395 (530)
CRUISE POWER REQUIRED (d)	KW (HP)	128 (172)	189 (253)	220 (295)	215 (288)(c)
ACCESSORY POWER	KW (HP)	1.5 (2)	2.2 (3)	[illegible].0 (8)	3.0 (4)(c)
TAKEOFF POWER REQUIRED	KW (HP)	174 (234)	202 (271)	234 (314)	218 (292)(c)
EMPTY WEIGHT	KG (LB)	758 (1670)	855 (1885)	1050 (2315)	1880 (4145)
PROPULSION (e) WEIGHT	KG (LB)	136 (299)	154 (339)	187 (412)	419 (923)

32541A

(a) Useful Load = Payload Plus Fuel

(b) SLTO: Sea Level Takeoff Thermodynamic Power. Gearbox torque limited to a lower rating

(c) Per engine

(e) Propulsion Weight includes engine(s), controls, exhaust pipe(s), oil system with cooler(s), fuel system, propeller(s) and starter-generator(s)

(d) Includes accessory power

TABLE XXXII. POINT DESIGN AIRCRAFT PRICE ANALYSIS: AVERAGE EQUIPPED AIRCRAFT WITH PROPELLERS, BUT WITHOUT ENGINES

CATEGORY	INDUSTRY ANNUAL SALES QUANTITY (UNITS)	COST PER KG (LB) OF GROSS WEIGHT ($)	AIRFRAME RETAIL PRICE ($)
II	9,600	46.30 (21)	52,700
IIIU	2,000	48.50 (22)	65,400
IIIP	2,000	90.40 (41)	131,300
IV	3,500	90.40 (41)	209,500

32542

(a) All Price Estimates are in 1976 Dollars to be Consistent with the Terms of the Task I Market Survey

TABLE XXXIII. AIRCRAFT PARAMETERICS - LINEAR INFLUENCE COEFFICIENTS

CATEGORY	$\frac{\partial}{\partial \text{ PAYLOAD}}$			$\frac{\partial}{\partial \text{ SFC}}$		
	TOGW	FUEL WEIGHT	CRUISE POWER KW/KG (EHP/LB)	TOGW KG/%ΔSFC (LB/%ΔSFC)	FUEL WEIGHT KG/%ΔSFC (LB/%ΔSFC)	CRUISE POWER KW/%ΔSFC (EHP/%ΔSFC)
II	3.43	0.315	0.197 (0.120)	5.87 (12.94)	2.14 (4.73)	0.556 (0.746)
III U	3.27	0.338	0.227 (0.138)	8.57 (18.9)	3.08 (6.8)	0.543 (0.728)
III P	3.363	0.350	0.247 (0.150)	11.73 (25.87)	4.97 (10.95)	0.483 (0.647)
IV	4.05	0.718	0.222 (0.135)	36.38 (80.2)	15.92 (35.09)	1.907 (2.556)

32543

TABLE XXXIV. AIRCRAFT SYNTHESIS ANALYSIS RESULTS, VARIATIONS IN CONFIGURATION AND RETAIL PRICE DUE TO ENGINE CHANGES (CONSTANT MISSION).

CATEGORY		II			III P			IV (a)		
ENGINE CONFIGURATION		BASELINE C9 (b)	ADJUSTED C9 (c)	AC 11.3	BASELINE C9 (b)	ADJUSTED C9 (c)	AC 11.3	BASELINE C9 (b)	ADJUSTED C9 (c)	AC 11.3
TAKE OFF GROSS WEIGHT	KG (LBS)	1313 (2894)	1315 (2899)	1296 (2858)	1837 (4049)	1789 (3944)	1746 (3849)	3127 (6894)	3008 (6834)	2803 (6180)
EMPTY WEIGHT	KG (LBS)	758 (1670)	759 (1673)	752 (1658)	1050 (2315)	1022 (2253)	1007 (2220)	1880 (4145)	1817 (4007)	1704 (3757)
PAYLOAD	KG (LBS)	363 (800)	363 (800)	363 (800)	454 (1000)	454 (1000)	454 (1000)	544 (1200)	544 (1200)	544 (1200)
FUEL WEIGHT	KG (LBS)	192 (424)	193 (426)	181 (400)	333 (734)	313 (691)	285 (629)	703 (1549)	647 (1427)	555 (1223)
ENGINE WEIGHT	KG (LBS)	60 (133)	60 (133)	65 (144)	106 (233)	105 (232)	113 (250)	100 (221) (d)	99 (218) (d)	106 (234) (d)
PROPULSION WEIGHT	(e) KG (LBS)	136 (299)	136 (299)	141 (310)	187 (412)	186 (411)	194 (428)	419 (923)	416 (917)	430 (949)
CRUISE POWER	KW (EHP)	128 (172)	128 (172)	126 (169)	220 (295)	218 (293)	215 (288)	215 (288) (d)	211 (283) (d)	206 (277) (d)
CRUISE SFC	Mg/J LB HR-EHP	82.4 (0.488)	82.8 (0.490)	77.7 (0.460)	81.7 (0.484)	78.5 (0.465)	73.5 (0.435)	79.6 (0.471)	76.8 (0.455)	72.0 (0.426)
AIRCRAFT RETAIL PRICE	(f) 1977 DOLLARS	62,500	62,500	64,600	143,600	139,300	139,000	233,300	222,500	210,800

