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STUDY OF AN ADVANCED GENERAL AVIATION TURBINE ENGINE (GATE)

Final Report

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DIVISION OF GENERAL MOTORS CORPORATION

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I. SUMMARY

The objective of the General Aviation Turbine Study (GATE) was to identify the best technology program for a small, economically viable gas turbine engine applicable to the general aviation helicopter and aircraft market for 1985-1990. The study considered turboshaft and turboprop engines in the 112 to 746 kW (150 to 1000 hp) range and turbofan engines up to 6672 N (1500 lbf) thrust.

The scope of the effort encompassed five tasks:

- Task I Market Analysis
- Task II Broad Scope Trade-off Studies
- Task III Evaluation of a Common Core Concept
- Task IV Technology Program Plan
- Task V Reporting

Based on the 4% annual growth rate anticipated within the next 10 years in general aviation aircraft production, a good market for new turbine engines was predicted for 1988 providing aircraft are designed to capitalize on the advantages of the turbine engine particularly its light weight and compact size. The 1988 turbine engine market was found to be essentially equal in terms of dollar volume in all power classes; however, the greatest impact on the general aviation field for a GATE engine exist under 447 kW (600 hp) because no new technology engines are currently planned in this class. Penetration of the fixed-wing aircraft market is required for attractive engine quantities. Turbine engines can achieve greater penetration into the general aviation market through improvements in cost, preformance, and TBO (time between overhaul). Any successful new design must carefully select a balance of these parameters to best meet the market needs. No significant market for turbofan engines under 6672 N (1500 lbf) thrust was found.

Parametric engine families were defined in terms of design and off-design performance, mass, and cost. These were evaluated in aircraft design missions selected to represent important market segments for fixed- and rotary-wing applications. Payoff parameters influenced by engine cycle and configuration changes were aircraft gross mass, acquisition cost, total cost of ownership, and cash flow. Significant advantage over a current technology, small gas turbine engines was found especially in cost of ownership and fuel economy for airframes incorporating an air-cooled high-pressure ratio engine. Gross mass reductions of 10 to 20% for the same capability was indicated. Mass savings were reflected in 8 to 20% lower ownership costs. A power class of 373 kW (500 hp) was recommended as the next frontier for technology advance where large improvements in fuel economy and engine mass appear possible through component research and development. The advanced turbine engine appears competitive with the piston engine in terms of installed performance and has a large advantage in engine mass; however, a large premium in price for the turbine engine appears inevitable based on manufacturing experience and forecasts through the late 1980's.

The technology plan recommended programs in component research applicable to small turbine engine compressors, combustors, turbines, seals, controls, gearing, and shafting, including on-going efforts in materials and engine airframe integration. Toward this end, 24 specific program plans were described and provided to NASA. It was also recommended that NASA serve as the catalyst to encourage introduction of useful new technology into engine designs through application studies and possibly core demonstrator programs as component R&D matures.

II. INTRODUCTION

The GATE (General Aviation Turbine Engine) study was sponsored by NASA to determine possible benefits to general aviation through development of the small gas turbine engine.

The gas turbine engine has made tremendous inroads in certain segments of general aviation today. Over 75% of new helicopters manufactured in the free world each year are powered by turbine engines, and this percentage is forecast to increase steadily as more turbine-powered machines reach the operating fleet.

Turbine engine use in fixed-wing general aviation aircraft is also growing, although the piston engine dominates under 298 kW (400 hp) shaft power. In the larger multiengine aircraft used for third-level carrier (commuter airline), corporate/executive, business/utility, and personal flying, turbine engine power is used nearly exclusively. Approximately 800 small turbine engines were produced in 1976 in North America to supply the demand for domestic fixed-wing aircraft production. An additional 500 were produced for domestic commercial helicopter production. In addition, nearly equal numbers of engines were produced to satisfy the requirements of foreign airframe manufacturers.

General Motors Corporation, Detroit Diesel Allison (DDA) Division, as the worlds leading supplier of small gas turbine engines for helicopters, shared NASA's interest in the project, and was one of four successful contractors selected to perform the GATE study. DDA's experience in this field includes the production of over 10,000 Model 250 engines at its Indianapolis facility. These engines ranged from 186 to 485 kW (250 to 650 hp) shaft power and accumulated over 10 million hours of operation.

The overall objective of the GATE study was to define the most effective program to develop and demonstrate advanced technologies for small-sized turbine engines for the 1985-1990 general aviation market. This objective is considered essential and timely in view of the expanding market in general aviation, the need for energy conservation, the demand for more stringent environmental controls, and the desire to keep the U.S. aircraft industry strong and internationally competitive.

One problem addressed in the study was that of achieving a high performance level in small gas turbine engines. In transferring technology demonstrated in the more efficient large engines to engines with much smaller flow paths, the rising importance of minimal tip clearance for the rotating blading and improved seal efficiency are well known. The increased cycle efficiency obtainable with high temperature is more difficult to obtain in the small engine because of aerodynamic constraints that tend to allow insufficient passage area for turbine blade cooling air thus limiting maximum cycle temperature.

Engine cost, another prime driver in small engine design was addressed. Aircraft gas turbine engine materials are relatively expensive and difficult to work, resulting in a costly engine. As aircraft size diminishes, powerplant costs become an increasing percentage of the total cost, until at some point, a less costly engine type may be selected. Nor can one excessively over emphasize cost to the detriment of performance because the additional weight of the engine and fuel required to perform a given mission will react on the airframe design and reflect in a less efficient and more costly total vehicle. Trade studies conducted by DDA were designed to identify the most effective cost/performance balance.

Inherently related to engine cost is commonality of core, of components, and of parts. Maximum commonality as a means of spreading costs over a larger production base is sought as a means of reducing engine price. Commonality of the engine core for application as a turboprop, turboshaft, or turbofan engine is considered in the design concept.

Noise and emission requirements for general aviation aircraft reflect the economic impact on the industry and the need for protecting the public from excessive noise and pollution. The need for considering environmental constraints in a new engine technology plan was evaluated.

Turbine engines can achieve greater penetration into the general aviation market if improvements can be made in cost, performance, and TBO (time between overhaul). Any successful new design must carefully select a balance of these parameters to best meet the market needs. It is the purpose of the GATE study to arrive at a conceptual engine design that does this—to identify the technology elements necessary and to describe a technology program plan for government sponsorship that will best support the effort.

Complex relationships are involved in properly selecting an engine for general aviation. Engine characteristics, i.e., specific fuel consumption (sfc), power-to-mass ratio (P/M), and power-to-volume ratio (P/V), impact the total vehicle cost of ownership (COO) sometimes more so than the cost of the engine, by affecting the gross mass (GM) of the vehicle for a given mission as well as the operating expenses once usage begins. If the vehicle has high use, operating expenses dominate and engine sfc and TBO considerations are paramount. With low use, capital costs control and engine initial cost takes on added significance. Noise and emission standards can adversely affect engine and propulsion performance and cost. Cost criticality of materials required by the design is another prime driver on engine cost. Fabrication technique is also a strong determinant of cost as is production rate. The mission requirements impact the sensitivity of the vehicle to engine characteristics; for instance, vehicles with high GM in relation to payload (i.e., long-range and/or high-power aircraft) tend to be the most sensitive to sfc and P/M ratio. Figure 1 shows the interactions of the market needs, the engine and air vehicle characteristics, and the cost of ownership.

The study attempts to analyze all of these factors in a systematic broad scope manner to determine the general aviation market needs and to arrive at a conceptual engine configuration best satisfying these needs. Both of these objectives are supportive to the main objective of determining the most effective technology program plan for government sponsorship.

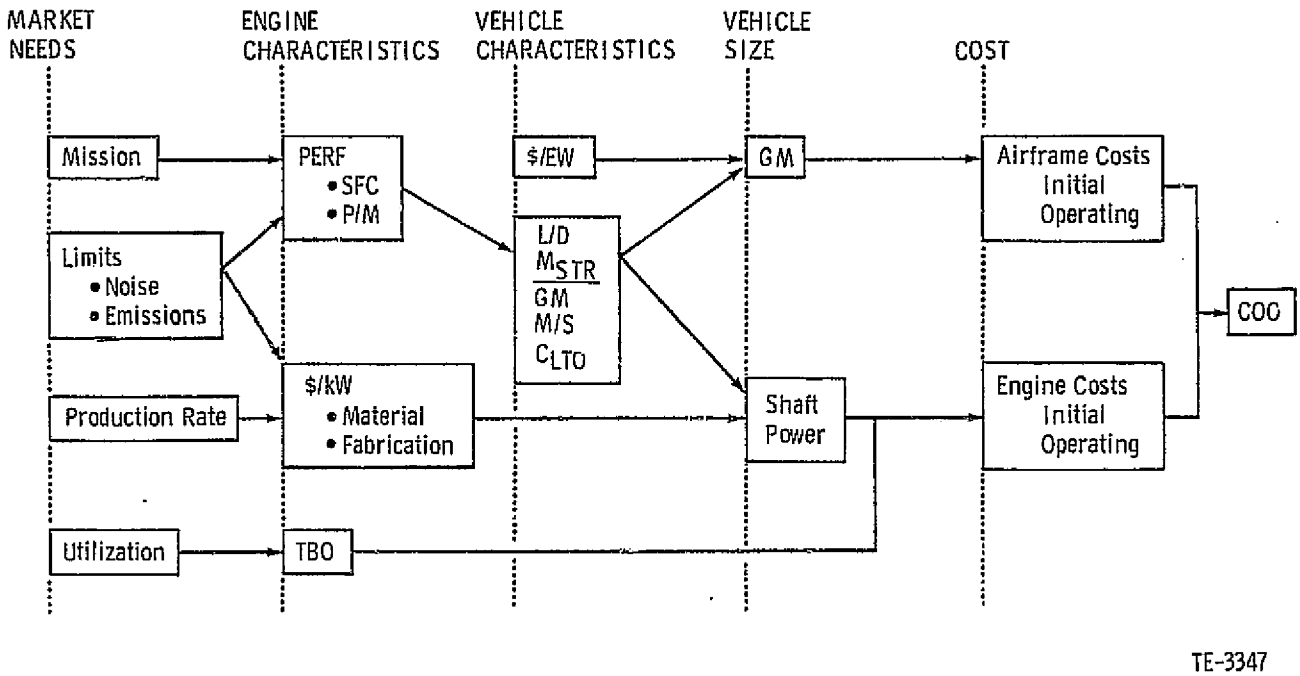

Figure 1. Interrelationship of vehicle system parameters and cost of ownership.

III. GENERAL APPROACH

The Gate study was divided into the following tasks:

- I—Market Analysis
- II--Broad Scope Trade-Off Studies
- III--Evaluation of a Common Core Concept
- IV--Technology Program Plan

MARKET ANALYSIS

The market analysis task was structured for maximum aircraft company involvement so that the forecasts would reflect the industry needs as accurately as possible. Representative levels of advanced engine performance and cost anticipated were provided early in the market research phase to seed projections and establish GATE market impact. In this phase of the program, DDA identified the turbine engine domain and forecast the engine market for turboshaft, turboprop, and turbofan engines by power class and production units to a 1988 scenario. Typical applications and corresponding missions were identified.

BROAD SCOPE TRADE-OFF STUDIES

The trade-off studies were begun early in the program to postulate advanced engine characteristics for the market survey. In this task, technology elements and propulsion requirements including noise and emission standards were identified. A parametric study engine matrix was defined and evaluated on a total vehicle cost of ownership basis. These efforts were supported by parametric maintenance studies to establish maintenance plans and criteria for the general aviation market. Optimum engines were selected for each mission and the potential benefits and penalties were compared with current engines.

EVALUATION OF A COMMON CORE CONCEPT

The potential for engine commonality was investigated to obtain the broadest range of market usage with a single basic engine.

TECHNOLOGY PROGRAM PLAN

Conceptional engine designs were implied to form a basis of creating a technology program plan to best serve the advanced engine needs of the general aviation market. The detailed plan included engine component and core programs.

IV. DISCUSSION OF RESULTS

4a. Market Analysis

APPROACH

In developing the approach to the market analysis, it was necessary to formulate a plan consistent with the needs of the overall GATE study. Consideration was also given to the availability of data, and emphasis was given to maximum correlation with various members of the general aviation industry. A flow chart of the plan is shown in Figure 2.

As a prerequisite to projecting the market for general aviation engines, it was necessary to forecast the market for the various sizes and types of aircraft. Contacts were made with the three largest manufacturers of fixed-wing general aviation aircraft in order to determine the categories used by the industry in forecasting markets. DDA conducts ongoing studies of the rotary-wing market so these forecast categories were well established. The forecast categories relevant to GATE and the current production models in that category are shown in Tables I, II, and III.

Upon identification of the relevant forecasting categories, historical shipment data back to 1970 was accumulated for each category. At this time it was determined that data on shipments on U.S. sales by foreign general aviation

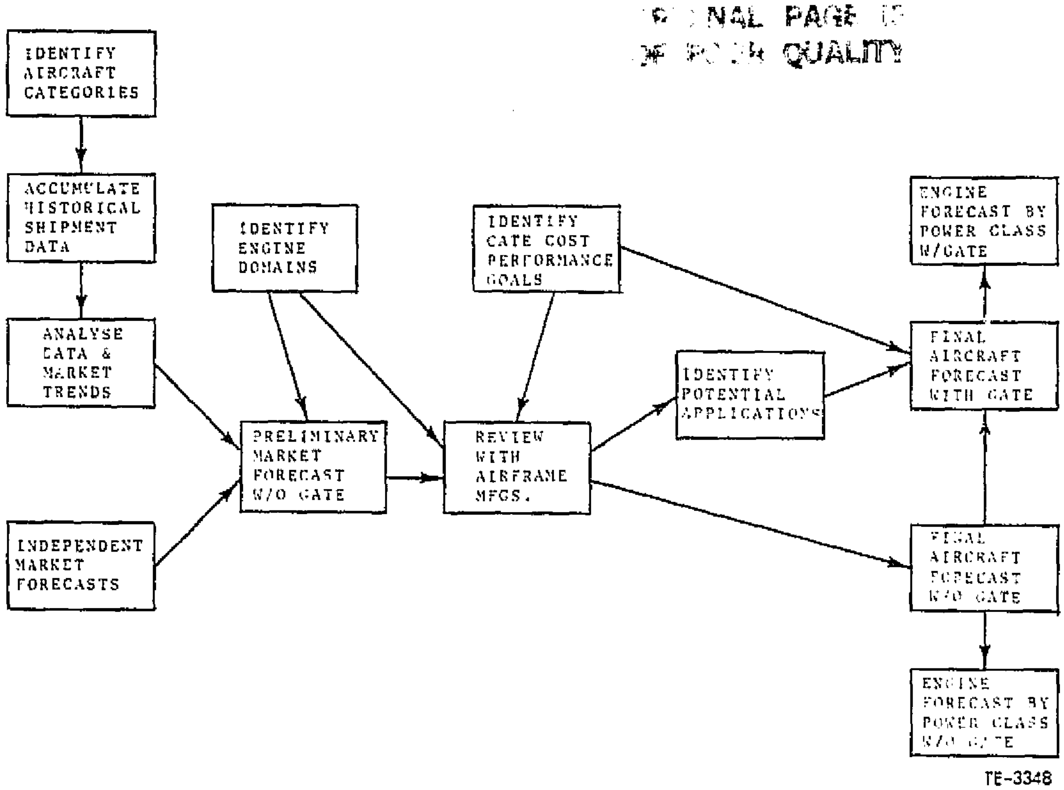

Figure 2. GATE Task I methodology.

TABLE I. - FORECAST GATE CATEGORIES-FIXED WING-PROPELLER DRIVEN

Category				Current aircraft
I	Trainer	2-4 place	Under 112 kW (150 hp)	Bellanca Citabria Series Cessna 150/152 Grumman American T-Cat/Lynx Piper Cherokee 140/cruiser Beech Sport 150 Beech Model 77
II	Light single engine	4 place fixed gear	112-150 kW (150-200 hp)	Cessna Skyhawk/Skyhawk HP Cessna Cardinal Piper Cherokee 150/Warrior-180/Archer Beech Sundowner 180 Grumman Cheetah/Tiger
III	Light single engine	4 place retractable gear	135-157 kW (180-210 hp)	Beech Sierra 200 Cessna Cardinal RG Mooney M20 C,F,J Piper Arrow -Turbo Arrow Rockwell 112B--112 TCA
IV	High performance single engine	4-7 place fixed gear	172-231 kW (230-310 hp)	Cessna Skylane Cessna 206--Turbo 206 Cessna 207--Turbo 207 Piper Cherokee Pathfinder-235 Piper Cherokee Six 260-300
V	High performance single engine	4-7 place retractable gear	186-324 kW (250-435 hp)	Bellanca 17-30, 31A, 31ATC Beech Bonanza F33, V35, A36 Cessna Centurion 210, Turbo Centurion Piper Cherokee Lance Rockwell 114 Bellanca Rocket
VI	Utility single engine	2-6 place	112-231 kW (150-310 hp)	Cessna 180, 185 Skywagon Maule Lunar Rocket M5-210,235 Piper Super Cub Bellanca Scout Helio Courier H-295, HT-295
VII	Single engine AG	1 place fixed gear	Under 336 kW (Under 450 hp)	Cessna AG Wagon Cessna AG Truck Cessna AG Carryall Piper Pawnee 235-260 Piper Pawnee Brave 285-300
VIII	Single engine AG	1 place fixed gear	Over 336 kW (Over 450 hp)	Emair Mai 600 hp Maib 900 hp Grumman AG Cat A,B, 450 hp, 525 hp, 500 hp Weatherly 201B Rockwell Thrust Commander 600-800 hp Ayres Turbo Thrust (PT-6) Marsh Turbo Thrust TPE 331 Frakes Turbo Cat

TABLE I. - (CONT)

Category				Current aircraft
IX	Light twin	4/7 place	239-447 kW (320-600 hp)	Beech Model 76 Beech Baron B55, B58, B58TC Cessna 337 Skymaster Cessna 310, Turbo 310 Piper Seneca II Piper Aztec F, Turbo Aztec F Ted Smith Aero Star 600, 601B
X	Twin engine cabin class unpress	6/10 passenger	432-559 kW (580-750 hp)	Cessna 402B 404 Titan Piper Navajo C., CR., Chieftain Rockwell Shrike
XI	Twin engine press	5-10 place under 4082 kg (9000 lbm)	336-634 kW (450-850 hp)	Cessna Pressurized Skymaster Cessna 340, 414, 421 Beech Duke, Pressurized Baron Ted Smith Aerostar Piper Pressurized Navajo
XII	Twin engine press		597-1268 kW (800-1700 hp) Over 4082.3 kg (9000 lbm)	Beech King Air C90, E90, A100, B100 Beech Super King Air 200 Piper Cheyenne Rockwell Turbo Commander 690B Cessna Conquest Swearinger Merlin IIIA, Merlin IVA Mitsubishi MU-2N MV-2P

TABLE II. - GATE FORECAST CATEGORIES-FIXED WING-THRUST DRIVEN

Category				Current aircraft
XIII	Light turbo-jet/ turbofan	5-8 place	Under 22,241N (5000 lbf) thrust Under 5216 kg (11,500 lbm) GTOM	No aircraft currently available
XIV	Med light turbojet/turbofan	8-10 place	17,793-26,689N (4000-6000 lbf) thrust 5216-6804 kg kg(11,500-15,000 lbm) GTOM	Learjet-24 Series Cessna Citation

TABLE III. - FORECAST GATE ROTARY WING CATEGORIES

Category			Current aircraft
I	Ultralight (recip)	Under 1270 kg (2800 lbm) GTOM	Enstrom F-28, 280 Hughes 300 Hiller 12E
II	Light	1270-2041 kg (2800-4500 lbm)GTOM	Bell 206 Hughes 500
III	Light utility	2041-3629 kg (4500-8000 lbm) GTOM	Bell 222
IV	Utility	3629-5216 kg (8000-11,500 lbm) GTOM	Sikorsky S-76 Bell 204, 205, 212

manufacturers was generally unavailable. Since the worldwide general aviation market is dominated by U.S. manufacturers, the ground rule was established with NASA concurrence that only production by U.S. domestic manufacturers be included in the forecast. The forecast includes installed engines only and does not include spares.

Once the historical shipments by category were accumulated, it was possible to study growth trends of each category. Several approaches to the trend analysis were taken including use of a least squares method. This method has limitations in as much as there were dramatic changes in the 1988 projection depending on the starting year. Introduction of a new model in a particular category can cause dramatic changes in the total shipments for the entire category resulting in erratic behavior in the trend analysis. A more realistic approach was to study each category individually as it is impacted by varying market conditions.

During this phase contact was also made with the Aviation Forecast Branch, General Aviation Division of the FAA. This branch has made projections of the general aviation fleet through 1988 as shown in Table IV. Using this data and subtracting historical attrition and exports resulted in a forecast of the new aircraft production required to support the forecast rates of fleet growth. Subsequent contacts within the general aviation industry indicated that the forecasts obtained in this manner are far more conservative than those generally used within the industry.

TABLE IV. - ESTIMATED ACTIVE GENERAL AVIATION AIRCRAFT BY TYPE OF AIRCRAFT (In Thousands)

As of January 1	Total	Fixed Wing, Piston, Single engine	Fixed Wing, Piston, Multiengine	Fixed Wing, Turboprop	Fixed Wing, Turbojet	Rotorcraft	Balloons, dirigibles, gliders
1972	131.1	109.1	15.5	1.3	1.2	2.5	1.7
1973	145.0	120.4	17.3	1.4	1.2	2.8	1.9
1974	153.5	126.1	18.7	1.9	1.4	3.1	2.3
1975	161.5	131.9	19.8	2.1	1.6	3.6	2.5
1976	168.5	137.5	20.3	2.5	1.8	3.8	2.5
1977*	181.6	147.7	22.2	2.9	2.0	4.1	2.7
1978*	190.5	154.3	23.6	3.2	2.2	4.3	2.9
1979*	196.9	158.9	24.7	3.4	2.4	4.5	3.0
1980*	203.7	163.8	25.9	3.7	2.6	4.6	3.1
1981*	213.3	170.8	27.5	4.1	2.8	4.8	3.3
1982*	226.0	180.2	29.5	4.6	3.1	5.1	3.5
1983*	233.5	185.3	30.9	5.0	3.4	5.3	3.6
1984*	237.3	187.5	31.8	5.3	3.6	5.4	3.7
1985*	243.3	191.5	33.0	5.7	3.8	5.5	3.8
1986*	250.7	196.4	34.4	6.2	4.1	5.7	3.9
1987*	258.7	201.6	36.0	6.7	4.5	5.8	4.1
1988*	267.0	207.1	37.6	7.3	4.8	6.0	4.2

*Forecast.

Note--An active aircraft must have a current registration and have been flown during the previous calendar year. It should be noted that historical data are estimates.

Further analysis was made using forecasts developed by other companies interested in general aviation. From these various sources, it was possible to prepare a preliminary forecast of aircraft production through 1988. Concurrent with this effort analysis of typical mission capabilities of the various categories of aircraft was conducted.

Comparisions were made between some of the existing piston and turboprop engines to determine the relative merits of each type. Table V shows a comparison of three similarly sized engines, a turboprop, a naturally aspirated piston, and a turbocharged piston. It can be seen from this comparison that the turbine engine has considerable advantage in mass, frontal area, and low-altitude cruise characteristics over either of the piston types. The turboprop has a cost and fuel consumption disadvantage over either of the two reciprocating types and an altitude cruise performance disadvantage over the turbocharged piston engine.

TABLE V. - ENGINE DOMAIN

Manufacturer	Lyc	Lyc	Allison
Model	IO-720-A1A	TIGO-541-D1A	250-B17B
Power max SL	298 kW (400 hp)	317 kW (425 hp)	298 kW (400 hp)
Max cruise SL	224 kW (300 hp)	237 kW (318 hp)	273 kW (366 hp)
Max cruise (20,000 ft)	--	237 kW (318 hp)	168 kW (225 hp)
Weight	257 kg (567 lbm)	318 kg (701 lbm)	88 kg (195 lbm)
Shaft sfc (cruise)	764 g/W·s (0.45 lb/hp-h)	764 g/W·s (0.45 lb/hp-h)	1103 g/W·s (0.65 lb/hp-h)
Frontal Area	0.465 m^2 (5 ft^2)	0.557 m^2 (6 ft^2)	0.167 m^2 (1.8 ft^2)
T.B.O.	1800 h	1200 h	3000 h
List price	$17,500	$29,700	$61,900
Overhaul cost	$ 8,750	$11,250	$22,500

Curtis-Wright Corporation was contacted regarding rotary-combustion (RC) engines. We were advised that work is continuing on an aircraft type RC engine, but no production commitment has been made. Further contacts with airframe manufacturers indicate that they have no current plans to use RC engines in future aircraft. The performance characteristics of RC engines are more similar to piston-type engines than to turbines. Therefore, for the remainder of the market study, it was assumed that rotary-combustion engine penetration, should it occur, would be included in the reciprocating engine forecasts.

Preliminary market forecasts were reviewed during visits to airframe manufacturers. Helpful information regarding markets, forecasts, missions, and potential applications for GATE engines was received.

The 1988 market was estimated based on historical data broken down into market segments and judgmentally projected based on the impact of engine quality on aircraft economics. Market forecasts were made on the basis of GATE engines having either a 20% better sfc with no change in cost or a 20% lower cost with no change in sfc as compared to current technology gas turbine engines. The market forecasts were made initially to these ground rules and were repeated during Task III, after definition of the selected engine concepts, with substantially the same results. The selected engine concepts did achieve a 20%

reduction in sfc, but with a cost penalty. The cost penalty, however, was judged to be offset by major reductions in mass, volume, and maintenance costs.

Improvements in engine sfc or cost were assumed to have a substantially equal effect on aircraft acquisition and ownership costs. Improvement in engine sfc impacts aircraft costs through reduction in gross mass to accomplish a given mission, thus reducing power requirement and engine cost as well as reducing airframe structural mass and cost. Engine cost reduction has no effect on the aircraft or its performance and reduces aircraft cost simply by the reduction in engine cost. GATE trade studies generally show that a change in sfc has greater influence than a change in engine cost on total cost of ownership and that sfc and engine cost have an approximately equal effect on total aircraft acquisition cost using a current technology gas turbine engine as a base. In some applications, engine mass is as much of a driver on ownership costs as engine cost. (Reference sensitivity data in Figures 61, 62, and 63.)

As a result of the airframer reviews, it was not possible to identify a viable market for under 6672N (1500 lbf) thrust turbofan engines. It was felt by the airframe manufacturers that passenger capacity for turbofan aircraft powered by under 6672N (1500 lbf) thrust engines would be insufficient to justify their relatively high initial and operating costs, especially when compared with a more fuel efficient turboprop. In addition, there would be major difficulties in certifying a turbofan-powered aircraft with only one pilot. The avionics requirements for aircraft operating in the realm for sufficient turbofan operating economy prohibit a low initial price aircraft.

MARKET PROJECTIONS

Following the reviews with the airframe manufacturers, the forecasts for aircraft production through 1988 were revised to reflect inputs from marketing departments of these companies. The resultant forecast for the non-GATE-impacted, single-engine production is shown in Table VI. It is noteworthy that the retractable gear categories show the greatest growth. The superior fuel economy of these types when compared to fixed-gear models with similar power and accommodations is a significant factor in this choice.

The utility category shows relatively little growth due to increased foreign competition in the international markets.

The light agricultural category shows a small percentage growth from 1975 as a result of unusually strong sales in that year. When considered from 1976 production, a 3% growth through 1988 is projected.

TABLE VI. - SINGLE-ENGINE FIXED WING AIRCRAFT
U.S. PRODUCTION QUANTITIES (1975 to 1988)

Class	Category	75	76	77	78	79	80	81	82	83	84	85	86	87	88	Average annual growth(%)
I	Trainer	2040	2035	2135	2279	2411	2551	2699	2855	3021	3196	3381	3577	3784	4003	5.3
II	Light fixed gear	3132	4066	3890	3979	4071	4165	4261	4359	4459	4562	4667	4774	4884	4996	3.6
III	Light retr gear	1170	1142	1219	1301	1388	1481	1580	1686	1799	1920	2049	2186	2332	2488	6.0
IV	High perf fixed gear	1832	1690	1851	1903	1956	2011	2067	2125	2184	2245	2308	2372	2439	2507	2.4
V	High perf retr gear	1079	1719	1874	1988	2066	2184	2293	2407	2527	2653	2786	2925	3017	3225	8.8
VI	Utility	725	757	806	820	816	837	835	843	851	860	869	878	887	896	1.6
VII	AG--under 336 kW (450 hp)	815	569	745	775	800	775	775	800	810	810	820	820	830	830	0.01
VIII	AG--336 kW (450 hp) & up	328	392	395	370	390	400	410	421	432	444	456	468	481	494	3.2

The multiengine non-GATE-impacted production forecast is shown in Table VII. All multiengine categories show good growth through 1988, with the unpressurized-cabin class being the weakest with some of the traditional customers for this class of aircraft moving up into pressurized aircraft.

The rotary-wing non-GATE-impacted production forecast through 1988 is shown in Table VIII. The limited capabilities of the ultralight category of helicopters is expected to inhibit growth of these types. The light category is expected to continue on its long-term growth pattern. New models such as the Bell 222 and the Sikorsky S-76 will spur considerable growth in the light utility and utility categories.

TABLE VII. - TWIN-ENGINE FIXED WING AIRCRAFT U.S. PRODUCTION QUANTITIES (1975 to 1988)

Class	category	'75	'76	'77	'78	'79	'80	'81	'82	'83	'84	'85	'86	'87	'88	Average annual growth (%)
IX	Light twin	1232	1142	1206	1274	1345	1420	1500	1584	1673	1767	1866	1970	2080	2196	4.5
X	Cabin-unpress	421	399	430	443	457	471	486	501	517	533	550	567	585	603	2.8
XI	Press-under 4082 kg (9000 lbm)	450	575	594	614	634	655	677	699	722	746	771	796	822	849	5.0
XII	Over 4082 kg (9000 lbm)	349	393	419	447	476	507	540	576	614	655	698	744	793	845	7.0

TABLE VIII. - ROTARY WING AIRCRAFT U.S. PRODUCTION QUANTITIES (1975 to 1988)

Category	'75	'76	'77	'78	'79	'80	'81	'82	'83	'84	'85	'86	'87	'88	Average annual growth (%)
Ultralight	189	258	220	324	324	244	275	260	250	240	240	240	240	240	1.9
Light	447	402	457	491	545	579	590	602	624	674	665	657	660	660	3.0
Light utility	--	--	--	--	39	58	80	100	118	120	120	180	180	200	19.9
Utility	166	98	90	100	158	161	176	135	150	150	150	210	260	290	4.4

GATE POTENTIAL CATEGORIES

It was determined through the course of the studies, that to make full use of the advantages afforded by turbine engines such as lower specific mass and drag, it was necessary to design the aircraft from the ground up to use turbine power. An example of this is shown in Figure 3. The Dornier Skyservant and the GAF Nomad N24 were designed to nearly identical missions with similar levels of airframe technology and power plant size. The Skyservant was designed to use a reciprocating engine, whereas the Nomad was designed for a turbine engine. It can be seen that the disadvantages of turbine engines such as higher cost and sfc can be offset if the aircraft is designed to make full use of the engines advantages.

It was determined through the studies of engine domains and airframer contacts that within the GATE cost and performance capabilities, that the areas with potential impact for GATE engines are those applications in which performance is of primary consideration and initial cost of equipment is a secondary consideration.

Single Engine

In the single-engine categories, it was determined that as a result of cost considerations the upper categories V, VI, VII, and VIII, all of which require

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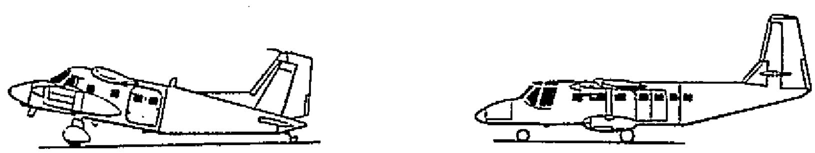
high performance, offered greatest potential for GATE engines. Figure 4 shows the high-performance, single-engine, retractable gear category as it might be impacted by the GATE program. The turbine penetration of the category would be at the expense of both piston-powered singles and piston-powered twins.

The impact on category VI utility single engine is shown in Figure 5. These are generally working class aircraft, frequently requiring STOL capabilities. Turbine engines are beneficial to this class of aircraft as a result of their cold weather starting capabilities, high power-to-mass ratio, and ability to run on a wider range of fuels than reciprocating engines. A GATE program could help domestic airframe manufacturers compete more effectively with the growing number of foreign manufacturers in the worldwide market.

Agricultural aircraft offer another potential application for turbine engines. Reliability, performance, noise, and adaptability to a wide range of fuels make turbine engines attractive to agricultural operators. In the lighter category of aircraft, turbine engines can offer the productivity of much larger aircraft while maintaining the handling characteristics of the smaller aircraft (Figure 6). In the larger AG category, the lack of availability of large reciprocating engines and demands for increased productivity will be major factors in causing turbinization of the fleet. A GATE program could accelerate this process (Figure 7).



	DESIGNED FOR RECIP POWER	DESIGNED FOR TURBINE POWER	
Type	Dornier Skyservant	GAF Nomad N24	
Power	Lyc IGSO-540 283 kW (380 hp)	Allison 250-B17B 298 kW (400 hp)	+ 5%
GTOM	4014 kg (8850 lbm)	4173 kg (9200 lbm)	- 4%
Passengers	2 + 12	2 + 16	+33%
Cabin Volume	8.2 m^3 (289 ft^3)	12.5 m^3 (440 ft^3)	+53%
Cruise Speed	76 m/s (170 mph)	85.8 m/s (192 mph)	+13%
T.O. 15 m (50 ft)	445 m (1460 ft)	293 m (960 ft)	-34%
Productivity	3283 (2040) seat km/h (mi/h)	4944 (3072) seat km/h (mi/h)	+51%
Fuel	17.4 (41) seat km/l (mi/gal)	20.4 (48) seat km/l (mi/gal)	+17%
Engine sfc	0.50	0.65	+30%

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Figure 3. Aircraft comparison.

4-7 Place 186-231 kW (250-310 hp)

Mission:

Distance	1667 km (900 NM) plus reserve
Load	5 passengers plus 36 kg (80 lbm) = 422 kg (930 lbm)
Speed	103 m/s (200 kn) at 6096 m (20 000 ft)
Runway	762 m (2500 ft)

Current Price Range:

$60,000-$125,000

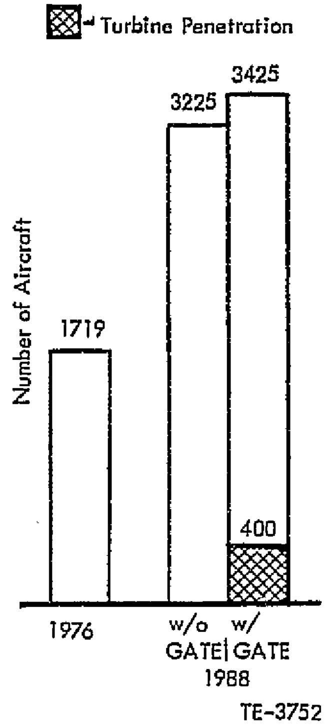
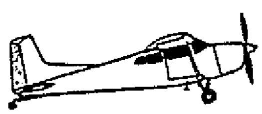


Figure 4. GATE category V--high-performance, single-engine, retractable gear aircraft.



2-6 Place 112-231 kW (150-310 hp)

Mission:

Distance	(185 km (100 NM) plus reserve
Load	2 passengers and 363 kg (800 lbm) = 517 kg (1140 lbm)
Speed	67 m/s (130 kn) at 1219 m (4000 ft)
Runway	305 m (1000 ft)
Special	Four missions without refueling

Current Price Range:

$25,000-$80,000

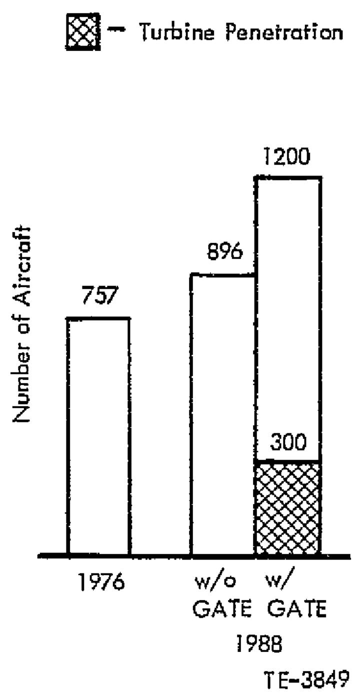


Figure 5. GATE category VI--utility, single-engine aircraft.

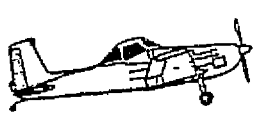
The four categories of single-engine aircraft with potential for turbinization were forecast to total approximately 5400 aircraft by 1988. A GATE program has the potential to expand this market to over 6000 aircraft with approximately 1400 of these being turbine powered (Figure 8).

Twin Engine

Engines used in the light twin, category IX, were considered too small to be economically turbine powered.

Twin-engine, unpressurized cabin class aircraft offer potential for some turbine penetration. These aircraft are frequently used by feeder airlines on the relatively short-haul missions. Noise and reliability are two major factors favoring turbine engines for this type missions. Improved turbine engines can increase the turbine penetration in category X as shown in Figure 9.

The smaller pressurized twins, category XI also offer some potential for GATE impact. These aircraft are currently all reciprocating engine powered. The advantages of turbine engines will be used in some of these aircraft by 1988 with increased penetration resulting from improved turbine engines. It is also expected that a GATE engine could give these aircraft sufficiently improved capabilities to expand the total market for the category (Figure 10).



1 Place 149-336 kW (200-450 hp)

Mission:

Distance	16.1 km (10 mi) shuttle
Load	1 pilot plus 680 kg (1500 lbm) = 757 kg (1670 lbm)
Speed	variable @ sea level
Runway	457 m (1500 ft)

Current Price Range:

$40,000-$75,000

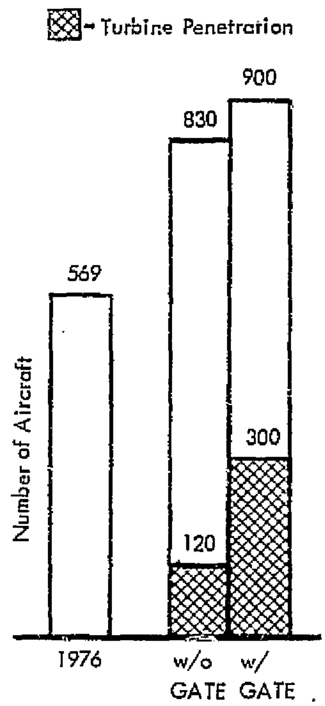
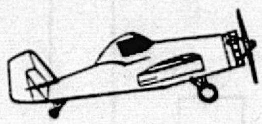


Figure 6. GATE category VII--single-engine aircraft aerial application.



1 Place 336-746 kW (450-1000 hp)

Mission:

Distance	32 km (20 mi) shuttle
Load	1 pilot plus 1134 kg (2500 lbm) = 1211 kg (2670 lbm)
Speed	variable @ sea level
Runway	457 m (1500 ft)

Current Price Range:

$65,000-$180,000

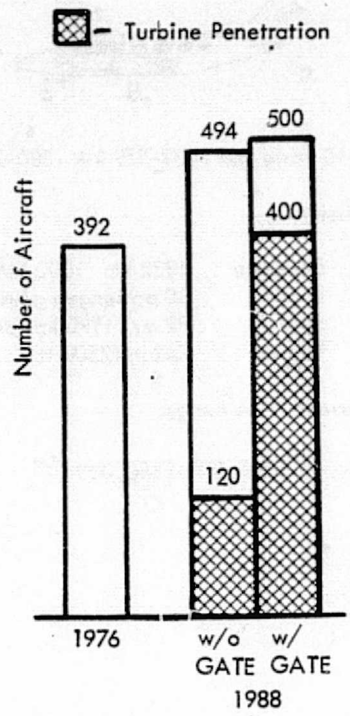


Figure 7. GATE category VIII--single-engine aircraft aerial application.

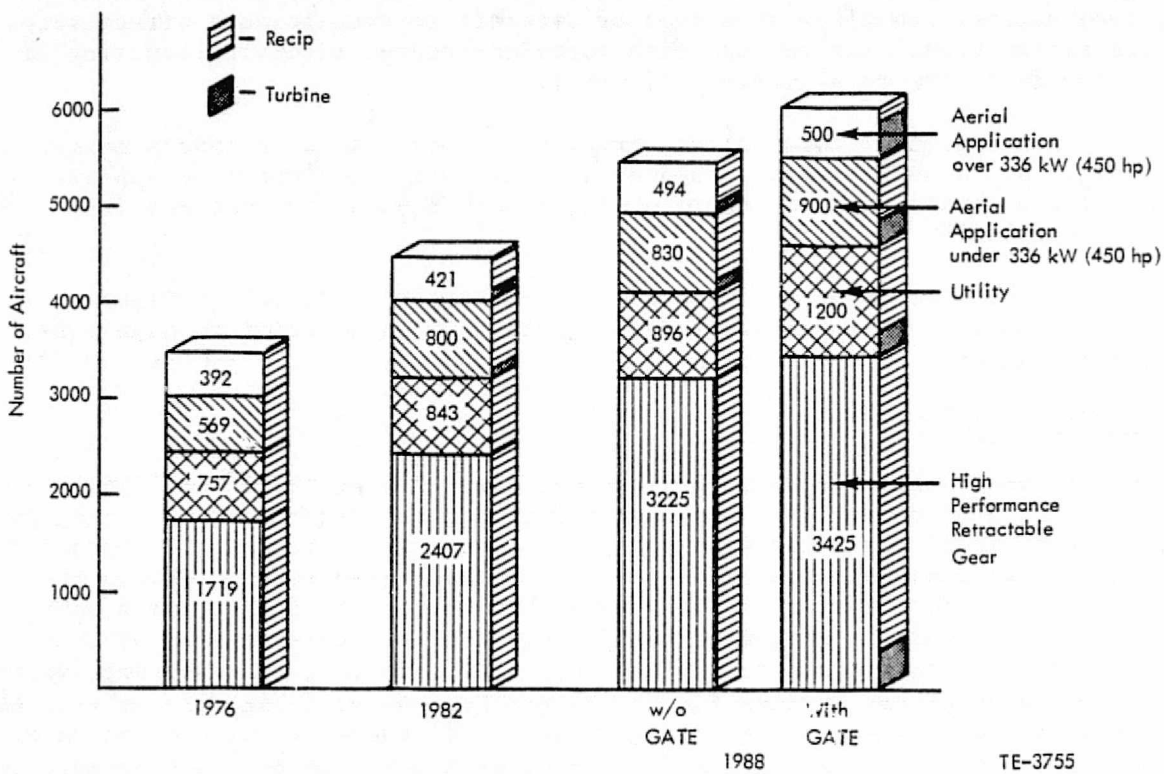
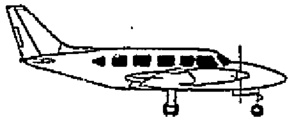


Figure 8. Single-engine, fixed-wing aircraft production forecast summary.



6-10 Passenger 433-559 kW (580-750 hp)

Mission:

Distance	1852 km (1000 NM) plus reserve
Load	10 passengers plus 91 kg (200 lbm) = 862 kg (1900 lbm)
Speed	98 m/s (190 kn) at 2438 m (8000 ft)
Runway	762 m (2500 ft)

Current Price Range:

$200,000-$350,000

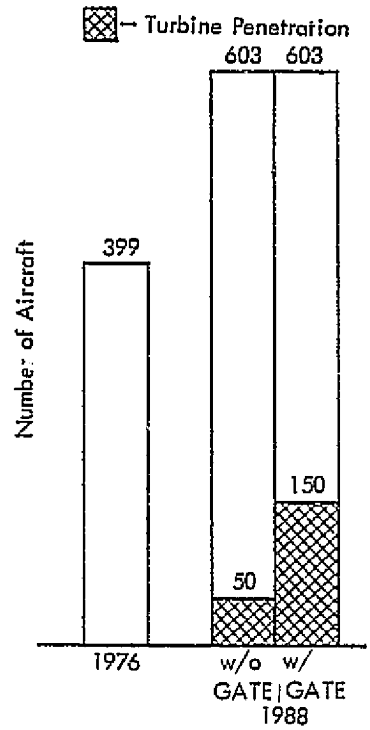


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Figure 9. GATE category X--twin-engine, cabin class, unpressurized aircraft.

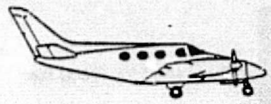
Category XII twin-engine aircraft over 4082 kg (9000 lbm) gross take-off mass (GTOM) produced by domestic manufacturers are all currently turbine powered. Improved engines can allow this type of aircraft to compete more effectively in the international markets and with turbofan-powered aircraft resulting in an expansion of the total market (Figure 11).

Domestic production of twin-engine aircraft is forecast to be approximately 4500 by 1988. A GATE program could expand the total production by approximately 100 aircraft with an increase in the turbine-powered versions from about 850 to 1300.

A twin-engine, fixed-wing production forecast summary is shown in Figure 12. The reduction in the light twin total was due to loss of sales to high-performance singles.

Rotary Wing

Since all domestically produced helicopters over 1270 kg (2800 lbm) GTOM are currently turbine powered; it was determined that the major area remaining for GATE impact was in the ultralight category. These aircraft are all currently piston-powered and their limited capabilities have restricted growth in the market. It was felt that a 20% less expensive engine resulting from a GATE program could result in increased turbine penetration and expansion of the total production for this category helicopter (Figure 13). The current availability of several new engines for the larger helicopter categories as well as the existence of new engine technology programs discouraged the prediction of major GATE impact in this class. A rotary-wing production forecast summary is shown in Figure 14 as allocated based on projections of helicopter production by class of helicopter.



5-10 Place 336-671 kW (450-900 hp)

Mission:

Distance	1667 km (900 NM) plus reserve
Load	7 passengers plus 69 kg (140 lbm) = 603 kg (1330 lbm)
Speed	123 m/s (240 kn) @ 6096 m (20 000 ft)
Runway	914 m (3000 ft)

Current Price Range:

$140,000-$425,000

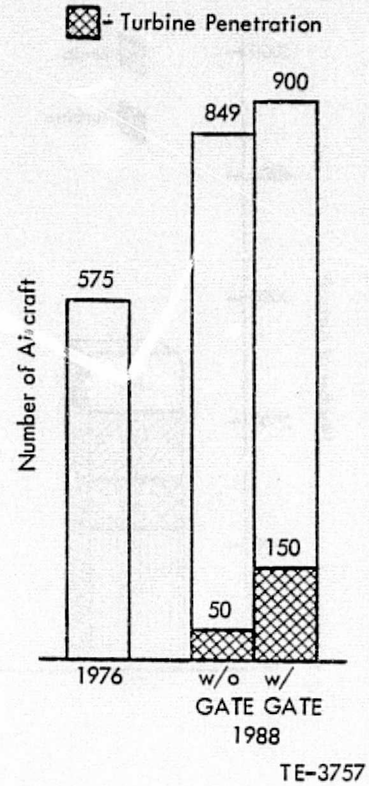


Figure 10. GATE category XI--twin-engine, pressurized aircraft under 9000 lb.

6-17 Place 820-1417 kW (1100-1900 hp)

Mission:

Distance	1852 km (1000 NM) plus reserve
Load	8 passengers plus 73 kg (160 lbm) = 689 kg (1520 lbm)
Speed	139 m/s (270 kn) @ 6706 m (22 000 ft)
Runway	914 m (3000 ft)

Current Price Range:

$500 000-$1 400 000

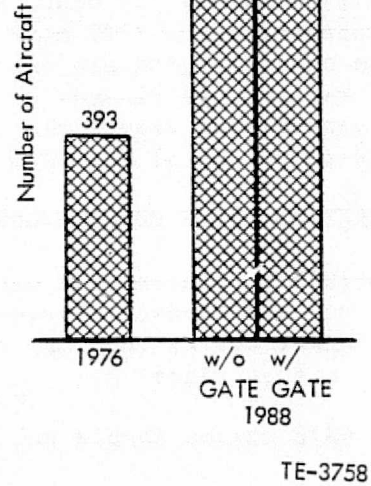


Figure 11. GATE category XII--twin-engine aircraft over 4077 kg.

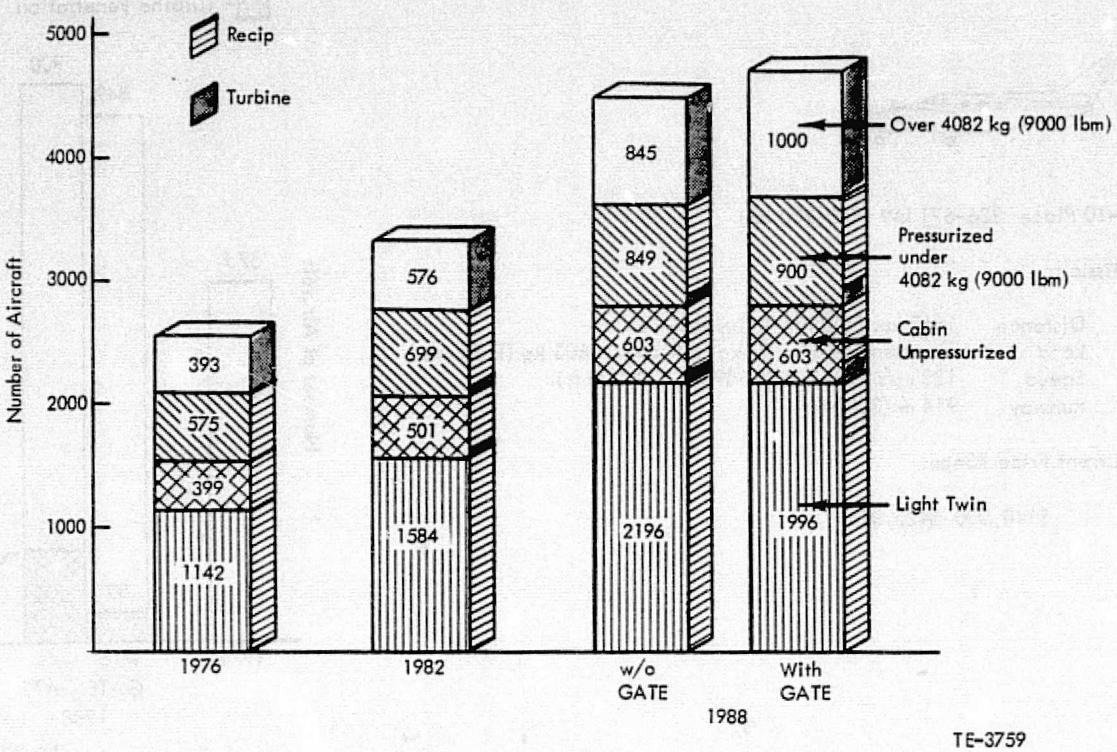


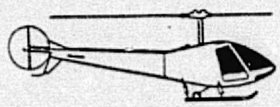
Figure 12. Twin-engine, fixed-wing aircraft production forecast summary.

ENGINE PRODUCTION FORECAST

From the aircraft production forecasts, it was possible to forecast the 1988 number of domestic airframe, manufacturer-installed turbine engines by power class. The market for reciprocating engines in 1988 is forecast to exceed 25,000 engines, all of which would be less than 299 kW (400 hp). The market for turbine engines is shown in Figure 15. Experience on the Detroit Diesel Allison Model 250 engine would indicate an international market equal in size to the domestic market in 1988 and additional sales equal to 10% of the installed engines for spare engines. The total world market would, therefore, be approximately 120% more than the quantities shown in Figure 15. It can be seen that the greatest unit impact from a GATE program would be in the under 447 kW (600 hp) classes of engines. From a dollar value of market viewpoint it can be seen from Table IX that the smaller engines still maintain a slight edge in potential for GATE impact.

MARKET ANALYSIS CONCLUSIONS

- 1988 turbine engine market is roughly equal in terms of dollar volume in all shaft power classes; however, the best opportunity for GATE exists under 447 kW (600 hp) because no advanced technology engines are planned in this class.
- GATE engine should be less than 447 kW (600 hp).
- Good market exists providing aircraft are designed to capitalize on the advantages of an advanced turbine engine.



2-3 Place 134-186 kW (180-250 hp)

Mission:

Distance	463 km (250 NM)
Load	3 passengers = 231 kg (510 lbm)
Speed	51 m/s (100 kn)

Current Price Range:

$50,000-$100,000

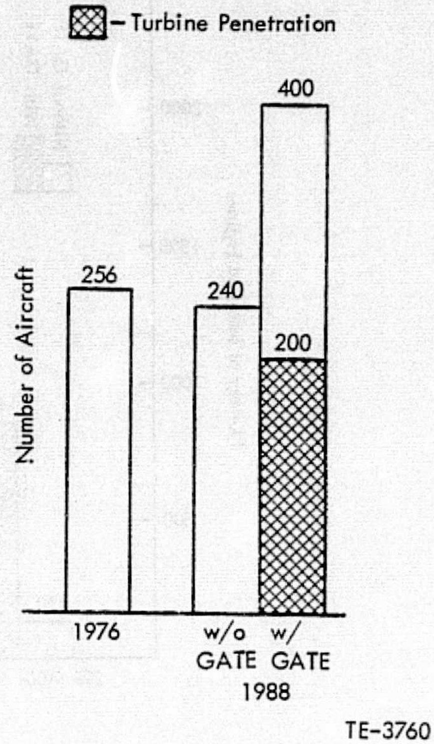


Figure 13. GATE rotary wing aircraft category I--ultralight (recip).

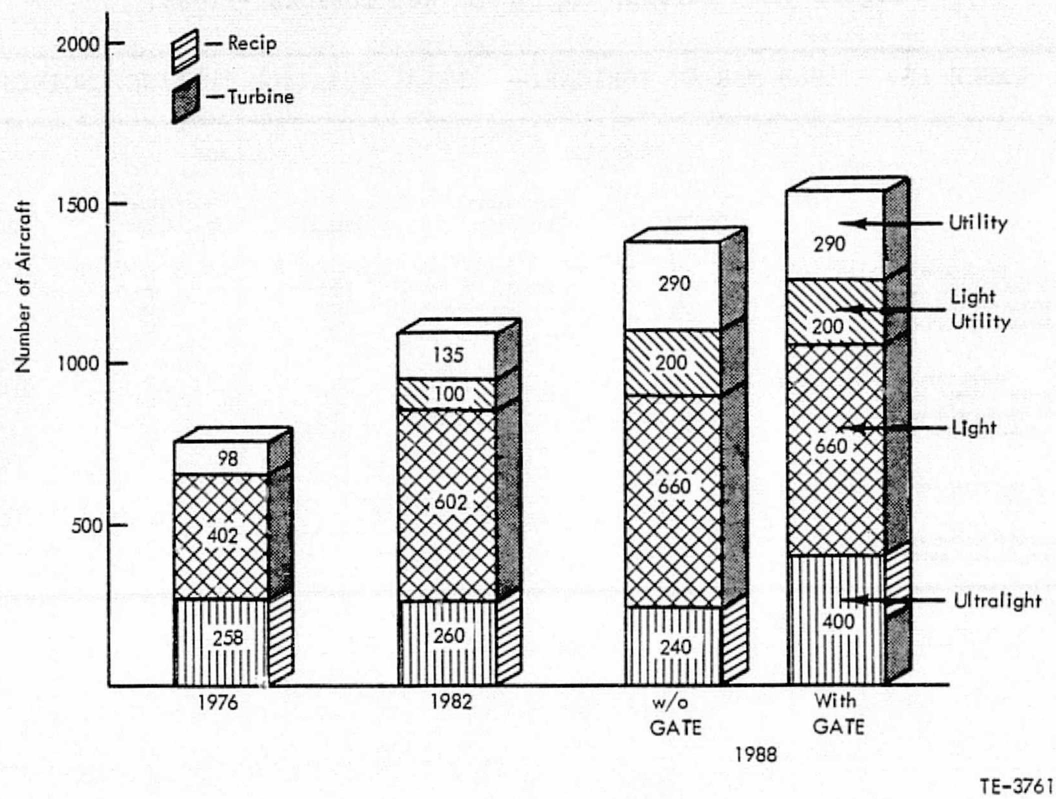


Figure 14. Rotary wing aircraft production forecast summary.

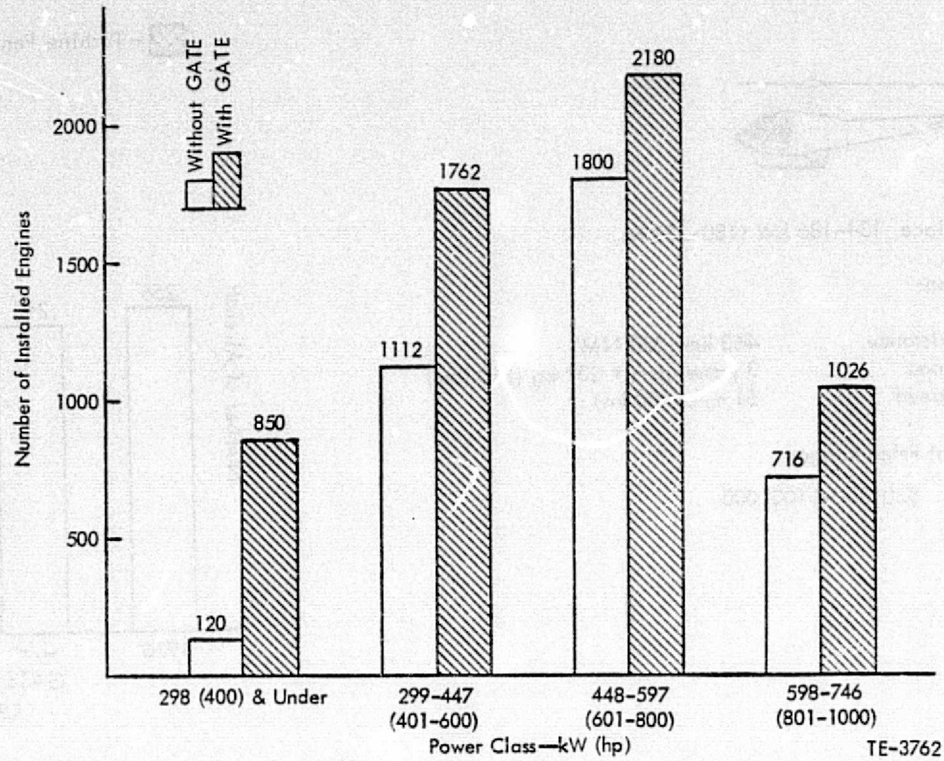


Figure 15. Turbine engine market forecast--1988.

TABLE IX. - 1988 MARKET FORECAST— GENERAL AVIATION TURBINE ENGINES

		Without gate		With gate		
		Engines	Est value* ($ millions)	Engines	Est value* ($ millions)	Δ VALUE ($ millions)
Turboprop	UNDER 298kW(400 hp)	120	5	650	29	+24
	299-447kW(401-600 hp)	452	25	1102	61	+36
	448-597kW(601-800 hp)	1020	79	1400	108	+29
	398-746kW(801-1000 hp)	536	54	846	84	+30
Turboshaft	UNDER 299kW(400 hp)	0	0	200	7	+7
	299-447kW(401-600 hp)	660	30	660	30	0
	448-597kW(601-800 hp)	780	49	780	49	0
	598-746kW(801-1000 hp)	180	15	180	15	0

Turbofan--no significant market under 6672N (1500 lbf) thrust

*1978: Turboprop $148/kW($110/hp)
Turboshaft $121/kW($90/hp)

TABLE X. - MISSIONS IDENTIFIED IN MARKET SURVEY

Fixed Wing	Shaft Power, kW(hp)	Range, km(Nm)	Payload, kg(lbm)	Speed, m/s(kn)	Runaway, m(ft)	Price Class, $ thousand
Heavy twin*	597(800)	2222(1200)	844(1860)	154(300)	762(2500)	1000
Light twin*	336(450)	1667(900)	680(1500)	134(260)	762(2500)	475
Cabin class twin (Unpress)*	336(450)	1852(1000)	1016(2240)	113(220)	762(2500)	400
AG (< 450)*	336(450)	3 h	1089(2400)	51(100)	305(1000)	110
AG (> 450)	597(800)	3 h	1542(3400)	51(100)	305(1000)	160
Utility single	261(350)	741(400)	726(1600)	82(160)	305(1000)	110
H.P. single (RG)	298(400)	1852(1000)	576(1270)	118(230)	610(2000)	160
Helicopter						
Ultralight	261(350)	333(180)	363(800)	57(110)	--	120
Twin	261(350)	833(450)	544(1200)	64(125)	--	500

*Missions exercised in Task II trade studies.

- No market for small turbofan of less than 6672 N (1500 lbf) thrust in 1988 time frame.
- Penetration of fixed-wing aircraft market required for attractive engine quantities.
- Representative missions recommended for investigation of gas turbine engine requirements for each market category are shown in Table X.

4b. Broad Scope Trade-Off Studies

TECHNOLOGY FORECAST FOR MARKET ANALYSIS

A study was made to establish representative trends for general aviation gas turbine engine cost, specific fuel consumption (sfc), and weight. These trends were used as a guide in estimating market potential of the small gas turbine engine, and also served to provide engine size-scaling relationships for the airplane/engine sizing computer program used in the trade-off studies. In the analysis of cost trends, relationships were also developed to judge the impact of production volume on unit costs. Turboshaft, turboprop, and turbofan engines were examined.

Effect of Engine Size on Weight, Performance, and Cost

As the scale size of an engine of a given configuration is reduced in the power range below 746 kW (1000 hp), there is a general trend for specific fuel consumption, specific mass (mass/power) and specific cost (cost/power) to increase.

One of the causes for these increases is the deterioration of component efficiencies as component sizes are reduced.

A study was made to determine representative trends of specific fuel consumption, specific mass, and specific cost versus shaft power for use as a guide in the Task I market forecast studies and in the Task II mission trade-off analyses. Scale effects on specific fuel consumption were run on two cycles (1) an 8:1 compressor pressure ratio (R_c), 1311 K (1900°F) rotor inlet temperature (RIT) current technology cycle and (2) a 14:1 R_c, 1478 K (2200°F) RIT advanced technology cycle.

Figure 16 shows the difference in compressor and gas turbine efficiency assumed for the two cycles using the 1.36 kg/s (3.0 lb m/sec) air flow 8:1 current technology engine as a base. Also shown are the effects of scale on sfc. The sfc scale effects were similar on a percentage basis, thus a typical line is shown. Scale effects on specific mass and cost were run on configurations representative of current and advanced technology cycles. The results are shown in Figure 17 and 18 for specific mass and specific cost, respectively. The effect of these trends on turboprop and turboshaft characteristics for current and advanced technology is shown in Figure 20 through 25.

The shaft power range from 112 to 746 kW (150 to 1000 hp) was analyzed. The sfc versus power trend resulted from computerized engine performance cycle runs at a series of airflow levels compatible with the selected shaft power range at sea level static standard (slss) inlet conditions while holding R_c and RIT constant. The scale effect was accounted for by applying estimated scale effects to the values of compressor efficiency, gas generator turbine efficiency, power turbine efficiency, and percent turbine cooling air used in the cycle as engine airflow rate was raised.

The specific mass versus power trend was obtained by making computer runs at a series of scale sizes compatible with the airflow rate range used in the performance study already described. A DDA gas turbine masses estimating program was used. It calculates component masses and total engine mass using suitable input data for a given set of configuration features and cycle parameters with the scale size keyed to the airflow rate. The weights obtained were then related to power by using the power versus airflow rate relationship established in the cycle performance scaling runs described above.

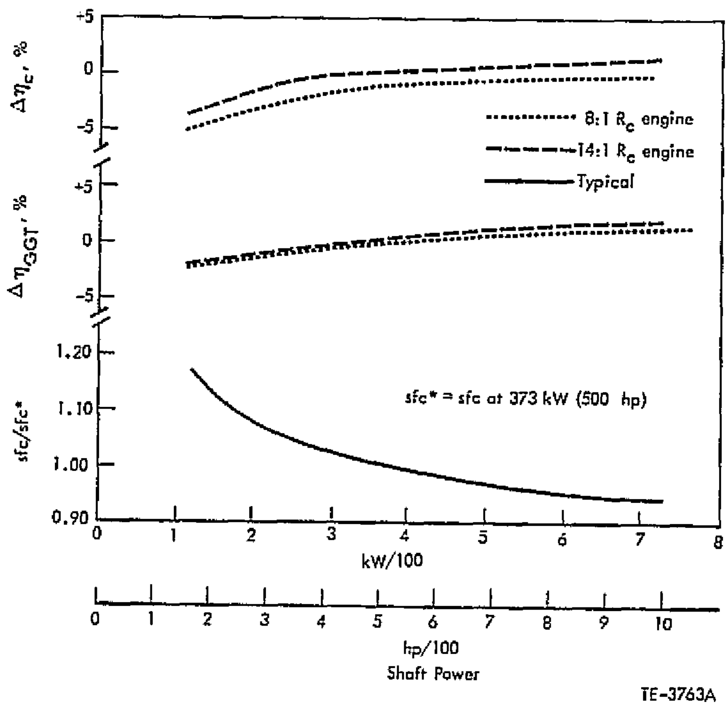


Figure 16. Turboshaft and turboprop engines sfc sensitivity to scale size relative trend at slss T.O.

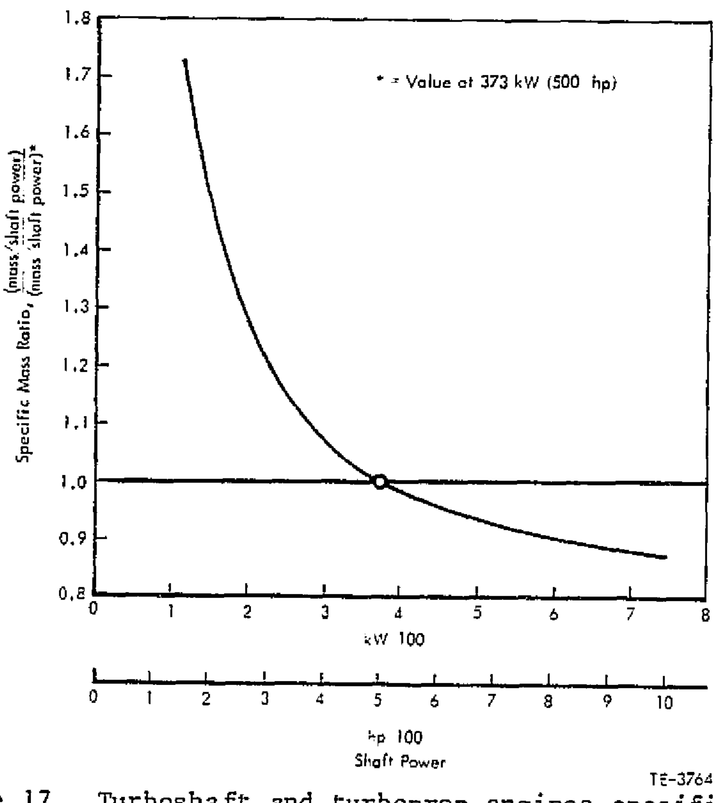


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Figure 17. Turboshaft and turboprop engines specific mass sensitivity to scale size relative trend at slss T.O.

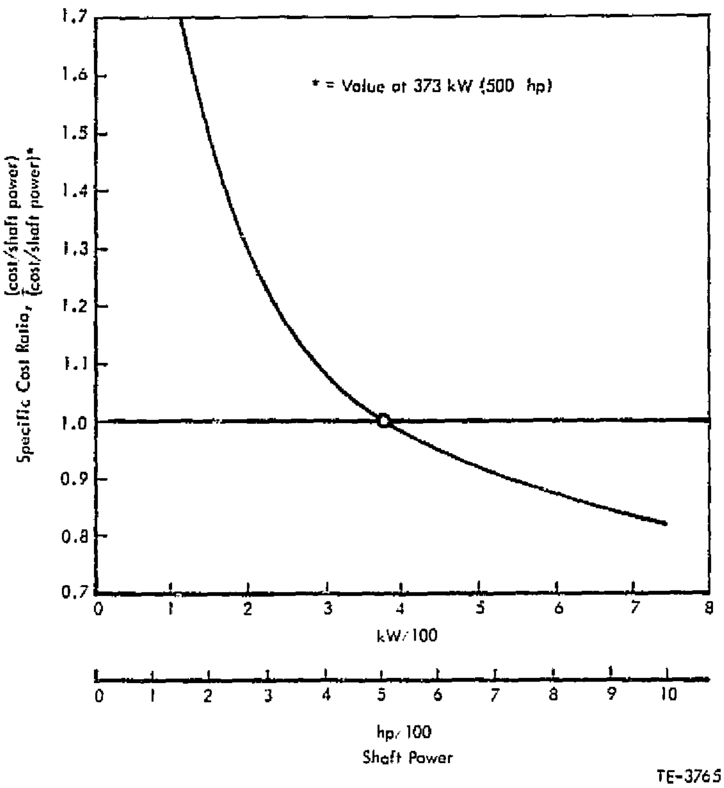


Figure 18. Turboshaft and turboprop engines specific cost sensitivity to scale size-relative trend at slss T.O.

The specific cost versus power trend was obtained by using a DDA cost-estimating computer program that is an auxilary to the previously memtioned masses program. The program calculates components and total engine manufacturing costs using as inputs the component masses plus component costs for the unity size engine. The component masses from the mass-estimating program are fed into the cost program. The unity size component prices were estimated by using the DDA refined Materials Index Factor (MIF) method. The scaled components costs were estimated by assuming that component cost varies with a selected power of the component mass. The costs were adjusted to a common production rate, total quantity, and specific calendar year economy.

These scaling trend curves were used in all of the turboshaft and turboprop mission trade-off studies. The desired scaled value of sfc, mass, or cost was obtained by multiplying the unity engine size values by the ratio of the trend curve ordinate values at the scaled shaft power divided by the ordinate value at the respective engine unity size shaft power.

Other important items which impact engine cost include:

- Ecomonic year of production
- Total quantity of engines produced
- Production rate

In the GATE cost studies constant economics was used to avoid the uncertainties of predicting future escalation rates; 1978 was used as the base year.

As the total production quantity of a given engine configuration increases the cumulative average cost normally decreases exclusive of other items. This is generally referred to as the learning curve effect.

As the production rate (engines per month) increases, the manufacturing costs normally decreases.

Effect of Engine Size and Production Quantity on Cost

Figure 19 illustrates a typical combined effect of total production quantity and engine power size on specific cost. The effect of production rate is also included since the overall time is held constant. These trends assume continous flow of production units over a 5-yr period. Tooling costs are assumed to increase proportionately to production rate. The figure shows effect of order-of-magnitude changes in production quantity. Typical aircraft engine production rates for small turbine engines are most nearly represented by the 1000 engine per year or 5000 engine quantity line.

Turboprop Engine Trends for Analysis

Published competitive turboprop engine data in the power range up to 745 kW (1000 hp) was reviewed along with DDA production engine data to estimate current levels for specific fuel comsumption, mass, and cost.

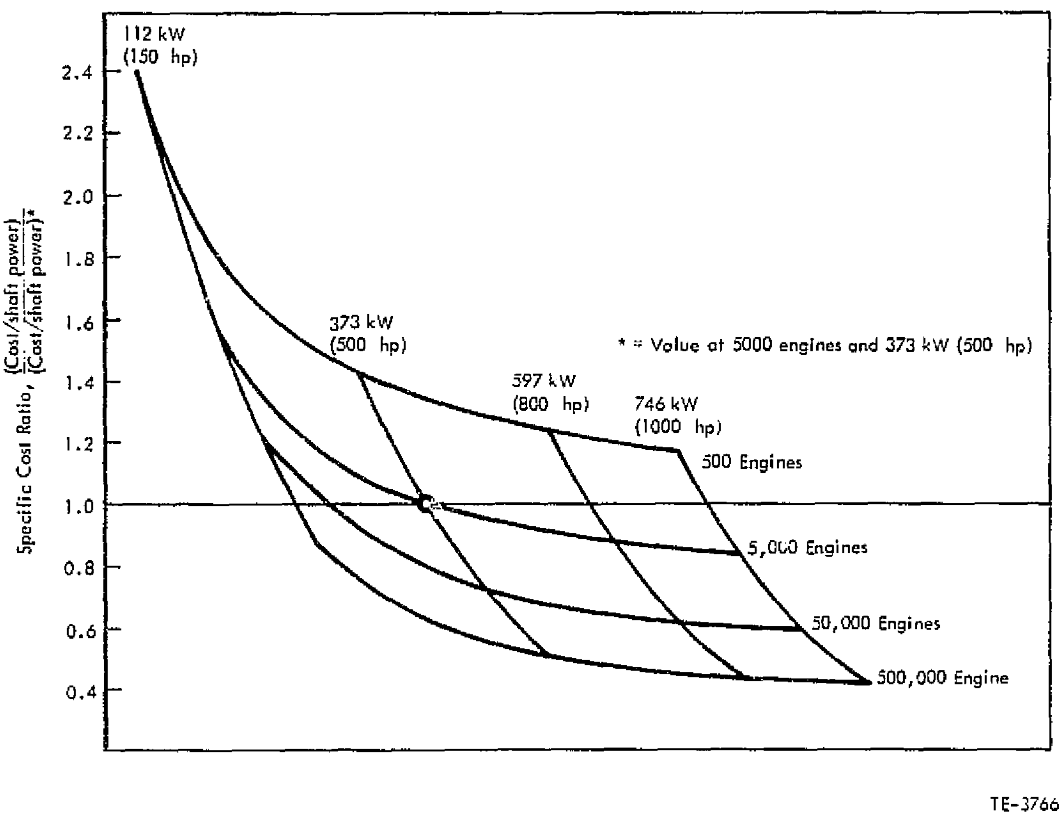


Figure 19. Turboshaft and turboprop engines production volume power size impact on cost-relative trends.

Figures 20, 21, and 22 are composite plots of this data in the form of relative specific fuel consumption versus shaft power, specific mass versus shaft power, and specific cost versus shaft power, respectively. In general, these plots show that sfc, specific mass, and specific cost increase as engine power rating is decreased. Superimposed on these plots are the scale effect trend lines described earlier. The 8:1 R_c, 1311 K (1900°F) RIT trend line is representative of a current technology engine (CTE) and the 14:1 R_c, 1478 K (2200°F) RIT trend line is typical of an advanced, air-cooled engine. The advanced technology engine (ATE) trend line is lower than the current technology engine trend line for sfc, specific mass, but higher for specific cost.

In interpreting the plotted competitive engine data, it is cautioned that the data may not be to a common definition base. For instance, it is not known whether the published competitive engine shaft power and specific fuel consumption data are guaranteed values or the normally more favorable average values or projected values. The engine price terms are also difficult to determine. Sources do not always qualify costs on the basis of list or OEM, effective year and engine quantity. Where data detail permitted, costs were adjusted to a 1978 base year.

Turboshaft Engine Trends

A review and analysis of current competitive and DDA turboshaft engines was made similar to the turboprop engine review described above. The results of this review are shown in Figures 23, 24, and 25, showing sfc, specific mass, and cost trends, respectivily. Mass data was adjusted to provide a standard drive shaft rotational speed as noted, and costs were adjusted to a 1978 base year.

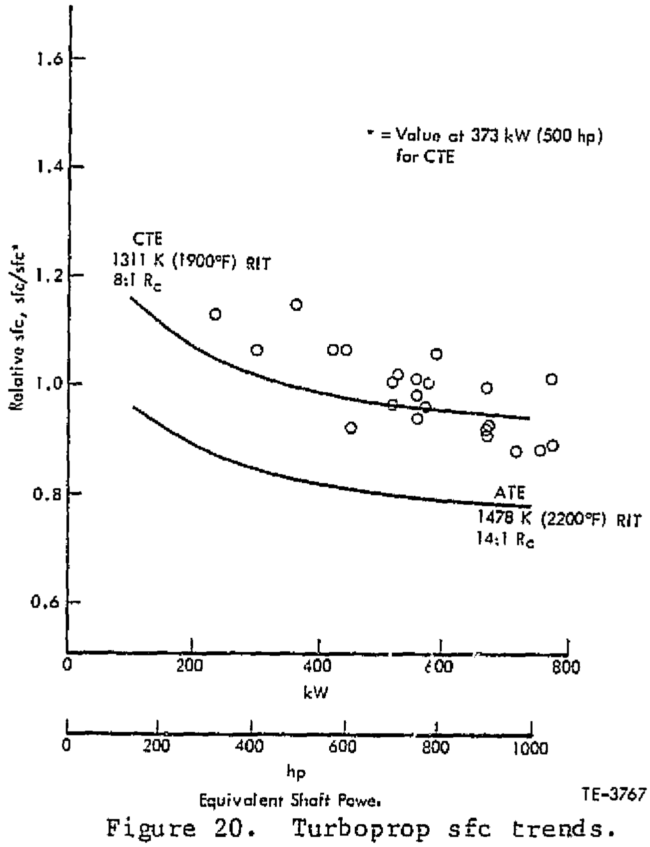


Figure 20. Turboprop sfc trends.

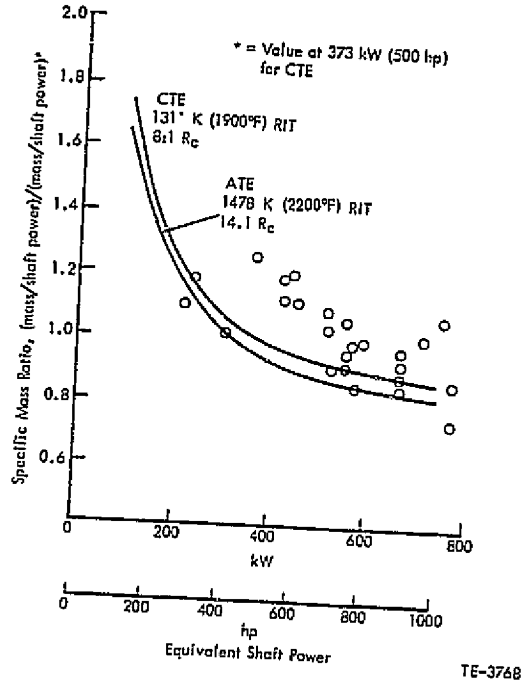


Figure 21. Turboprop mass trends.

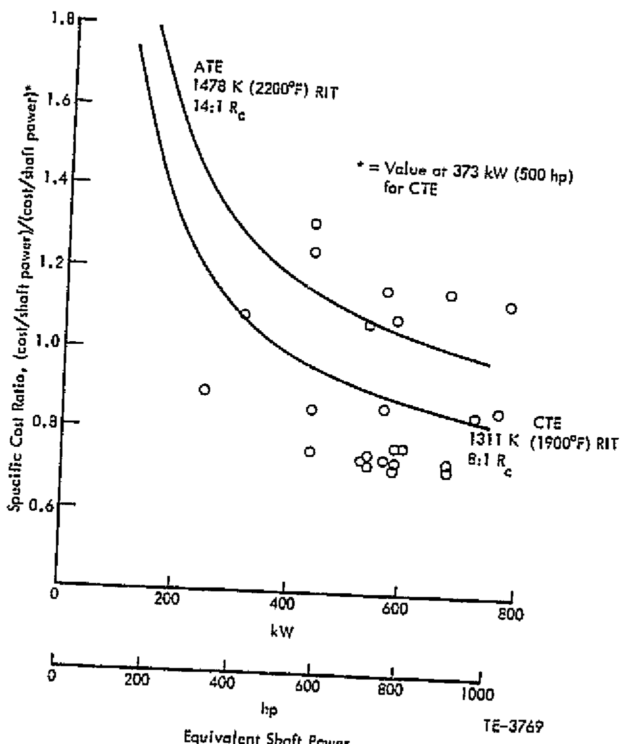


Figure 22. Turboprop cost trends.

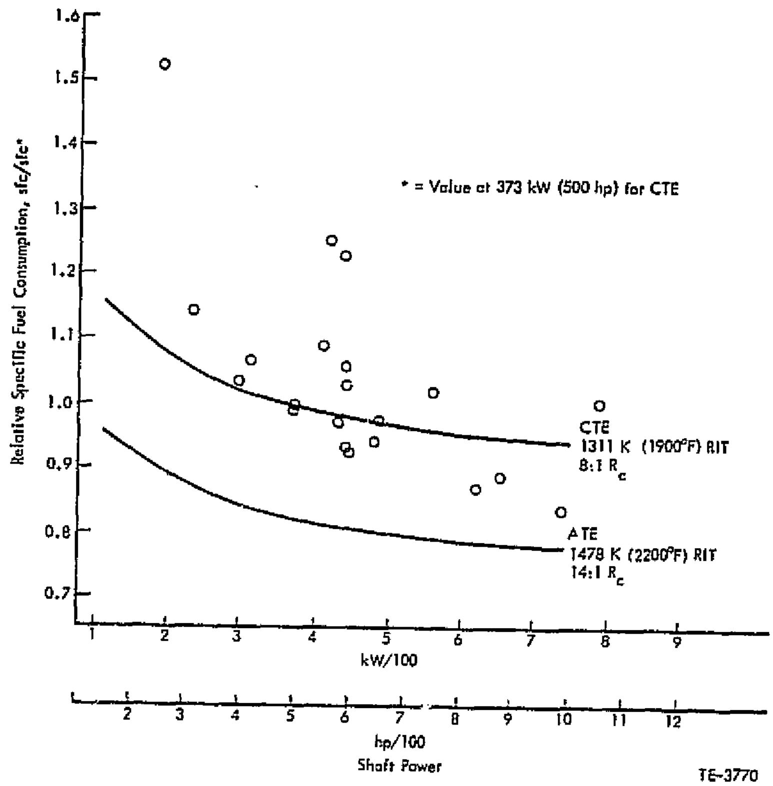


Figure 23. Turboshaft sfc trends.

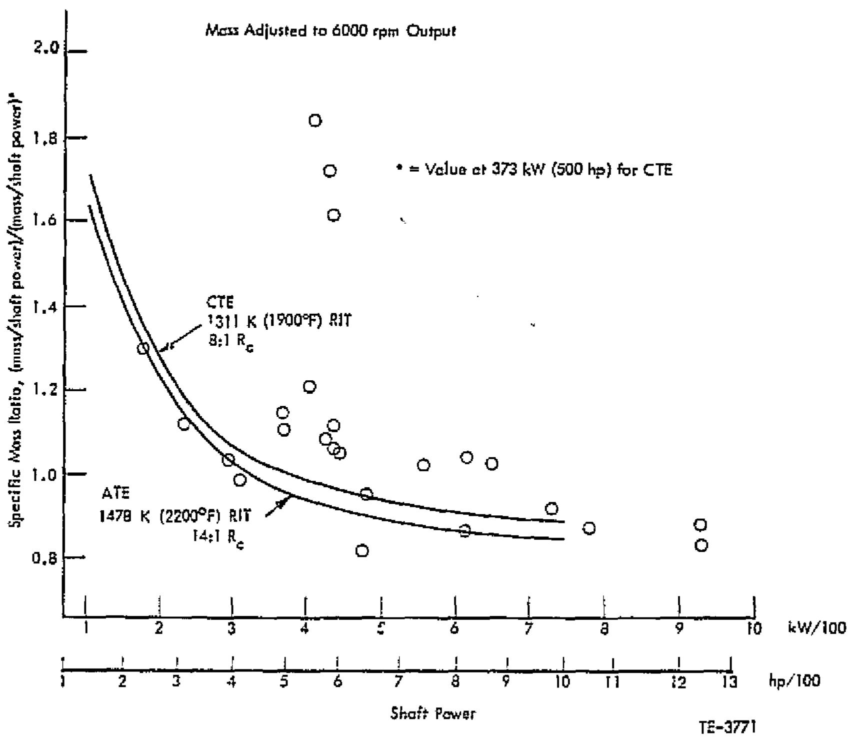


Figure 24. Turboshaft mass trends.

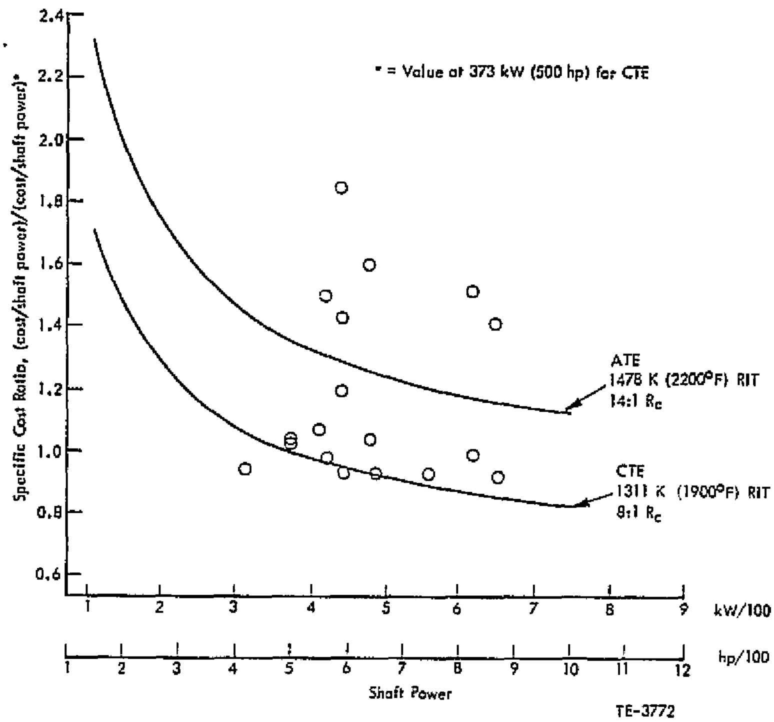


Figure 25. Turboshaft cost trends.

Note that again significant improvements in sfc are shown for the advanced cycle, but that this gain is accompanied by an increase in engine cost. These trends were examined again in greater detail in the Broad Scope Trade-Off Studies.

COST PERFORMANCE TRADE STUDIES

Approach

Cost/performance trade studies were conducted for six defined missions representing important market segments for the small gas turbine engine. For each of these missions, a representative basepoint aircraft configuration was established representing current aircraft design practice. Gas turbine engines were evaluated in a computerized system that generated comparisons in aircraft design, gross mass and economics. The payoff parameters considered were minimum acquisition cost, minimum direct operating cost, and minimum cash flow requirement as determined for the complete engine/airframe combination. Aircraft gross mass was also an important parameter particularly from the fuel conservation standpoint, but also because for comparisons conducted among gas turbine engines, the gross mass was the major driver on costs.

The evaluation process involved complete definition of the current technology basepoint gas turbine engine as well as the matrix and candidate engines in terms of design and off-design performance, mass, dimensions, initial cost and maintenance cost. Engine-scaling procedures were applied as described in the section on Engine Size Effects.

The goal of the study was to improve as much as possible on a modern gas turbine engine. For this purpose, a scalable study engine representing performance and cost characteristics of an advanced DDA Model 250 was selected to represent current production technology. The hardware configuration of this engine entered production in 1978 at 485 kW (650 hp). Long production experience with the basic engine frame has resulted in highly competitive performance and price. This engine, designated CTE (for current technology engine) or CTE* (when the price is increased to reflect a hypothetical case of no previous production experience on the model) forms the standard for measurement of cost/performance-related improvements.

Two engine matrices were generated using single and dual centrifugal stage compressors selected for performance and cost advantages in small engine application. These matrices provided a basis for selection of engine technology features. Pressure ratio, turbine temperature and turbine configuration were included in the evaluations. Candidate engines were defined and evalutated at a nominal, 373 kW (500 hp) base, and in turn were compared to the CTE and CTE* in both fixed-wing and rotary-wing applications.

Sensitivity studies were conducted to evaluate component and cycle parameters in terms of their impact on the general aviation aircraft design gross mass and economics of performing the specified design mission. Selected technology elements were qualitatively or quantitatively evaluated.