(a) twin engine aircraft, others are single engine
(b) based on task I engine data
(c) based on revised task II engine data
(d) each engine
(e) propulsion weight includes engine(s), controls, exhaust pipe(s), oil system with cooler(s), fuel system, propeller(s) and starter-generator(s)
(f) includes engine price

33883

TABLE XXXV. L^2C^2 FINAL SCHEDULE DEFINITIONS

		CAT.	II	IIIU	IIIP	IV
INSURANCE/YR.	$		2120	2625	3125	4240
HANGAR/YR.	$		900	1000	1600	2600
AIRCRAFT + PROP. SERVICE/HR.	$		4.10	4.10	7.61	7.61

ENGINE SERVICE/HR.

MTCE BASIC - $8/HR.
TBO @ 3500 HRS.: 30% OF ENG. RETAIL PRICE
HOT SECT. INSP.: IGNORE (INCL. IN MTCE.)

MISC. COSTS: FIXED/YR.	1% of Acq. →			
: VARIABLE/HR.	1.50	1.80	2.50	3.00

ACQUISTION: 20% DOWN + 80% FINANCED @ 10%, 5 YRS.
30% RESALE = 0.92 x RETAIL PRICE

32545

TABLE XXXVI. COMPARISON OF GATE 1988 CATEGORY II AIRCRAFT WITH TURBOPROP -vs- RECIPROCATING POWER: CONSTANT AIRCRAFT SIZE; VARIABLE PERFORMANCE

	GATE CATEGORY II	CHANGE RELATIVE TO GATE ENGINE		CATEGORY II WITH RECIPROCATING ENGINE CONSTANT TO WEIGHT & CRUISE POWER
		DELTA	PERCENT	
ENGINE TAKE-OFF POWER KW(HP)	174.4 (234)	----	---	174.4 (234)
MAX. T.O. WEIGHT KG(LB)	1312.7 (2894)	----	---	1312.7 (2894)
STANDARD EMPTY WEIGHT KG(LB)	757.5 (1670)	99.8 (220)	+13	857.3 (1890)
USEFUL LOAD KG(LB)	555.2 (1224)	99.8 (220)	-18	455.4 (1004)
USABLE FUEL KG(LB)	192.3 (424)	49.9 (110)	-26	142.4 (314)
PAYLOAD WITH FULL FUEL KG(LB)	363 (800)	49.9 (110)	-14	313 (690)
MAX. CRUISE SPEED m/s (kts)	87.4 (170)	2.57 (5)	-3	84.9 (165)
ALTITUDE m(FT)	3048 (10000)	----	---	3048 (10000)
CRUISE POWER KW(HP)	126.8 (170)	----	---	128.6 (170)
RANGE KM(NM)	1297 (700)	447 (240)	-34	852 (460)
TAKE-OFF DISTANCE OVER 15.24 M (50 FT)	487.7 (1600)	----	---	487.7 (1600)
LANDING DISTANCE OVER 15.24 M (50 FT)	426.7 (1400)	----	---	426.7 (1400)
WING AREA M^2 (FT^2)	13.75 (148)	----	---	13.8 (148)

32546

TABLE XXXVII. COMPARISON OF GATE 1988 CATEGORY IV AIRCRAFT WITH TURBOPROP -vs- RECIPROCATING POWER: CONSTANT AIRCRAFT SIZE; VARIABLE PERFORMANCE

	GATE CATEGORY IV	CHANGE RELATIVE TO GATE ENGINE		CATEGORY IV WITH RECIPROCATING ENGINE CONSTANT TO WEIGHT & CRUISE POWER
		DELTA	PERCENT	
ENGINE TAKE-OFF POWER KW(HP)	217.7 (292)	----	---	(a)
MAX. T.O. WEIGHT KG(LB)	3127.1 (6894)	----	---	3127.1 (6894)
STANDARD EMPTY WEIGHT KG(LB)	1880.2 (4145)	234.9 (518)	+12	2115.1 (4663)
USEFUL LOAD KG(LB)	1247 (2749)	234.9 (518)	-19	1011.9 (2231)
USABLE FUEL KG(LB)	702.6 (1549)	117.5 (259)	-17	585.1 (1290)
PAYLOAD WITH FULL FUEL KG(LB)	544.3 (1200)	117.5 (259)	-22	426.8 (941)
MAX. CRUISE SPEED m/s (kts)	128.6 (250)	8.2 (16)	-6	120.4 (234)
ALTITUDE m(FT)	5486.4 (18000)	----	---	5486.4 (18000)
CRUISE POWER KW(HP)	211.8 (284)	----	---	211.8 (284)
RANGE KM(NM)	2223 (1200)	560 (306)	-26	1656 (894)
TAKE-OFF DISTANCE OVER 15.24 M (50 FT)	670.6 (2200)	----	---	670.6 (2200)
LANDING DISTANCE OVER 15.24 M (50 FT)	548.6 (1800)	----	---	548.6 (1800)
WING AREA M^2 (FT^2)	20.2 (217)	----	---	20.2 (217)

32547

(a) If Cruise is at 75 Percent, T.O. Power would be 282.6 KW (379 HP). This would give a T. O. Distance of Less than 2200 Feet.

TABLE XXXVIII. COMPARISON OF GATE 1988 CATEGORY II AIRCRAFT WITH TURBOPROP -vs- RECIPROCATING POWER: EQUAL AIRCRAFT PERFORMANCE; VARIABLE SIZE

	GATE CATEGORY II	CHANGE RELATIVE TO GATE ENGINE		CATEGORY II WITH RECIPROCATING ENGINE CONSTANT MISSION
		DELTA	PERCENT	
ENGINE TAKE-OFF POWER KW(HP)	174.4 (234)	-----	----	174.4 (234)
MAX. T. O. WEIGHT KG(LB)	1312.7 (2894)	161.5 (365)	+12	1474.2 (3250)
STANDARD EMPTY WEIGHT KG(LB)	757.5 (1670)	138.8 (306)	+18	896.3 (1976)
USEFUL LOAD KG(LB)	555.2 (1224)	-----	---	555.2 (1224)
USABLE FUEL KG(LB)	192.3 (424)	22.7 (50)	+12	215 (474)
PAYLOAD WITH FULL FUEL KG(LB)	363 (800)	-----	---	363 (800)
MAX. CRUISE SPEED m/s (kts)	87.4 (170)	-----	---	87.4 (170)
ALTITUDE m(FT)	3048 (10000)	-----	---	3048 (10000)
CRUISE POWER KW(HP)	126.8 (170)	14.9 (20)	+12	141.7 (190)
RANGE KM(NM)	1297 (700)	-----	---	1297 (700)
TAKE-OFF DISTANCE OVER 15.24 M (50 FT)	487.7 (1600)	73.2 (240)	+15	560.8 (1840)
LANDING DISTANT OVER 15.24 M (50 FT)	426.7 (1400)	-----	---	426.7 (1400)
WING AREA M^2 (FT^2)	13.75 (148)	1.21 (13)	+9	14.96 (161)

32548

TABLE XXXIX. COMPARISON OF GATE 1988 CATEGORY IV AIRCRAFT WITH TURBOPROP -vs- RECIPROCATING POWER: EQUAL AIRCRAFT PERFORMANCE; VARIABLE SIZE