Engine noise and emission characteristics were studied to determine impact of the new technology, and regulatory constraints were reviewed to forecast the probable limits for 1985-1990.

Mission Requirements

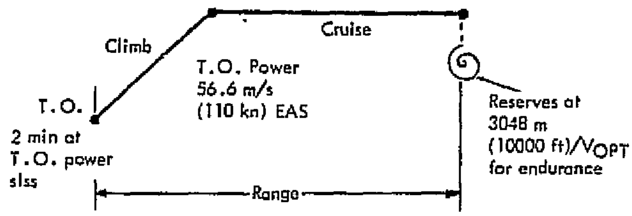
Typical missions were defined for all general aviation categories investigated in the Task I market study. Representative cases were selected for trade studies from market categories VII through XI for the fixed-wing aircraft and Category II for the helicopter as shown in Table X.

Fixed-wing missions used in the trade studies are shown in Figure 26 in terms of typical cruise altitude, air speed, payload, and range. Airframe specific cost values used in assessing the airframe cost in the economic analysis are shown. Also, the major engine sizing conditions considered in the analysis are specified. Figure 27 presents similar information for the rotary-wing aircraft. Cabin size of the reference aircraft was scaled appropriately to meet the payload requirements of the selected missions.

Airframe Characteristics

Airframe characteristics based on aerodynamic and mass data obtained from the manufacturers were applied in the study. Airframe cost data was obtained from published information from such sources as GAMA (General Aviation Manufacturers Association).

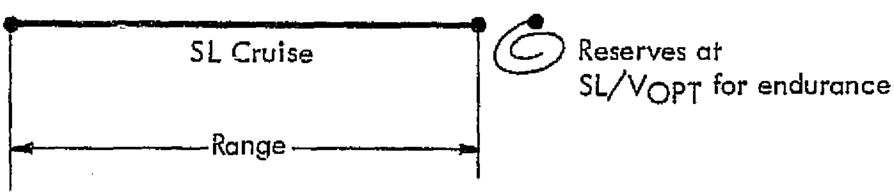
The basic analysis technique employed a completely described reference aircraft and simply resized it to exactly meet the mission requirement for each engine examined. Thus the primary aircraft characteristics such as design wing loading, aspect ratio, base drag, structural mass fraction, and airframe specific cost were unchanged except for alterations resulting from scale effects and changes related to propulsion mass fuel economy and geometry associated with each engine considered. Aerodynamics were synthesized to represent the geometric configurations as detailed in Table XI.



Mission	Unpressurized Twin	Light Twin	Heavy Twin	Light Agricultural
T.O. Allowance	yes	yes	yes	yes
Climb Allowance	yes	yes	yes	none
Cruise Alt/TAS, m/(m/s) (ft/kn)	3660/113 (12K/220)	7315/134 (24K/260)	9144/154 (30K/300)	SL/51 (SL/100)
Reserve Time, min	45	45	45	0
Range, km (NM)	1852 (1000)	1667 (900)	2222 (1200)	556 (300) 3 hr
Payload, kg (lb) (includes crew)	1016 (2240)	680 (1500)	843.7 (1860)	1089 (2400)
Specific Cost, \$/kg Empty Mass(\$/lbm EM)	110.89 (50.30)	124.56 (56.50)	187.39 (85.00)	44.09 (20.00)
Critical Engine Sizing Cond			• Cruise & OEI Climb at 1524m (5000 ft)	SL, 51.4 m/s (100 kn) 4.57 m/s (900 ft/min) rate of climb

TE-3784A

Figure 26. Fixed-wing missions.



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Mission	Light Single	Light Twin
Cruise Vel, m/s (kn) TAS	56.6 (110)	64.3 (125)
Reserve Time, min	30	45
Range, km (NM)	333 (180)	833.4 (450)
Payload, kg (lb)	363 (800)	544 (1200)
Specific Cost, \$/kg Empty Mass (\$/lbm Empty Mass)	132 (60)	265 (120)
Critical Engine Sizing Conditions		
• SL V_{max}, m/s (kn) TAS	61.7 (120)	77.2 (150)
• 305 m/30 m/s TAS (1000 ft/57 kn) OEI 305 K (90°F) day	NA	yes

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Figure 27. Rotary-wing missions.

TABLE XI. - DESCRIPTION OF REFERENCE AIRCRAFT

Aircraft type	Fixed wing				Rotary wing	
Configuration	Unpressurized twin	Light twin	Heavy twin	Light AG	Light single	Light twin
Places (includes crew)	9-11	6-8	7-9	1	3-4	5-6
Wing:						
Loading, kPa (lb/ft^2)	1.58 (33)	1.58 (33)	1.58 (33)	1.01 (21)		
Aspect ratio	9	9	9	6		
Sweepback, degrees	3	3	3	0		
Thickness/chord, avg	0.14	0.14	0.14	0.14		
Taper ratio	0.45	0.45	0.45	0.63		
Horizontal tail:						
Area ratio, tail to wing	0.28	0.28	0.28	0.17		
Vertical tail:						
Area ratio, tail to wing	0.20	0.20	0.20	0.06		
Main rotor:						
No. of blades					2	2
Disc loading, kPa (lb/ft^2)					2.68 (5.6)	2.68 (5.6)
Solidity					0.07	0.07
Tip speed, m/s (ft/sec)					210 (690)	210 (690)
Tail rotor:						
No. of blades					2	2
Solidity					0.16	0.16
Tip speed, m/s (ft/sec)					187.5 (615)	187.5 (615)

*Hopper capacity, m^3 (ft^3) = 1.50 (53) (400 U.S. gal).

In this type of analysis, the mission is fixed, as are the basic airplane characteristics, and changes in aircraft gross mass, wing area, and engine power size basically reflect differences in the quality of the propulsion system. Fundamentally, gross mass changes calculated for a change in engine characteristics are a result of a change in propulsive mass fraction, which is the percentage of total gross mass required for the installed engine, fuel, and fuel system. Complex interactions are treated interatively to arrive at a solution, for example engine mass is affected by engine specific power (engine mass per unit of power) and the power requirement at the sizing condition. It in turn is dependent on gross mass and airframe drag which are influenced by fuel mass and engine geometry, which depends on engine power size. Fuel mass is affected primarily by engine-specific fuel consumption and power requirements at cruise.

Economic Model

The economic model for general aviation aircraft developed for the GATE study is described in detail in the appendix. Cost data calculated for the fixed- and rotary-wing aircraft were:

- Total acquisition cost, $
- Direct operating cost, $/flight hour
- Total Cost of ownership, $
- Cash flow requirement, $

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Total acquisiton cost (TAC) is the total selling price of the engine/airframe combination. The engine is priced at list. Direct operating cost (DOC) is the hourly cost of operating the airplane and includes the cost of fuel and oil, maintenance, depreciation and insurance based on an annual use. The total cost of ownership (TCO) is the sum of the airplane cost (TAC) and the operating expenses over a prescribed period of time. The cash flow requirement (CFR) is the sum of the yearly net cash outflow for the specified ownership cycle. Cash outflow items include the initial payment, annual payments, and certain variable and fixed operating costs. Cash inflow items include investment tax credit and tax savings resulting from allowable deductions for depreciation and operating expenses.

Details of economic evaluation methods are shown in the appendix. Included is a summary of the cost standards used in the analysis. A partial summary is shown in Table XII. Fuel cost values used as a base in GATE are shown in Table XIII.

TABLE XII. - ECONOMICS OF AIRCRAFT OWNERSHIP

COST METHODOLOGY BASED ON:
- 1967 ATA Standard (doc)
- AIAA Paper 67-828 (doc)
- TDR AX-0000-590 (doc)
- Rockwell cash flow analysis (CFR)
- Aircraft operation cost summaries

Economic standards: (MY 1978)	Fixed wing	Helicopter
Fuel cost, \$/l(\$/gal)	0.22(0.83) and .33(1.24)	0.22(0.83) and 0.33(1.24)
Oil cost, \$/l (\$/gal)	2.51(9.50)	2.51(9.50)
Depreciation period, yr	8	8
Labor rate (including burden), \$/h	20	20
Annual use, h/yr	600,900	360,600
Annual insurance rate, %	1	5
Annual rate of depreciation, %	25	25
Annual interest rate, %	10	10
Down payment rate, %	10	10
Resale value, %	40	40
Rate of tax saving, %	52	52
Residual value, %	20	20
Hangar rental, \$/yr	3540	--
Aircraft registration, \$ + \$/kg (\$/lb)	25 + 0.077(0.035)	--
Turbine engine OEM price:		
Quantity, total units	5000	5000
Rate, units/mo	80	80
Units, for cum avg price	5000	5000

TABLE XIII. - COSTING

Fuel cost, \$/l (\$/gal)*	High	Medium	Low
80 Octane	0.24(0.90)	0.22(0.83)	0.21(0.79)
100 Octane	0.25(0.95)	0.22(0.85)	0.22(0.810
Jet fuel	0.22(0.83)	0.20(0.77)	0.18(0.68)

Economic base: 1978 (1 March)

*Reference: Business Aviation 7/11/77.

Engine Cost

DDA used the material index factor (MIF) method for cost estimation of the engine concepts in this study. One of the chief advantages of the MIF costing method is its ability to measure the impact of advanced technology on the cost of a whole family of engines before they are detailed. A cost model is prepared from an engineering layout of a basic point design engine using the DDA MIF costing method. This cost model is factored from latest production and advanced development experience. Selected information from the MIF Cost Model is then programmed into the Design Math Model together with changes for the concept under study. From the computer programmed for the Revised Math Model, it is possible to get relative section weights, section costs, and engine costs resulting from iterations of various design parameters direct without benefit of further engineering drafting.

The materials index factor method of estimating engine costs is a series of calculations that has been derived from DDA refinements of original work by the late R. J. Maurer of the Naval Air Development Center (NADC).

After studying many different parameters used as cost indicators of aircraft engines, Mr. Maurer found that the best indication of engine cost was the materials index factor. The MIF may be defined as the sum of relative indices of cost ("weighting factors") times their respective required raw material weights. The material cost indices, as shown in Table XIV, are derived by multiplying the relative material costs by their relative factors of machinability. For engine applications, DDA considers that many of these indices are outdated and otherwise inaccurate. For these reasons, (1) the indices are used selectively—i.e., DDA uses special new indices for exotic blade and vane materials; (2) the indices are continually in process of modernization, using data similar to that gathered under DDA's recent contract N62269-76-M-6616 with NADC; and (3) errors are minimized in DDA costing by equating Maurer factor data to actual costs determined for production engines.

TABLE XIV. - MATERIAL INDICES FOR MIF TECHNIQUE

	Major case, disk, spacer, shaft						Turbo blades & vanes		
Material classification	Ti	A	B	C	D	Conv	A	B	Conv
Relative material cost	7.0	3-4	4-5	5-7	7-10	3.0*	1.5	2.0	1.0
Relative machining costs	1.5	1.9	3.1	4.0	3.5	1.0	1.5	2.0	1.0
Relative weighting factor	10.5	6.7	14.0	24.0	29.8	3.0*	2.5	4.0	1.0
Typical materials	6Al-4V 6Al-6V-2 S_n	17-4PH SS A-286 Creek Ascoloy	Hastelloy X Hastelloy B Inco 706	L-605 Inco 718 Inco 625	Waspaloy Rene-40 Astroloy	321 SS Carbon Steel Aluminum	IN-100 Inco 713	Udimet-500 Udimet-700 SM-302	Hastelloy C Stellite-21

*Substitute value by DDA.

The Maurer factor is based on the total raw weight or material requirements of the engine. No recognition was made, in the original concept, as to whether or not a product has an efficient utilization of material or an inefficient one. The total Maurer factor can be changed only by changing design configuration so as to affect material mix and weight, or by changing the processing efficiency to affect material utilization. For example, processing efficiency may be improved by use of "near net" raw material shapes.

The DDA MIF method of costing a production engine compensates for materials utilization. First, the finished weights (FW) of all the parts are computed. Material utilization factors (MUF) are estimated/computed on the basis of actual part shape and form. The material indices (MI), which include the fabricating difficulty, are assigned from a modified Maurer factor table. These three factors (FW, MUF, MI) are multiplied to form MIF factors, which quantitatively represents both material and labor for each part. The MIF factors are divided by a value representing the average material utilization for small turbine engines built at DDA. It has been determined that this material utilization value--e.g., the raw material weight divided by the finished material weight--for small DDA-built turbine engines is 3.36. The aforementioned quotient is then multiplied by a K factor to give the material cost of the various engine sections. These costs are then summed to give the total manufacturing cost of the engine except for assembly, test, and proprietary accessories. The cost of assembly, test, and controls/accessories are estimated by DDA experts (by examining similar production costs) and added to the other engine costs factored by MIF from the FW of the materials. This then is the recurring manufacturing cost of the engine under study.

The K factor, as explained in a paper given at NADC, Philadelphia, 20 November 1975, by L. L. Robinson, B. A. Zolezzi, and D. K. Hanink, is a combination of four factors which must be weighed in order to reach an accurate dollar cost. These four factors are (1) X factor related to factory efficiency, which also takes into consideration normal material utilization; (2) Y factor considers rate of production of a study engine in relation to the facilities normal rate of production; (3) Z factor relates a given production quantity of production which includes anticipated learning, and (4) T factor in which economic escalation is related to time. Since DDA does not have dedicated engine facilities, a parametrically derived K for a specific engine model is affected by abnormally low production rates on other engines being produced concurrently in the facility.

The determination of accurate costs depends on determination of an accurate value of K. The DDA method used for the determination of an accurate value of K was to examine the cost history of the T63 engine, compute and total the various materials index factors for the engine, multiply the sum of the MIF factors by K/3.36, and equate this total to a real average cumulative cost of the engine (MIF x K/3.36 = actual manufacturing cost). From this equation the K value can be determined for a given quantity of engines, rate of production, and economic period. The K value can be corrected for changes in these three variables. For example, a few years ago a K factor was established for the average cumulative cost per engine of 2000 T63/250 engines at a rate of 70 per month. K was found to be 20.8.

Since that time engine costs for labor and material, as experienced at DDA, have escalated 40% (T factor). A new value for K can therefore be calculated as 1.4 x 20.8 = 29.12. However, this K factor should also be corrected for production rate. The plant efficiency (X factor) is considered to be unchanged. It is estimated that procurement cost will increase by 6% due to decreasing the rate of production from 70 to 21 per month (Y factor). The 6% value is derived from analysis of current production costs and is predicated on accounting procedures that relieve a particular model of fixed plant overhead costs in nearly direct proportion to its reduction in rate per month--i.e., DDA fixed costs are not segregated and assigned to a given model "in perpetuity" as would be the case with a dedicated facility. The previous value of K can be corrected as K = 29.12 x 1.06 = 30.86.

This value of K must now be corrected for a total production quantity such as 2500 engines (Z factor). The average cumulative cost of the 2500 engines will be less than that of 2000 engines. The reduction in cost can be accomplished by application of the values contained in the 90% learning tables. Values for 2000 (0.3149) and 2500 (0.3044) are applied to K by the ratio (0.3044/0.3149). This results in a K of 29.82, which DDA arbitrarily elected to round off to a slightly more conservative value of 30. This is, in fact, the value of K used for costing of a recently proposed DDA production engine.

To accurately determine the learning rate experienced at DDA, a cost history of the T63 engine was compiled. The engine was manufactured during the period from 1966 to 1970. Table XV is a summary of the cost history for that engine. Engine cost was refined for economics and for lot size. The tabulation is graphically illustrated in Figure 28. Note that the first lot of five engines did not follow the log-log linear relationship as well as the remaining lots. Therefore, this point was excluded from the learning curve calculation. The cumulative average costs of the first 13 engines were assigned a cost of unity, and all other cumulative average costs were shown as ratios of unity.

TABLE XV. - T63 ENGINE COST HISTORY

Lot number	Quantity in lot	Cumulative total	Cumulative average ratio
1	5	5	1.0199
2	8	13	1.0000
3	13	26	0.8917
4	63	89	0.7392
5	70	159	0.7050
6	653	812	0.5037
7	1303	2115	0.4264
8	1743	3858	0.3894

The learning curve was determined by two methods:

1. Graphical illustration on log-log paper (Figure 28) and a comparison with an MMI slope analyzer.

(Derived from production record of costs for 250 HP helicopter engine)

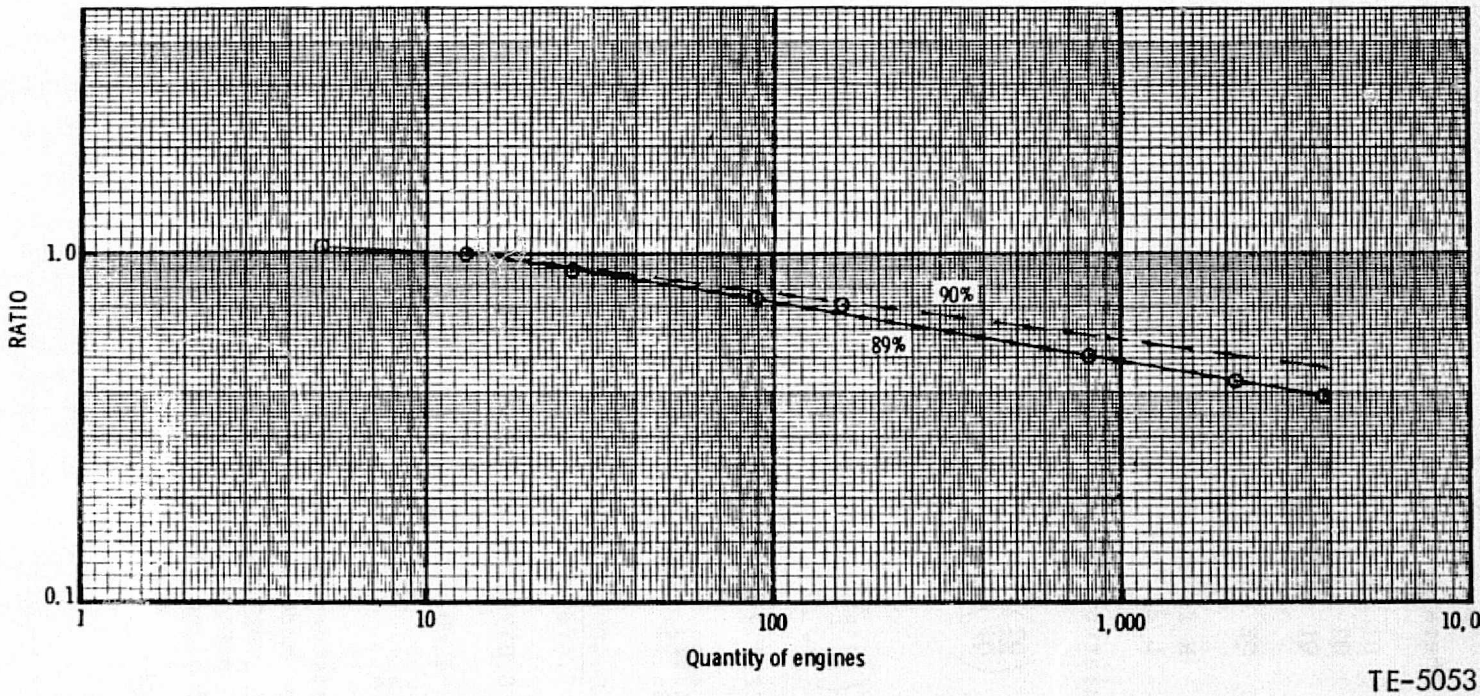

Figure 28. Log-log linear learning curve.

2. Mathematical determination using the formulae.

$$\frac{\text{Q1 cost}}{\text{Q2 cost}} = \left(\frac{Q2}{Q1}\right)^N \qquad \text{Log \% L} = \text{N Log 2}$$

where:

Q1 is the lower cumulative production quantity
Q2 is the higher cumulative production quantity
Q1 cost is the cumulative average cost for production quantity Q1
Q2 cost is the cumulative average cost for the production quantity Q2
N is the slope of the learning curve
L is learning

A single calculation follows:

$$\frac{\text{Q1 cost}}{\text{Q2 cost}} = \left(\frac{Q2}{Q1}\right)^N \text{; Log \% L} = \text{N Log 2}$$

$$N = \frac{\text{Log \% L}}{\text{Log 2}}$$

$$\frac{1.000}{0.3894} = \left(\frac{3858}{13}\right)^N$$

$$2.5683 = (296.77)^N$$

$$N = \frac{\text{Log } 2.5683}{\text{Log } 296.77}$$

$$\frac{\text{Log \% L}}{\text{Log 2}} = \frac{0.4096}{2.4785}$$

Log % L = 0.0499, as the slope is negative

Log % L = -1.00 + 0.0499 = 9.9501 - 10

% L = 89.1%

Although the history of the T63 engine plots to a learning curve of 89%, recent DDA engine model values have been subjected to 90% learning curve factors. This is judgmental and intends to reflect such improvements as DTUPC programs which permit new parts to be manufactured initially at somewhat nearer optimum efficiency than in the 1960's. This is expected to result in lower initial costs and, consequently, a "flatter" progression toward the cumulative average cost of 2500 engines.

Calculation of GATE Engine Costs

An engine parts list derived from a given GATE point design drawing was used as a unity cost model. Materials were identified by the Design and Materials Engineering Groups, and finished weights were provided by the Weights Group.

All engine estimated costs were factored to a common basis of 5000 units at 80 per month and given in 1978 dollars. Historical cost data and recent cost study results for a wide range of DDA small gas turbine engine configurations were reviewed as described in the beginning of this section on Engine Cost Estimation. Factors derived from this review were applied using Materials Index Factor (MIF) methodology to obtain realistic acquisition cost estimates for GATE engines. A study was made of the different materials required together with the material use and processing differences for each GATE configuration. These physical differences formed the basis for factors used in differential costing by the MIF technique and were plugged into the design computer program that iterated design changes and their resultant cost changes.

Cost data was generated by MIF methodology as described for those engine configurations that stressed design simplicity and minimum parts count. This cost data was then compared with similar cost data generated for more sophisticated engines that stressed performance. Cooled and uncooled turbine engine configurations were examined from a cost context, and these results applied in the cost/performance trade studies.

By comparing candidate engine 26 to engine 29 shown in Tables XVI (SI units) and XVII (customary units), it can be seen that by air cooling the turbine and designing to a higher RIT, 2200°F vs 1950°F, the weight decreased 10% and the cost decreased 6% while the sfc remained about the same. The lower weight, lower cost, and slightly better sfc gives the 2200°F air-cooled turbine engine an advantage when considering total cost of ownership (TCO). Similarly, it can be seen by comparing candidate engine 30 to engine 26, also shown in Tables XVI and XVII, that by designing with two smaller compressor wheels with a compressor pressure ratio of 14 and two smaller turbine wheels in engine 30, in place of one larger compressor wheel with a compressor pressure ratio of 10 and one larger turbine wheel (2200°F air cooled), that the two-stage compressor and turbine engine is only 3% heavier, 2% more costly, but has a 5% improvement in sfc. Because of its better sfc, candidate engine 30 has a lower cost of ownership (TCO) than engine 26 despite a small increase in acquisition cost and weight.

TABLE XVI. - CANDIDATE ENGINE DATA
(SI units)--UNITY SIZE

Engine	26	27	28	29	30
Technology	ATE	ATE	ATE	ATE	ATE
Type of compressor	1-C	1-C	1-C	1-C	2-C
Type of GP turbine	1-A	2-A	1-R	1-A	2-A
Air-cooled GP turbine	YES	YES	YES	NO	YES

TABLE XVI. - (CONT)

	Design point performance, slss T.O. Turboshaft and turboprop w/o gear box loss				
R_c	10	10	10	10	14
RIT, K	1478	1478	1478	1339	1478
Shaft power, kW	372.8	372.8	372.8	372.8	372.8
Airflow, kg/s	1.340	1.349	1.268	1.625	1.400
sfc, g/W·s	86.41	86.39	82.03	87.22	82.34
	Turboshaft engine data (incl red gears, 6000 rpm output)				
Mass, kg	65.5	66.6	65.7	73.1	67.2
Length, m	0.511	0.531	0.503	0.544	0.643
Diameter, m	0.444	0.447	0.437	0.478	0.452
OEM Price, ($) *	62,200	63,422	58,830	66,170	63,562
Premature R.R./1000 hr	0.53	0.53	0.53	0.50	0.53
Maintenance cost, $/fl hr					
30 hr/mo util	18.47	18.77	17.42	18.88	18.81
50 hr/mo util	18.05	18.34	17.02	17.83	18.38
	Turboprop engine data (incl prop gear box, 2000 rpm output)				
Mass, kg	79.1	80.5	79.3	88.3	81.2
Length, m	0.907	0.927	0.899	0.940	1.039
Diameter, m	0.444	0.447	0.437	0.478	0.452
OEM Price, $ *	74,764	76,233	70,714	79,537	76,401
Premature R.R./1000 hr	0.45	0.45	0.45	0.41	0.45
Maintenance cost, $/fl hr					
50 hr/mo util	18.24	18.60	17.26	19.57	18.64
75 hr/mo util	17.59	17.93	16.64	18.90	17.97

*Cumulative average price 5000 engs, 80/mo, 1978 base year.
C - centrifugal
A - axial
R - radial

TABLE XVII. - CANDIDATE ENGINE DATA (customary units)--UNITY SIZE

Engine	26	27	28	29	30
Technology	ATE	ATE	ATE	ATE	ATE
Type of compressor	1-C	1-C	1-C	1-C	2-C
Type of GP turbine	1-A	2-A	1-R	1-A	2-A
Air-cooled GP turbine	YES	YES	YES	YES	YES
	Design point performance slss T.O. Turboshaft and turboprop w/o gearbox loss				
R_c	10	10	10	10	14
RIT, ^{o}F	2200	2200	2200	1950	2200
shp	500	500	500	500	500
Airflow, lbm/s	2.954	2.974	2.795	3.583	3.086
sfc, lbm/hp·hr	0.5114	0.5113	0.4855	0.5162	0.4873

TABLE XVII. - (CONT)					
Turboshaft engine data (incl red gears, 6000 rpm output)					
Weight, lb	144.4	146.9	144.8	161.2	148.2
Length, in.	20.1	20.9	19.8	21.4	25.3
Diameter, in.	17.5	17.6	17.2	18.8	17.8
OEM price, $ *	62200	63422	58830	66170	63562
Premature R.R./1000 hr	0.53	0.53	0.53	0.50	0.53
Maintenance cost, $/fl hr					
30 hr/mo util	18.47	18.77	17.42	18.88	18.81
50 hr/mo util	18.05	18.34	17.02	17.83	18.38
Turboprop engine data (incl prop gearbox 2000 rpm output					
Weight lb	174.4	177.5	174.9	194.7	179.0
Length, in.	35.7	36.5	35.4	37.0	40.9
Diameter, in.	17.5	17.6	17.2	18.8	17.8
OEM price, ($) *	74764	76233	70714	79537	76401
Premature R.R./1000 hr	0.45	0.45	0.45	0.41	0.45
Maintenance cost, $/fl hr					
50 hr/mo util	18.24	18.60	17.26	19.57	18.64
75 hr/mo util	17.59	17.93	16.64	18.90	17.97

*Cumulative average price 5000 engs 80/mo, 1978 base year
C - centrifugal; A - axial; R - radial

In addition to the many design parametric iterations compared to a unity sized engine for effect on acquisition cost and TCO, additional technology elements were considered and their cost effectiveness evaluated. Advanced state-of-the-art technology elements evaluated for their effect on cost when physically incorporated into the selected candidate study engines were dual property turbines, ceramic turbine stators, composite material gearbox case, Lamilloy* combustors, and axial-centrifugal compressors. The effect on acquisition costs was evaluated by MIF methodology from the differential bills of materials and processing complexity of the considered technology change. More complete technical description of these elements and tables showing their effect on cost are given in this report.

Conclusions on Engine Costing

In general the DDA MIF methodology has allowed costs to be plotted as a parameter of design. This can be observed in the many charts showing costs and how they are affected by different specific design changes. The overall cost analysis also indicates that production experience is as much or more of a cost driver than material content resulting from engine technology. DDA studies show that the acquisition cost of an advanced technology engine (ATE) is only slightly more than that of a current technology engine (CTE) when similarly compared. The real life situation of comparing an ATE just going into production to a CTE of the same horsepower evolved from a long production run shows an appreciable increase in the acquisition cost of the newer engine.

This concept is shown graphically in Figure 29. In this illustration relative turbine engine costs have been adjusted to constant economics for an actual production run of over 12,000 engines. From this experience the cost of a

*Lamilloy is a registered trademark of the General Motors Corporation.

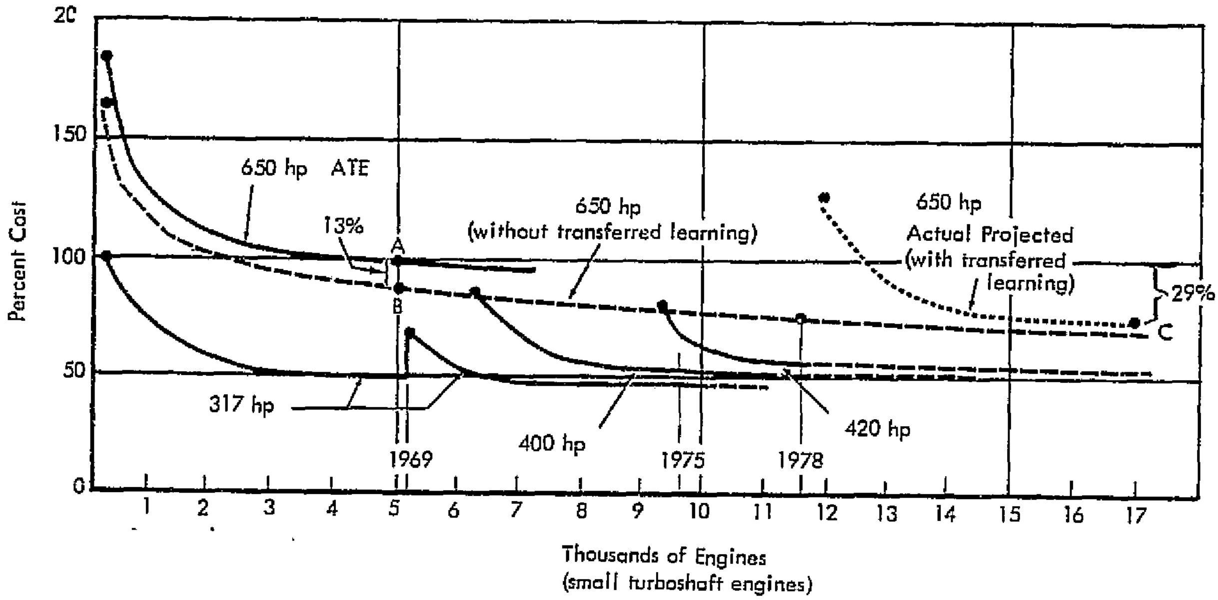

Figure 29. Comparative average manufacturing costs--CTE and ATE type turbine engines.

hypothetical current technology growth engine (CTE) of greater power, 485 kW (650 hp), has been projected assuming no previous production experience (or transferred learning) applied to this design. The cost of a more advanced technology engine (ATE) of the same power, 485 kW (650 hp), but of different design has also been projected. The two differently designed 485-kW (650-hp) engines (ATE) and (CTE) show different average costs for 5000 engines. The cost is approximately 13% greater for the advanced technology engine (Figure 29 point A vs point B). If the 485-kW (650-hp) ATE cost at 5000 units is compared to the current technology 485-kW (650-hp) CTE average cost after another 5000 small turbines have been produced concurrently, the 485-kW (650-hp) ATE average cost of 5000 units (point A) is 29% greater than the 485-kW (650-hp) growth version CTE average (point C). Despite the 29% lower acquisition cost for the CTE (point C) than for the ATE (point A), the total cost of ownership (TCO) is significantly less for the ATE engines as is shown in Table XVIII.

Engine Maintenance

The GATE maintenance cost analysis was divided between turboprop and turboshaft powerplants. This division resulted from different typical general aviation usages for twin-engine, fixed-wing and single-engine, rotary-wing applications. Tables XIX and XX show the principal difference in use (hours per year).

TABLE XVIII. - "OPTIMUM" ENGINES			
	Heavy twin	Unpr twin	Hel twin
NOMINAL SP, kW (hp) (* Flat Rated)	820 (1100)*	403 (540)	298 (400)
Cycle	14:1 1478°K (2200°F)	14:1 1478°K (2200°F)	10:1 1478°K (2200°F)
Configuration	2 STG CENTR 2A GPT 2 SPOOL	2 STG CENTR 2A GPT 2 SPOOL	1 STG CENTR 1 RADIAL AIRCOOLED 2 SPOOL
Tech elements	Lamilloy combustor Ceramic stators Composite GB Dual property GP turbine		
Benefits compared to a current technology engine (with production base)			
sfc improvement, %	20	20	20
Specific mass improvement, %	23	23	24
CM, %	-21	-11	-12
TAC, %	-7	+5	+1
TCO, %	-20	-11	-8
Fuel reduction, %	32	23	24

TABLE XIX. - TURBOSHAFT MAINTENANCE STANDARDS	
Basic Study - Turboshaft	
Aircraft	Single-engine helicopter
Use	360-600 h/yr
Max operating time	5000 h

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TABLE XX. - TURBOPROP MAINTENANCE STANDARDS	
Basic Study - Turboprop	
Aircraft	Twin engine
Use	600-900 h/yr
Max operating time	5000 h

It is obvious that the annual utilization for a turboprop vs a turboshaft application varies from the same (600 h/yr) to almost three to one (900 h/yr/360 h/yr). Since operating costs may vary somewhat as an indirect function of annual utilization, direct comparisons between turboprop and turboshaft engines should be done where annual utilization is equal or nearly so.

A maximum operating time (MOT) of 5000 engine operating hours was selected. This value was used instead of on-condition for several reasons. Two principal ones were the desire to inspect the engines after 5 to 7 yr and the belief that 5000-hr design technology would be pretty well within the state of the art of small engine design by the time that GATE concepts entered production. The high time operator would achieve the selected 5000-hr MOT within 7 yr. A low time operator or an aircraft in storage might run the risk of dry seals leading to severe oil leaks or engine damage. A few years ago, a major airline experienced a strike which meant that their turboprop-powered aircraft sat about 3 weeks. Upon reentry into service, a series of premature engine removals resulted which were thought to be caused by a "dry bearing" condition at start-up.

DDA has seen evidence of some engine distress through lack of use. Engines that have not been run often can be subject to damage immediately after starting while oil that has drained away from bearings and seals is pumped back into place. Since low annual time operators could fall into this category of inordinate wearout characteristics, a 5 to 7 yr time-related inspection could enhance the safety of operation.

Operators should plan for the benefits of turbine-powered aircraft. TBO values can greatly exceed usual piston engine levels. Inherent premature removal rates may vary significantly for different missions. Of course, operators are more concerned about operational removal rates since these directly impact aircraft availability and operational cost. Operational rates are the sum of engine-inherent (quality, design life, installation, etc) and engine-noninherent (foreign object damage such as rocks or birds, pilot error, improper maintenance, dirty fuel, nonspec oil, secondary damage resulting from aircraft problems, etc). Operational removal rates exclude removals for time (TBO) and convenience. Typical reasons for a convenience removal include using an engine from an aircraft on ground (AOG) aircraft to replace a removed engine in another aircraft thereby allowing the second aircraft to become operational. Sensitivity studies can be made to assist potential turbine-powered aircraft users in the selection of engine-aircraft combinations for their intended use. These studies can help illustrate the risk of operating cost variance from the anticipated norm. If a sensitive cost driver, such as a high ratio of take-off power occurrences versus operating time, can be isolated, the user might be able to select equipment/maintenance plans to guard against high costs.

A typical sensitivity chart (Figure 30) shows the relationship of unscheduled engine removals as a part of total engine removals plotted as a function of TBO and premature removal rate for a given engine flying hour per month use. Close review of Figure 30 shows increasing unscheduled removals after passing 3000-hr TBO and moving toward 7500-hr TBO. The rate of change is pronounced at 0.4/1000 premature removals and becomes greater as premature removal rate increases. Since unscheduled removals plague commercial operators from an aircraft availability and, therefore, revenue generation and reputation for reliability, these factors could play an important role in the decision concerning aircraft acquisition and operation.

The results shown in Figure 30 were determined using a DDA operating and support cost computer simulation model (OS 590). This model was furnished to the USAF as CDRL Item No. A005 of Contract F33657-77-C-0425, Reduced Cost Turbine Engine Concepts. Various combinations of TBO and premature removal rate were passed through the simulation. Typical results are plotted on Figure 30. The data plotted as intuitively expected until the area for dominance between

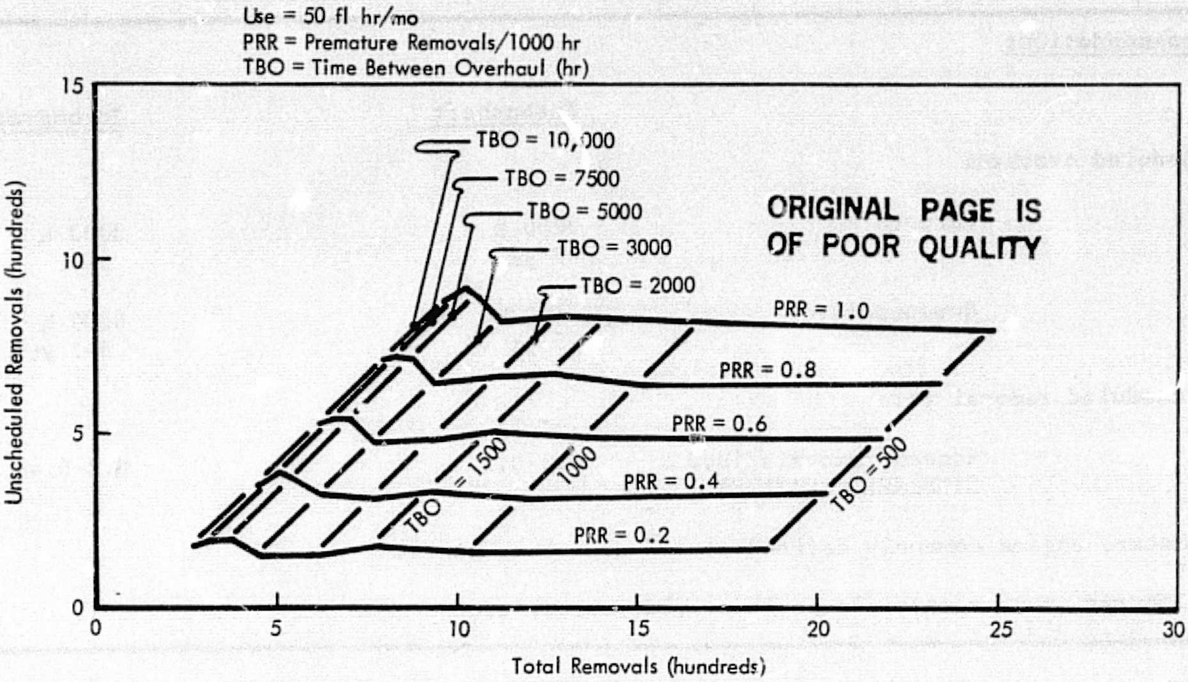

Figure 30. TBO and PRR relationships--100 A/C, 15-yr forecast.

scheduled removals versus unscheduled removals was reached. The area of instability showed that spending money to increase TBO values substantially beyond 5000 h had little payoff for operational availability.

The maintenance studies resulted in a recommendation set depicted in Table XXI. Again, turboshaft and turboprop distinctions are made. In addition, a further distinction results from the recognition of two major user classes - corporate and non corporate. The turboshaft engine usually lives in a more unfriendly environment than the typical turboprop. Rotary-wing vibration levels generally exceed fixed-wing levels. Demanding mission profiles occur more often in a rotary-wing appplication. Therefore, a maintenance driver, Unscheduled Removal Rate, is substantially higher for turboshaft engines than a comparable technology turboprop engine.

The random removal rate leads to a lower noncorporate TBO for the turboshaft. Corporate TBO was recommended at 3000 h. The tendency is toward super safety. This attitude is most understandable when the consideration is made for risk of loss of senior people. This attitude is the result of the importance placed on continuity of operations involving key management personnel availability. A similar consideration toward extra safety is shown by municipal and state aircraft operators who are entrusted with the safety of elected and other key government officials.

Finally, the calendar time/TBO relationship is influenced by other considerations. Tax write-offs, resale value, use, and many other factors influence the values recommended. The financial opportunities vary for corporate and noncorporate operators. The recommended overhaul times were selected to give a nominal best business fit for each user and powerplant combination.

TABLE XXI. - SCHEDULED OVERHAUL RECOMMENDATIONS		
Recommendations	Turboshaft	Turboprop
Scheduled overhaul		
Corporate	3000 h 5 yr	3000 h 5 yr
Noncorporate	4500 h 5 yr	6000 h 5-7 yr
Unscheduled removal rate		
Random removals/1000 h (INHERENT, MATURE)	0.3-0.5	0.2-0.4

- Mature engine commonly defined as 10^6 operating hours.
- Inherent engine removals exclude: fod, error, etc.

The engine removal plan follows from the TBO and type of application assumptions. The premature removal rate (PRR) for each basic engine configuration was estimated. A typical set of PRR estimates is depicted by Table XXII. It is readily seen that turbine temperature is a PRR driver. A more careful review shows that the PRR threshold is higher for a turboshaft engine than for a turboprop. This threshold difference may be generally attributed to the more unfriendly environment common to rotary-wing applications.

TABLE XXII. - PROJECTED PREMATURE REMOVAL RATES

Turboshaft						Turboprop					
ENG	PRR	RIT*	ENG	PRR	RIT*	ENG	PRR	RIT*	ENG	PRR	RIT*
1	0.53	(1)	16	0.52	(1)	1	0.39	(1)	16	0.38	(1)
2	0.56	(2)	17	0.60	(3)	2	0.41	(2)	17	0.44	(3)
3	0.61	(3)	18	0.53	(1)	3	0.45	(3)	18	0.39	(1)
4	0.55	(1)	19	0.61	(3)	4	0.40	(1)	19	0.45	(3)
5	0.58	(2)	20	0.55	(1)	5	0.43	(2)	20	0.41	(1)
6	0.63	(3)	20A	0.50	(1)	6	0.46	(3)	20A	0.41	(1)
7	0.59	(1)	21	0.63	(3)	7	0.42	(1)	21	0.47	(3)
8	0.62	(2)	22	0.55	(1)	8	0.45	(2)	22	0.41	(1)
9	0.68	(3)	23	0.63	(3)	9	0.49	(3)	23	0.47	(3)
10	0.62	(1)	24	0.53	(1)	10	0.45	(1)	24	0.30	(1)
11	0.66	(2)	25	0.61	(3)	11	0.48	(2)	25	0.45	(3)
12	0.72	(3)	26	0.53	(4)	12	0.53	(3)	26	0.45	(4)
13	0.68	(1)	27	0.53	(4)	13	0.49	(1)	27	0.45	(4)
14	0.72	(2)	28	0.53	(4)	14	0.53	(2)	28	0.45	(4)
15	0.80	(3)	29	0.50	(1)	15	0.59	(3)	29	0.41	(1)
			30	0.53	(4)						

* RIT—(1) 1339 K(1950°F); (2) 1450 K(2150°F); (3) 1561 K(2350°F); (4) 1478 K(2200°F).

The maintenance action distribution is a relative cost driver. A common maintenance plan is assumed for both turboprop and turboshaft engines. The distribution shown by Table XXIII provides for overhaul for time expired (TBO) removals and a variable maintenance level distribution for PRR. The distribution is really a function of failure cause and associated repair level. Values used are nominal experience for small 298 kW (400 hp) class turboshaft and turboprop engines.