	GATE CATEGORY IV	CHANGE RELATIVE TO GATE ENGINE		CATEGORY IV WITH RECIPROCATING ENGINE CONSTANT MISSION
		DELTA	PERCENT	
ENGINE TAKE-OFF POWER KW (HP)	217.7 (292)	99.2 (133)	+46	316.9 (425)
MAX. T.O. WEIGHT KG (LB)	3127.1 (6894)	615.1 (1356)	+20	3742.2 (8250)
STANDARD EMPTY WEIGHT KG(LB)	1880.2 (4145)	474.0 (1045)	+25	2354.2 (5190)
USEFUL LOAD KG(LB)	1247 (2749)	141.1 (311)	+11	1338 (3060)
USABLE FUEL KG(LB)	702.6 (1549)	141.1 (311)	+20	843.7 (1860)
PAYLOAD WITH FULL FUEL KG(LB)	544.3 (1200)	----	---	544.3 (1200)
MAX. CRUISE SPEED m/s(kts)	128.6 (250)	----	---	128.6 (250)
ALTITUDE m(FT)	5486 (18000)	----	---	5486 (18000)
CRUISE POWER KW(HP)	211.8 (284)	41.8 (56)	+20	253.5 (340)
RANGE KM(NM)	2223 (1200)	----	---	2223 (1200)
TAKE-OFF DISTANCE OVER 15.24 M (50 FT)	670.6 (2200)	121.9 (400)	-18 (a)	548.6 (1800)
LANDING DISTANCE OVER 15.24 M (50 FT)	548.6 (1800)	----	---	548.6 (1800)
WING AREA M^2 (FT^2)	20.2 (217)	3.9 (42)	+19	24.1 (159)

32549

(a) Performance is Equal Except for Take-Off Distance.

TABLE XL. AIRCRAFT IMPROVEMENTS WITH GATE TURBOPROP OVER RECIP ENGINES- FOR A CONSTANT MISSION

	% GATE IMPROVEMENT	
	CAT. II	CAT. IV
TOGW	12	20
EMPTY WT. (PRICE)	18	25
CRUISE H.P. REQ'D	12	20
FUEL REQ'D	12	20
TAKEOFF DIST.	13	−22 (ACCEPT.)

EQUAL PAYLOAD, ALT., RANGE, VEL., LANDING DIST.

32550

TABLE XLI. SUMMARY OF COMMON CORE APPROACH

COMMON CORE APPROACH	CONFIGURATION -COMPRESSOR -DESIGN NO.	DESCRIPTION	GEARBOX RATING KW (HP)	WEIGHT KG (LB)	THERMODYNAMIC POWER(a) DESIGN KW (HP)	THERMODYNAMIC POWER(a) SHAVING RANGE KW (HP)
ONE FRAME SIZE PLUS SHAVING	C9 2010	BASIC 2010 DESIGN PLUS WIDE RANGE FLOWPATH SHAVING	365.5 (490)	93.5 (206)	365.5 (490)	198 - 422 (265)-(565)
TWO FRAME SIZE PLUS SHAVING	C9 2010	BASIC 2010 DESIGN PLUS REDUCED RANGE FLOWPATH SHAVING	365.5 (490)	93.5 (206)	365.5 (490)	317 - 422 (425)-(565)
	C9 2010	SCALED 2010 DESIGN PLUS REDUCED RANGE FLOWPATH SHAVING	224 (300)	65.8 (145)	224 (300)	198 - 280 (265)-(375)
TWO FRAME FAMILY	AC 11.3 3013	3010 DESIGN MODIFIED FOR COMPONENT REMOVAL	410 (550)	92.2 (203)	422 (565)	----
	C9 2013	2010 DESIGN APPROACH DERIVED FROM 3013 DESIGN	205 (275)	78.1 (172)	250 (335)	----

32551

(a) SLS Turbine Inlet Temperature 1504°K (2250°F)

TABLE XLII. TWO FRAME FAMILY PERFORMANCE SUMMARY (SEA LEVEL STATIC, UNINSTALLED)

ENGINE CONFIGURATION	POWER KW(a) (HP)	FUEL CONSUMPTION μg/J (LB/HP-HR)	AIRFLOW KG/S (LB/SEC)	T.I.T. °K (°F)	PR
BASELINE AC 11.3	422 (565)	78.2 (0.465)	1.30 (2.86)	1504 (2250)	11.3
REMOVE AXIALS C9	250 (335)	87.5 (0.518)	1.0 (2.20)	1389 (2040)	9.0
C9 WITH IGV AND REMATCH	197.7 (265)	91.9 (0.544)	0.79 (1.75)	1394 (2050)	8.2

(a) THERMODYNAMIC RATING

32552

TABLE XLIII. RELATIVE COST SUMMARY (FOR EQUAL WEIGHT) FOR DESIGN 3013-AC 11.3 COMMON CORE, DESIGN 3011-AC 11.3 FREE TURBINE TURBOPROP AND DESIGN 3012 FREE TURBINE TURBOSHAFT.