TABLE XXIII. - MAINTENANCE PLAN

- Engine Removal Plan

  TBO = 5000 h

  PRR = function of use and temperature

- Distribution of Maintenance Repair Level

Time expired	Depot/distributor
Premature removal, %	
30	Depot/distributor overhaul
40	Depot/distributor major repair
20	FBO major repair
10	FBO minor repair

FBO = Fixed Base Operator

The functional maintenance was valued with respect to dollar cost. Each cost element was related to OEM price as shown in Table XXIV except for nominal FBO repair costs and engine removal and installation. The values shown are typical of total cost. No attempt was made to apportion labor and material costs for each repair level. It was further assumed that capital investment is recovered through burden or overhead charges contained in the overhaul/repair cost structure.

The OEM price was related to factory cost for the engine. A 0.52 factor (Table XXV) was used to provide dollars for all elements above cost to manufacture. Although values for each individual element may change from engine manufacturer to manufacturer, this factor was considered representative to support this program trade study.

TABLE XXIV. - BASELINE MAINTENANCE INPUT	
Distributor	O/H COST = (.65) (OEM price)
Distributor	Major repair cost = (0.33) (O/H cost)
FBO	Major repair cost = $500
FBO	Minor repair cost = $100
Engine installation = $50 + 4 m-h at $20.00/h	
Engine removal = 3 m-h at $20.00/h	
FBO corresponds to Fixed Base Operator	

TABLE XXV. - PRICE STRUCTURE
List Price = OEM price x 1.5
Factory Cost X 1.52 = OEM price
0.52 factor includes:
• General and administrative
• Profit
• Product liability
• Warranty

Current Technology (Baseline) Engine

An engine configuration was selected to represent current technology in the small gas turbine field. It was used as a baseline engine for comparative purposes with the advanced technology matrix and candidate study engines. Pertinent performance, size, mass and cost data for the CTE are shown in Table XXVI and XXVII at a shaft power size of 373 kW (500 shp).

TABLE XXVI. - CURRENT TECHNOLOGY ENGINE DATA (SI units)		
1-stage centrifugal compressor 2-stage axial gas generator turbine 2-stage axial power turbine (unity size)		
Engine identification	CTE	CTE*
Performance, slss T.O.		
Turboshaft and turboprop w/o prop gearbox loss		
R_c	8.5	8.5
RIT, K	1316	1316
Shaft power, kW	373	373
sfc, μg/W·s	103	103
Turboshaft engine data (6000 rpm output)		
Mass, kg	86.6	86.6
Length, m	0.91	0.91
Diameter, m	0.56	0.56
OEM price, $	49,399	56,424
Maintenance cost, $/fl hr		
30 h/mo util	23.37	26.67
50 h/mo util	22.45	25.63
Turboprop engine data (incl prop gearbox. 2000 rpm output)		
Mass, kg	105	105
Length, m	1.11	1.11
Diameter, m	0.54	0.54
OEM price, $	64,709	73,910
Maintenance cost, $/fl hr		
50 h/mo util	25.16	28.73
75 h/mo util	25.20	28.77

CTE--Current Technology Engine
CTE*--Current Technology Engine with price adjusted to no prior manufacturing experience basis.

Study Engines

A matrix of 22 turboshaft engines and their turboprop derivities were selected for the initial phase of the Task II Broad Scope Trade-Off Studies. The matrix consisted of 12 two-stage centrifugal compressor engines (Nos. 4 through 15), and 10 single-stage compressor engines (Nos. 16 through 25). The unity size of these engines was approximately 615 kW (825 hp). Unity size performance, mass, price, dimensions, and maintenance cost were estimated for each of these engines for use as input data into the mission trade-off studies.

TABLE XXVII. - CURRENT TECHNOLOGY ENGINE DATA (Customary units)

1-stage centrifugal compressor
2-stage axial gas generator turbine
2-stage axial power turbine
(unity size)

Engine identification	CTE	CTE*
Performance, slss T.O.		
Turboshaft and Turboprop w/o prop gearbox loss		
R_c	8.5	8.5
RIT °F	1910	1910
shp	500	500
sfc, lbm/shp·h	0.61	0.61
Turboshaft engine data (6000 rpm output)		
Weight, lbm	191	191
Length, in.	35.8	35.8
Diameter, in.	21.9	21.9
OEM price, $	49,399	56,424
Maintenance cost, $/fl hr		
30 h/mo util	23.37	26.67
50 h/mo util	22.45	25.63
Turboprop engine data (incl prop gearbox 2000 rpm output)		
Weight, lbm	232	232
Length, in.	43.7	43.7
Diameter, in.	21.2	21.2
OEM price $	64,709	73,910
Maintenance cost, $/fl hr		
50 h/mo util	25.16	28.73
75 h/mo util	25.20	28.77

CTE--Current Technology Engine
CTE*--Current Technology Engine with price adjusted to no prior manufacturing experience basis

The performance was obtained by running computerized cycle calculations at the slss T.O. design point and at a series of flight Mach number, altitude, and power setting conditions applicable to the particular mission understudy. For turboprop input data, shaft power was adjusted for prop gearbox loss and converted to thrust by assuming the following propeller efficiencies:

Flight Condition	Prop Efficiency
Climb-one engine operative	0.78
Climb-all engines operative	0.83
Cruise-all engines operative	0.915

The effect of power and bleed air extraction was included in the cycle calculations. The requirements utilized in this study are listed below and apply to the unity engines.

	Fixed-wing applications	Rotary-wing applications
Power extraction/engine, kW (hp)	2.94 (4)	2.94 (4)
Bleed air extraction, kg/sec (lbm/sec)	0.045 (0.1)	0 (0)

The unity size masses were estimated with a computerized components mass analysis program that takes into account a complex set of mass-sensitive parameters. The unity size prices were estimated by first estimating the factory costs using a cost-estimating computer program with input that includes component mass and material index factors (MIF's). The factory costs were converted to OEM selling prices by applying factors to account for such items as:

- General and administrative expenses
- Product liability
- Warrantee
- Development
- Profit

The estimated engine dimensions were a by-product of the mass analysis. The engine maintenance costs were estimated with an operational and support computer program.

Dual- and Single-Stage Compressor Engine Matrix

Table XXVIII gives an overview of the configuration, pressure ratio, and turbine rotor inlet temperature variations in the 22 matrix engines, 4 through 25.

TABLE XXVIII. - OVERVIEW OF MATRIX ENGINES
(TURBOSHAFT AND TURBOPROP) UNITY SIZE : APPROX 615 kW (825 hp)

Ident. No.	Comp R_c	Turb RIT, K (°F)	No. of Stages and Types Comp	G.G. Turb	Power Turb
4	10	1339 (1950)	2-C	2-A	2-A
5	10	1450 (2150)	2-C	2-A	2-A
6	10	1561 (2350)	2-C	2-A	2-A
7	12	1339 (1950)	2-C	2-A	2-A
8	12	1450 (2150)	2-C	2-A	2-A
9	12	1561 (2350)	2-C	2-A	2-A
10	14	1339 (1950)	2-C	2-A	2-A

TABLE XXVIII. - (CONT)					
Ident. No.	Comp R_c	Turb RIT, K (°F)	No. of Stages and Types		
			Comp	G.C. Turb	Power Turb
11	14	1450 (2150)	2-C	2-A	2-A
12	14	1561 (2350)	2-C	2-A	2-A
13	16	1339 (1950)	2-C	2-A	2-A
14	16	1450 (2150)	2-C	2-A	2-A
15	16	1561 (2350)	2-C	2-A	2-A
16	10	1339 (1950)	1-C	1-RI	2-A
17	10	1561 (2350)	1-C	1-RI	2-A
18	10	1339 (1950)	1-C	2-A	2-A
19	10	1561 (2350)	1-C	2-A	2-A
20	10	1339 (1950)	1-C	1-A	2-A
21	10	1561 (2350)	1-C	1-A	2-A
22	8.5	1339 (1950)	1-C	1-A	2-A
23	8.5	1561 (2350)	1-C	1-A	2-A
24	5.5	1339 (1950)	1-C	1-A	2-A
25	5.5	1561 (2350)	1-C	1-A	2-A

A-Axial flow
C-Centrifugal
RI-Radial Inflow

Performance and Cost Comparison of Dual and Single Stage

Figures 31, 32 and 33 show the relative sfc, specific mass and specific cost of the 12 two-stage compressor engines. Figures 34, 35, and 36 show similar data for the 10 single-stage compressor engines.

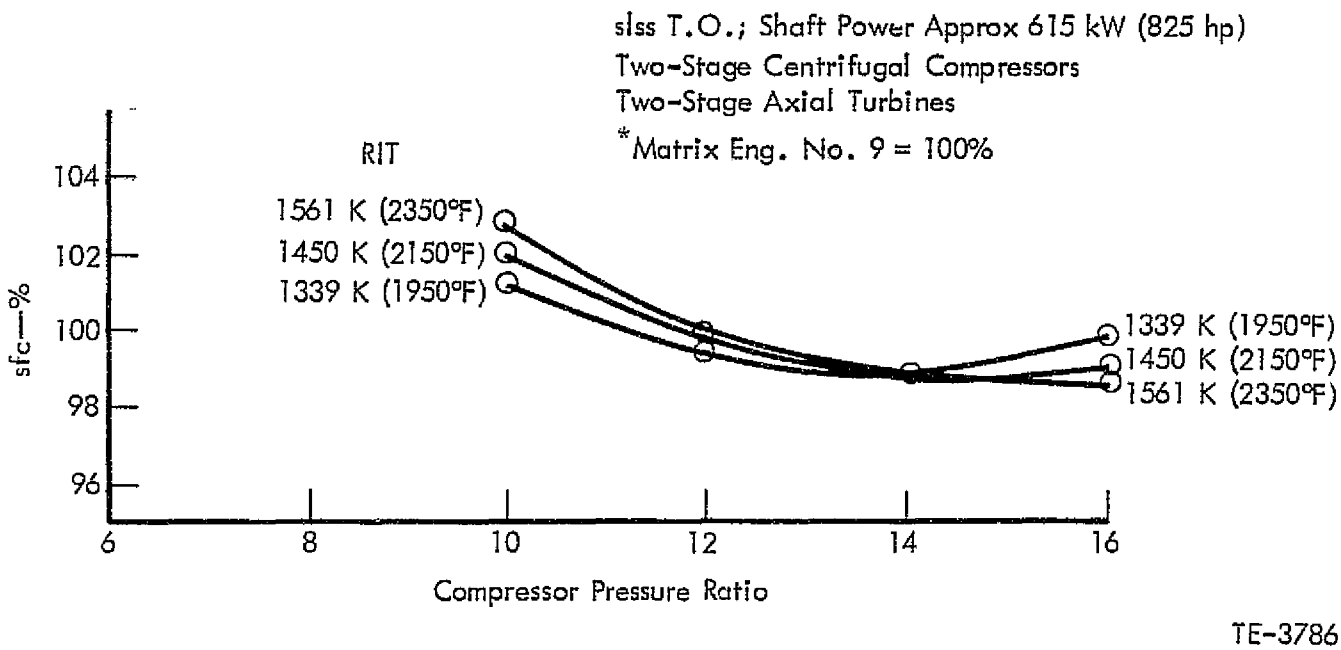

Figure 31. GATE parametric engine study--two-stage centrifugal compressor (engine sfc).

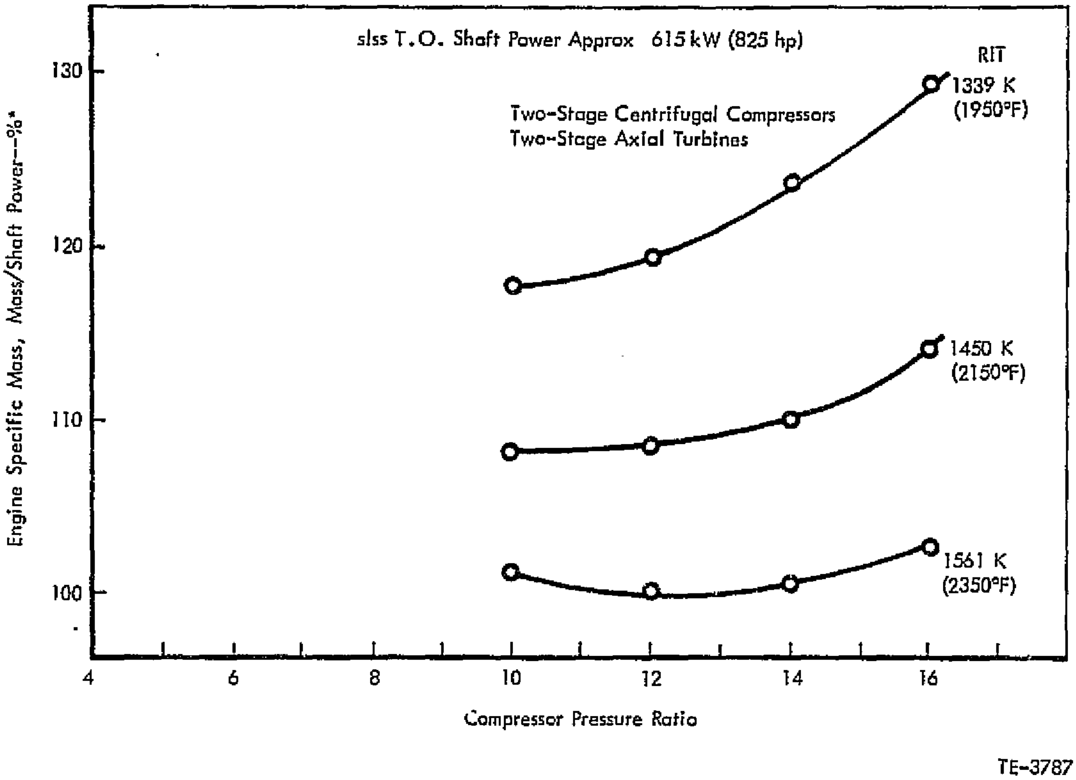

Figure 32. GATE parametric engine study--two-stage centrifugal compressor (engine mass).

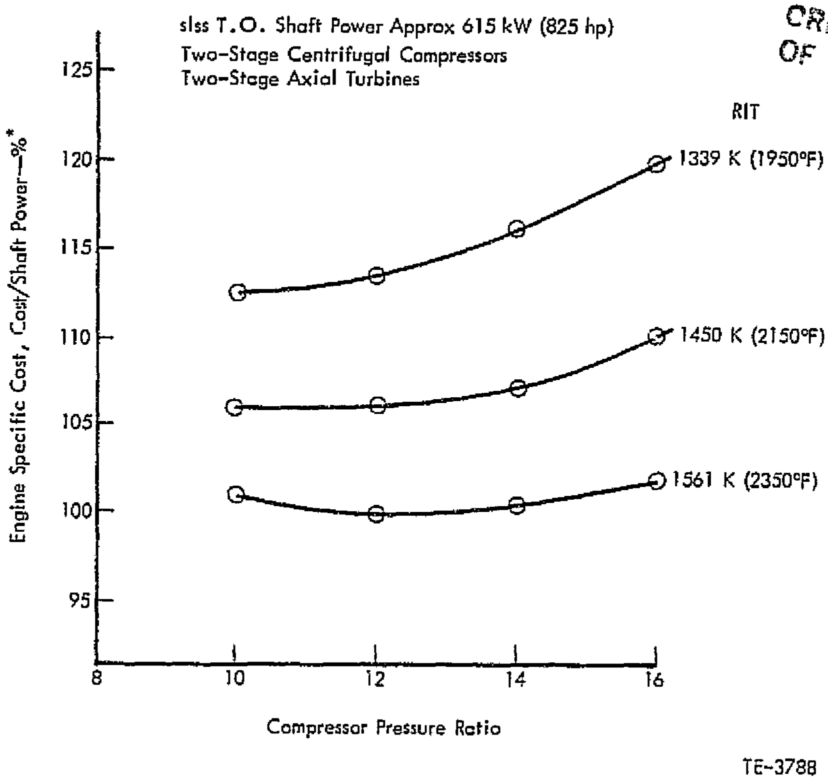

Figure 33. GATE parametric engine study--two-stage centrifugal compressor (engine cost).

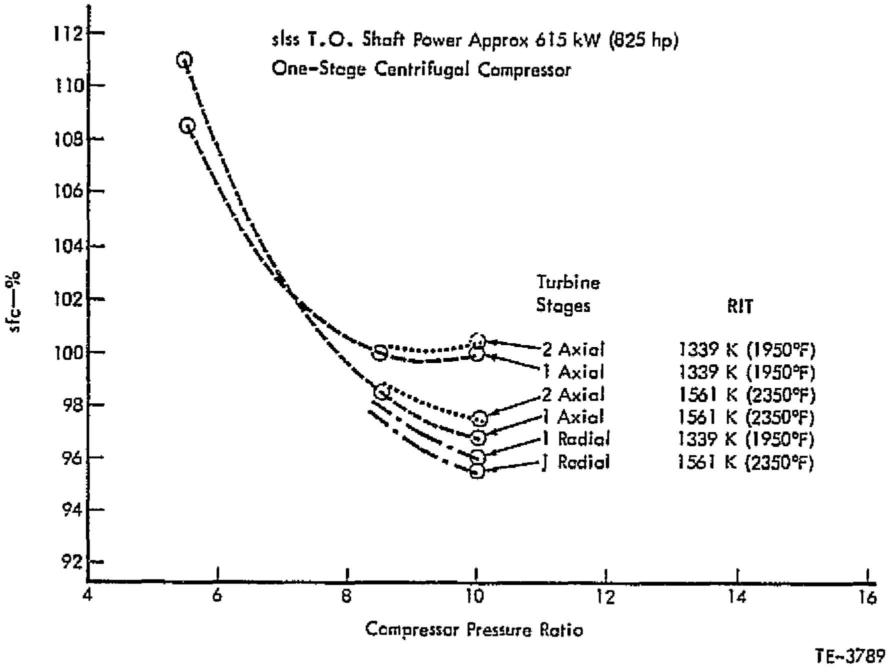

Figure 34. GATE parametric engine study--one-stage centrifugal compressor (engine sfc).

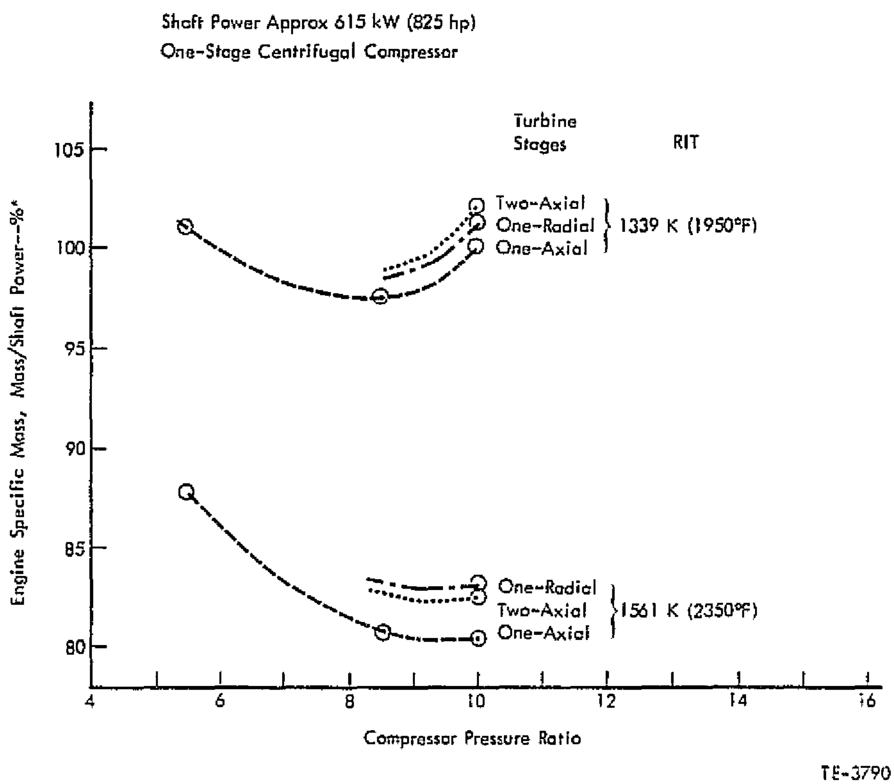

Figure 35. GATE parametric engine study--one-stage centrifugal compressor (engine mass).

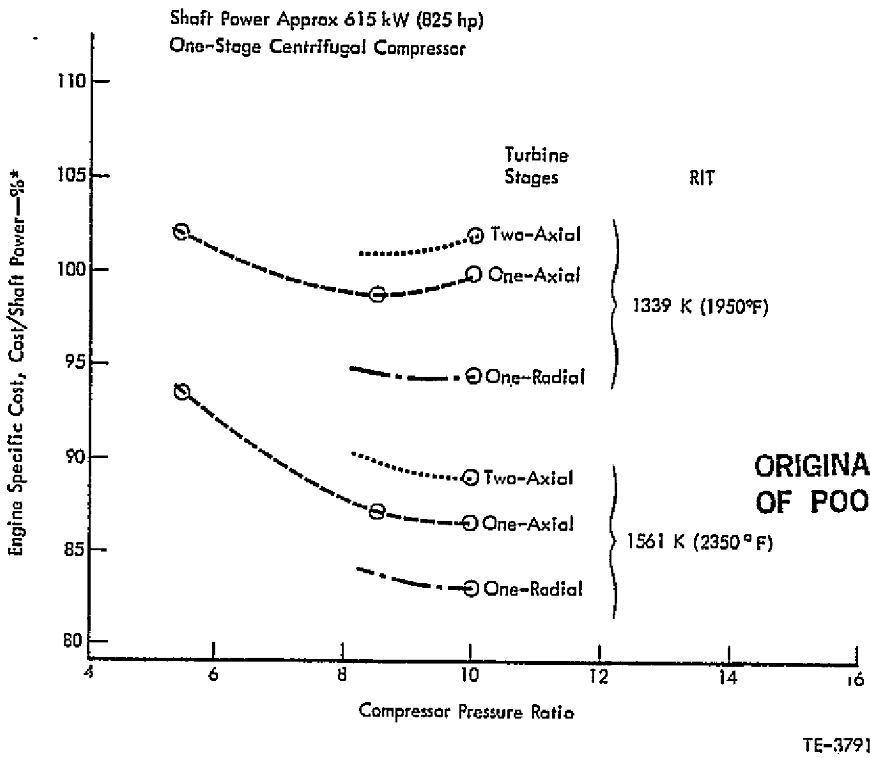

Figure 36. GATE parametric engine study—one-stage centrifugal compressor (engine cost).

In general these curves show the following:

- sfc decreases as compressor pressure ratio increases except for low turbine temperatures at high pressure ratios.
- Engine-specific mass decreases as turbine inlet temperature increases.
- For the single-stage compressor engines, specific mass decreases with compressor pressure ratio up to a range of 8.5-9.5 R_c then increases for higher pressure ratios.
- For the two-stage compressor engines, the specific mass increases with compressor pressure ratio over the 10 to 16 R_c range studied except for the high turbine inlet temperature (1561 K (2350°F)) engine that bottoms out at about 12 R_c.
- The specific cost trends follow the specific mass trends already discussed.
- For the single-stage compressor engines, the sfc and specific mass decrease progressively as the gas generator turbine configuration is changed from two-stage axial to one-stage axial to one-stage radial.

Mission Evaluation of Dual Stage

The dual-stage centrifugal compressor engines (12 engine matrix) were evaluated in each of the four fixed-wing and two rotary-wing vehicle/mission applications.

The results for the unpressurized twin are shown in Figures 37 and 38. Figure 37 shows normalized values of aircraft design gross mass (gm), engine size specified in terms of rated shaft power at sea level static-standard day conditions (SP), and total aircraft (airframe plus engine) acquisition cost (TAC). Figure 38 completes the presentation of the unpressurized twin economic results in terms of direct operating cost (DOC), total cost of ownership (TCO), and cash flow requirement (CFR). Both figures plot these normalized results as a function of the design cycle parameters compressor pressure ratio (R_c) and turbine rotor inlet temperature (RIT). The cycle trend shown in these figures indicate a preference for high turbine inlet temperature and a relatively flat trend in R_c for GW, SP, and TAC. The DOC, TCO, and CFR results indicate a preference for R_c around twelve. It is noted that the GW, SP and TAC generally follow previously presented engine specific mass, specific fuel consumption, and specific cost trends. However, the DOC, TCO, and CFR are showing the influence of "scatter" in the engine maintenance cost trends (i.e., crossover in the 1450 and 1561 K (2150 and 2350°F) RIT results at low R_c values).

Figure 39 shows the results for the pressurized light twin application. Because of the similarity in trends and a desire to reduce the amount of data presented, only GW, TAC, and TCO results will be shown for the remaining fixed- and rotary-wing applications. The cycle trends in Figure 39 again indicate a preference for high RIT and a R_c around 12. Figure 40 shows the results for the pressurized heavy twin and Figure 41 the results for the light agricultural application. Generally speaking, the trends for these two applications are similar to the unpressurized twin and pressurized light twin.

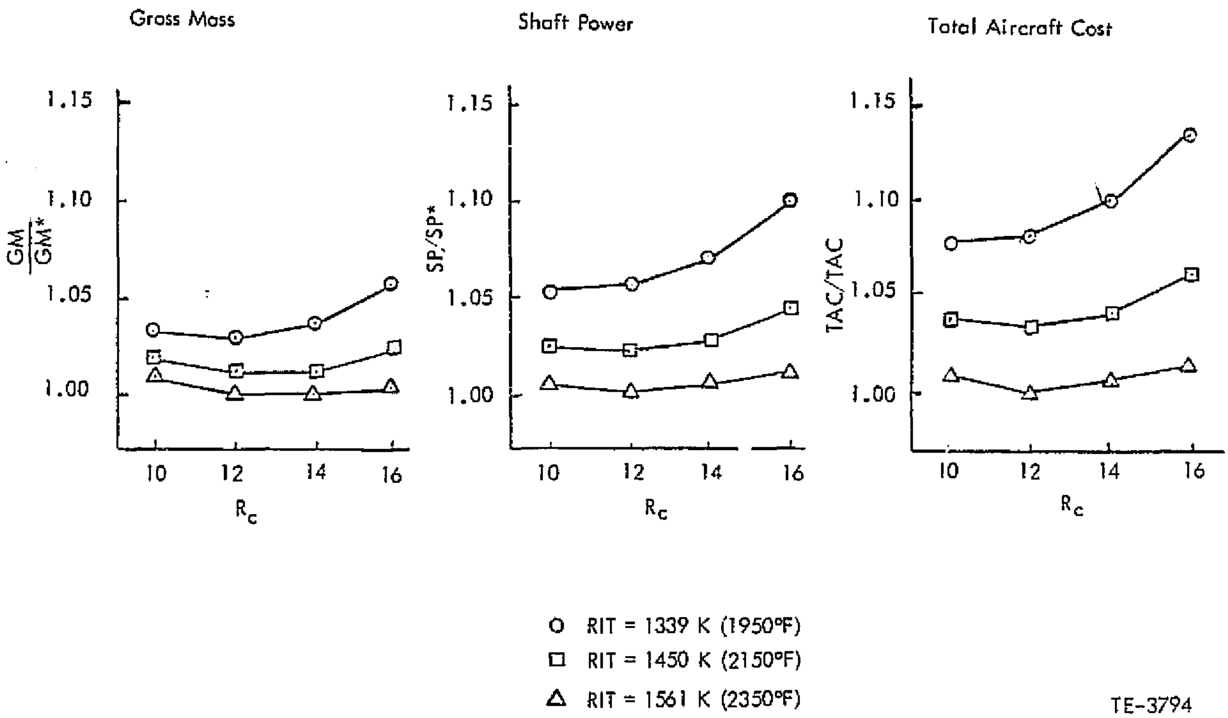

Figure 37. Dual-stage centrifugal compressor engine matrix--gross mass, power, and total cost of ownership and cash flow requirement trends (unpressurized twin).

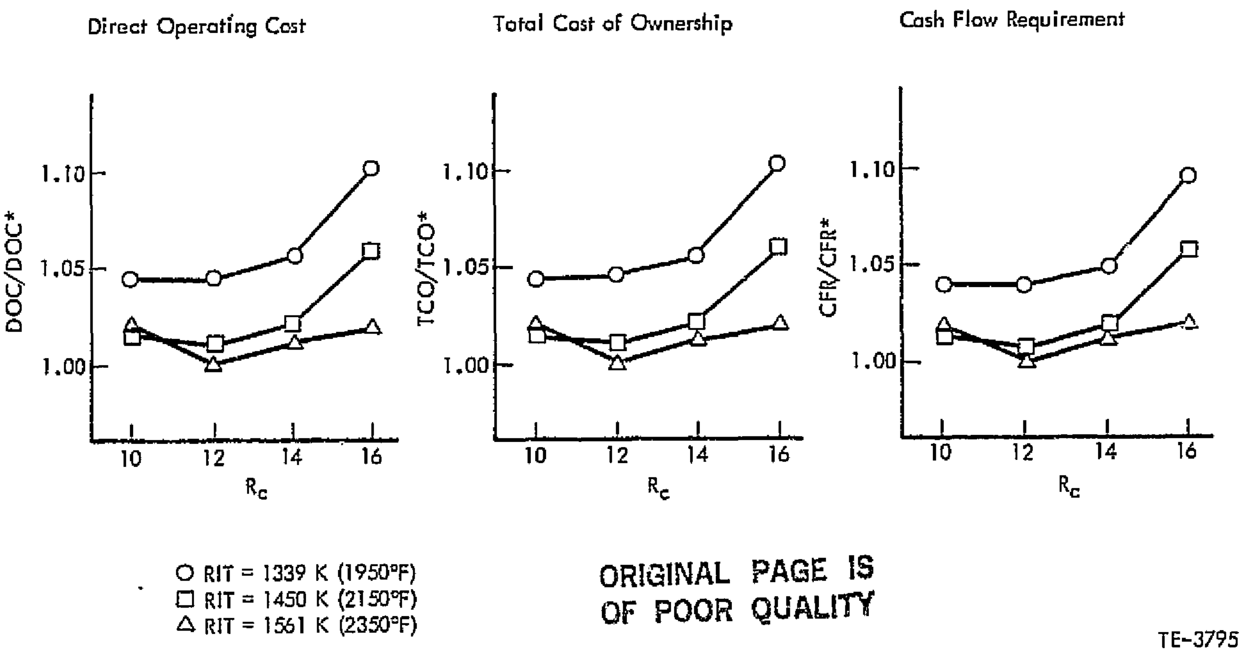

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Figure 38. Dual-stage centrifugal compressor engine matrix--direct operating cost, total cost of ownership, and cash flow requirement trends (unpressurized twin).

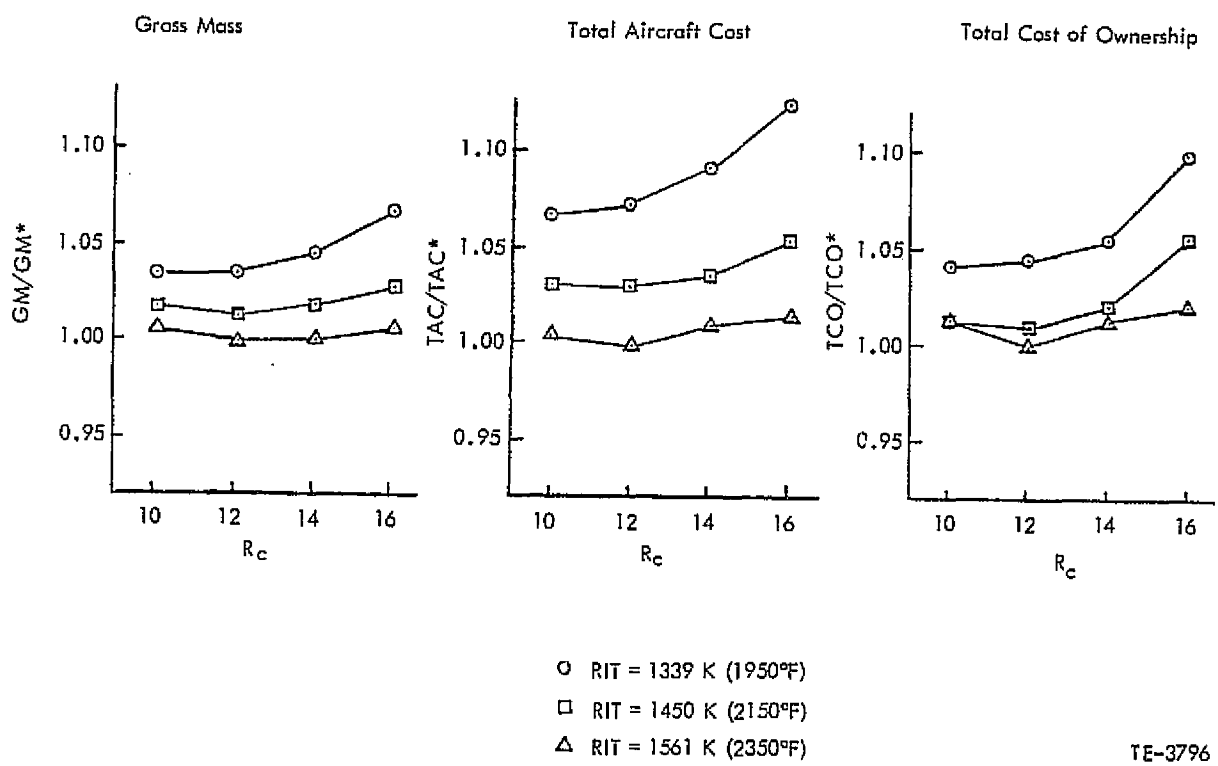

Figure 39. Dual-stage centrifugal compressor engine matrix--gross mass, total aircraft cost, and total cost of ownership trends (light twin).

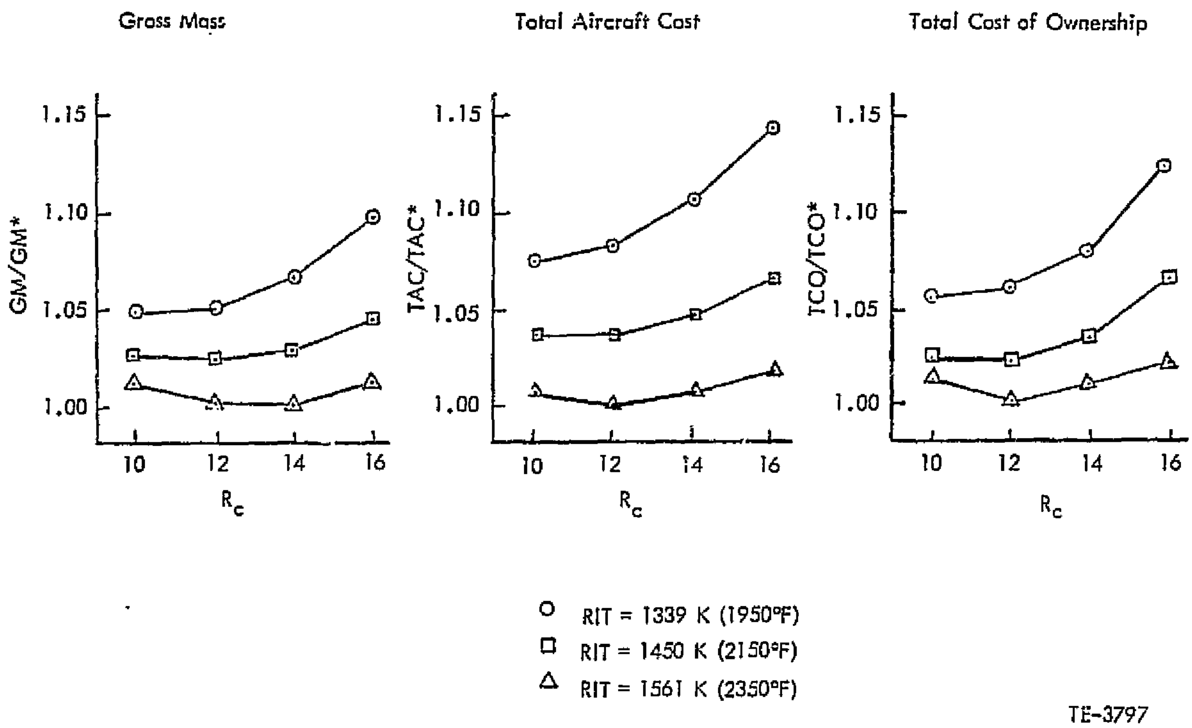

Figure 40. Dual-stage centrifugal compressor engine matrix--gross mass, total aircraft cost, and total cost of ownership trends (heavy twin).

The results for the two rotary-wing applications are presented in the same format as the fixed-wing trends. Figure 42 shows the results for the light single-engine helicopter, and Figure 43 the light twin-engine helicopter. Both applications indicate a preference for high RIT and, except for the TCO, exhibit a relatively flat trend for the range of R_c values evaluated. With respect to the TCO, the influence of engine maintenance cost trends is again producing crossovers in the 1450 and 1561 K (2150 and 2350°F) RIT results.

A summary of the cycle selections from the preceding trend curves for each vehicle/mission application are shown in Table XXIX. The selection criteria used was either minimum GM and TAC or minimum TCO. All applictions examined prefer 1561 K (2350°F) RIT regardless of the selection criteria used. The fixed wing applications indicate a preference for R_c ranging from 12 to 14, whereas the rotary-wing applications prefer 10 to 14 R_c. The overall optimum selection from the dual-stage centrifugal engine evaluations was determined to be the high pressure ratio (R_c = 14), high turbine inlet temperature cycle because it tended to provide the lowest gross weight and total aircraft cost at little compromise in total cost of ownership.

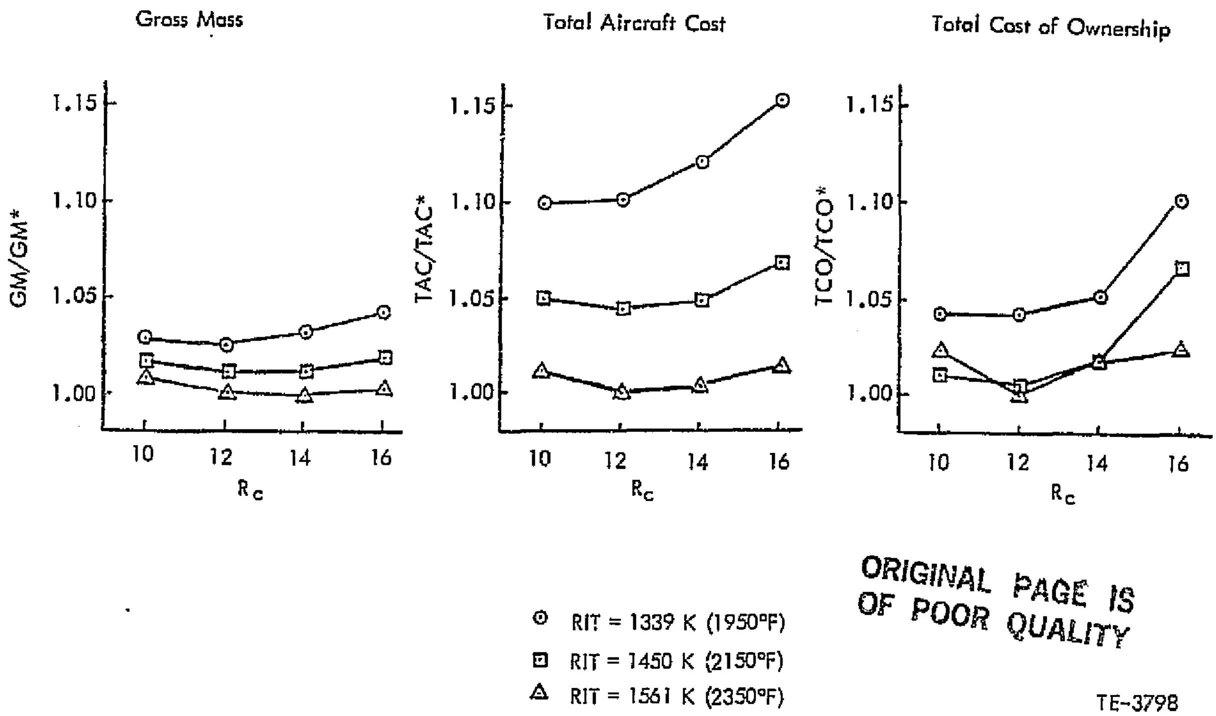

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Figure 41. Dual-stage centrifugal compressor engine matrix--gross mass, total aircraft cost, and total cost of ownership trends (light agricultural).

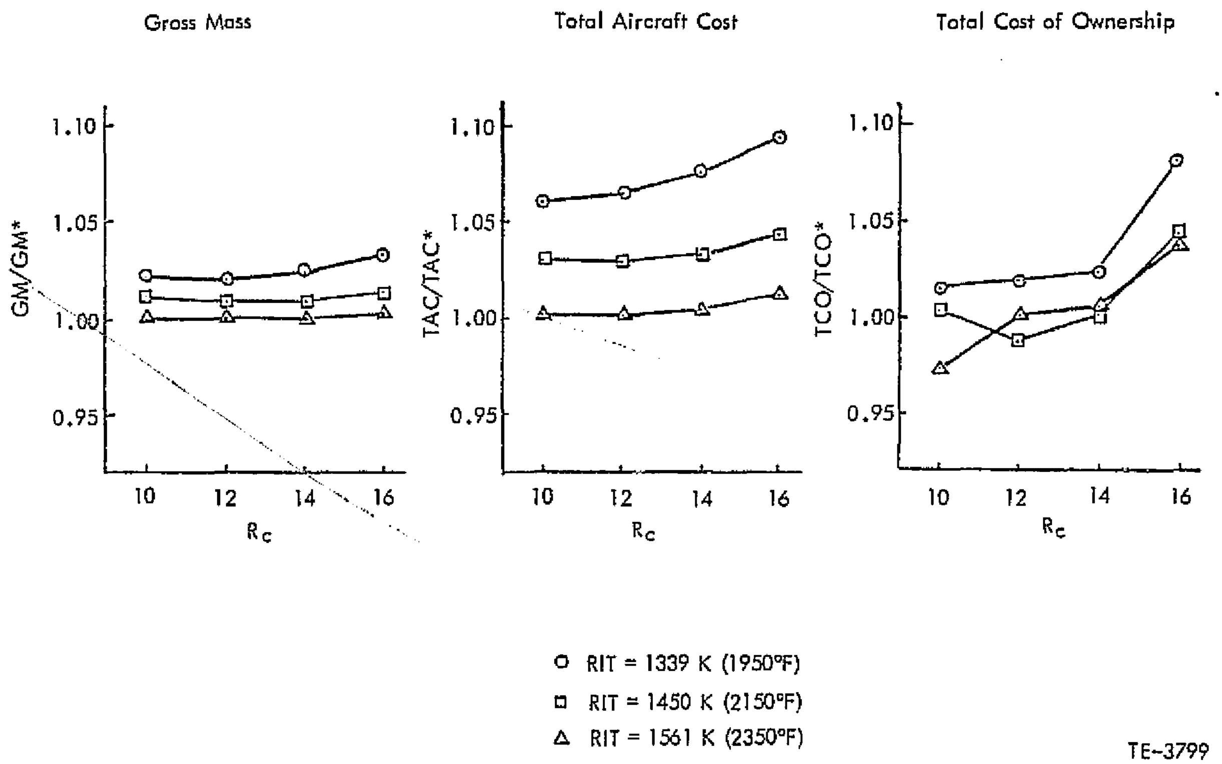

Figure 42. Dual-stage centrifugal compressor engine matrix--gross mass, total aircraft cost, and total cost of ownership trends (helicopter-light single).

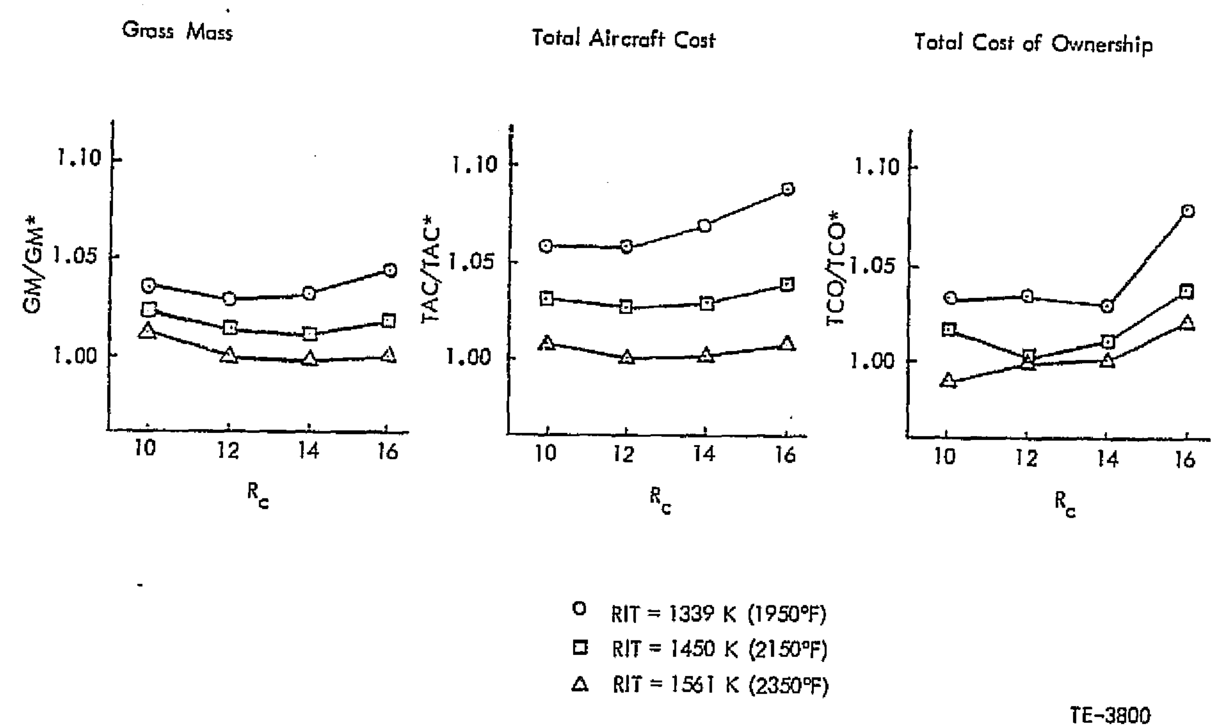

Figure 43. Dual-stage compressor engine matrix--gross mass, total aircraft cost, and total cost of ownership (helicopter-light twin).

TABLE XXIX. - SUMMARY OF CYCLE SELECTIONS

	Lowest GM and TAC selection		Lowest TCO selection	
	R_c	RIT, K (°F)	R_c	RIT, K (°F)
Fixed wing				
Unpressurized twin	12-14	1561(2350)	12	1561(2350)
Light twin	12-14	1561(2350)	12	1561(2350)
Heavy twin	12-14	1561(2350)	12	1561(2350)
Light agricultural	12-14	1561(2350)	12	1561(2350)
Rotary wing				
Light single	10-14	1561(2350)	10	1561(2350)
Light twin	12-14	1561(2350)	10	1561(2350)

Table XXX shows a GM comparison for a CTE versus ATE. The current technology engine has a single-stage centrifugal compressor (R_c = 8.5) with a relatively low RIT, whereas the advanced technology engine incorporates a dual-stage centrifugal compressor (R_c=14) with high RIT. The GM comparison in Table XXX lists the magnitude of the mass increase obtained if a CTE is used instead of an ATE in each of the fixed- and rotary-wing applications. It is noted that the heavy twin produces the largest mass advantage for the ATE, i.e., the most stringent requirement in cruise altitude, velocity, range, and payload indicates the largest payoff for the ATE. Table XXX also lists the ATE sea level-rated power sizes for each of the applications. Using data provided in Table XXX, three of the six vehicle/mission applications were selected for the remaining engine studies. The selected vehicle/missions and reasons for their selection follow:

- Unpressurized twin--This application shows the largest fixed-wing aircraft GM advantage for the ATE (compared to the CTE) in the 450 kW (600 hp)/and under non-flat-rated engine size.
- Pressurized twin (heavy)--This application indicates the largest GM advantage for the turboprop ATE.
- Light twin helicopter--This application shows the largest GM advantage for the turboshaft ATE.

The selected missions are denoted in Table XXX by an asterisk.

TABLE XXX. - CURRENT TECHNOLOGY ENGINES VERSUS ADVANCED TECHNOLOGY ENGINES GROSS MASS COMPARISON

	GM, % (ATE base)	ATE sea level-rated kW(hp) (flat rated)
Fixed wing		
Unpressurized twin*	+14	365(490)
Light twin	+18	410 (550)
Heavy twin*	+31	753 (1010)
Light agricultural	+7	507(680)
Rotary wing		
Light single	+8	276(370)
Light twin*	+14	283(380)

*Mission selected for further studies.

Mission Evaluation of Single Stage

The single-stage centrifugal engines (10 engine matrix) were evaluated in the selected vehicle/mission application, i.e.. unpressurized twin. heavy twin, and light twin helicopter. The results for the unpressurized twin are shown in Figure 44 as plots of normalized GM and TCO. The GM and TCO results are plotted as a function of:

- R_c for lines of constant RIT.
- RIT for lines representing a high pressure turbine (HPT) configuration for a constant pressure ratio of 10.

The cycle trends shown in Figure 44 indicate a preference for the 1561 K (2350°F) RIT and an R_c of 10. The radial inflow is indicated to be the preferred HPT configuration. The preference indicated for the radial inflow HPT configuration is a result of lower sfcs, acquisition costs, and maintenance costs relative to the one- and two-stage axial HPT. Comparison of the one- and two-stage axial to the radial inflow configurations shows the axial configurations to have 2 to 4% higher sfcs, 5 to 7% higher engine acquisition costs, and 8 to 12% higher engine maintenance costs. The larger advantage for the radial inflow HPT is at 1950°F because sfc and cost improvements are greater than the improvements indicated at 2350°F.

Figure 45 shows the results for the heavy twin and Figure 46 the results for the light twin helicopter. In general, the trends for these two applications are similar to the unpressurized twin. It is noted that the heavy twin provides the largest change in the normalized GM and TCO results (i.e., the sensitivity to changes in design cycle parameters is double that indicated for the light twin helicopter). Cycle selections from the preceding trend curves for each vehicle/mission are listed in Table XXXI under the selection criteria used. The overall optimum selection for the single-stage centrifugal compressor engine configuration was determined to be the 10 R_c, high RIT cycle with a radial inflow HPT.

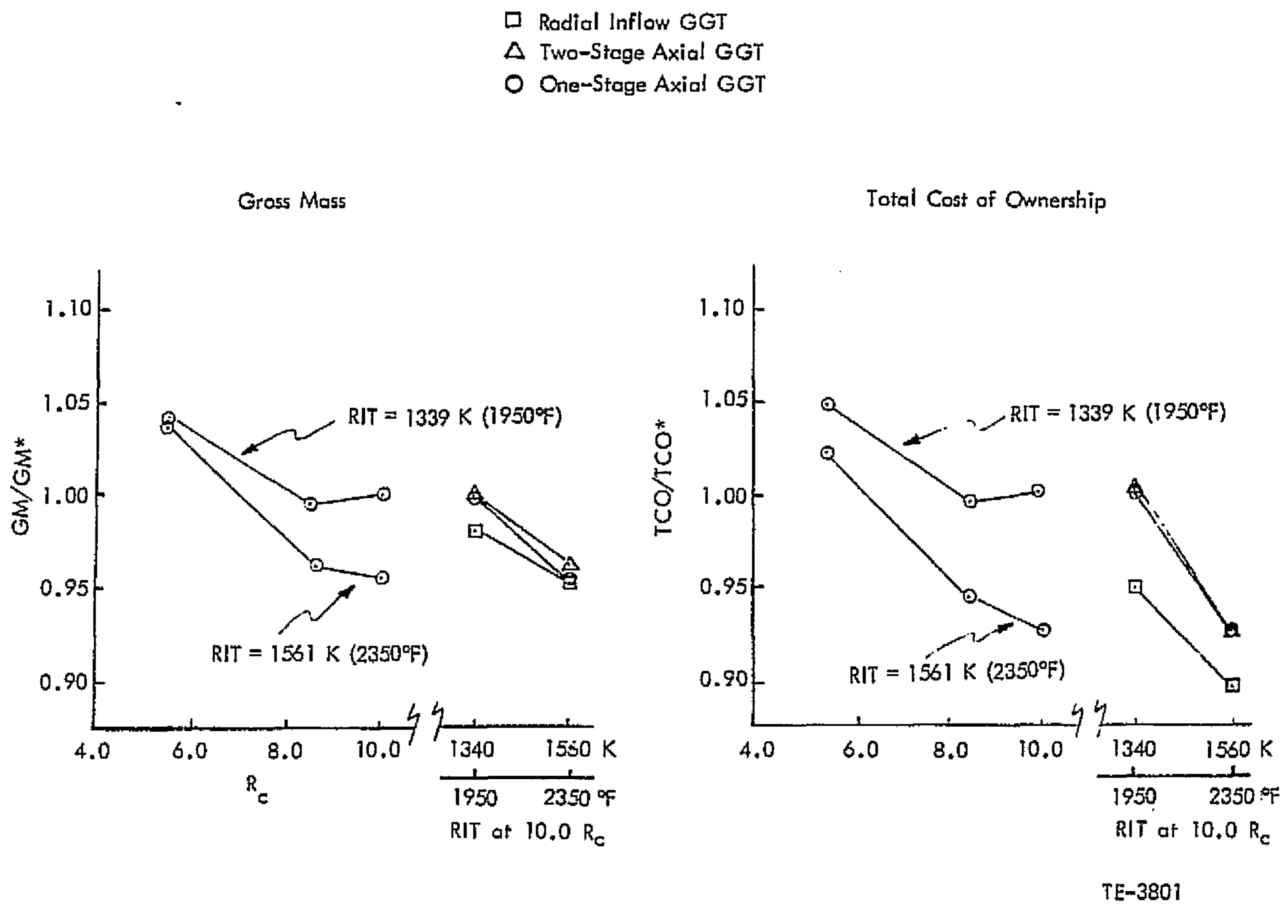

Figure 44. Single-stage centrifugal compressor engine matrix -gross mass and total cost of ownership trends (unpressurized twin).

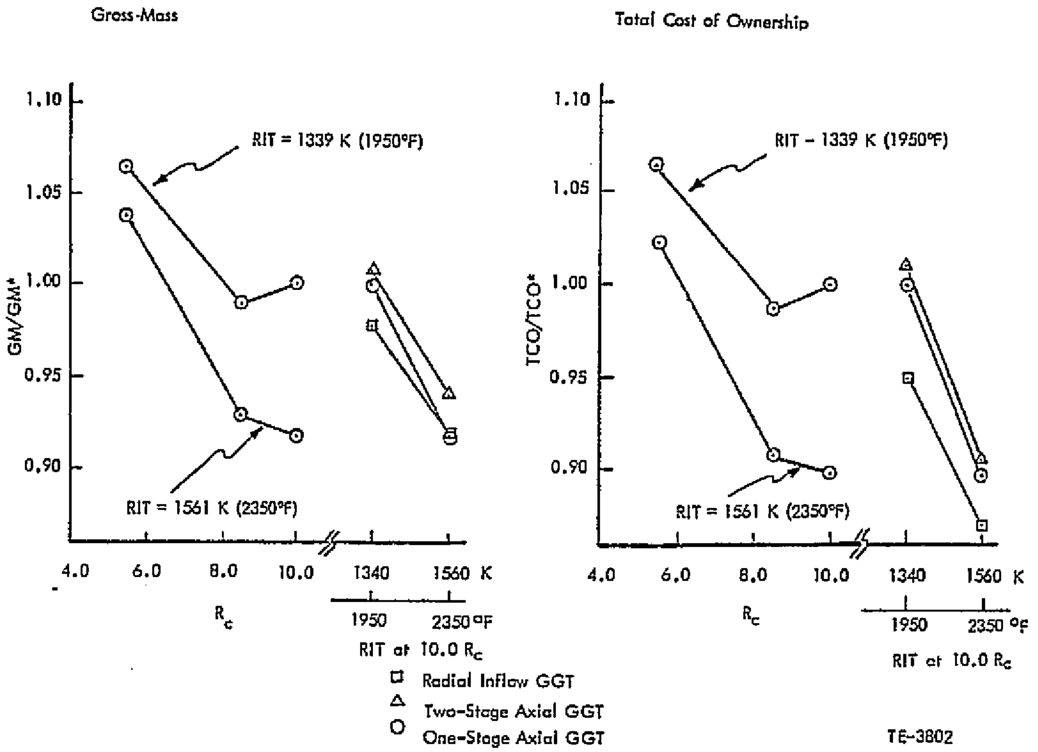

Figure 45. Single-stage centrifugal compressor engine matrix--gross mass and total cost of ownership trends (heavy twin).

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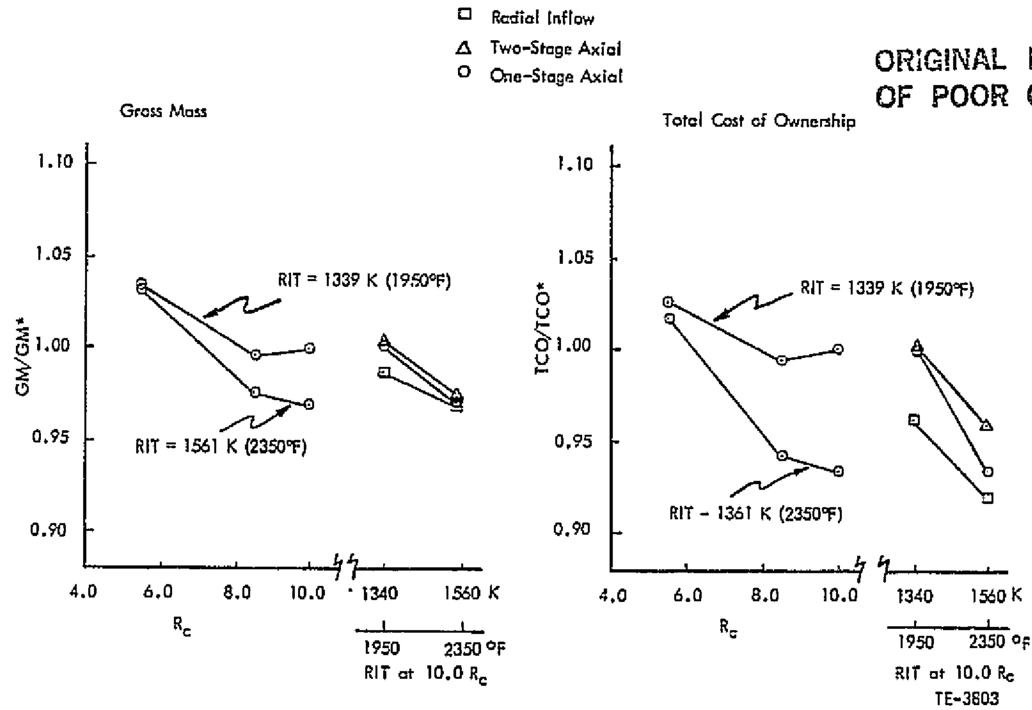

Figure 46. Single-stage centrifugal compressor engine matrix--gross mass and total cost of ownership trends (helicopter-light twin).

TABLE XXXI. - CYCLE SELECTION ONE-STAGE CENTRIFUGAL COMPRESSOR MATRIX						
	Lowest GM & TAC selection			Lowest TCO selection		
Fixed wing	R_c	RIT, K(°F)	GGT Configuration	R_c	RIT, K(°F)	GGT Configuration
Unpressurized twin	10	1561(2350)	R OR 1-A (1)	10	1561(2350)	R
Heavy twin	10	1561(2350)	R OR 1-A	10	1561(2350)	R
Rotary wing						
Light twin	10	1561(2350)	R OR 1-A	10	1561(2350)	R

(1) Gas generator turbine configuration
R = Radial inflow GGT
1-A = One-stage axial GGT

Candidate Engines

Five candidate engines (Nos. 26 through 30. Table XVI—SI units and Table XVII—customary units) were selected for the final phase of the mission trade-off studies. 373 kW (500 hp) shaft power was selected as the design size for these engines. The shaft power size was chosen in recognition of the market potential near this power level and in order to focus on a high performance engine design in a significantly smaller power class than is currently available or under development.

Performance, mass, dimensions, price and maintenance costs were estimated for the use as input in the mission trade off studies. Estimation procedures were similar to those described earlier for the matrix engine estimates.

Tables XVI and XVII list the configuration type, estimated design point performance, mass, dimensions, price, reliability, and maintenance costs for both the turboshaft and turboprop versions of these five candidate engines.

It is noted that the TCO and DOC values quoted in the candidate engine comparisons are for a fuel cost of $0.22/1 ($ 0.83/gal) and utilization rate of 600 hr/yr for the fixed wing applications and 360 hr/yr for the rotary wing application. The period of ownership is 8 years for both fixed and rotary wing (reference Table XII).

Engine Component Comparisons

These five candidate engines provide a basis for the following engine components comparisons:

1.	Axial versus radial inflow HPT configuration selection for the single stage Centrifugal Compressor engine (Design RIT = 1478 K (2200°F))	Engine Nos. 26 versus 27 versus 28
2.	Cooled versus uncooled one-stage axial HPT Selection for the single-stage compressor	Engine Nos. 26 versus 29
3.	Single-stage versus dual-stage centrifugal compressors for the dual-stge axial LPT and HPT engines	Engine Nos. 27 versus 30

- Comparison 1 Axial versus Radial Inflow HPT

The results of a single-stage axial, a two-stage axial, and a single-stage radial inflow HPT engine evaluation in the unpressurized twin are shown in Table XXXII (i.e. candidate engine 26 versus 27 versus 28). The results are shown as persent changes in GM, TAC, and TCO with the one-stage axial HPT configuration (26) as the reference. This table indicates the two-stage axial HPT configuration (27) to be slightly heavier in GM (0.2 to 1.0%) and from 1 to 2% higher in TAC and TCO. The one-stage radial inflow HPT (28) results indicate a 0.5 to 2% reduction in GM and a 2 to 4% reduction in TAC and TCO when compared with the one-stage axial HPT engine (26). Therefore, the one-stage radial inflow HPT configuration (28) is preferred over the one or two-stage axial turbines (26 and 27) in this comparison.

TABLE XXXII. - AXIAL VERSUS RADIAL INFLOW HPT CONFIGURATION STUDY RESULTS
(percent change from one-stage axial HPT engine 26)

Mission	Heavy twin		Unpressurized twin		Light twin helicopter	
Engine ID	27	28	27	28	27	28
HPT configuration	2-A	1-R	2-A	1-R	2-A	1-R
GM, %	+1.0	-0.5	+0.4	-2.2	+0.2	-2.2
TAC, %	+2.0	-1.6	+1.5	-4.1	+0.9	-3.3
TCO, %	+1.8	-2.2	+1.3	-4.6	+0.8	-4.0

- Comparison 2 Cooled versus Uncooled HPT

An evaluation of a cooled versus uncooled HPT engine configuration (i.e., candidate engine 26 versus 29). Both engines have a single-stage centrifugal compressor with a design R_c of 10, a one-stage axial HPT, and a two-stage axial low-pressure turbine (LPT). Engine 26 has a design RIT of 1478 K (2200°F) (cooled) versus engine 29, which has a design RIT of 1339 K (1950°F) (uncooled). The results of this comparison are shown in Table XXXIII as percent changes in GM, TAC, and TCO, with engine 26 as the reference and indicate a preference for the cooled HPT turbine (26). Although the engine with an uncooled HPT (29) is competitive in the heavy twin, it is shown to be from 2 to 3% higher in GM, 5% higher in TAC, and 4 to 5% higher in TCO for the unpressurized twin and light twin helicopter, respectively.

Engine 29 becomes competitive in the heavy twin because the constant bleed air extraction, 0.045 kg/s (0.1 lbm/sec), produces a relative performance improvement for engine 29 when going from the unpressurized twin sizing/cruise altitude and Mach 3657.6 m/0.35 M_n (12,000 ft/0.35 M_n) to the heavy twin condition 9144 m/0.50 M_n (30,000 ft/0.50 M_n). The unity size maximum cruise power TSFC for 29 at 3657.6 m/0.35 M_n (12,000 ft/0.35 M_n) is approximately 0.5% higher than 26, however, at 9144 m/0.50 M_n (30,000 ft/0.5 M_n) the TSFC for engine 29 is approximately 2.5% lower than engine 26. Further discussion of the design trades involved in choosing a cooled or uncooled turbine is provided in the Technology Element Section.

TABLE XXXIII - COOLED VERSUS UNCOOLED TURBINE STUDY RESULTS
(Percent change from cooled HPT engine configuration 26)

Mission	Heavy twin	Unpressurized twin	Light twin helicopter
Engine ID	29	29	29
GM, %	-0.1	+2.3	+2.8
TAC, %	0	+5.0	+5.3
TCO, %	-0.2	+4.6	+4.8

- Comparison 3 Single-Stage versus Dual-Stage Centrifugal Compressor

An evaluation of a single-stage versus a dual-stage compressor engine can be made by comparison of configurations 27 and 30, respectively. The single-stage has a design R_c of 10 whereas the dual stage has an R_c of 14. Both engines have two-stage LPT and HPT and design RIT of 1478 K (2200°F). The results of this comparison are shown in Table XXXIV as percent changes in GM, TAC, and TCO with engine 30 as the reference.

TABLE XXXIV. - SINGLE-STAGE VERSUS DUAL-STAGE CENTRIFUGAL COMPRESSOR STUDY RESULTS
(Percent change from dual-stage compressor engine 30)

Mission	Heavy twin	Unpressurized twin	Light twin helicopter
Engine ID	27	27	27
Compr. Configuration	one-stage	one-stage	one-stage
GM, %	+18.9	+7.6	+2.7
TAC, %	+22.7	+11.0	+1.5
TCO, %	+24.1	+12.6	+2.5

The results in Table XXXIV indicate a preference for the dual-stage centrifugal compressor (30) for all aircraft configurations. Even though GM, TAC, and TCO were only slightly greater (from 1.5 to 2.7%) for the light twin helicopter, they progressed to 7.6-12.6% for the unpressurized twin and to 18.9-24.1% for the heavy twin.

Candidate Engine Comparison

A summary comparison can be made for these five candidate engines to indicate the best selection for each aircraft application. Normalized GM and TCO results for each of the four single-stage centrifugal compressor (R_c = 10) engines plus one dual-stage centrifugal compressor (R_c = 14) engine are shown in Figures 47 through 52. Figures 47 and 48 show the results for the unpressurized twin, Figures 49 and 50 show results for the heavy twin, and Figures 51 and 52 the results for the light twin helicopter application. Figures 47 through 50 indicate the dual-stage centrifugal candidate engine 30 to be the optium selection and the single-stage centrifugal candidate engine 28 to be the "next best" in the fixed-wing applications. Figures 51 and 52 indicate candidate engine 28 to be the optium selection and engine 30 to be a close "next best" in the light twin helicopter.

Engine 28 performed better than 30 in the twin helicopter because no bleed air was provided by the engines, whereas, in the fixed wing applications, bleed air was extracted from the engines. As a result, installed performance for engine 30 was better than 28 in the fixed wing vehicles; however, without bleed extraction, the performance of engine 28 was calculated to be approximately equal to that of engine 30.

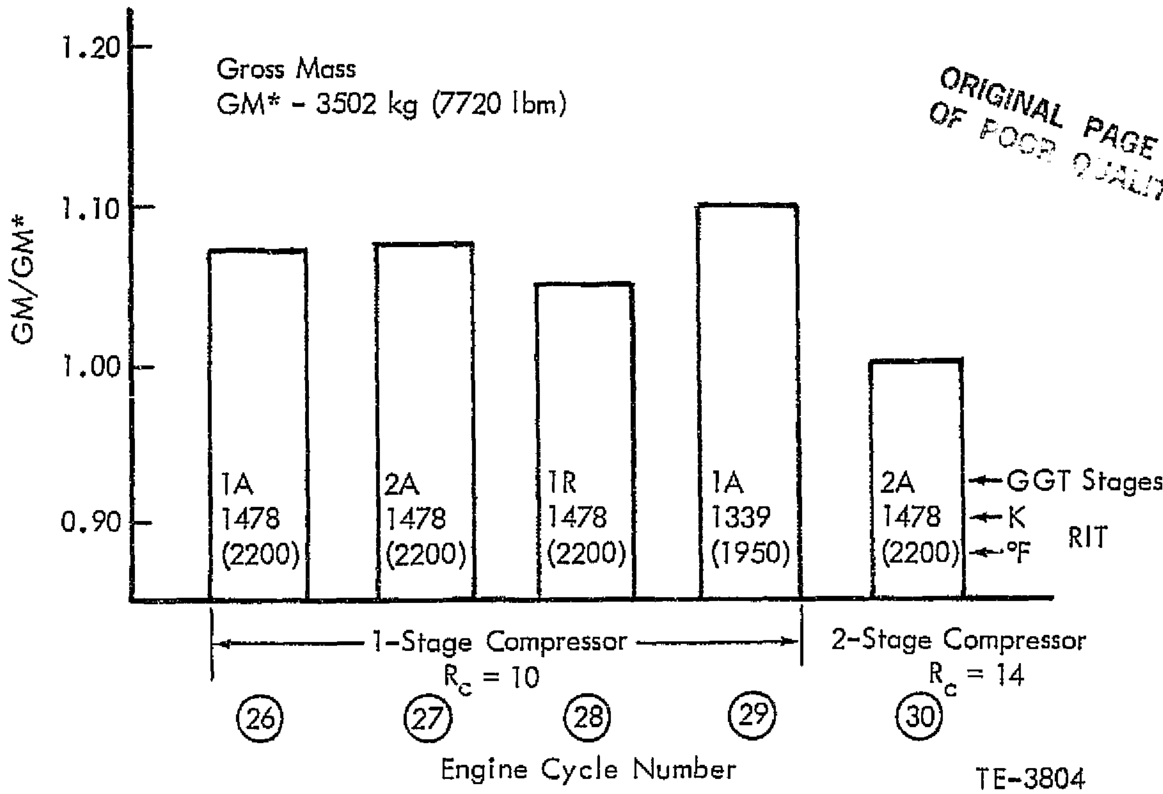

Figure 47. GATE candidate engines-gross mass trends (unpressurized twin).

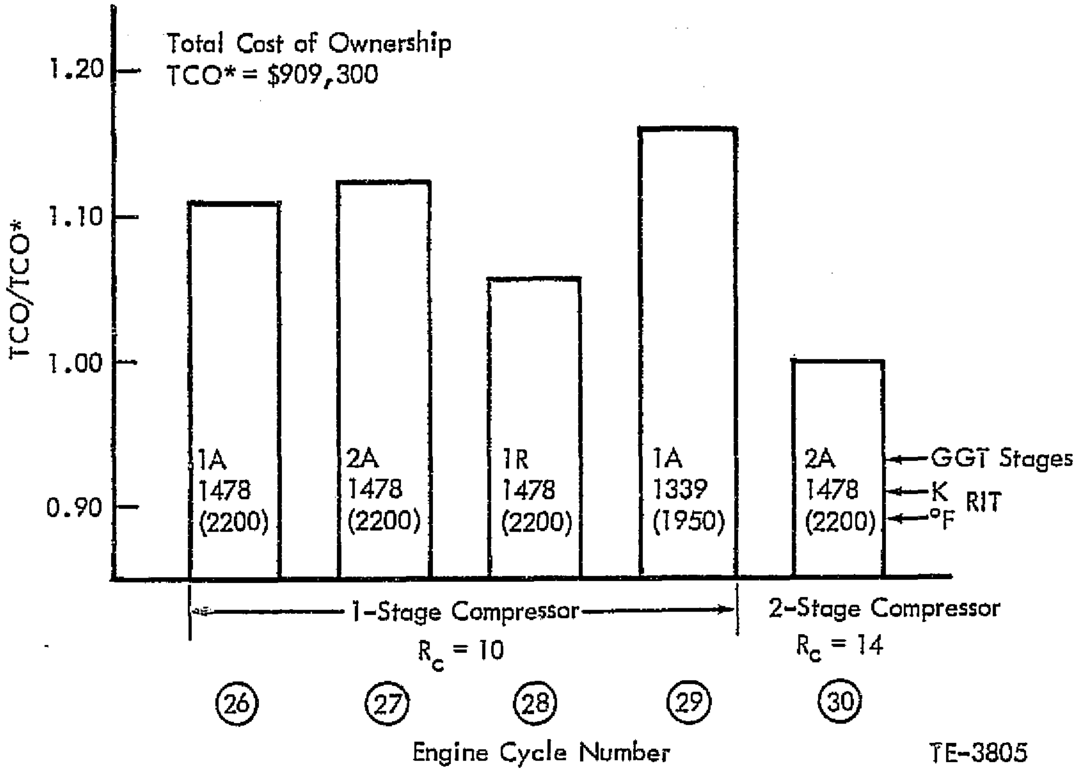

Figure 48. GATE candidate engine--total cost of ownership trends (unpressurized twin).

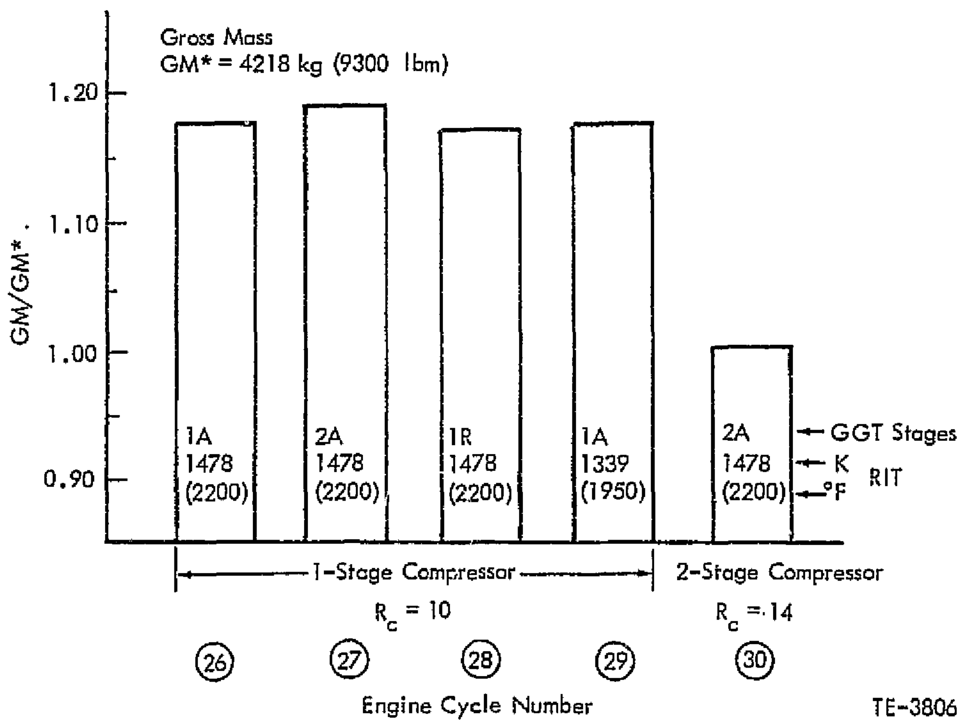

Figure 49. GATE candidate engines-gross mass trends (heavy twin).

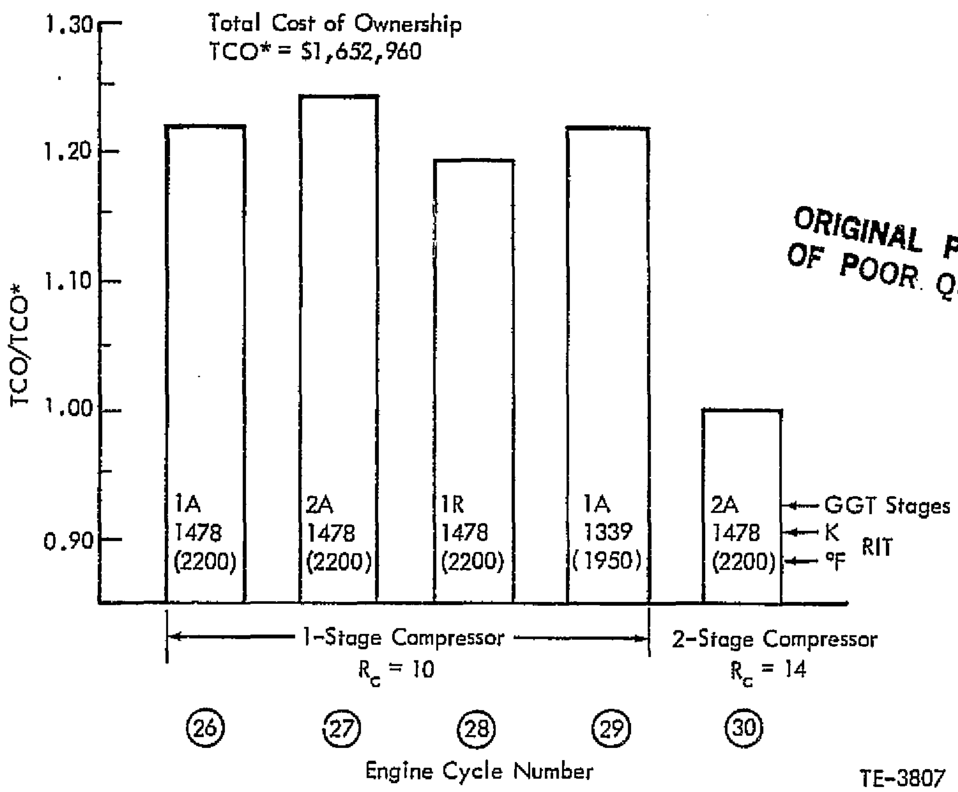

Figure 50. GATE candidate engines-total cost of ownership trends (heavy twin).

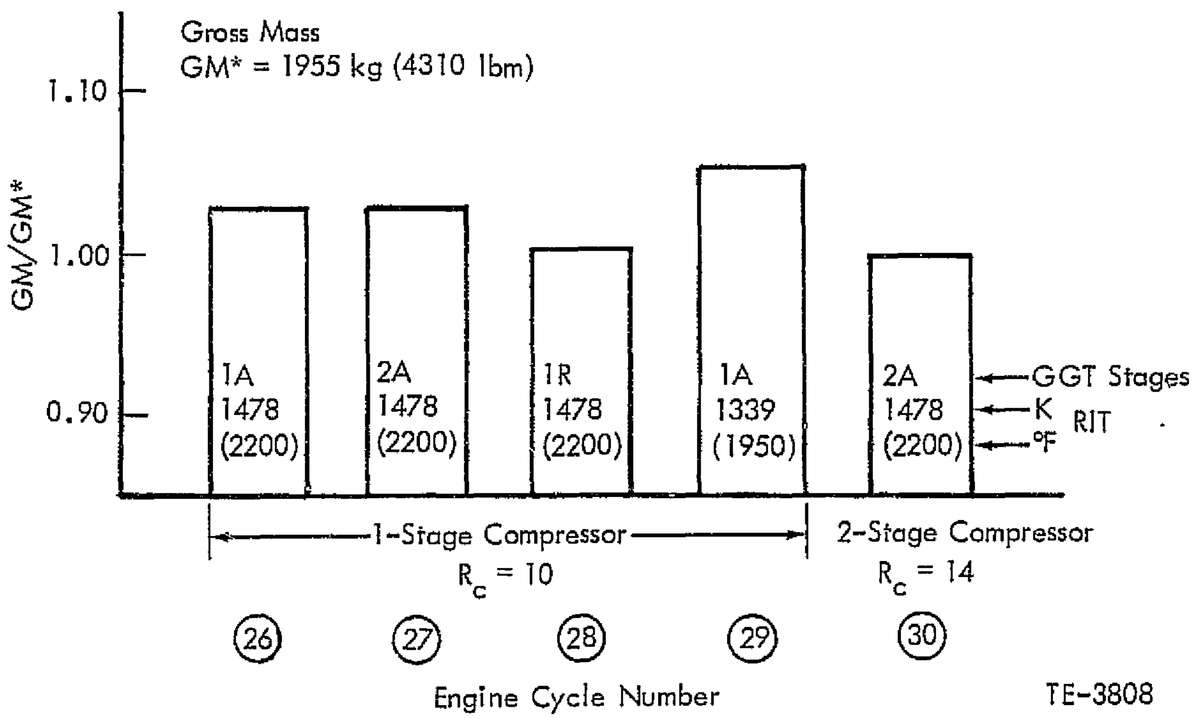

Figure 51. GATE candidate engines-gross mass trends (helicopter-light twin).

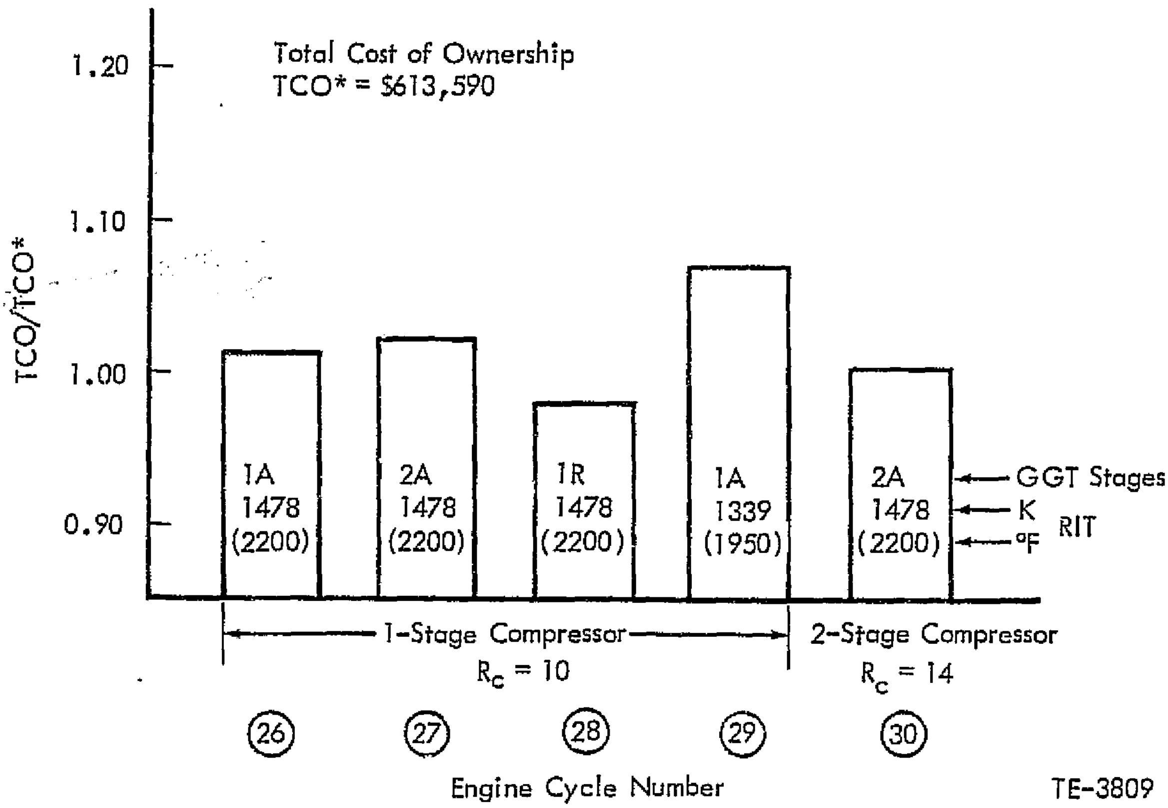

Figure 52. GATE candidate engines-total cost of ownership trends (helicopter-light twin).

Table XXXV shows the effect of bleed and power extraction on shaft specific fuel consumption (sfc) for engine cycles 28 and 30.

TABLE XXXV. - INSTALLATION EFFECT ON SHAFT SPECIFIC FUEL CONSUMPTION (Unity size engine)

Cycle	28			30		
Power Ext, kW (hp)	0(0)	2.98(4)	2.98(4)	0(0)	2.98(4)	2.98(4)
Bleed--(lbm/sec)	0(0)	0(0)	0.045(0.1)	0(0)	0(0)	0.045(0.1)
sfc @ slss T.O.P.	0.486	0.492	0.529	0.488	0.491	0.509
Bleed, % of $W_{a_{TOT}}$	0	0	3.8	0	0	3.3

At slss/takeoff power setting, with zero bleed, engines 28 and 30 sfc values are essentially the same. When 0.045 kg/s (0.1 lbm/sec) bleed is extracted, the sfc for engine 30 is shown to be 4% lower than that of engine 28. (Note that bleed, when expressed as a percent of engine airflow, is 3.8% for 28 and 3.3% for 30.)

It is noted that bleed air for the 10:1 engine (28) was extracted at compressor discharge and interstage for the 14:1 engine (30). The performance of 28 could probably be improved by bleeding the diffuser at a lower pressure than compressor discharge.

ATE Versus CTE Study Results

A comparison of the engine characteristics for the GATE-selected engines (28 and 30) versus two versions of a current technology engine (with and without production base) are shown in Table XXXVI and Table XXXVII. Table XXXVI shows the turboprop characteristics and Table XXXVII the turboshaft. Note that the asterisk indicates the no production base CTE. Figures 53 and 54 show the relative GM and TCO results in bar chart form for each engine and mission application examined. Relative DOC, TAC, and fuel are also shown in Figures 55, 56, and 57. Figure 53 indicates significant GM advantages for both engines 28 and 30 in all three mission applications. The reductions in gross mass are summarized in Table XXXVIII.

TABLE XXXVI. - ENGINE COMPARISONS (TURBOPROP)

Identification	28	30		
Technology	ATE	ATE	CTE*	CTE
Type of compressor	1-C	2-C	1-C	10C
Type of GP turbine	1-R	2-A	2-A	2-A
Compressor pressure ratio	10	14	8.5	8.5
GP rotor inlet temp, K(°F)	1478(2200)	1478(2200)	1316(1910)	1316(1910)
Air-cooled GP turbine	1-R	2-A	none	none
Shaft power, slss, kW(hp)	373(500)	373(500)	373(500)	373(500)
sfc, μg/W·s (lbm/hp·h)	82.0(0.485)	82.3(0.487)	103(0.61)	103(0.61)
Mass, kg(lbm)	79.4(175)	81.2(179)	105(232)	105(232)
OEM price, 1978 $	70714	76401	73910	64709
Specific mass, g/W(lbm/hp)	0.21(0.35)	0.218(0.358)	0.282(0.463)	0.282(0.463)
OEM specific price, $/kW($/hp)	190(142)	205(153)	198(148)	173(129)
Maintenance cost (50 hr/mo util), $ fl/h	17.26	18.64	28.73	25.16
TBO, h	5000	5000	1500	1500

TABLE XXXVII. - ENGINE COMPARISONS (TURBOSHAFT)

Identification	28	30		
Technology	ATE	ATE	CTE*	CTE
Type of compressor	1-C	2-C	1-C	1-C
Type of GP turbine	1-R	2-A	2-A	2-A
Compressor pressure ratio	10	14	8.5	8.5
GP rotor inlet temp, K(°F)	1478(2200)	1478(2200)	1316(1910)	1316(1910)
Air-cooled GP turbine	1-R	2-A	none	none
Shaft power slss, kW(hp)	373(500)	373(500)	373(500)	373(500)
Airflow, kg/s (lbm.sec)	1.27(2.79)	1.40(3.09)	--	--
sfc, μg/W·s(lbm/hp·h)	82.0(0.485)	82.3(0.487)	103(0.61)	103(0.61)
Mass, kg (lbm)	65.8(145)	67.1(148)	86.6(191)	86.6(191)
OEM price, 1978 $	58830	63562	56424	49399
Specific mass, g/W(lbm/hp)	0.176(0.290)	0.180(0.296)	0.232(0.382)	0.232(0.382)
OEM specific price, $/kW($/hp)	158(118)	170(127)	152(113)	133(99)
Maintenance cost (30hr/mo util) $/fl h	17.42	18.81	26.67	23.37
TBO, h	5000	5000	1500	1500

TABLE XXXVIII. - PERCENT GM REDUCTION (CTE as reference gross mass)		
Engine ID	28	30
Heavy twin	8	21
Unpressurized twin	7	11
Light twin helicopter	12	12

Figure 53 also indicates the preference for the dual-stage centrifugal engine (30) over the single-stage centrifugal engine (28) in both fixed-wing missions. The twin helicopter mission results show both 28 and 30 at the same GM.