COMPONENT RELATIVE COST: BASELINE								TOTAL
GEARBOX & AIR INLET	COMPRESSOR	COMBUSTOR	TURBINE	COLD HSG	HOT HSG	ACCY SYSTEM	A&T	
0.20	0.16	0.06	0.20	0.02	0.08	0.24	0.06	1.0
GATE 3013								
0.24	0.16	0.04	0.14	0.02	0.05	0.12	0.05	0.82
GATE 3013 WITH FABRICATION TECHNOLOGY								
0.192	0.096	0.04	0.084	0.02	0.05	0.12	0.05	0.652
GATE 3011								
0.25	0.16	0.04	0.20	0.02	0.07	0.16	0.07	0.97
GATE 3011 WITH FABRICATION TECHNOLOGY								
0.20	0.096	0.04	0.12	0.02	0.07	0.16	0.07	0.776
GATE 3012								
--	0.16	0.04	0.20	0.02	0.07	0.16	0.05	0.70
GATE 3012 WITH FABRICATION TECHNOLOGY								
--	0.096	0.04	0.12	0.02	0.07	0.16	0.05	0.556

32553

TABLE XLIV. OEM COST: EXPRESSED IN DOLLARS FOR A PRODUCTION RATE OF 500 PER YEAR

DESIGN NUMBER	CONSTANT WEIGHT 227 KG (500 LB)	CONSTANT POWER 365.5 KW (490 HP)	CONSTANT POWER 422 KW (565 HP)
3013	81823	----	44885
3011	96791	55891	---
3012	69849	33963	---

32430

TABLE XLV. AC 11.3/C9 COST SUMMARY

OEM BASE: $ 44885 @ 500/YR

		ENGINE COST RATIO	(a) K_2	OEM PRICE UNIT	OEM PRICE A + B (b)	OEM PRICE A (c)
GEARBOX & AIR INLET	A (d)	0.24390	0.8	1710.00	2194.48	1710.00
	B (e)	0.04878	0.8	484.48		
COMPRESSOR	A	0.09756	0.6	521.34	1248.07	521.34
	B	0.09756	0.6	726.73		
COMBUSTOR	A	0.04878	1.0	434.44	434.44	434.44
TURBINE	A	0.08536	0.6	456.17	1092.06	456.17
	B	0.08536	0.6	635.89		
COLD HSG	A	0.01220	1.0	108.61	260.02	108.61
	B	0.01220	1.0	151.41		
HOT HSG	A	0.03659	1.0	325.84	628.65	325.84
	B	0.02439	1.0	302.81		
ACCY SYSTEM	A	0.12195	1.0	1086.13	1388.94	1086.13
	B	0.02439	1.0	302.81		
A&T	A	0.04878	1.0	434.45	585.86	434.45
	B	0.01220	1.0	151.41		
TOTAL: OEM PRICE					7832.52	5076.98
SELLING PRICE (1.5 X OEM)					11748.78	7615.47

32555

(a) K_2: FABRICATION TECHNOLOGY FACTOR
(b) AC 11.3 COMMON CORE
(c) C9 (AC 11.3 DERIVATIVE)
(d) A UNITS: PRODUCTION RATE - 15165/YR
(e) B UNITS: PPODUCTION RATE - 7525/YR