Figure 54 indicates significantly lower TCO results for both engine 28 and 30 in all three missions applications. The TCO reductions are summarized in Table XXXIX.

TABLE XXXIX. - PERCENT TCO REDUCTION (CTE with production base as reference)		
Engine ID	28	30
Heavy twin	4	20
Unpressurized twin	5	11
Light twin helicopter	8	6

Figure 54 also indicates a greater TCO advantage for the dual-stage centrifugal engine configuration (30) in the fixed-wing missions. The twin helicopter results indicate the single-stage centrifugal engine (28) to have a TCO approximately 2.5% lower than the dual-stage centrifugal engine.

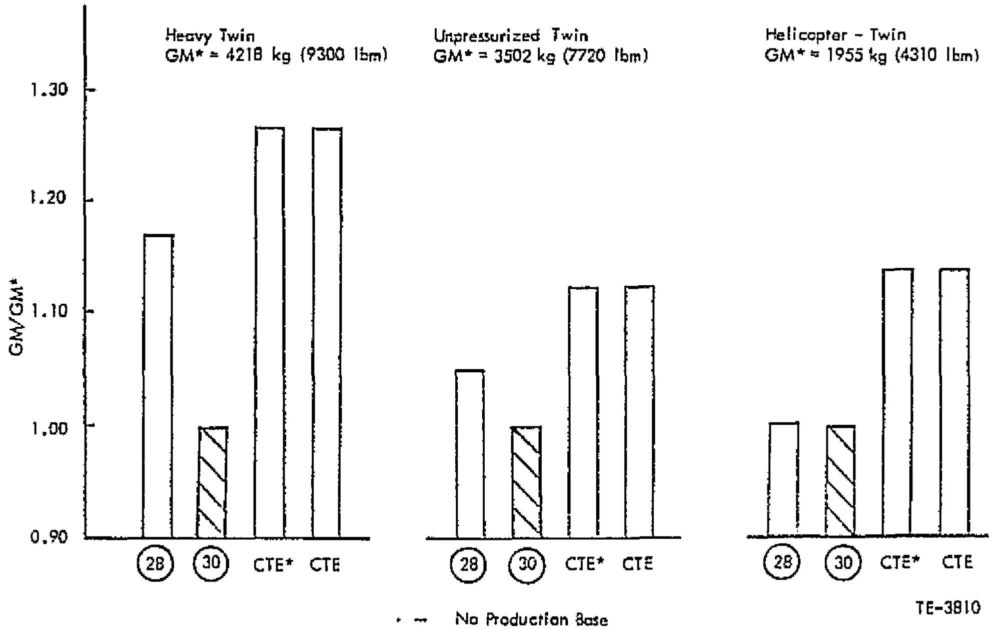

Figure 53. Gross mass comparison--best advanced technology engines versus current technology engines.

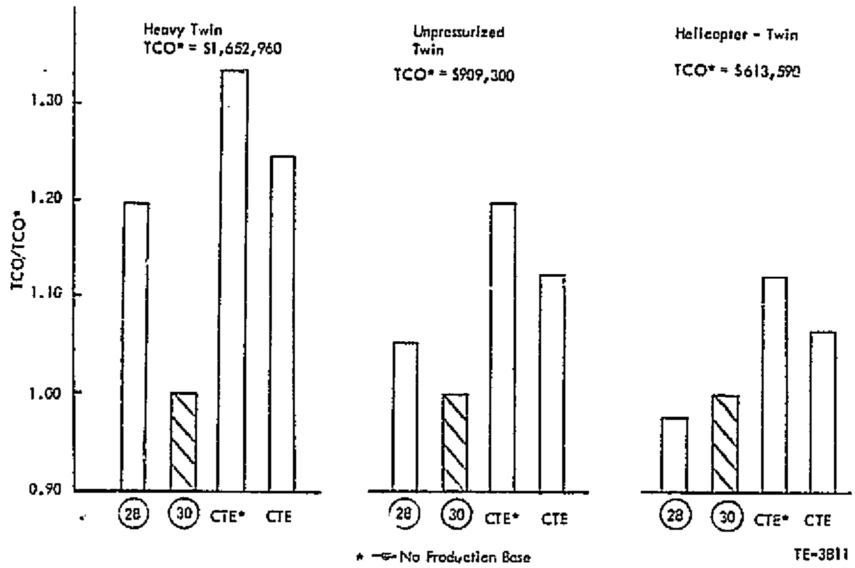

Figure 54. Total cost of ownership comparison--best advanced technology engines versus current technology engines.

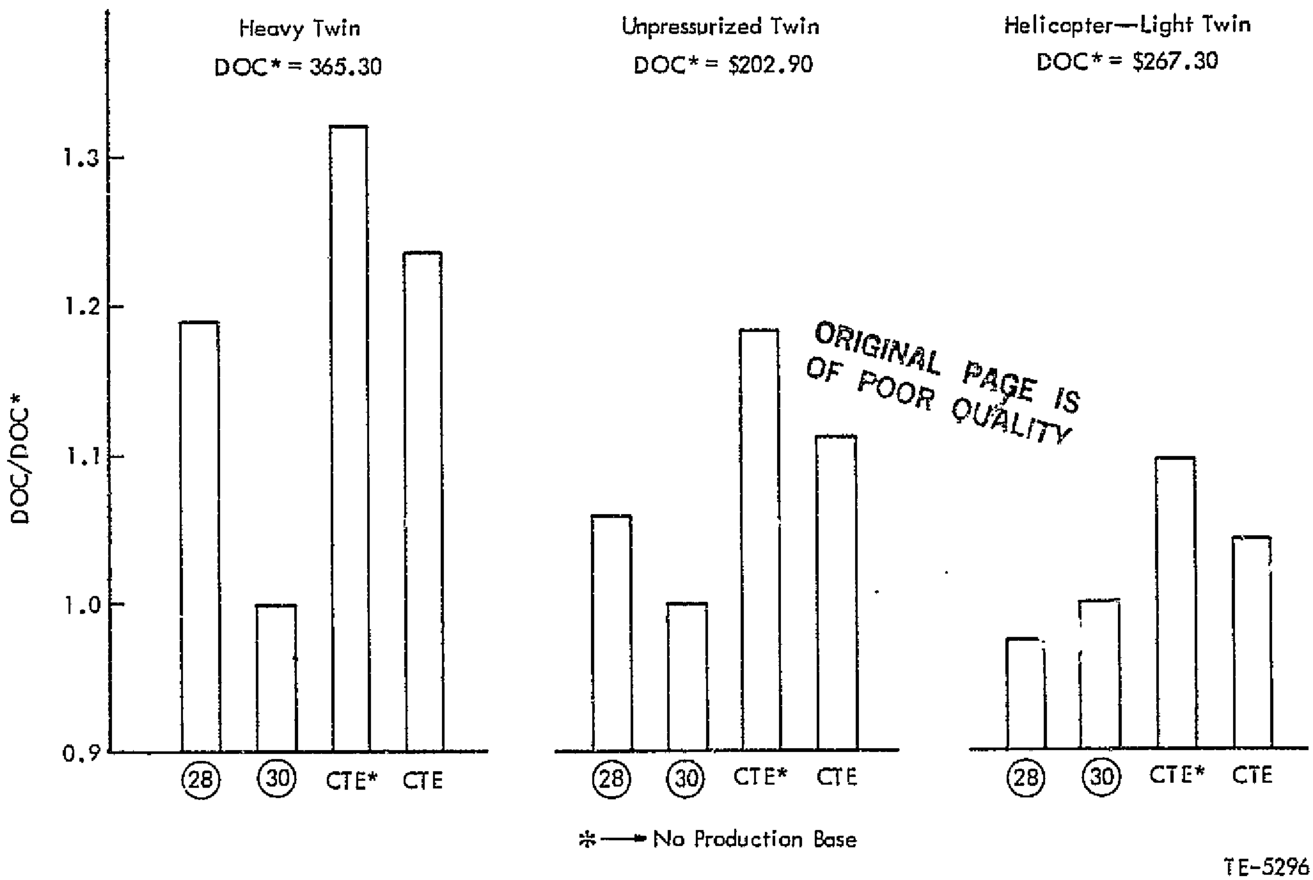

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Figure 55. Direct operating cost comparison--best advanced technology engines versus current technology engines.

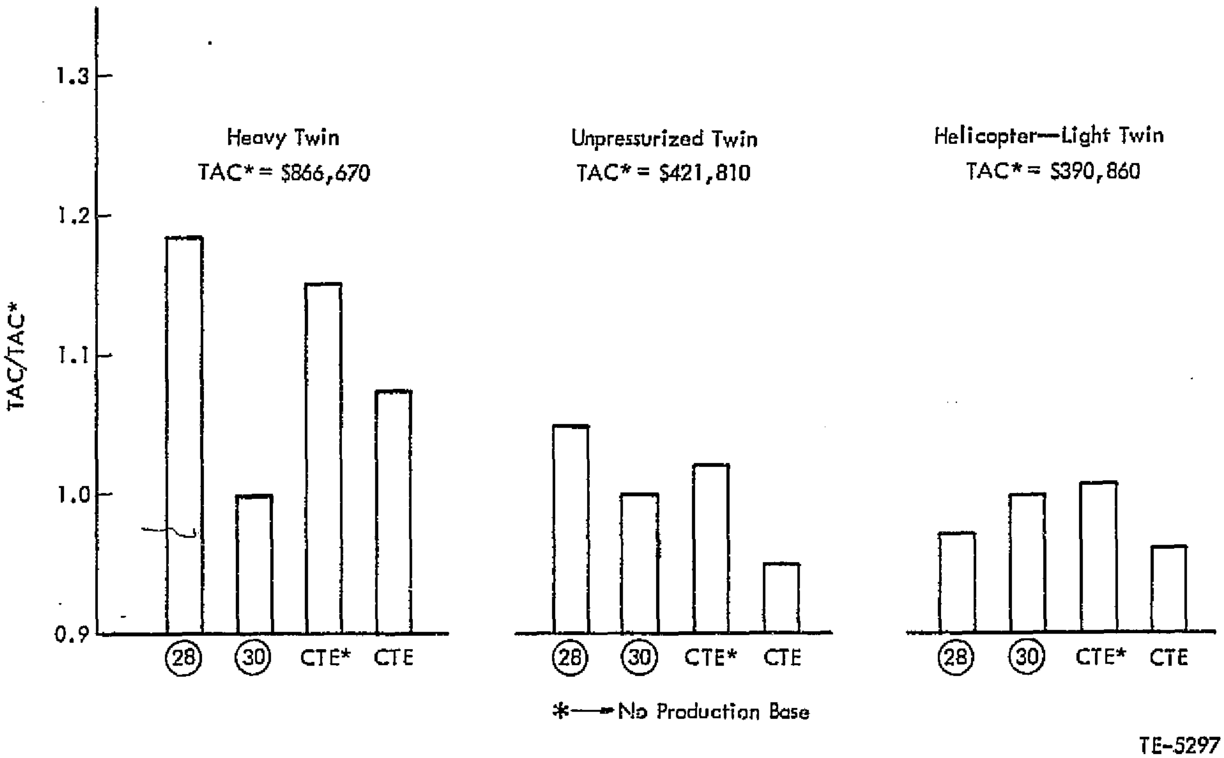

Figure 56. Total aircraft cost comparison—best advanced technology engines versus current technology engines.

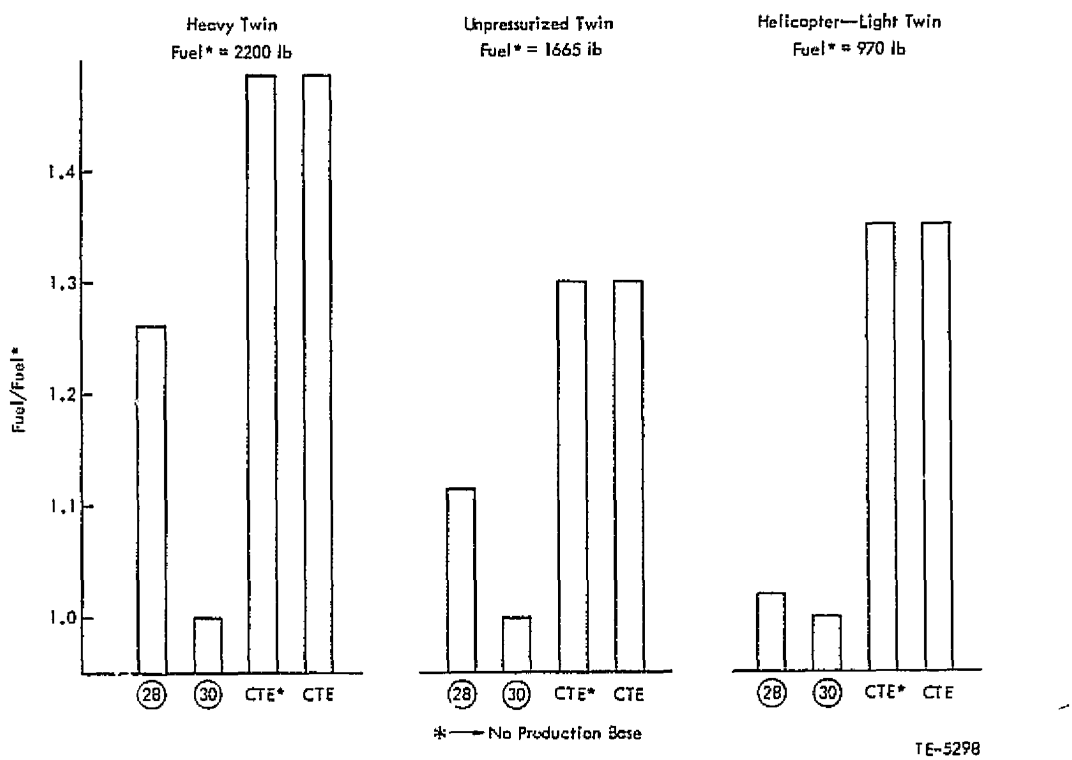

Figure 57. Mission fuel comparison—best advanced technology engines versus current technology engines.

The DOC trends shown in Figure 55 essentially duplicate the trends shown by the TCO results in Figure 54. The TAC results shown in Figure 56 indicate the current technology engine with production base to be the least cost selection for the unpressurized twin and the light helicopter applications. However, for the relatively more expensive heavy twin aircraft, the advanced technology dual centrifugal compressor engine is shown to be optimum. Figure 57 indicates the large reduction in mission fuel usage obtained with the advanced technology engines (28 and 30) when compared to the current technology engines in each of the three applications. This trend in higher fuel usage is a significant factor in the higher TCO and DCO levels calculated for the current technology engines.

Tables XL and XLI show a comparison* of a CTE (with and without production base) and a two-stage centrifugal compressor, high pressure ratio, high turbine temperature ATE in the unpressurized twin vehicle mission. These tables are presented in order to illustrate the magnitude of the various cost components calculated in this study.

TABLE XL. - UNPRESSURIZED TWIN SUMMARY
Use = 600 h/yr and fuel = 0.22 $/l (0.83 $/gal)

ENGINE ID	CTE	CTE*	Representative ATE
Gross mass, kg (lbm)	3835(8455)	3835(8455)	3368(7425)
GM, %	(base)	(0)	(-12.2)
Required SL-rated SP, kW(hp)			
● Initial cruise (3.658 km(12,000 ft)/113m/s(220kn)/MCP	400(535)	400(535)	365(490)
● OEI climb (1.524 km(5000ft)/56.6m/s(110kn)/TOP	369(495)	360(495)	328(440)
Cruise (3.658km (12,000ft)/113m/s(220kn)TAS)			
● Fuel rate, l/h (gal/h)	234(61.8)	234(61.8)	177(46.7)
● TSFC/power setting, mg/N·s (lbm/lbf·h)/% MCT	12.2(.43)/86	12.2(.43)/86	10.2(.36)/87
Price, $			
● Airframe	180,870	180,870	160,880
● Engines (2)	202,590	231,400	218,560
Total	383,460	412,270	379,440
* TAC, %	(Base)	(+7.5)	(-1.0)
DOC, $/fl h	215.72	229.64	183.99
DOC, %	(Base)	(+6.4)	(-14.7)
TOC, $	973,940	1,038,500	822,190
TCO, %	(Base)	(+6.6)	(-15.6)

*Denotes no production base.

Table XL shows the significantly reduced fuel rate for the representative ATE resulting from a combination of reduced aircraft size (12% reduction in GM) and the more fuel efficient engine (16% better TSFC's). Comparison of the

*Note: This comparison was completed using the mission/cost results obtained from uninstalled engine performance data, i.e., no customer bleed or power extraction penalties. It is also noted that the ATE engine in this study was an early study engine configuration with respect to performance and cost. Performance was essentially the same. However, the cost numbers are large when compared to the final level of costs for the final candidate ATE engines.

TABLE XLI. - UNPRESSURIZED TWIN SUMMARY— CONTINUED
DOC BREAKDOWN— $/fl h Util = 600 hr/yr and fuel = $0.22/1 ($0.83/gal)

ENGINE BREAKDOWN	CTE A/C	CTE Engine	CTE* A/C	CTE* ENGINE	ATE A/C	ATE ENGINE
Fuel and oil	—	52.34	—	52.34	—	39.58
Insurance	3.02	3.38	3.02	3.85	2.68	3.65
A/C Maintenance	18.16	—	18.16	—	17.47	—
Engine Maintenance	—	52.51	—	59.96	—	35.17
Depreciation	37.68	42.21	37.68	48.21	33.52	45.54
Registration fee	0.52	—	0.52	—	0.47	—
Hangar rental	5.90	—	5.90	—	5.91	
Subtotals	65.28	150.44	65.28	164.36	60.05	123.94
A/C plus eng total	215.72		229.64		183.99	

*Denotes no production base.

production to the no production base CTE shows a 7.5% increase in TAC and an approximate 6.5% increase in DOC and TCO. Comparison of the CTE (with production base) and the ATE shows a 1% reduction in TAC for the ATE. The DOC and TCO comparison shows an approximate 15% reduction for the ATE.

Table XLI shows the aircraft and engine DOC breakdown for the representative ATE and current technology engines. This table shows that 70% of the total DOC is engine oriented. Approximately one-third of the engine-oriented DOC is fuel and oil cost, one-third is maintenance, and one-third depreciation costs. The engine maintenance costs (MC) tabulated in Table XLI are maintenance costs for two engines sized to meet the unpressurized twin requirements.

Turbine Engine versus Piston Engine Trade-Offs

The competitive positions of an advanced turbine engine (Candidate Engine 30) relative to a "typical" current and advanced (1988 technology) naturally aspirated piston (NAP) engine was studied in both the unpressurized twin and light twin helicopter applications.

Table XLII shows the ATE and assumed NAP engine characteristics used in the study. These data indicate significant advantages for the piston engine in both sfc and price along with a large weight disadvantage with respect to the ATE. It is noted that TCO and CFR values could not be calculated in this comparison due to the lack of piston engine maintenance cost. The piston engines were assumed to have a cooling air drag equivalent to 7% of the total aircraft drag and a prop efficiency of 85%. The lower prop efficiency was used because of the thicker blade section required to absorb piston engine firing order stresses.

Figure 58 shows the gross mass (GM) and total aircraft cost (TAC) results for the unpressurized twin application. Both current and advanced piston engines are shown to have a significantly higher GM than the ATE (30 and 7%, respectively). However, the piston engines indicate a 35% to 45% lower TAC depending on the technology level.

TABLE XLII. - ENGINE COMPARISONS TURBOPROP VERSUS PISTON			
Identificaton	30	P1	P2
Technology	ATE	NAP-C	NAP-A
Type of compressor	2-C		
Type of GP turbine	2-A		
Compressor pressure ratio	14		
GP rotor inlet temp, K(°F)	1478(2200)		
Air-cooled GP turbine	2-A		
Shaft power, slss, kW(hp)	373(500)	298(400)	298(400)
sfc, µg/w·s (lbm/hp·hr)	82.3(0.487)	68(0.40)	59(0.35)
Mass, kg(lbm)	81.2(179)		
OEM price, 1978 $	76401		
Specific mass, g/W(lbm/hp)	0.218(0.358)	0.821(1.35)	0.55(0.9)
OEM specific price, $/kW($/hp)	205(153)	31(23)	31 (23)
Maintenance cost (50 hr/mo util) $/fl h	18.64	?	?
TBO, h	5000	?	?

Figure 59 shows the GM and TAC results for the light twin helicpoter. In this application the current piston engine has a GM 15% higher than the ATE, and the advanced technology piston engine has approximately the same GM as the ATE. The piston engines are shown to have a 30 to 35% lower TAC.

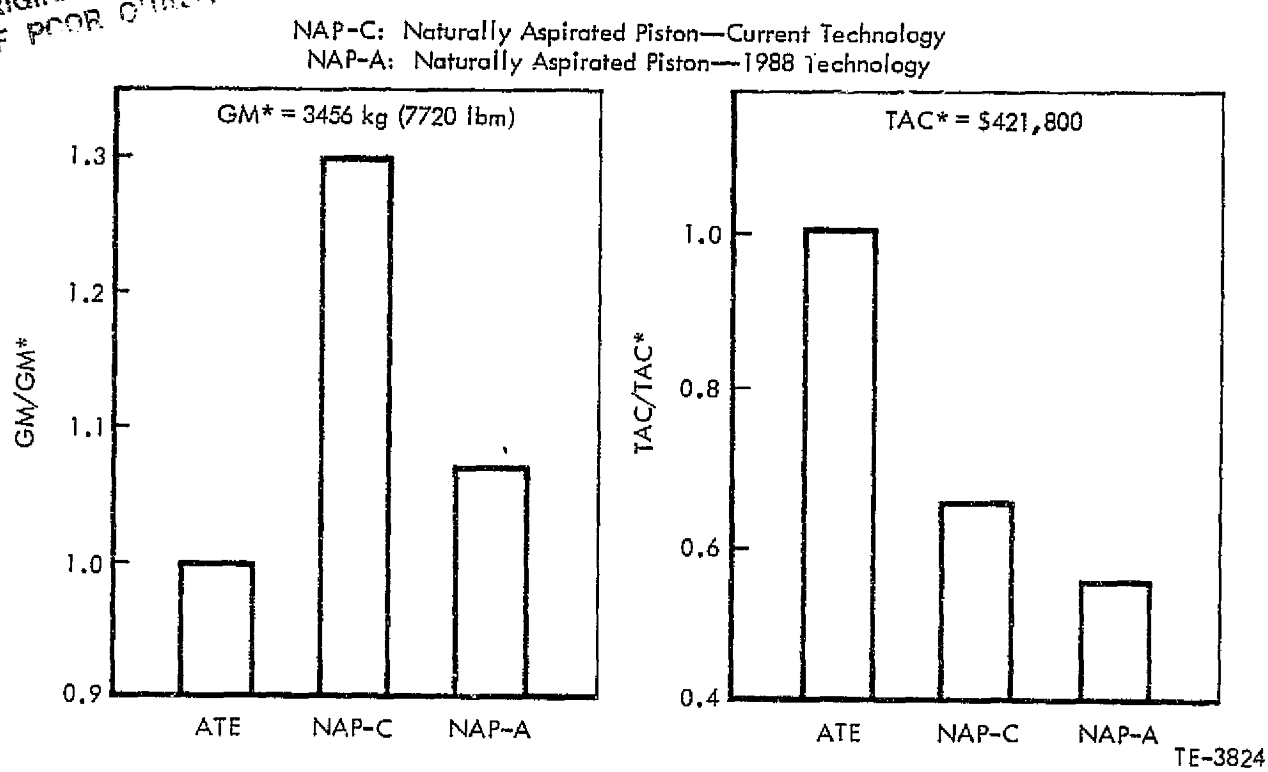

Figure 58. Gross mass and total aircraft cost comparison--advanced gas turbine versus piston (unpressurized twin).

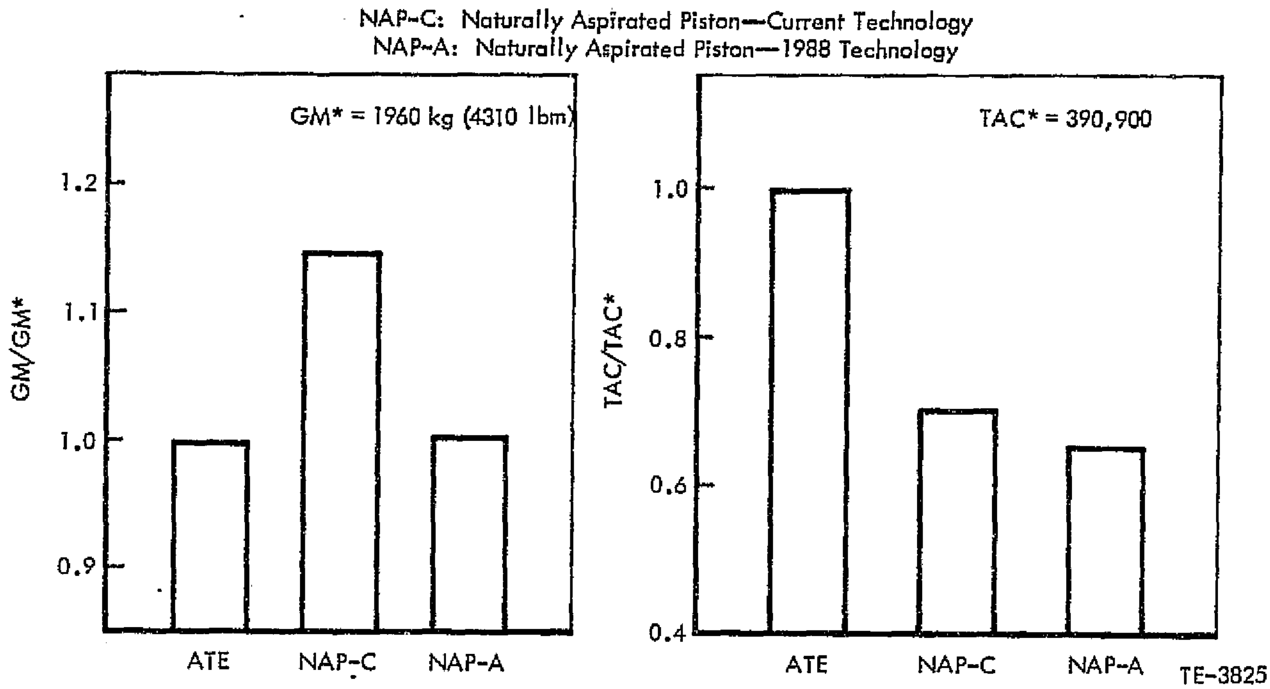

Figure 59. Gross mass and total cost of ownership comparison--advanced gas turbine versus piston (helicopter--light twin).

Figure 60 shows the effect of reducing OEM price of the ATE on total aircraft cost (unpressurized twin only). This figure indicates that for the ATE to be economically competitive with the piston engine (PE), the OEM price of the ATE would have to be approximately 35 to 150% higher than the PE prices. As a result, DDA forsees the ATE initially replacing CTEs, not the piston engines.

It is noted that along with the previously indicated gross mass reductions, the turbine engine provide other advantages. The following is a list of the benefits of a turbine engine when compared with a piston engine.

- Lighter weight
- Smoother operation
    - improved ride comfort
    - allows use of more efficient prop
    - eases installation requirements
- Lower frontal area
- Reduced installation volume
- Greater reliability
- Longer TBO
- Multiple fuel usage
- Competitive installed fuel consumption

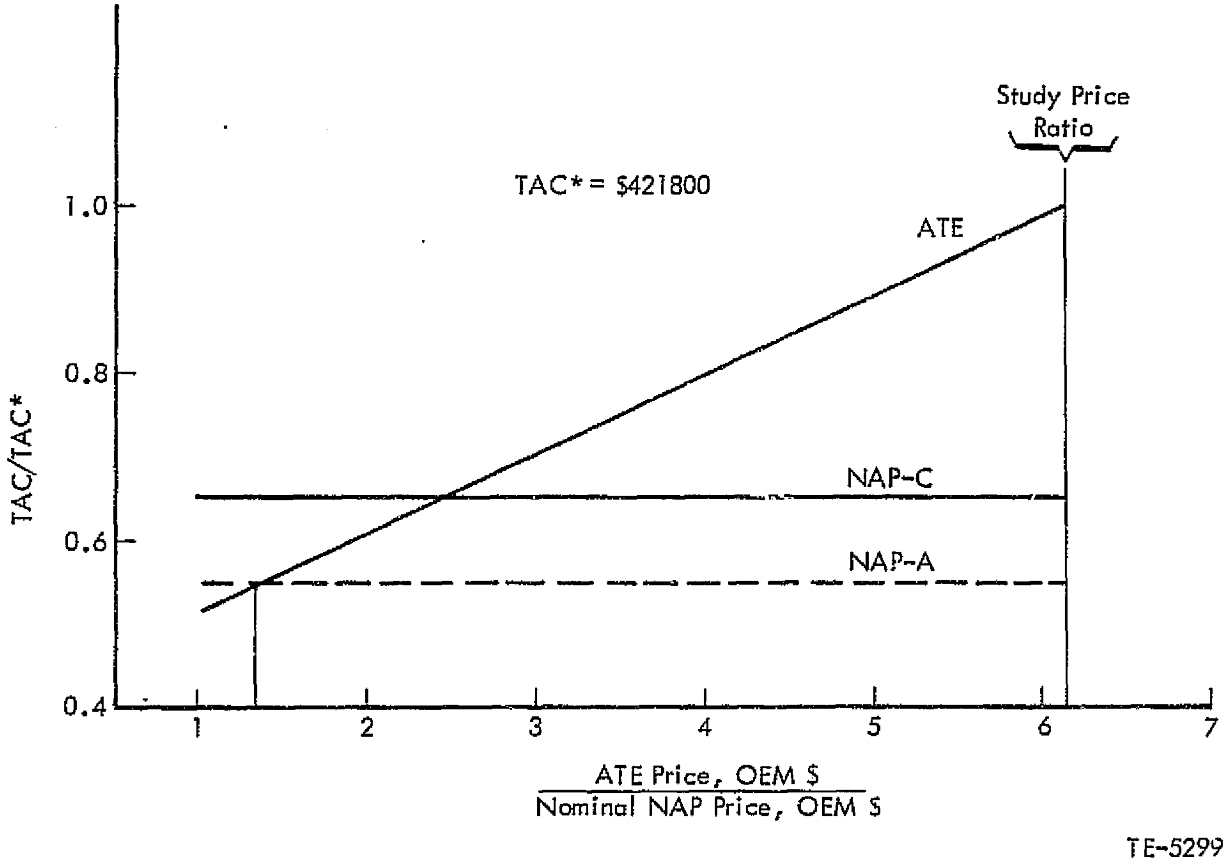

Figure 60. Total aircraft cost versus ATE to NAP engine price ratio (unpressurized twin).

Technology Elements

The technology elements evaluated in this study effort include:

- Dual property turbine
- Ceramic turbine stator
- Advanced composite gearbox case
- Lamilloy* combustor
- Uncooled HPT blades and vanes
- Axial-centrifugal compressor

The purpose of each variation was to help determine the most cost-effective design, thereby substantiating engine configuration choices. A brief quantitative review of each technology element follows. The results of a quantitative evaluation using the unpressurized twin application of the dual property turbine, the ceramic turbine stator, and the composite gearbox case are also

*Lamilloy is a registered trademark of the General Motors Corporation.

included in the discussion. Utilization rate of 600 h/yr, a fuel cost of \$0.22/1 (\$0.83/gal) and a depreciation period of 8 yr were used for the comparisons.

Dual Property Turbine

Small gas turbine engines generally use cast turbine wheels with integral blades. The prime material property required in the blades is resistant to the high gas temperatures. The wheel bore is at a much lower temperature but must resist high tangential stress hence requiring a high strength material. A dual property turbine consists of a cast ring with integral blades of one material diffusion bonded to a hub of another material. The two materials can be selected to a more nearly optimize blade and wheel design than is possible by using a single material. The improved blade material can increase part service life reducing overhaul costs. The wheel can be somewhat lighter and shorter since a higher allowable bore stress is possible. The wheel may be made of powdered metal and then hot isostatic pressed (HIPed) to improve the powdered metal density and strength.

While the extra operation required to produce a dual property turbine wheel makes the wheel more expensive than a monolithically cast wheel (both with integral blades), the dual property wheel produces a more optimum design in terms of component weight and life. The dual property turbine has been incorporated in engine 29 and quantitatively analyzed and compared to engine 29 CT. Both engines are of an uncooled design. Engine characteristics applied in the trade-off study are shown in Table XLIII. Results are reported in the following section which indicate a significant savings in total cost of ownership for the engine configured with the dual property turbine as shown in Table XLIV.

TABLE XLIII. - ENGINE COMPARISONS--TURBOPROP

Turbine rotor configuration	Cast turbine	Dual property turbine
Engine ID	29 CT	29
Type of compressor	1-C	1-C
Type of GP turbine (stage/configuration)	1-A	1-A
Compressor pressure ratio	10	10
GP rotor inlet temp, K (^oF)	1339(1950) (uncooled)	1339(1950) (uncooled)
Power Turbine (stage/configuration)	2-A	2-A
SP, slss, kW (hp)	373(500)	373(500)
sfc, μg /W·s (lbm/hp·h)	87.22(0.5162)	87.22(0.5162)
Mass, kg (lbm)	88.5(195)	88.5(195)
OEM price, 1978 \$	72987	79537
Maintenance cost (50 h/mo util) \$	44.10	19.57
TBO, h	1500	5000

TABLE XLIV. - DUAL PROPERTY TURBINE EVALUATION (UNPRESSURIZED TWIN).		
Engine ID	29CT	29
Vanes	Cast X40	Cast M509
HPT blades	M246 Cast Assy	M247 HIPed into
HPT wheels	M246 Cast Assy	PA IN792 assy
LPT blades and wheels	IN713 Cast Assy	IN792 Cast assy and HIPed
GM, kg (lbm)	3747 (8460)	3747 (8460)
ΔGM, kg (lbm)	(base)	(0)
TAC, $	459,760	484,750
ΔTAC, $	(base)	(+24,990)
TCO, $	1,331,340	1,056,940
ΔTCO, $	(base)	(-274,450)

Ceramic Turbine Stator

DDA is currently engaged in developing a number of ceramic components for small gas turbine engines under a NASA contract (ref NASA CR-135230). Ceramic materials offer the advantage of having a low coefficient of thermal expansion, maintaining their strength at high (turbine) temperatures, and resisting oxidation and sulfidation. These properties make them suitable for consideration as turbine stator materials. For any given compressor pressure ratio there is a fairly wide range of turbine temperatures that will yield near optimum specific fuel consumption. The highest turbine temperature consistent with good fuel economy will result in the smallest engine as specific power output increases with turbine temperature. Use of high gas temperatures currently requires special costly stator metals and coatings to resist surface deterioration and cracking from differential expansions. Air cooling is required to help keep metal temperatures at safe limits. Ceramic material stators would require no air cooling; hence, cycle performance would be improved. The vane sections with their thin trailing edges are currently subject to cracking from differential thermal expansions caused by part geometry and by variation in gas temperatures through the stator nozzle passages. The low thermal expansion characteristics of ceramics would reduce this cracking problem, which causes overhaul replacements and cost. The stator also usually forms a gas path seal with the turbine rotor drum and/or blade tips. The lower thermal expansion characteristics of ceramics is expected to result in a more stable seal clearance throughout the range of operating conditions and environments permitting use of smaller clearances and hence again improving sfc. Engine 31 was configured to reflect mass and cost changes estimated for the use of a ceramic HPT stator (vanes and blade tip shroud) for comparison with engine 26 with its standard metal, air-cooled vanes and coated tip shroud. Engine characteristics developed are shown in Table XLV. A quantitative analysis and comparison was then completed for this item.

TABLE XLV. - ENGINE COMPARISONS—TURBOPROP		
Turbine stator configuration	Conventional X40	Silicon Carbide
Engine ID	26	31
Type of compressor	1-C	1-C
Type of GP turbine (stage/configuration)	1-A	1-A
Compressor pressure ratio	10	10
GP rotor inlet temp, K (°F)	1478(2200)	1478(2200)
Power turbine (stage/configuration)	2-A	2-A
SP, slss, kW (hp)	373(500)	373(500)
sfc, μg /W·s (lbm/hp·h)	86.41(0.5114)	86.41(0.5114)
Mass, kg (lbm)	78.9(174)	78.9(174)
OEM price, 1978 $	74764	74516
Specific mass, kg/k' lbm/hp)		
OEM specific price, $/kW ($/hp)		
Maintenance cost (50 h/mo util), $	18.24	18.17
TBO, h	5000	5000

Table XLVI indicates that both TAC and TCO slightly favor the engine incorporating the ceramic turbine stator.

TABLE XLVI. - CERAMIC TURBINE STATOR EVALUATION (UNPRESSURIZED TWIN)		
Engine ID	26	31
GM, kg (lbm)	3751 (8270)	3751 (8270)
ΔGM, kg (lbm)	(base)	(0)
TAC, $	461,430	460,260
ΔTAC, $	(base)	(-1170)
TCO*, $	1,010,550	1,008,300
ΔTCO, $	(base)	(-2250)

*600 h/yr use and 0.22 $/l (0.83 $/gal) fuel cost.

Advanced Composite Gearbox Case

The accessory drive gearbox cases for the basic study engines is a cast aluminum material. Accessories such as starter, generator, alternator, oil pump, and fuel pump are mounted on the face of the case. The accessories are driven by the gears arranged inside the case in a gear train driven by the engines main rotor usually by means of a radial drive shaft. The main loads on the gear case are maneuver loads, which cause bending loads at the accessory/case mounting flange. The accessories used with small engines are themselves small; hence, flange bending loads are usually small. The case casting tolerance and minimum wall thickness are as low as possible but are often disproportional to that required. Also the low modulus of aluminium may permit excessive deflection during periods of high operating loads causing gear and bearing misalignment and consequent wear or early failure. Advance composite materials offer varied combinations of material properties and fabrication techniques from which an improved case material may be selected to fit the requirements of any potential application. Ultimate strengths and modulus in the range of two to five times aluminum are available. Composites can be mold or layed-up and these and other techniques can be combined to build the desired geometry and properties in each section of a part. Composite density may be equal to aluminum but part mass will likely be much less for the same stiffness. Engine 32 was comfigured with estimated composite accessory gearbox case mass and cost for comparison with engine 26 as shown in Table XLVII. A quantitative analysis and comparison were made with results as shown in Table XLVIII, which shows GM, TAC, and TCO results slightly favoring the use of an advanced composite gearbox case.

TABLE XLVII. - ENGINE COMPARISONS--TURBOPROP

Gearbox case material	Cast aluminum	Fiberglass polyamide
Engine ID	26	32
Type of compressor	1-C	1-C
Type of GP turbine (stage/configuration)	1-A	1-A
Compressor pressure ratio	10	10
GP rotor inlet temp, K (^oF)	1478(2200)	1478(2200)
Power turbine (stage/configuration)	2-A	2-A
SP, slss, kW (hp)	373(500)	373(500)
sfc, μg /W·s (lbm/hp·h)	86.41(0.5114)	86.41(0.5114)
Mass, kg (lbm)	78.9(174)	78.9(174)
OEM price, 1978 $	74764	74579
Specific mass, kg/kW (lbm/hp)		
OEM specific price, $/kW ($/hp)		
Maintenance cost (50 h/mo util), $	18.24	21.53
TBO, h	5000	5000

Lamilloy Combustor

High performance engine designs impose combustor operating conditions of high pressure and of high inlet and outlet temperatures. These conditions pose formidable liner wall cooling problems especially when combined with the high surface-to-volume ratio characteristics of small reverse flow annular combustors. Lamilloy construction is one of the most effective methods known for cooling at these severe design conditions. It uses 50% less cooling flow than convection/film—the next best system. DDA has conducted rig and engine tests and analysis on a variety of cooling methods including:

TABLE XLVIII. - ADVANCED COMPOSITE GEARBOX EVALUATION (UNPRESSURIZED TWIN)		
Engine ID	26	32
GM, kg (lbm)	3751 (8270)	3747 (8260)
ΔGM, kg (lbm)	(base)	-4.54 (-10)
TAC, $	461,430	460,120
ΔTAC, $	(base)	(-1310)
TCO*, $	1,010,550	1,008,040
ΔTCO, $	(base)	(-2500)

*600 h/yr use and 0.22 $/1 (0.83 $/gal) fuel cost.

- Transpiration (Lamilloy)
- Convection film--roughened walls
- Impingement film
- Convection film--smooth walls
- Tangential film
- Convection
- Effusion

All the basic engine configurations in this study contained a Lamilloy combustor which is considered necessary for combustor life.

Lamilloy is a DDA patented material made by diffusion bonding several layers of sheet metal that have been photo chemically etched with interconnected holes and grooves. The finished material has an accurately controlled porosity that can be varied as desired over the sheet area. Individual sheets are formable and can be welded during manufacture and/or repair. A relatively simply and smooth combustor shell results from use of this material. Less pressure drop results when transpiration cooling is used hence, cycle performance is improved. Porosity is varied over different areas of the combustor to suit the local heat load conditions thus minimizing combustor thermal distortions. Service life should therefore, be improved and overhaul cost reduced.

The low-cooling flow requirements of the Lamilloy combustor permit use of increased cooling flow for other purposes. One study indicated that effective use could be made of this air to improve turbine inlet termperature patterns, which would result in a 10% decrease in inherent turbine failures.

A combustor design using conventional materials consists of a series of overlapping tubular deflector rings connecting two end cover bodies. These deflector rings are assembled with crimped bands interposed at overlap area to form passages admitting cooling air into the combustor at axial intervals. Cooling air is also admitted through punched holes in the end bodies, and deflector plates are also commonly used around each fuel nozzle as it enters through the combustor wall. Thus a large number of individually pre-formed pieces must be welded together during fabrication of a conventional combustor. More area of material is required in the conventional design as a result of the crimped bands and overlaps. More labor time is required to form, locate and weld these individual pieces.

Up to eight sheets of Lamilloy must presently be butt-welded together to form a combustor. Currently production of the lamilloy sheets involves a considerable amount of hand labor and sheet size is limited. Cost is, therefore, fairly high. Improved facilities are planned that should cut material cost by two-thirds. Present technology does not permit the use of an automatic welding process on Lamilloy because of its inherent porosity. The use of manual welding also results in increased cost. Combustor cost estimates have been made for conventional versus Lamilloy designs which show current Lamilloy part prices up to 2.5 times that of the conventional part price. The new facilities noted above would reduce the Lamilloy part cost by 50%. Further cost reduction studies are being made aimed at eventual cost equality.

One specific design study done for a GATE-type engine with a foldback combustor yielded the following results:

	Combustor construction	
	Conventional	Lamilloy
Material	Hastelloy X	Hastelloy X
Weight, lbm	8	8
Price*	$2218	$3648
Combustor life, h	Unsatisfactory	5000

*Note: Price based on 5000 engines at 80 per month and expressed in 1978 dollars.

The two combustors were comparable in weight. While the Lamilloy combustor was projected to cost 64% more than the conventional design, it is interesting to note that a conventional combustor design with satisfactory life could not be achieved.

Three plys or layers of etched sheet stock are commonly used. There is a minimum ply thickness required for handling during etching and for part stiffness and pressure-loading considerations. The Lamilloy sheet often is thicker and may be heavier than the conventional material sheet. Since less Lamilloy material is used because of its butt-weld construction, combustor part mass is usually equal to or less than that of an equivalent conventional design. Considerable detail design time and effort is required to define a combustor sufficiently to ensure equivalent performance and hence to permit good mass comparison. Such effort was considered outside the scope of this project. No quantitative mass analysis could, therefore, be accomplished for this item.

The payoff comes when Lamilloy is developed so that a Lamilloy combustor is at least no heavier and possibly lighter than a conventional combustor. Temperature profiles into the turbine will be improved and the life of turbine blades and vanes increased.