TABLE XLVI. RELATION OF THE COMMON CORE ENGINE PRICE TO THE PROJECTED FIXED WING AND HELICOPTER MARKET

<table>
<tr><td colspan="2"></td><td colspan="5">FIXED WING</td><td rowspan="2">HELICOPTER</td></tr>
<tr><td colspan="2">CATEGORY</td><td>II</td><td>III U</td><td>III P</td><td>IV</td><td>AG</td></tr>
<tr><td colspan="2">NUMBER OF ENGINES PER YEAR (a)</td><td>6480</td><td>1160</td><td>575</td><td>5940</td><td>1010</td><td>1120 (b)</td></tr>
<tr><td>DESCRIPTION</td><td>WT.
KG
(LB)</td><td colspan="6">ENGINE RETAIL PRICE $ (c)</td></tr>
<tr><td>C9 ONE FRAME</td><td>93.5
(206)</td><td colspan="5">← 8210 →</td><td rowspan="5"></td></tr>
<tr><td>C9 FRAME I</td><td>93.5
(206)</td><td colspan="2"></td><td colspan="3">← 11445 →</td></tr>
<tr><td>C9 FRAME II</td><td>65.8
(145)</td><td colspan="2">← 9450 →</td><td colspan="3"></td></tr>
<tr><td>AC 11.3</td><td>92.2
(203)</td><td colspan="2"></td><td colspan="3">← 11750 →</td></tr>
<tr><td>C9 - DERIVED FROM AC 11.3</td><td>78.1
(172)</td><td colspan="2">← 7615 →</td><td colspan="3"></td></tr>
<tr><td>AC 11.3 FREE TURBINE</td><td>81.5
(179)</td><td colspan="5"></td><td>27350</td></tr>
</table>

(a) FOR ONE MANUFACTURER PRODUCING ½ OF THE FIXED WING OEM ENGINES PLUS 35% SPARES

(b) DUE TO THE SMALL NUMBER OF GATE DERIVATIVE ENGINES FOR THE HELICOPTER ASSUMES ONE MANUFACTURER WILL CAPTURE TOTAL MARKET PLUS 35% SPARES

(c) RETAIL PRICE = 1.5 × OEM PRICE

32554

TABLE XLVII. CORE ENGINE COST FEATURES COMPARED TO CURRENT TECHNOLOGY

FEATURE	COMPONENT	PERCENT COST REDUCTION
REDUCE NUMBER OF COMPONENTS	ONE COMPRESSOR STAGE REPLACES TWO	10
	ONE TURBINE STAGE REPLACES THREE	16
NEW DESIGN CONCEPTS	VAPORIZING PLATE COMBUSTOR REPLACES ATOMIZER	2
	FULL AUTHORITY ELECTRONIC CONTROL REPLACES HYDROMECHANICAL	12
CYCLE BENEFITS	HIGH SPECIFIC OUTPUT REDUCES ENGINE SIZE THEREBY REDUCES COST	9.1
TOTAL COST REDUCTION		49.1%

32065

REFERENCES:

1. ANON: "Q-Fan for General Aviation" December 1973; Hamilton Standard Division. NASA CR-114665

2. Anon: "Aircraft Piston Engine Exhaut Emissions Symposium", Lewis Research Center, September 14-15, 1976. NASA CP-2005

3. Jones, C., Lamping D. et al "An Update of the Direct Injected Stratified Charge Rotary Combustion Engine Developments at Curtiss-Wright". February 1977. SAE 770044

4. Anon: "Aircraft Engine Emissions - A Conference held at Lewis Research Center, Cleveland, Ohio". May 18-19, 1977. NASA Conference Publication 2021

5. Willis, Edward A.: "General Aviation Energy-Conservation Research Programs at NASA-Lewis Research Center". NASA TM-73884, October 1977

6. Diehl, L. "Reduction of Aircraft Gas Turbine Pollutant Emissions - A Status Report". June 1978. NASA TM-78870

7. Anon: "Business Aircraft & FAR 36". January 1977. Business and Commerical Aviation

8. Little, J., Russell, R.E. "Status Report - Subsonic Aircraft Noise Reduction". March 1976. ASME 76-GT-116

9. Rudey, R. "The Impact of Emission Standards on the Design of Aircraft Gas Turbine Combustors". SAE 760909

10. Bresnahan, D., Sievers, G. NASA Quiet, Clean, General Aviation Turbofan (QCGAT) Program Status. December 1976. ASME 77-GT-77

11. The Status of Small, Cooled, Axial Flow Turbines. H.F. Due, A.E. Easterling and J.E. Haas. In AGARD proceedings No. 229, "High Temperature Problems in Gas Turbine Engines. NATO, 19-23 September 1977