Uncooled HPT Blades and Vanes

Air-cooled blades and vanes are cast hollow so that cooling air can be passed through their lengths. Sheet metal baffles may be inserted into the hollow to help distribute the air to obtain uniform cooling of the blade or vane material. A complicated core is required for each blade and vane. Core location is critical to providing specified wall thickness. Casting scrap rate is higher compared to an uncooled part. Cost is higher due to the added core and the increased scrap rate. Air-cooled casting costs may be up to 2 to 3 times that of uncooled parts. Blade masses are usually only slightly different. Wheel design stresses would be similar.

A lower TIT cycle temperature is needed with the uncooled design 1339 K versus 1478 K (1950° versus 2200°F). The lower temperature attempts to provide same turbine bore temperature at maximum power for the uncooled turbine as was estimated for the air-cooled turbine to achieve equivalent design safety margins. This lower cycle temperature changes the sizing and matching of the various engine components to obtain the desired power output. Greater cycle airflow is required in the uncooled design. Overall diameter and length are increased. Mass and cost of the compressor and combustor components increased significantly. These cost increases were over twice that of the turbine blades and vanes. Even with the lower TIT turbine wheel temperature, estimates indicated that service life would be reduced to 1500 h. A quantitiative analysis and comparison was completed for this item. Engine configuration 29 was established as an uncooled version of engine 26. Since the engine cycle was so great a contributor to the overall changes, the results of the analysis were presented as Engine Component Comparison 2 on page 65.

Axial-Centrifugal Compressor

Consideration was given to evaluation of an axial-centrifugal compressor in the program. Preliminary review of this design indicated little likelihood that the concept would be competitive costwise with the dual centrifugal configuration. The rationale leading to this conclusion may be outlined as follows. Work (compression ratio) in the axial and centrifugal stages should be nearly equal for maximum surge margins. A practical pressure ratio of 1.4 is assumed for each axial stage. Three axial stages would be required (with a centrifugal stage) for an overall pressure ratio of 10. Four axial stages would be required for an overall pressure ratio of 14. These overall ratios span the range of interest. Each axial stage is usually cast separately, and its cost is less than that of a centrifugal compressor. Two axial stages would be likely to cost more than a centrifugal stage. Thus the dual centrifugal is cost effective throughout the pressure ratio range. In addition, the dual centrifugal compressor is expected to operate without the need for bleeds or variable geometry. The axial-centrifugal very likely would need bleeds and/or variable geometry even with equal work split. If a single axial stage were used, variable geometry would be required to provide surge margin (by matching the operating characteristics of the two components at off-design conditions). Bleeds and particularly variable geometry would add cost. They would also add complexity and unreliability to the control system.

Centrifugal compressors above a pressure ratio of about 8.5 usually require acceleration bleeds. This is in the range of the single-stage axial plus centrifugal compressor. In the dual centrifugal configuration, however, each stage would be below this value so no bleed should be necessary. A more detailed analysis of this configuration was considered outside the scope of this program.

Sensitivity Studies

Three types of sensitivity plots were developed for the GATE design studies.

- Type I--GM, TAC, and TCO sensitivity to engine sfc, engine mass, and engine cost
- Type II--TCO sensitivity to use and fuel cost
- Type III--TCO sensitivity to component efficencies, cooling air, and leakage

Type I

Sensitivity data was generated to show the effect of changes in engine sfc, engine mass, and engine cost on the unpressurized twin, pressurized twin (heavy), and light twin helicopter design gross mass and economic parameters (TAC & TCO). Figures 61, 62, and 63 show sensitivites with the current technology as a base. These figures indicate that sfc is the primary driver on TCO for this relatively low-cost engine. Figures 64, 65, and 66 show comparable sensitivites using a two-stage centrifugal compressor, high R_c, high RIT advanced turbine engine as base. Note that cost is the primary driver on TCO for this relatively high cost representative ATE.

Type II

Figures 67, 68, and 69 summarize fuel cost and use trades comparing a representative advanced engine to the current engine technology as affecting TCO. The three figures indicate that as fuel cost and/or use increase the greater the TCO advantage of the representative ATE over the CTE. Also, the more stringent the mission requirements (higher cruise altitude, velocity, range, or payload) the greater the advantage of the ATE.

Type III

Engine cycle studies were made on one of the matrix engine (Engine 21) to determine the sensitivity of engine horsepower and sfc to variations in various engine component performance items at the slss T.O. design point. The items varied were:

- Compressor efficiency
- Gas generator turbine efficiency

C-2

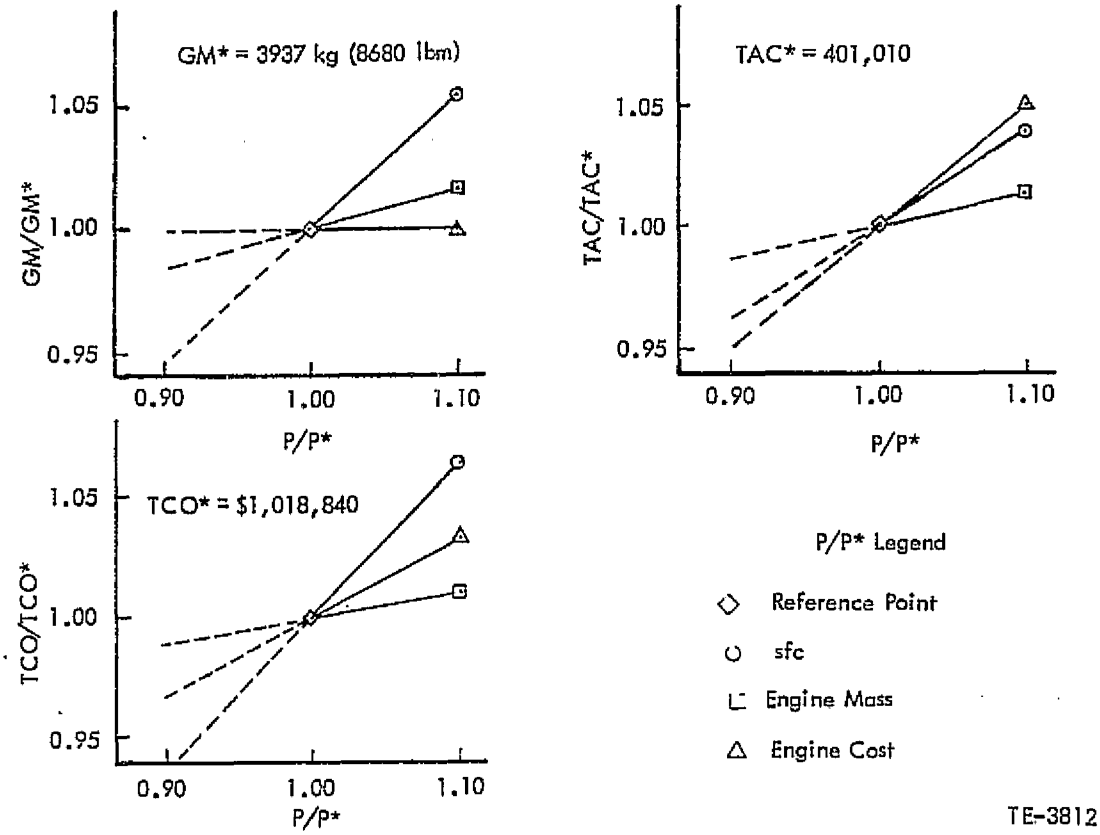

Figure 61. Engine sfc, mass, and cost sensitivity data--CTE (unpressurized twin).

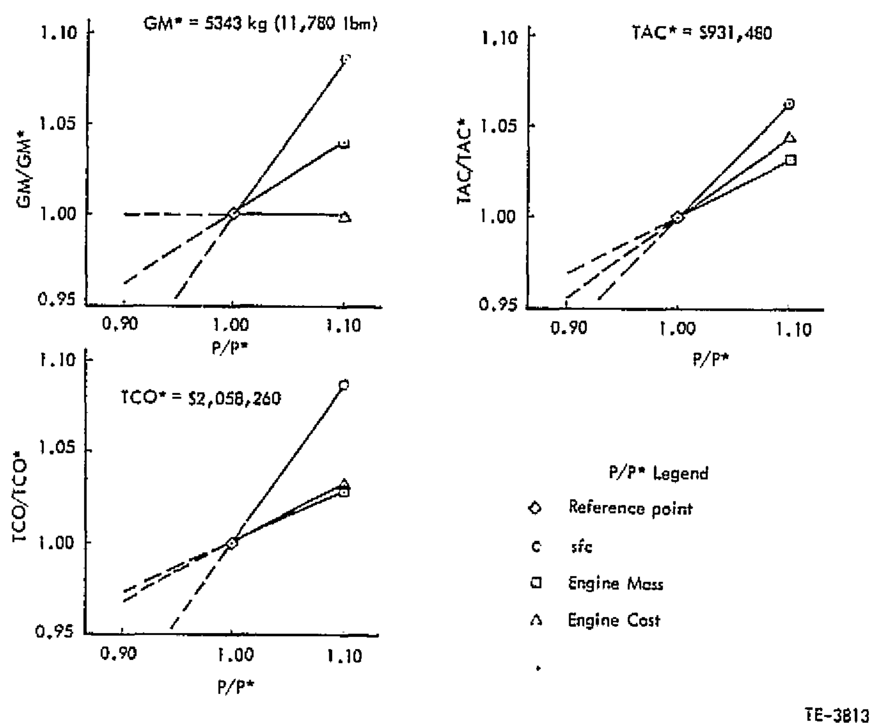

Figure 62. Engine sfc, mass, and cost sensitivity data--CTE (heavy twin).

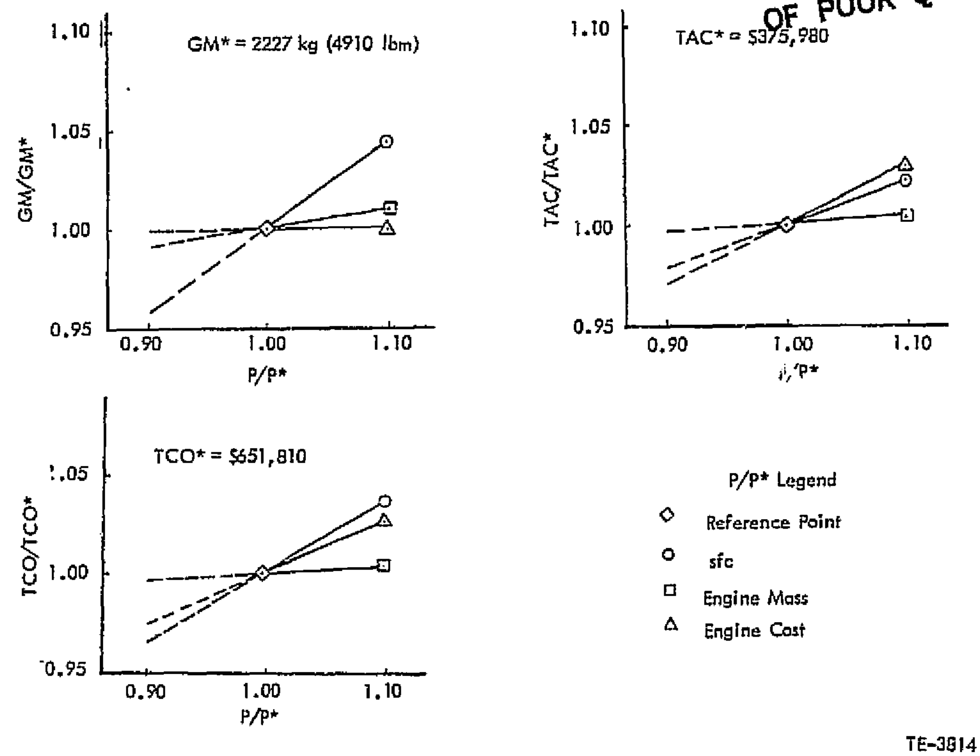

Figure 63. Engine sfc, mass, and cost sensitivity data--CTE (helicopter-twin).

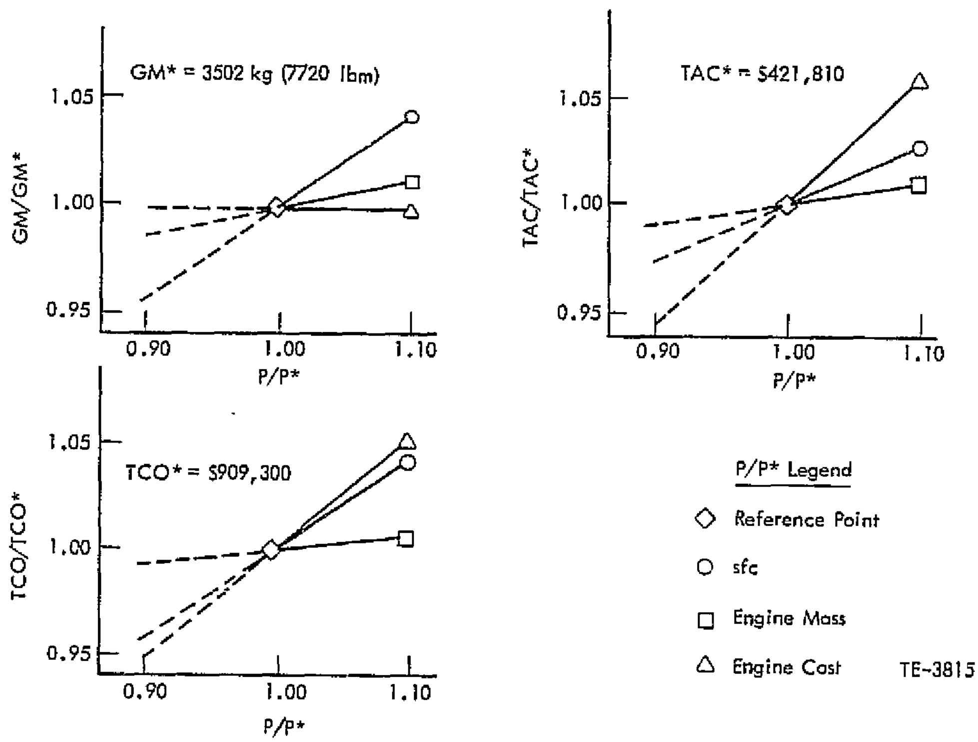

Figure 64. Engine sfc, mass, and cost sensi:ivity data—ATE (unpressurized twin).

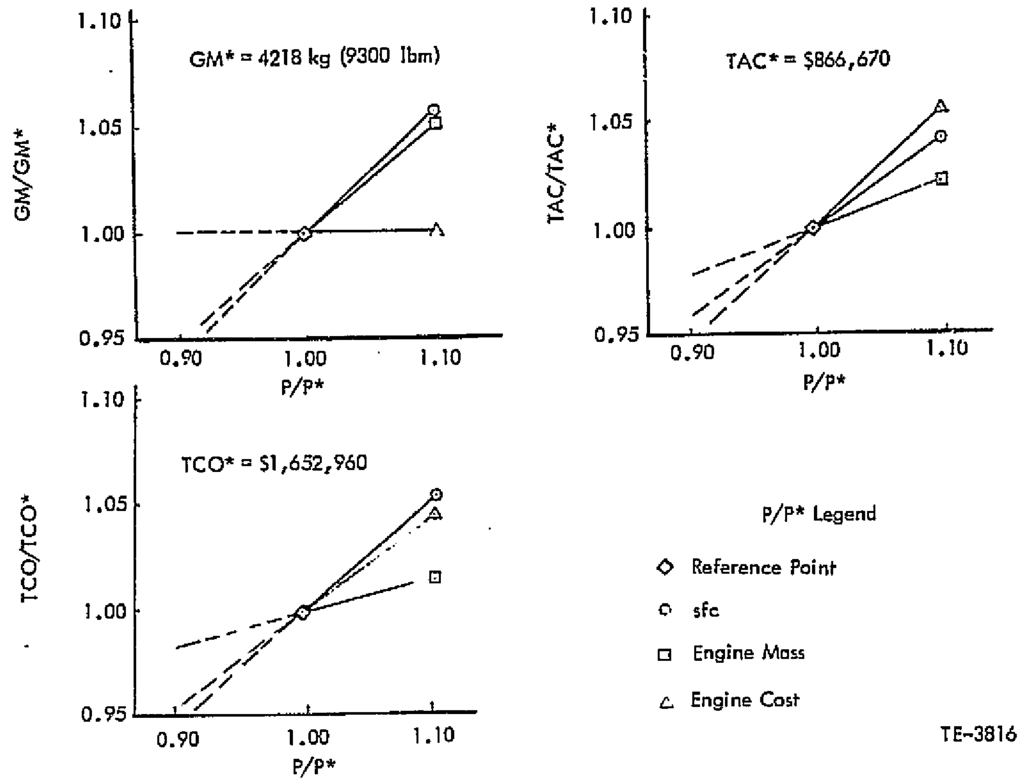

Figure 65. Engine sfc, mass, and cost sensitivity data--ATE (heavy twin).

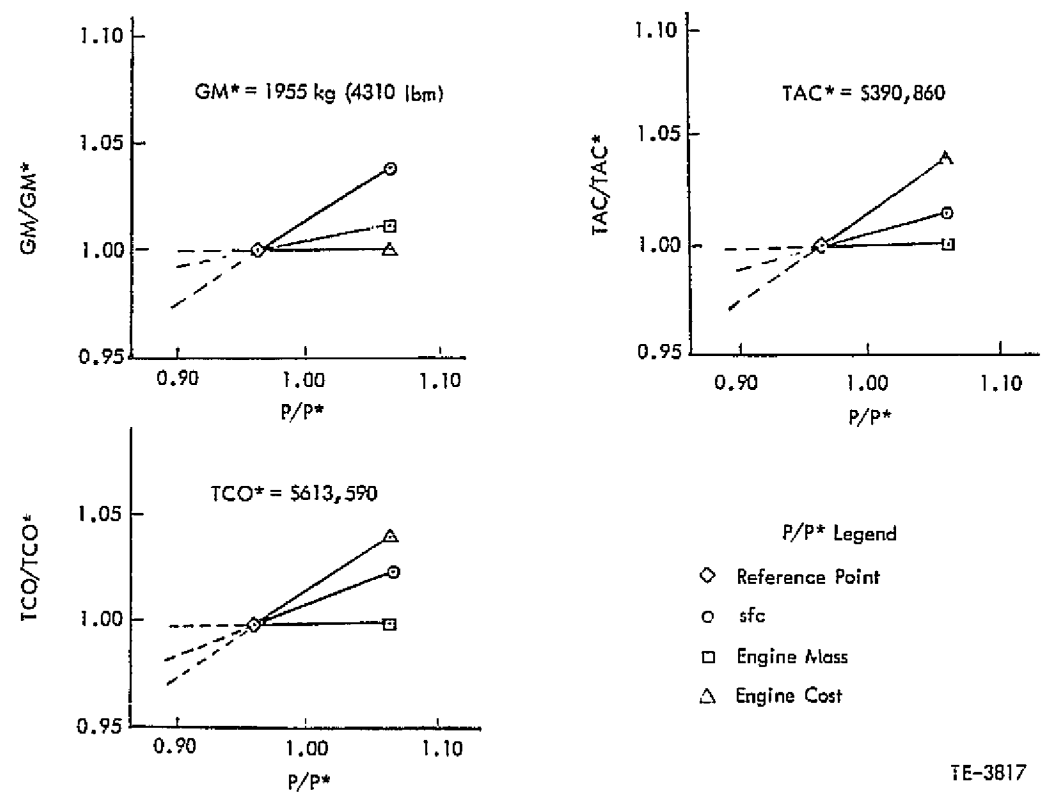

Figure 66. Engine sfc, mass, and cost sensitivity data--ATE (helicopter-twin).

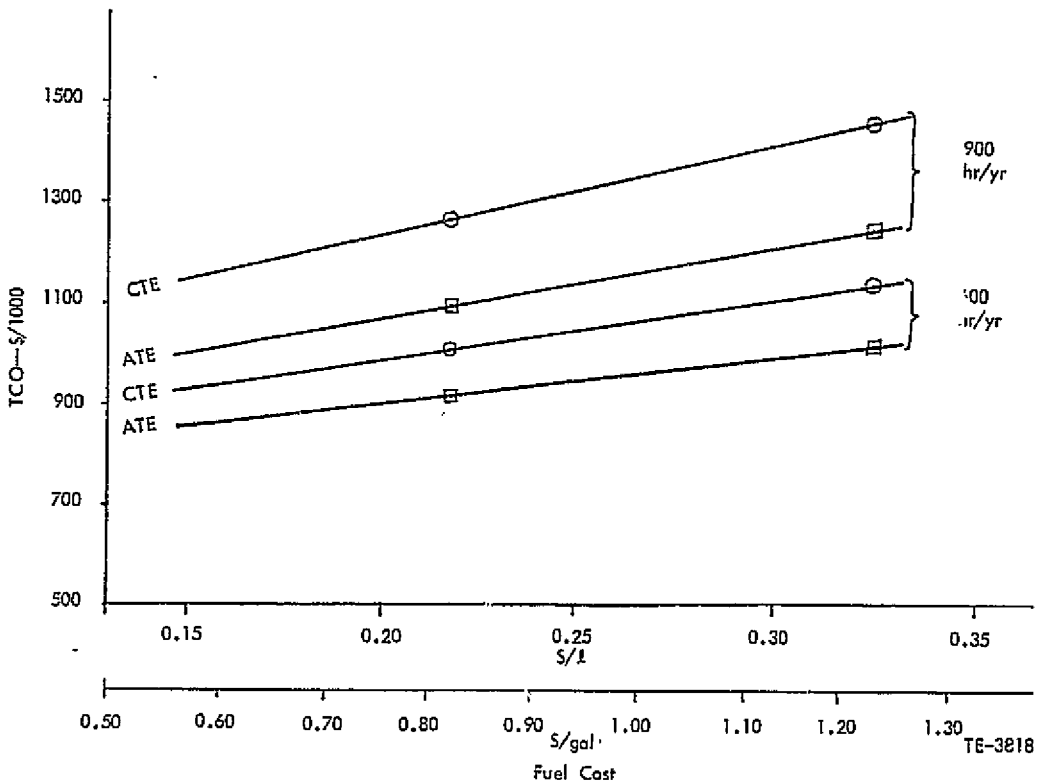

Figure 67. Total cost of ownership sensitivity to use and fuel cost (unpressurized twin).

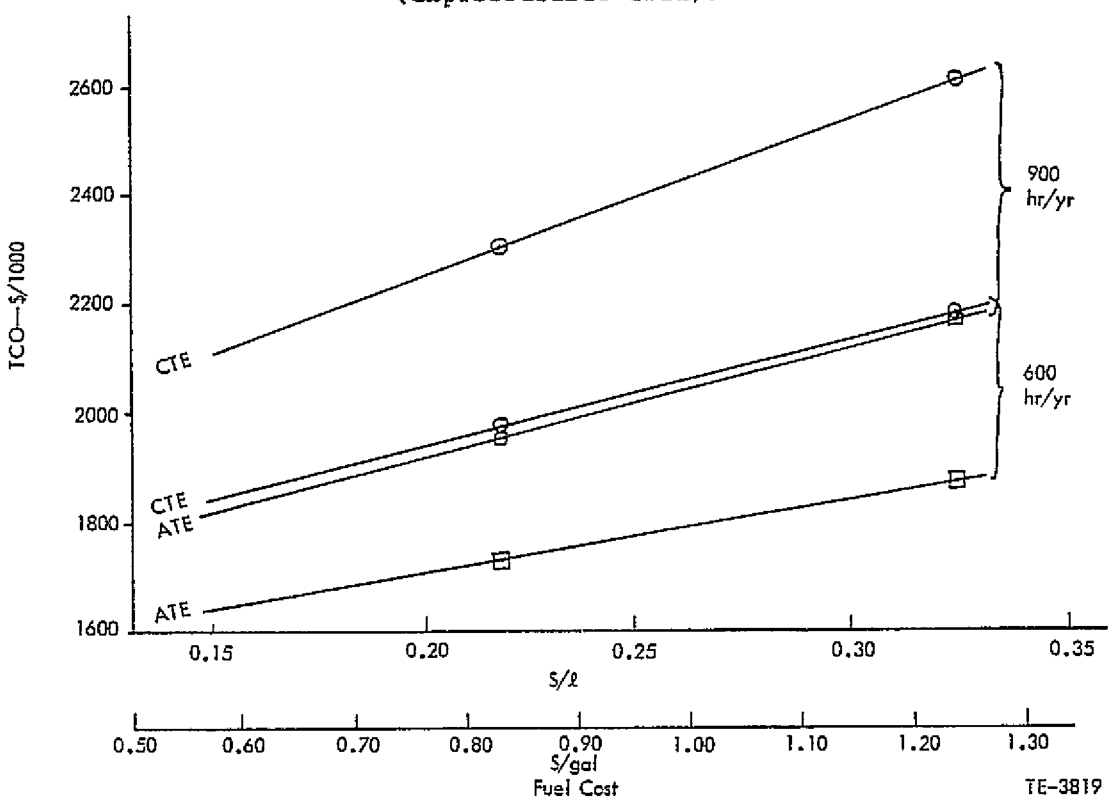

Figure 68. Total cost of ownership sensitivity to use and fuel cost (heavy twin).

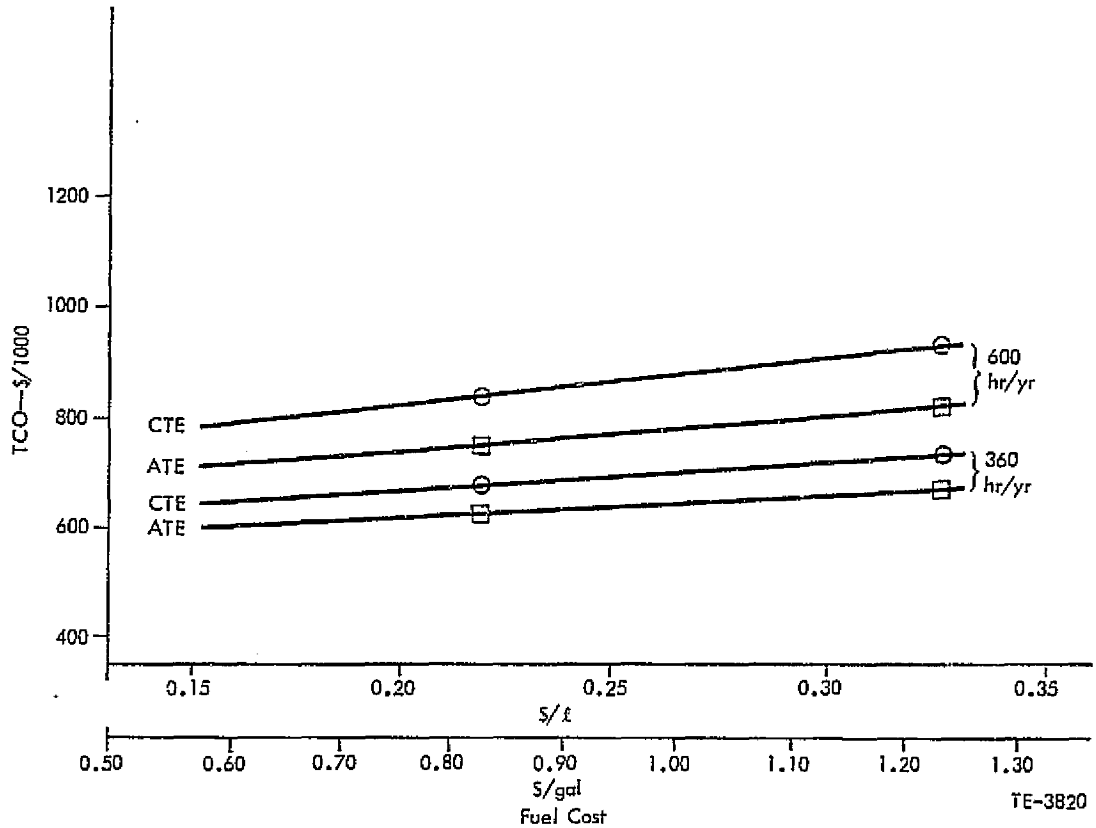

Figure 69. Total cost of ownership sensitivity to use and fuel cost (helicopter-twins).

- Power turbine efficiency
- Turbine cooling airflow rate
- Overboard air leakage rate

Each item was varied separately while holding all other values at their base values.

This engine data was then used in mission trade studies to determine the sensitivity of vehicle TCO to engine component performance variations. Three of the six vehicle/mission combinations were studied. The results of these studies are summarized in the following figures:

- Figure 70—unpressurized twin
- Figure 71--pressurized twin (heavy)
- Figure 72--light twin helicopter

<u>Environmental Considerations</u>

A forecast of the regulatory environment was made for 1985 to 1990 for the general aviation gas turbine engine. Noise and emission regulatory requirements predicted for the small turboshaft and turboprop engine for this time frame appeared to be satisfied by the technology now in hand.

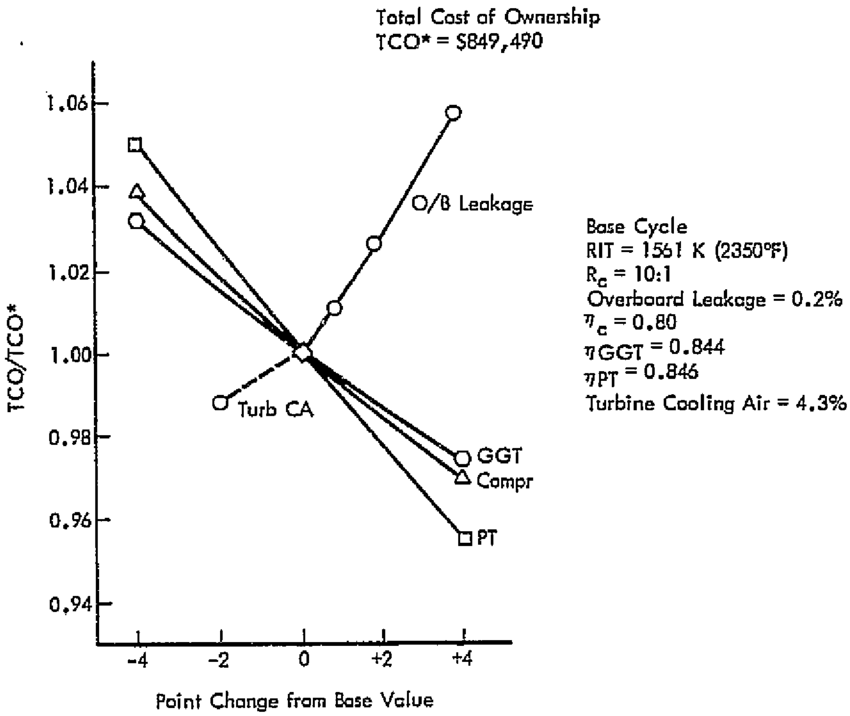

Figure 70. Component efficiency, cooling air, and leakage sensitivity data (unpressurized twin).

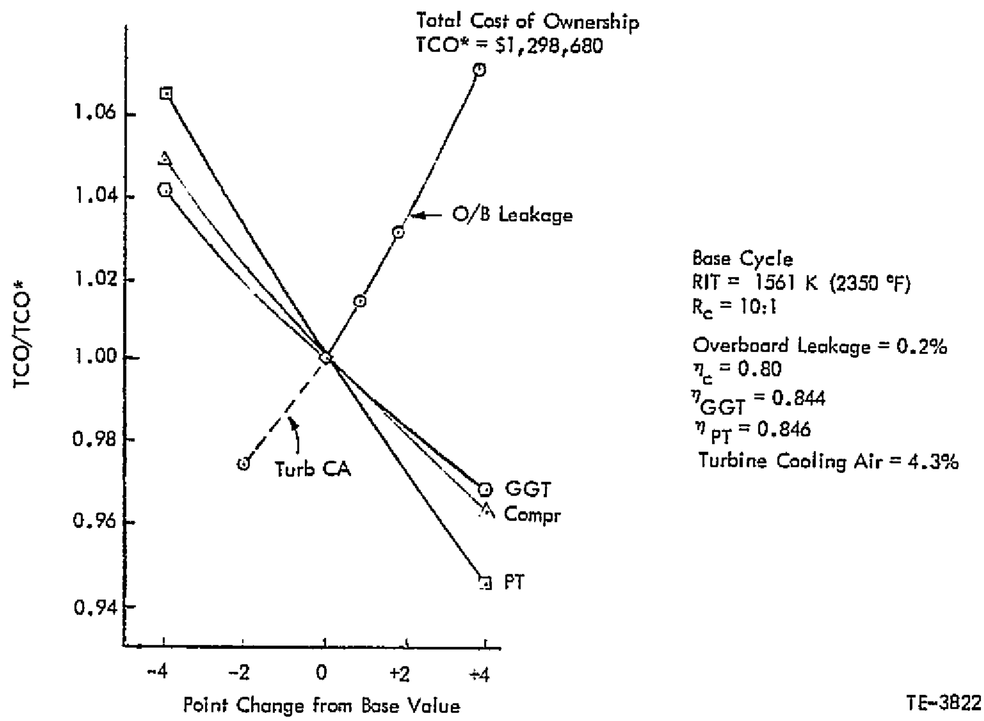

Figure 71. Component efficiency, cooling air, and leakage sensitivity data (heavy twin).

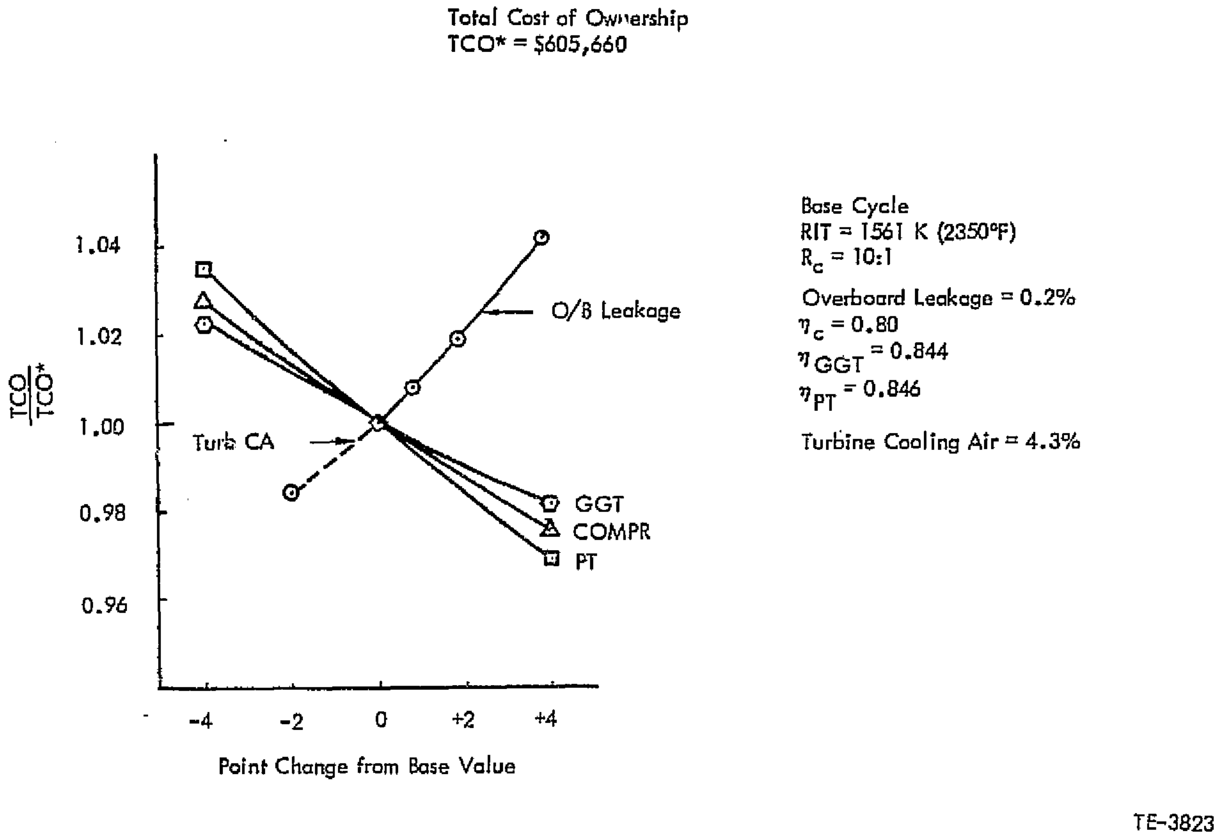

Figure 72. Component efficiency, cooling air, and leakage sensitivity data (helicopter-twin).

Noise

Turboshaft Engine Noise

Small turboshaft engines radiate noise from the compressor inlet, engine case, reducton gears, and the engine exhaust. Noise radiating from the exhaust is generated by several sources—jet, turbine, and a third component, generally called "core noise," thought to originate in the combustor. The first two sources are generally negligible for turboshaft engines since the exhaust velocity is very low (122 m/s (400 ft/s) or less) and turbine tones occur at very high frequencies (above 20 KHz).

Engine case and gear-radiated noise are also usually very low in terms of contribution to the engine noise signature, thus leaving compressor and core/combustion noise as the dominant sources. The noise emisson characteristics of the small turboshaft engine have changed substantially in the past 16 yr as a direct result of engine aerothermal cycle development and improved component efficiencies. The cycle trend toward increased pressure ratio and turbine temperature to obtain reduced fuel consumption has changed the small turboshaft noise signature from exhaust noise (core/combustion) dominated with little or no noise contribution from the compressor to compressor noise dominated as shown in Figure 73.

The net result of the engine development trend to date has made the current engines about 3 dBA more quiet than the initial engines even though takeoff power has more than doubled for the DDA production engines shown.

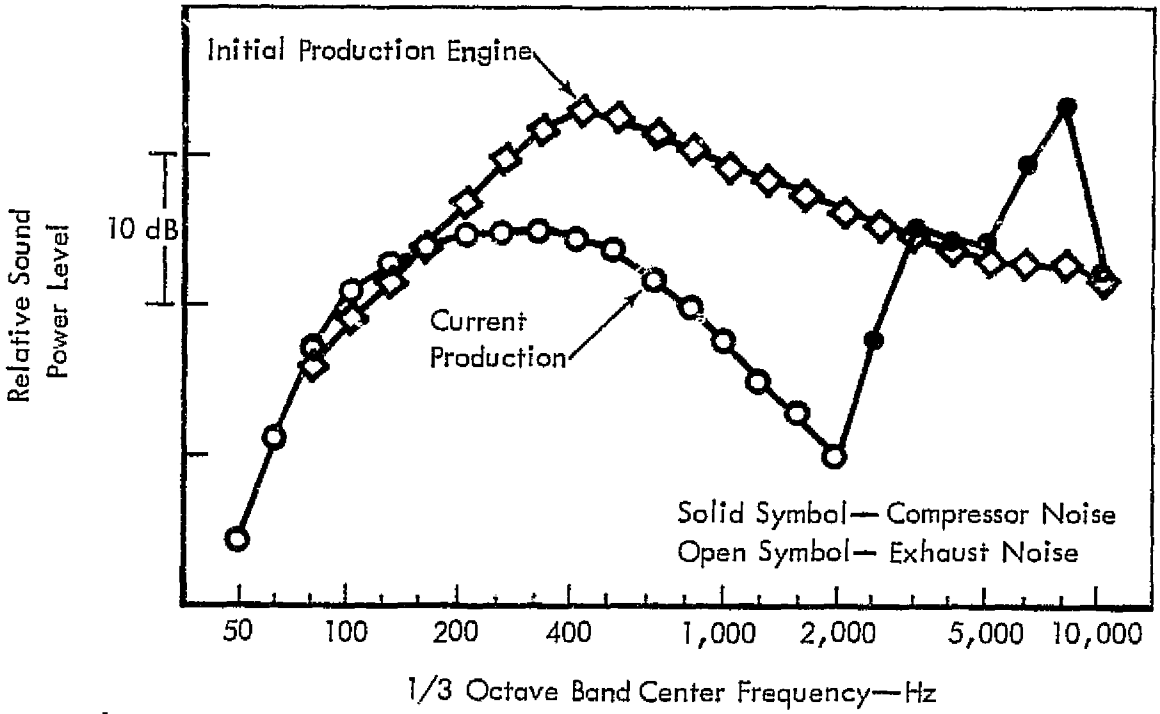

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Figure 73. Comparison of initial and current production engines at takeoff power.

GATE Engine Noise

The engine descriptons selected from the GATE matrix for final consideration are shown in Table IL along with a current production engine which was selected as the base for noise comparisons.

TABLE IL. - GATE TURBOSHAFT AND TURBOPROP ENGINES-UNITY SIZE 373 kW (500 hp) CANDIDATE ENGINES-DESIGN POINT DATA

Engine no.	26	27	28	29	30	Current Production
Technology	ATE	ATE	ATE	ATE	ATE	CTE
Type of compr	1-C	1-C	1-C	1-C	2-C	1-C
Type of GP turb	1-A	2-A	1-R	1-A	2-A	2-A
Aircooled GP turb	yes	yes	yes	no	yes	no
Performance, slss T.O.						
R_C	10	10	10	10	10	8.14
RIT, K (°F)	1478 (2200)	1478 (2200)	1478 (2200)	1478 (2200)	1478 (2200)	1322 (1920)
Shaft power, kW (hp)	372.8 (500)	372.8 (500)	372.8 (500)	372.8 (500)	372.8 (500)	484.7 (650)
Airflow, kg/s (lb/s)	1.340 (2.954)	1.[illegible]9 (2.974)	1.268 (2.795)	1.625 (3.583)	1.400 (3.086)	2.495 (5.5)
sfc, μg/W·s (lb/hp·h)	86.41 (.5114)	86.39 (.5113)	82.03 (.4855)	87.22 (.5162)	82.34 (.4873)	100.03 (.592)

Current core/combustion noise prediction methods do not accurately predict the reduction in noise radiated from the engine exhaust shown in Figure 73 and, therefore, are not considered reliable indicators of the effect of engine cycle changes on exhaust noise. However, predictions made using the methods described in references 1 and 2 agreed reasonably well with test measurements for the base engine (+3 dB) and when applied to the GATE engine cycles showed a noise reduction with increasing pressure ratio. Noise reductions of 2 and 7 dB, respectively, were obtained at a pressure ratio of 14. Correlating the historical noise reduction trend with engine sfc and projecting to the GATE sfc range indicated a 5 to 7 dB reduction (Figure 74).

The engine used as a noise reference base has a single-stage centrifugal compressor which has a supersonic inducer tip relative Mach number above about 85% speed making Multiple-Pure-Tones (MPT) the dominant inlet noise. Figure 75 shows the inducer tip relative Mach number as a function of compression ratio for advanced single- and two-stage centrifugal compressors. As can be seen, the change from the base engine to the GATE single stage R_c 10 is small (0.02 Mach) and occurs in a Mach number range when MPT strength usually begins to roll-off so that only a small change is expected. Using a two-stage centrifugal compressor to obtain a pressure ratio 14 will reduce the inducer tip Mach number required to 1.25 with a corresponding reduction in MPT noise. Figure 76 presents a comparison of a single- and two-stage compressor which are similar to those used in the noise base engine and the GATE R_c 14 engine. This figure shows that, for a constant size, the increase in Mach number for the single-stage compressor should result in about a 1 dB increase and the decrease in Mach no. for the two-stage should give a 2 dB decrease in inlet noise. Scaled to GATE engine size, the change relative to the base engine should be a 1 to 2 dB decrease for single-stage compressors, and a 4 to 5 dB decrease for the two-stage compressor.