12. Arnold, D., Balje, O.E. "High Temperature Potential of Uncooled Radial Turbines". ASME 77-GT-46

13. Wood, H., Performance Potential of Single-Stage Gas Turbine Engines. SAE 739135

14. Metzger, F.B., Worobel, R., "New Low-Pressure Ratio Fans for Quiet Business Aircraft Propulsion". SAE 730288

15. Federal Register, 17 July 1973, Vol 38 No. 136, Part II

APPENDIX A
LIST OF SYMBOLS AND ABBREVIATIONS

Ag	-	Agricultural
Assy	-	Assembly
ATR	-	Area Taper Ratio
B	-	British Thermal Unit
C_{DP}	-	Profile Drag Coefficient
C_f	-	Coefficient
C_L	-	Lift Coefficient
CO	-	Carbon Monoxide
COMPON	-	Component
Co	-	Isentropic Spouting Velocity
CR	-	Cost Ratio
dB	-	Decibels
Del	-	Delivery
Demo	-	Demonstrator
Des	-	Design
DIA	-	Diameter
DN	-	Bearing Bore Diameter Times Speed
DOC	-	Direct Operating Cost
DOD	-	Department of Defense
DS	-	Directionally Solidified
D_S	-	Specific Diameter
DTC	-	Design-To-Cost
Eff'y	-	Efficiency
EHP	-	Equivalent Horsepower
EPA	-	Environmental Protection Agency
EPNdB	-	Equivalent Perceived Noise Decibels

APPENDIX A (Continued)

F	-	Fahrenheit
^oF	-	Degrees Fahrenheit
FAA	-	Federal Aviation Administration
Fab	-	Fabrication
FAR36	-	Federal Aviation Regulation Part 36
F/A	-	Fuel Air Ratio
FT	-	Feet
g	-	gravitational constant, grams
GAMA	-	General Aviation Manufacturers Association
H	-	Enthalpy
Had	-	Adiabatic Head
HP	-	Horsepower
HR	-	Hour
ICAO	-	International Civil Aviation Organization
IGV	-	Inlet Guide Vanes
IN	-	Inch
Insp	-	Inspection
Instrum	-	Instrumentation
J	-	Joules
J_C	-	Joules Constant
K	-	Kelvin
^oK	-	Degrees Kelvin
KG	-	Kilogram
KM	-	Kilometer
Kn	-	Kilonewton
Knots	-	Nautical Miles Per Hour

APPENDIX A (Continued)

KTAS	-	Knots, Air Speed
LTO	-	Landing Take Off
L^2C^2	-	Limited Life Cycle Cost
LB	-	Pound
M	-	Meter
MATE	-	Materials for Advanced Turbine Engines
MAX	-	Maximum
Min	-	Minute
MISC	-	Miscellaneous
M, m	-	Meter
mm	-	Millimeter
MPH	-	Miles Per Hour
MTCE	-	Maintenance
N	-	Newtons
N	-	Rotational Speed
NM	-	Nautical Mile
NO_X	-	Oxides of Nitrogen
N_S	-	Specific Speed
OBJ	-	Objective
OEM	-	Original Equipment Manufacturer
ORC	-	Overrunning Clutch
OV	-	Overall
P	-	Pressure
PAX	-	Passenger
PCA	-	Percent Cost Aircraft
PM	-	Powder Metal

APPENDIX A (Continued)

PR	-	Pressure Ratio
PWR	-	Power
QCGAT	-	Quiet Clean General Aviation Turbofan
^{o}R	-	Degrees Rankine
R/C	-	Rate of Climb
RECIP	-	Reciprocating
REL	-	Relative
Req'd	-	Required
REV	-	Revolution
ROI	-	Return On Investment
RPM	-	Revolutions Per Minute
S	-	Second
Sect	-	Section
SFC	-	Specific Fuel Consumption
SLS	-	Sea Level Static
SLTO	-	Sea Level Take-Off
S/N	-	Serial Number
T	-	Temperature
T1	-	Engine Class Thrust Less Than 36 KN (8000 lbs)
TBO	-	Time Between Overhaul
THC	-	Total Hydrocarbons
Ti	-	Titanium
TIT	-	Turbine Inlet Temperature
TO	-	Take-Off
TOGW	-	Take-Off Gross Weight

APPENDIX A (Continued)

U	-	Wheel Speed
V	-	Volume
vs	-	Versus
VSTT	-	Variable Speed Training Target
W_a	-	Airflow (Absolute)
WT	-	Weight
$\frac{\partial}{\partial \text{Payload}}$	-	Rate of Change of Column Heading with Respect to Payload
$\frac{\partial}{\partial \text{sfc}}$	-	Rate of Change of Column Heading with Respect to SFC
Δ	-	Incremental and/or Delta
ΔP	-	Pressure
η	-	Efficiency
ρ_o	-	Stagnation Density
μ	-	Micro
θ	-	Ratio of Station Temperature to Standard Temperature
δ	-	Ratio of Station Density to Standard Density