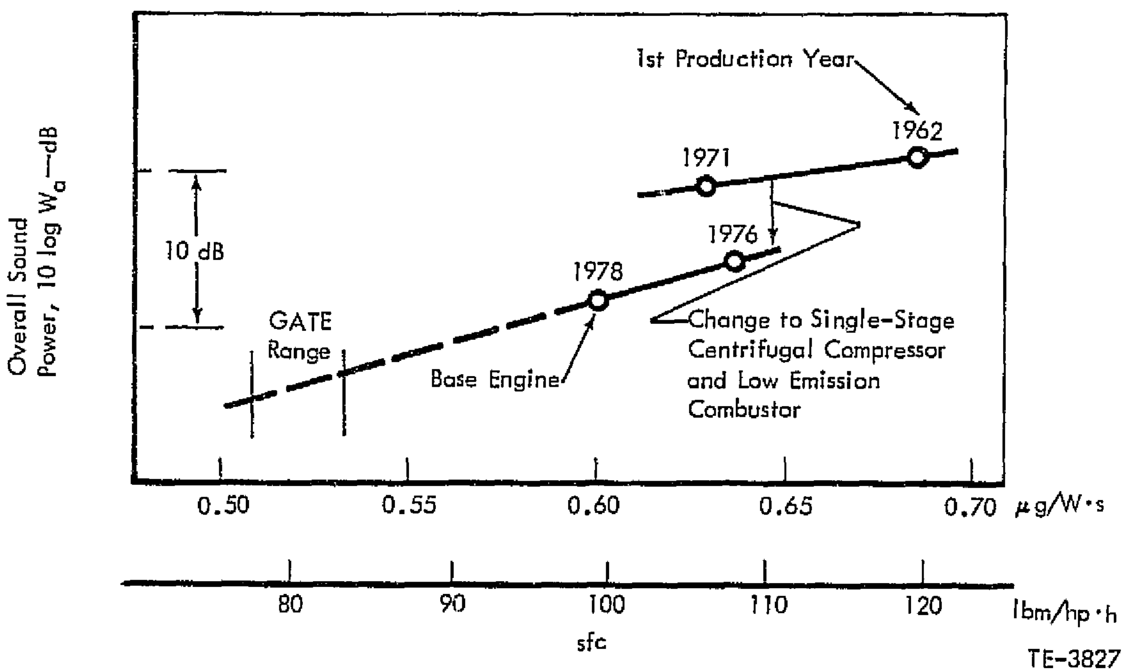

Figure 74. Turboshaft engine exhaust noise as a function of sfc.

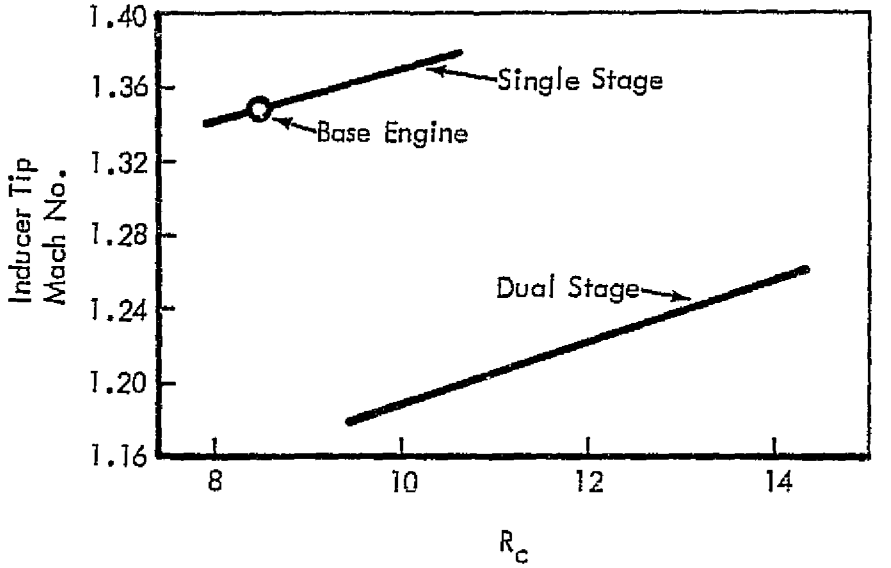

Figure 75. Inducer tip Mach number for single- and dual-stage centrifugal compressors.

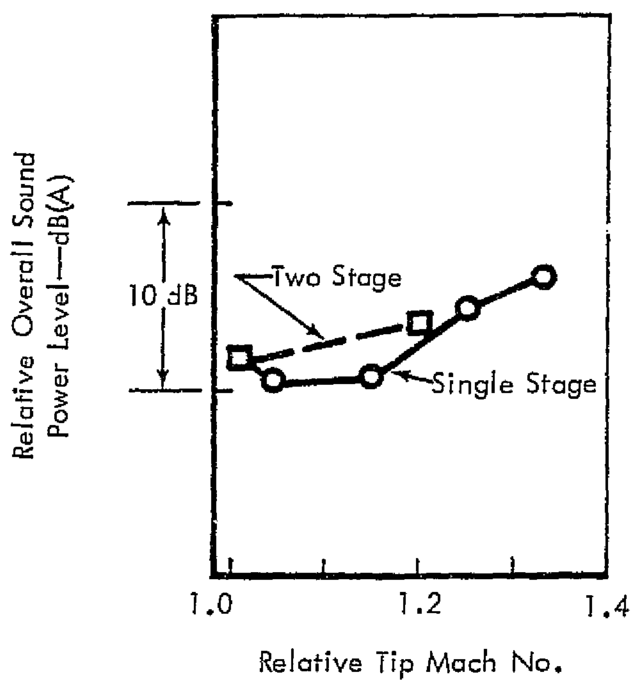

Figure 76. A weighted sound power level for single- and two-stage centrifugal compressors.

Effect of Turbine Power on Propeller-Driven A/C and Helicopter Noise
Turboprop

The use of turbine power reduces propeller-driven aircraft noise in two ways.

- The direct contribution of the engine is reduced. The exact contribution of the current reciprrcating engines has not been defined but for aircraft of less than 907 kg (2000 lbm) gross mass the propeller and engine generate about the same overall sound power under static conditions. In flight, propeller noise is diminished, expecially the higher blade pass harmonics, because of the improved air inflow conditions, while engine exhaust noise is not so affected and can be easily identified in the aircraft flyover signature (3)* as seen in Figure 77.

- Turbine power permits the use of thinner, more efficient propeller designs, primarily because the propeller does not have to accomodate the firing order stresses experienced with reciprocating engines. Figure 78 shows that noise reductions of the order of 5 dB can be obtained through this change in propeller design. (3)

The use of turbine power also offers a third, indirect means of reducing the certification noise levels for propeller driven A/C. Certification noise levels for aircraft certified under section F of FAR Part 36 consist of two parts

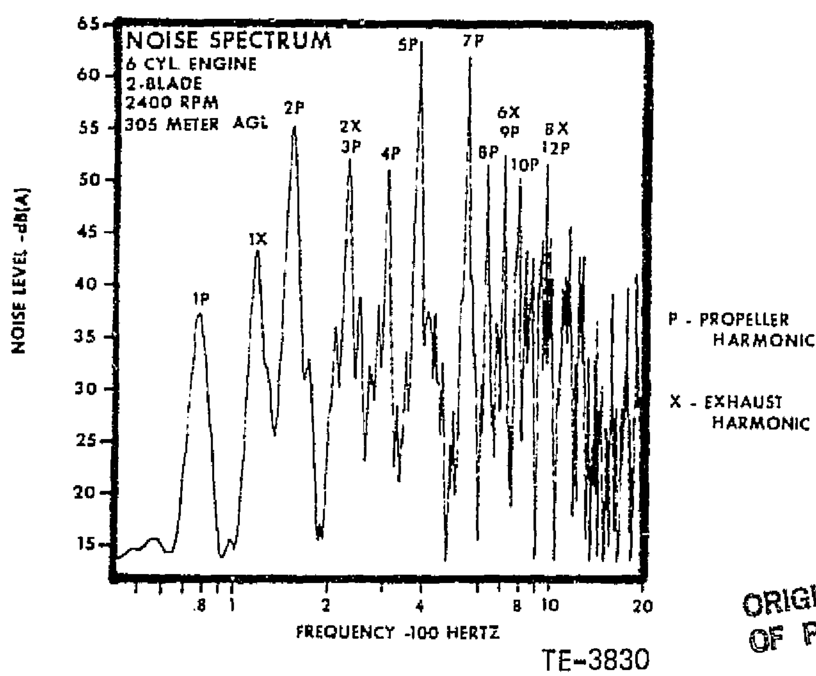

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Figure 77. Narrow band frequency spectrum for the flyover noise of a typical single-engine, general aviation aircraft.

* Numbers in parentheses refer to references listed at the end of this report.

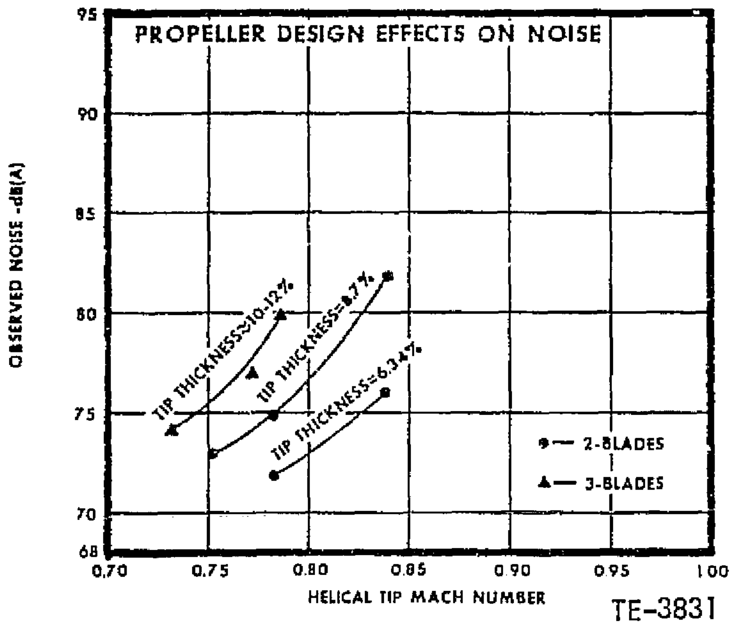

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Figure 78. Influence of propeller section properties on the observed noise.

(1) the actual measured level and (2) an aircraft performance correction. Taking advantage of reduced power plant mass (0.213 kg/kW (0.35 lbm/hp) for turbine versus 0.912 kg/kW (1.5 lbm/hp) for reciprocating engines) to increase climb performance would produce an additional noise reduction increment.

Helicopter

The bulk of the current helicopter fleet is turbine powered, with only some very early designs and very light craft using reciprocating engines. Turbine engines powering current helicopters in the 907-1646 kg (2000-4000 lbm) class make a small contribution to total helicopter sound power. Engines of the GATE technology level will contribute somewhat more primarily because of the increase in compressor inlet noise. An assessment of the possible contribution was made by modifying the base engine noise to simulate the GATE candidate engine No. 29, and scaling to sizes appropriate for the Hughes 500D and Sikorsky S61 helicopters. The engine noise was added to helicopter noise as observed during hover, and the combined noise used to determine the EPNL level for a 152 m (500 ft) flyover at cruise speed. The net effect was no increase on flyover noise. Differences between engine and rotor noise directivity account for the low sensitivity of flyover EPNL to compressor noise. Peak engine noise occurs well forward of the helicopter, whereas peak rotor noise occurs aft so the two sources do not combine on a peak basis. The choice of a single-stage compressor or inlet configuration (side inlet rather than front) could alter this result. Treated inlet ducts may be required in GATE-powered helicopters.

Certification Noise Levels

The purpose of noise certification is to insure that the best available noise reduction technology that is technically feasible and economically reasonable is incorporated in aircraft of new design. As a result, reductions in the certification noise levels are paced by introduction of new aircraft that demonstrate the effectiveness of the noise-reduction technology incorporated in their design. In this respect, engines shown in the GATE study probably will not affect propeller-driven aircraft certification levels in the mid-1980's, but would provide the technology base for reduction at a later time. Figure 79 shows measured noise levels for certificated (5) propeller-driven aircraft. Certification noise levels for FAR-36 in 1980 are shown, along with a decrement based on the technology just now emerging in repsonse to the 1980 requirements and a additional decrement showing the estimated benefit of introducing GATE-level technology.

Figure 80 shows the helicoptor certification noise level proposed by the FAA (7), which is very probably close to the actual certification requirements through the mid-1980s. Any reduction in requirement is wholly dependent on rotor noise reduction. Reducing rotor-type Mach number has been shown to be a nonproductive means of reducing rotor noise (8), however, the data spread shown in Figure 80 indicates the possibility of noise reduction through rotor design.

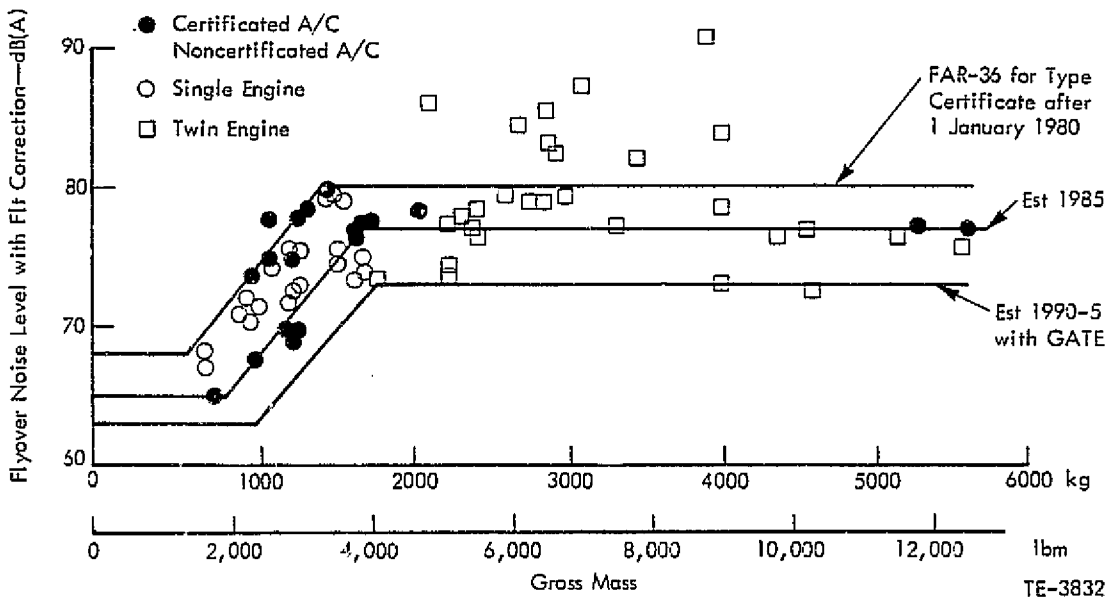

Figure 79. Certification noise levels for small propeller-driven aircraft.

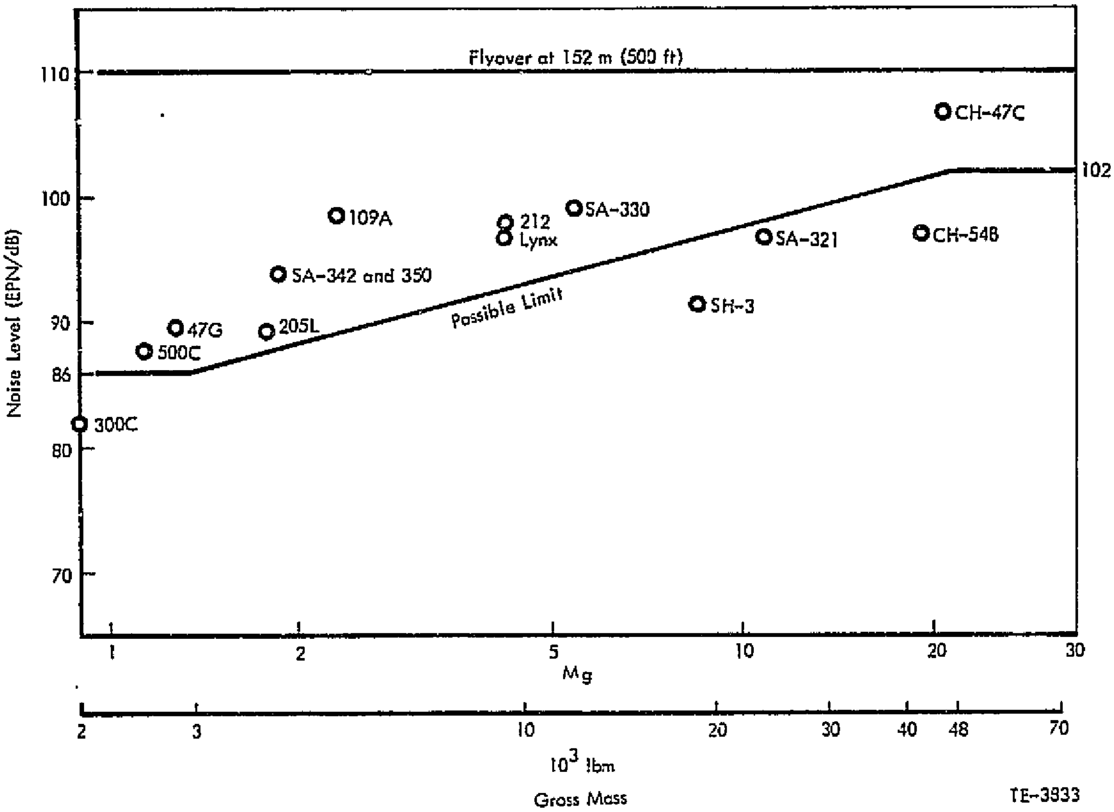

Figure 80. Possible noise limit for type certification of helicopters.

Emissions

Originally, the GATE study included means to incorporate the considerable impact the Federal regulations for control of aircraft exhaust emissions have on the design of general aviation engines. Because rule making was still in process, the exact amount of impact was not known but was expected to depend on the following factors:

- The severity of the control the Enviromental Protection Agency applied to small turbine engines in 1985 and beyond.
- The discriminatory nature of the regulations as they are applied to different GATE engine applications i.e., do they preclude use of the "optimum core"?
- The level of emission control technology that has been developed and is applicable in the time frame of this study

However, early in the program, the EPA advised DDA that they intended to deregulate engines used for general aviation. Subsequently, they published proposed rule making, which confirmed this approach, by deleting the requirement to control gaseous pollutants. As a result of these actions, pollution control requirements and their impact were dropped from the GATE study.

EPA Regulations

The control of emissions from aircraft engines is specified in the United States by the regulations of the Environmental Protection Agency (9). These regulations presently call for the control of exhaust emissions (hydrocarbons, carbonmonoxide, and oxides of nitrogen and smoke) and of fuel-venting emissions from all engines including those used in general aviation. Turboshaft engines, which are not considered a significant source, are not regulated.

In response to these regulations, the GATE study was designed to include those cost and mass penalties which would be required for engines to comply with the stringent emission control requirements for general aviation.

- Change in EPA Direction

Early in the contract period, the EPA advised industry of their intention to deregulate general aviation engines along with other proposed changes in regulations. The EPA's thinking was confirmed through the distribution of Draft Changes to the 1973 rules. This intent (to deregulate general aviation) has now been substantiated by the publication of a rules change proposal (10).

The EPA rationale for this change in position follows:

"Recent studies have concluded that the air quality impact at major air terminals is much more significant than that at the smaller, general aviation airports and further, that the major aircraft contributors at the major air terminals are the commercial aircraft and not general aviation aircraft."

For large general aviation airports where general aviation traffic is a significant fraction of the total, it was found that CO approaches the ambient air quality standard only at the runway where people are exposed for only brief periods and, therefore, cannot be construed to be a problem. HC and NO_x emissions were found to be less that 100 ton/yr at any general aviation airport. Therefore, it is clear that emissions from general aviation airports do not provide strong justification for a program of federal standards applicable to general aviation aircraft (10).

Additional substantiation of EPA's action was given when they stated that the pollution control of general aviation engines was not as cost effective as that of other sources (i.e., automobiles), and that the, "resources available to the EPA for the pursuit of achievement of the national air quality standards are substantially limited," and could best be expended controlling other sources.

- Impact of Deregulation

The result of the EPA proposed deregulation of general aviation turbine engines was to divorce all consideraton of special pollution control requirements from the GATE study. This was done because the remaining EPA requirements for control smoke an fuel venting are state-of-the-art requirements that are already incorporated in the design and production of present DDA small turbines. This change in impact is shown in Figure 81.

	GATE Engines Controlled	Pollutants Controlled	Technology Level	Impact on GATE
Start of Program (1)	Turbofan Turboprop	HC CO NO_x Smoke	Research	• Requires Additional Develop • Gas Generators Have Increased Cost, Weight, Complexity • Conflicting Requirements for Turboprops and Turbofans
		Fuel Venting	Production	
End of Program (2)	Turbofan Turboprop	Smoke Fuel Venting	Production	• Emission Control Not a Factor

(1) EPA Rules for Aircraft, 40CFR87, 17 July 1973
(2) EPA Proposed Rules Changes, 40CFR87, 24 March 1978

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Figure 81. Impact of EPA emissions rule making on GATE study.

Summary

The engine configurations selected as optimum for the various GATE applications studied are shown in Table XVIII. Table XVIII indicates the size (kW (hp)) cycle, configuration, and technology elements for the selected engines along with a listing of their benefits compared to current engine technology in small gas turbine engines.

In summary:

- Most benefit in aircraft economics for a GATE engine was found in the 597-746 kW (800-1000 hp) class.

- Current technology gas turbine engines can be offered at lower prices principally as a result of an existing production base.

- The advanced turbine engine in the 224-447 kW (300-600 hp) class offers the potential for lighter more efficient aircraft than can be achieved with current turbine engines and at moderate reduction in ownership costs.

- The low cost of the piston engine compared to turbine engines is the primary factor in its favor.

4c. Evaluation of a Common Core Concept

APPROACH

Having identified that the GATE engine should be an advanced technology, air-cooled, high pressure-ratio engine in the 373 kW (500 hp) class, attention was directed to obtaining the broadest application of the gas generator core to general aviation requirements. The obvious solution was to configure the engine so that turboprop, turboshaft, and turbofan variants could be obtained with the least modification and development problems.

ENGINE CONFIGURATION

The engine configuration was reviewed in terms of maximum usage of the gas generator core defined in the trade studies. Turboprop and turboshaft versions were desired to satisfy the fixed wing and helicopter markets. The possibility of a turbofan variant was also considered. Although no viable market for a small turbofan engine was forecast for 1985-1990, the life of the engine frame would be expected to reach at least the year 2000. By that time a small fan engine application could appear, thus it was decided to configure an engine which would also be adaptable to a turbofan conversion. By core commonality to all three variants, cost reduction through increased core production could be achieved.

The trade studies indicated a strong trend toward high pressure ratio and high turbine temperature. Since the studies were broad based, iterations through the total engine design process were not made; therefore, where differences between individual engine configurations were small, selections could not be made. A two-stage centrifugal compressor engine at a pressure ratio of about 14 showed up well with an aircooled two stage axial turbine and a two stage power turbine. A simpler engine using a single-staged centrifugal compressor at a pressure ratio of 10, and a cooled radial inflow turbine was also highly rated. Axial centrifugal compressor configurations were not examined in detail because of their inherent cost disadvantage at the higher pressure ratios preferred in the general aviation application.

Foldback combustors featuring transpiration cooling were applied to achieve a more compact engine and provide adequate liner cooling.

The choice of a single versus a two-shaft engine included the considerations discussed below.

Performance

Matching propeller and engine aerodynamic characteristics at off-design mission operating conditions are much improved with the two-shaft design which permits independent selection (scheduling) of the gas generator and the power turbine speeds. The two-shaft system also permits improved overall engine design point performance since each turbine component can be designed for maximum efficiency at its primary operating speed. SFC and DOC are consequently significantly improved.

A two-shaft engine would be better for low flight speed applications resulting from greater turbine expansion ratio.

The gas generator of the two-shaft engine is not affected by large transient load variations which can cause a 20% rotor speed droop.

Mass and Cost

An output shaft failure mechanically unloads the driving turbine permitting high instantaneous acceleration until detected and corrected by the control system. Such acceleration of a single-shaft rotor system is slow enough to be easily controlled since the compressor would still be absorbing power. The power turbine of a two-shaft rotor system must be better protected from such a possible overspeed condition by a more complex control system, and/or controlled turbine blade shedding. Attention to these requirements during the engine design can result in achieving satisfactory safety levels with little increase in mass. Location of the combustor over the turbine, for instance, adds some containment and current FADEC control incorporate automatic power turbine governing plus a redundant protection system.

The single-shaft system has fewer operating parameters; therefore, fewer condition monitoring-control system sensors are required. The control system will be somewhat simpler to design but should not vary significantly in price, mass, or reliability since in either design a full authority digital electronic control (FADEC) is assumed.

The single-shaft T56 uses the engine compressor to generate negative torque and negative propeller thrust during flight idle operation on landing approach. Propeller blade angle is still positive, and positive propeller thrust can be achieved quickly by increasing engine fuel flow and power. The use of negative propeller blade angle with positive torque can achieve the same results but is usually more difficult to control with the same sensitivity. This latter mode would be required with the two-shaft system configuration. However, small aircraft may not need propulsion system contribution to decelerate for landing relying instead solely upon wing and tail control surface (and landing gear) drag, which may be entirely sufficient.

A prior DDA design study resulted in a single-shaft version of the free power turbine XT701 engine. Comparative calculated masses were 500 and 535 kg, respectively, indicating only a 7% mass penalty against the free power turbine system.

The single-shaft system generally has fewer parts, which often translates into slightly less engine cost. Fewer rotor support bearings may be required.

The free power turbine system permits a smaller, lighter starter and starter drive train since only the gas generator rotor must be accelerated rather than the complete engine and propeller. Similarly, the propeller brake, if used, would be smaller since less rotating inertia mass must be decelerated.

The propeller is not mechanically coupled to the high drive-powered compressor. In event of a turbine failure, the propeller is not immediately decelerated, and no large drag forces are imposed upon the airframe. In a twin engine application, such a drag would be asymmetric and would impose high aircraft tail structure loads.

The possibility of such deceleration forces in single-shaft systems such as the T56 has led to the incorporation of a safety coupling that decouples the propeller from the engine when a preselected negative torque value is exceeded. Stronger, heavier aircraft tail structures would otherwise be required.

Counterrotation of the gas generator and power turbine rotors is generally preferred. Gyroscopic loads of the two rotors are thus opposed and tend to cancel each other. Therefore, lighter engine and A/C structure may be possible.

Operational

The two shaft engine can have reduced prop speed for low noise considerations, since the two turbine speeds can be selected independently.

The gas generator rotor can be operated on the ground by itself (without propeller rotation) for on-wing check-out of engine accessory performance thus facilitating maintenance and repair operations. Aircraft accessories are generally driven by the power turbine shaft system and would still require propeller rotation during installation check-out.

Commonality

With respect to commonality considerations, the two-shaft engine permits better turbine performance for shaft engines and permits matching of turbine-to-fan speed for fan engines.

POWER RANGE

A nominal 373 kW (500 shp) engine designed to operate with an air-cooled turbine has considerable latitude in rated power and thus a broadened set of potential applications with fairly small sacrifice in efficiency as shown in Figure 82. Examination of the 14:1 compressor pressure ratio engine configuration No. 30 indicates that the engine derated 20% by reducing turbine temperature 125 K (225°F) would increase sfc less than 5%. Increasing turbine temperature 56 K (100°F) could provide approximately 5% more power with a 1% penalty in sfc while retaining the two-stage power turbine. These estimates include appropriate change in vane and blade cooling air and turbine efficiency and involve relatively inexpensive resetting of the turbine nozzle areas. Using a three-stage power turbine would yield somewhat more power and better sfc as shown, but would be a more costly modification.

Engine Selection

Engine 30 appeared best overall in all applications studied. Engine 28 was somewhat better in the helicopter. A comparison of the 10:1 R_c engine (28) against the 14:1 R_c engine (30), which has been shown to be optimum in the fixed wing application, provides the following GM and TCO trade-off percentages.

Heavy Twin

Engine 28 would produce a 17% heavier design vehicle than engine 30 and would have a 19% higher TCO.

Unpressurized Twin

Engine 28 would produce a 5% heavier design vehicle than engine 30 with a 6% higher TCO.

Helicopter-Twin

Engine 30 would produce approximately the same design vehicle gross mass as engine 28, but would have a 2.5% higher TCO.

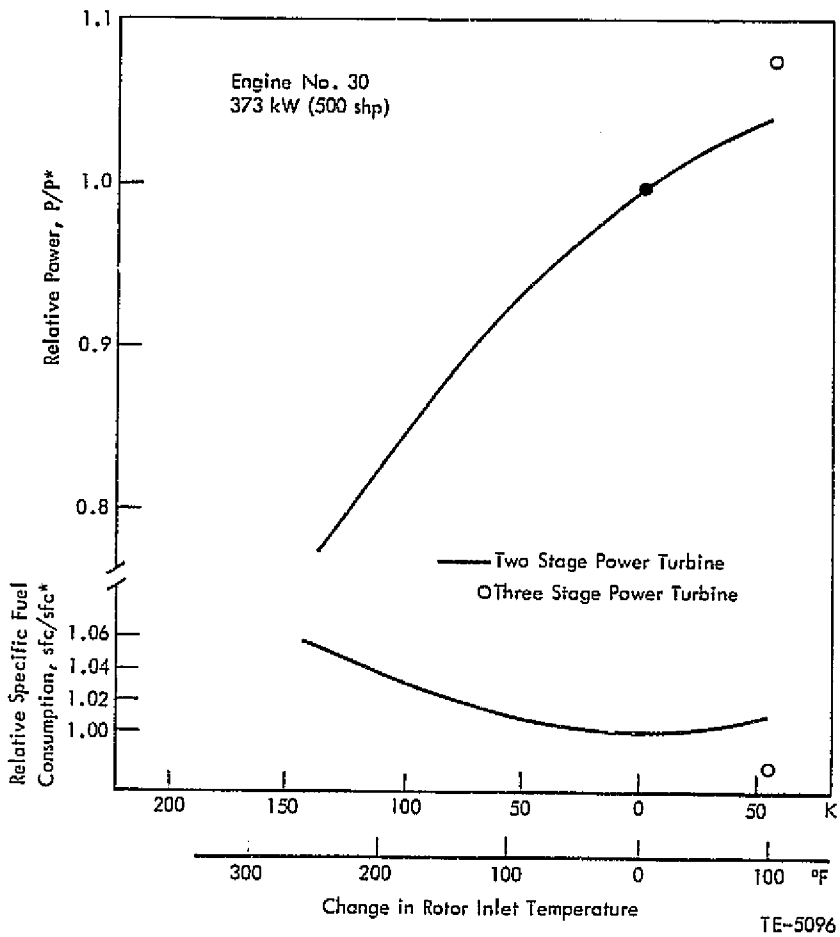

Figure 82. Effort of rated rotor inlet temperature.

4d. Technology Program Plan

DDA prepared a plan that delineated our view of the proper content of a government sponsored program designed to develop and demonstrate advanced technologies for small general avaiation turbine engines. The program plan included the scope, schedules, and cost projections.

Part of the task was to provide DDA's view of NASA's role in the GATE program. DDA recommended a role strongly oriented to sponsoring meaningful basic research at the engine component level to develop the data base required to ease the introduction of new technologies into engine development programs at the engine company facilities. In performing this function, NASA should also sponsor studies such as GATE as well as preliminary design studies to serve as a catalyst to encourage the application of new technology. The strong part NASA played in early aircraft gas turbine engine component applied research was cited for its excellence and continued usefulness in guiding design choices in engine development efforts. Although core demonstrators sponsored by NASA may have merit in basic investigations of the interrelationships of components, most major efforts in work of this scope should be oriented toward a development effort and be user sponsored. Commercial engine development and certification should be user sponsored and based on market drivers.

Specific recommendations related to NASA's role in GATE were to perform and sponsor component research applicable to a 373 kW (500 hp) class gas turbine engine to provide basic data to achieve

- Reduced manufacturing cost
- Improved component performance
- Engine/airframe integration
- Improved gearing

Figure 83 shows the overall plan from the GATE study and recommended GATE follow on to a continuing program of research and development on all gas turbine engine components and systems. Further appliciation studies are recommended, and the need for core demonstrator work is shown as R & D efforts on the small engine components mature. Approximately 25 detailed technology programs were defined as required in support of the DDA concept of NASA's role in GATE. Titles of these programs and areas of highest benefit are shown in Table L.

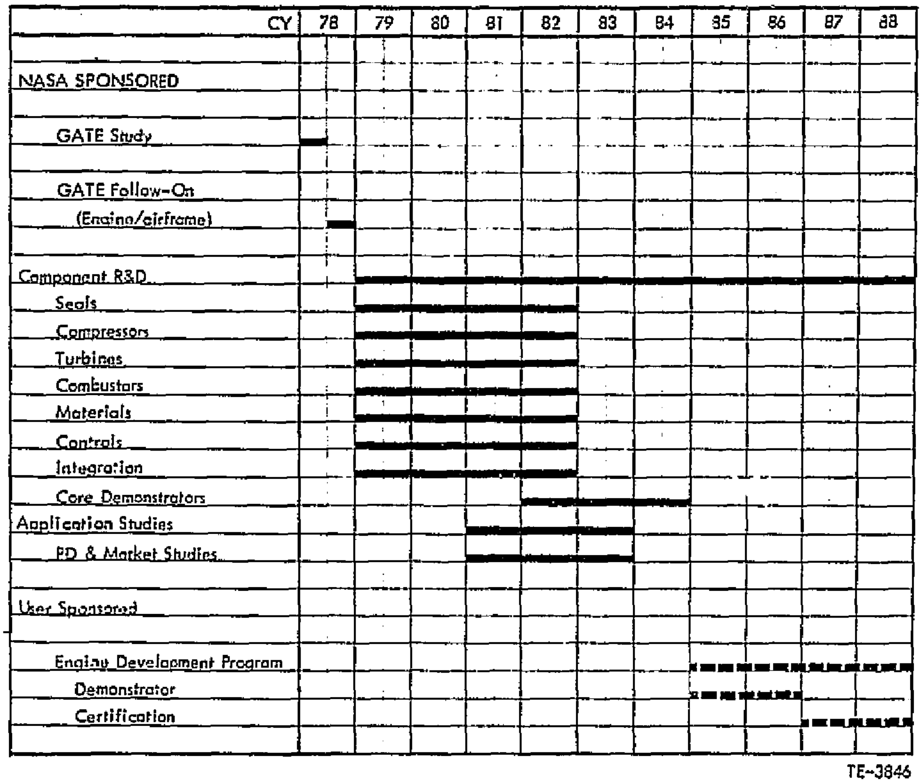

Figure 83. Task IV--technology plan.

TABLE L. - GATE TECHNOLOGY PLAN

Title	Benefit
Material and Processes	
Dual property titanium impeller	Reduce cost
Lamilloy combustor fabrication tech	Reduce cost
Rejuvenation of turbine components	Reduce cost of ownership
Abradable seals	Improve performance and life
Structural control for cast TI components	Improve quality
Thermal barrier coatings	Improve life
Gearbox and Shafting	
Composite shafting	Reduce cost and weight
High performance PM gears	Reduce cost
Composite material gear housings	Reduce cost and weight
Propeller reduction gear general arrangement	Reduce cost and weight
Failure tolerant ball and roller bearings	Improve bearing reliability
Spiral bevel gear load capacity tests	Reduce cost and weight
Advance Structure	
Ceramic turbine vanes and tip shrouds	Reduce cost
Fluid Dynamics	
Improved sealing, small gas turbines	Improve performance
Inlet configuration studies	Improve performance
Exhaust configuration studies	Improve performance
Aerotherm	
High efficiency small air-cooled turbine	Improve performance
Small high pressure ratio compressor	Improve performance
No. 1-stage dev of 2-stage centrifugal compressor	Improve performance
Low-cost prechamber combustor	Reduce cost
Controls	
Control system conceptual design	Define requirements
High reliability, low cost electronic control dev	Reduce cost, improve reliability
Fuel handling system development	Reduce cost, weight, size
Application	
Advanced twin turboprop concept study	Define payoff

V. SUMMARY OF RESULTS

MARKET ANALYSIS

General aviation aircraft sales were forecast to increase substantially over the next 10-yr period, realizing an average annual increase in US general aviation and helicopter airframe production of 4%. This represents an increase of from approximately 16,000 units per year in 1976, to over 25,000 units in 1988.

During this time, the piston and turbine engine are expected to share the propulsion market. The piston engine will remain firmly established in the smaller power sizes up to 224 to 298 kW (300 to 400 hp), while turbine power could predominate at the higher powers. Other shaft power concepts such as the rotary combustion engine are not expected to enter into significant contention.

Turbofan engines have found good acceptance in general aviation; however, in the sizes of interest in the GATE study, i.e., less than 6672 N (1500 lbf) thrust, no substantial market was anticipated. Customer acceptance of propellers has not been a problem in the GATE class of aircraft, and although jet power is attractive in terms of speed, the potential of the turboprop seems insurmountable for the short term. Turboprop speeds are sufficiently high to cause little difference in block-to-block times for the average trip. In addition, the turboprop fuel economy advantage could be an increasingly important deterrent to the penetration of the turbofan engine into smaller general aviation aircraft.

Potential markets identified for a GATE engine were nearly equal in total dollar volume above and below 447 kW (600 hp). The market was heavily dependent on GATE engine acceptance for fixed-wing applications. Above 447 kW (600 hp), current development programs in the engine industry are expected to result in a strong base from which to launch commercial turboshaft, turboprop, and turbofan engine programs. Below 447 kW (600 hp), no new technology programs had been identified. As a result, it was recommended that the major part of the study effort be directed toward an engine in the 373 kW (500 hp) class to define the most viable engine concept, and a supporting technology program for the concept.

BROAD SCOPE TRADE-OFF STUDIES

Air vehicle classes and related missions representing important market segments were used in trade studies to identify the best general aviation turbine engine concepts. Pay off parameters considered were minimum acquisition cost, minimum direct operating cost and minimum cash flow as determined for the complete engine/airframe combination sized to meet design mission requirements. Aircraft gross mass was also an important parameter since it was a major driver on costs and engine power required.

The "bogey" in the study was a "current technology" gas turbine engine. DDA's latest Model 250 small gas turbine engine which entered production in 1978 was used to represent the current technology base. This engine is a highly competitive machine in terms of performance, mass, and cost and represented a formidable state of the art. For the purpose for this study, the engine was considered scalable to other sizes, and its cost was adjusted to the study standards for two cases assuming (1) a hypothetical case with no production base or inherited learning and (2) inherited learning, i.e., the situation which exists when a manufacturer introduces a new model in a long production run of similar models. The cost difference resulting from "learning " was found to be a major factor in comparing the costs of new advanced engines with those already in production.

Parametric engines were defined in terms of design and off-design performance, mass, geometry, and acquisition and maintenance costs. Related hardpoint engines and components were used to guide the parametric designs. Scaling procedures were developed to appropriately modify engine characteristics as the engines were sized to match the varying airframe and mission demands. Engine parametric designs covered a range of pressure ratio from 5.5 to 16 at turbine rotor inlet temperature from 1339 to 1561 K (1950 to 2350°F). Two-stage centrifugal compressors were examined with two-stage axial gas generator turbines and two-stage axial power turbines. One stage centrifugal compressor engines were studied with gas generator turbine variants including two-stage axial, one-stage axial, and radial inflow. Sensitivity studies were accomplished at the component level to measure impact on the vehicle gross mass and economics.

The parametric studies showed the GATE engine should be high pressure ratio and air cooled. Significant economic benefits for the complete aircraft were found as a result of improved sfc and engine mass, even though engine cost was somewhat higher than a new turbine engine using current technology. Table LI summarizes engine configurations and results for three applications representing a heavy twin, an unpressurized cabin class twin and a light helicopter twin.

TABLE LI. - TASK II "OPTIMUM" ENGINES

	Heavy twin	Unpr twin	Hel twin
Nominal shaft power, kW(hp) (*flat rated)	820(1100)	403(540)	298(400)
Cycle	14:1 1478K(2200°F)	14:1 1478K(2200°F)	10:1 1478K(2200°F)
Configuration	2-Stage Centrifugal 2-A GPT 2 spool	2-Stage Centrifugal 2-A GPT 2 spool	1-Stage centrifugal 1-radial air-cooled 2 spool
Benefits compared to current technology engine (with production base)			
GM, %	-21	-11	-12
TAC, %	-7	+5	+1
TCO, %	-20	-11	-8
Fuel reduction, %	32	23	24

The engine concepts selected for GATE featured a high pressure ratio compressor, either 14:1 pressure ratio in a two-stage centrifugal, or 10:1 pressure ratio in a one-stage centrifugal; the turbine temperature selected was 1478 K (2200°F) with an air-cooled two-stage axial, high-pressure turbine for the 14:1 engine, and an air-cooled, radial inflow turbine for the 10:1 engine. Other engine features included Lamilloy combustor, ceramic turbine stators, composite gearbox and a dual property high-pressure turbine.

The GATE engines realized significant improvements in airframe size and economics compared to the current technology engine. Aircraft gross mass was reduced from 11 to 21%, acquisition costs were lower by 7% to higher by 5% depending on the application, but total cost of ownership over the 8-yr period used in the study was lower in each case by 8 to 20%. These economic comparisons apply to the case where the advanced engine competed with an existing current technology engine (i.e., with price advantages consistent with inherited learning). In addition, mission fuel requirements were reduced by 23 to 32% which results from a 20% improvement in engine fuel efficiency and a 23 to 24% improvement in engine specific mass. These engine improvements react strongly on the aircraft by reducing the gross mass required to perform the mission with consequent reduction in drag and engine power size.

The relative engine performance and costs for the best advanced engines compared to the current technology engines are shown in Table LII for turboprop and shaft engine configurations. Note that the advanced engine cost increases are from 3 to 13% when compared to a new engine using current technology. Although cost is of paramount importance in the commercial world, the trade

TABLE LII. - RELATIVE PERFORMANCE AND COST—ADVANCED VS CURRENT TECHNOLOGY

373kW(500 hp) GAS TURBINE ENGINES

	Current Technology		Selected GATE Technology	
			Pressure ratio turbine temp, K(°F)	
	Baseline engine (no inherited learning)	Baseline engine (inherited learning)	10 1478 (2200)	14 1478 (2200)
Turboprop	Reference	% Change	% Change	% Change
sfc	100	none	20% better	20% better
mass	100	none	24% lighter	23% lighter
cost	100	12% less	4% less	3% more
maintenance cost	100	12% less	40% less	35% less
Turboshaft				
sfc	100	none	20% better	20% better
mass	100	none	24% lighter	23% lighter
cost	100	12% less	4% more	13% more
maintenance cost	100	12% less	35% less	30% less

studies showed that the new engine advantages in fuel economy (sfc), mass, and maintenance cost more than offset the initial cost increase on a cost of ownership basis.

Sensitivity studies comparing the turbine and piston engines showed that engine costs were the biggest factor favoring the piston engine. The advanced turbine engine appears competitive in terms of installed performance, and has a large advantage in engine mass, however, the cost differentials are extreme as shown in Figure 84.

EVALUATION OF A COMMON CORE CONCEPT

An engine configuration adaptable to turboprop, turboshaft, and turbofan variants with minimum redesign was chosen featuring a separate power turbine with provisions for forward centerline power output. This type of engine offers the greatest flexibility for turboprop and turboshaft applications, and offers increased potential for furture turbofan engine derivitives. Although market projections for the late 1980s indicated a lack of demand for small turbofan engines, the possibility for eventual need for commercial or military application was not overlooked.

An analysis of the market potential for the advanced technology GATE engine indicated that the GATE program could have a considerable impact on the future of general aviation. In the 400-600 shp class, an additional 650 engines per year was forecast for 1988. The advanced technology small engines, in allowing considerable downsizing of the aircraft for various missions permits the building of highly fuel-efficient aircraft. While there may be some question about the industry's capabilities for using this technology in all product lines in 1988, the turbine-powered aircraft market of the 1990s can be completely dominated by the advanced technology engine-powered vehicles.

TECHNOLOGY PROGRAM PLAN

The GATE study showed significant advantages for an air-cooled, high pressure ratio small gas turbine engine. The recommended size in the 373 kW (500 hp) class addresses to a new frontier for small engine technology as the next step following the current U.S. Army program for a technology demonstrator at 597 kW (800 hp). Figure 85 shows how specific fuel consumption trends in small gas turbine engines could be affected.

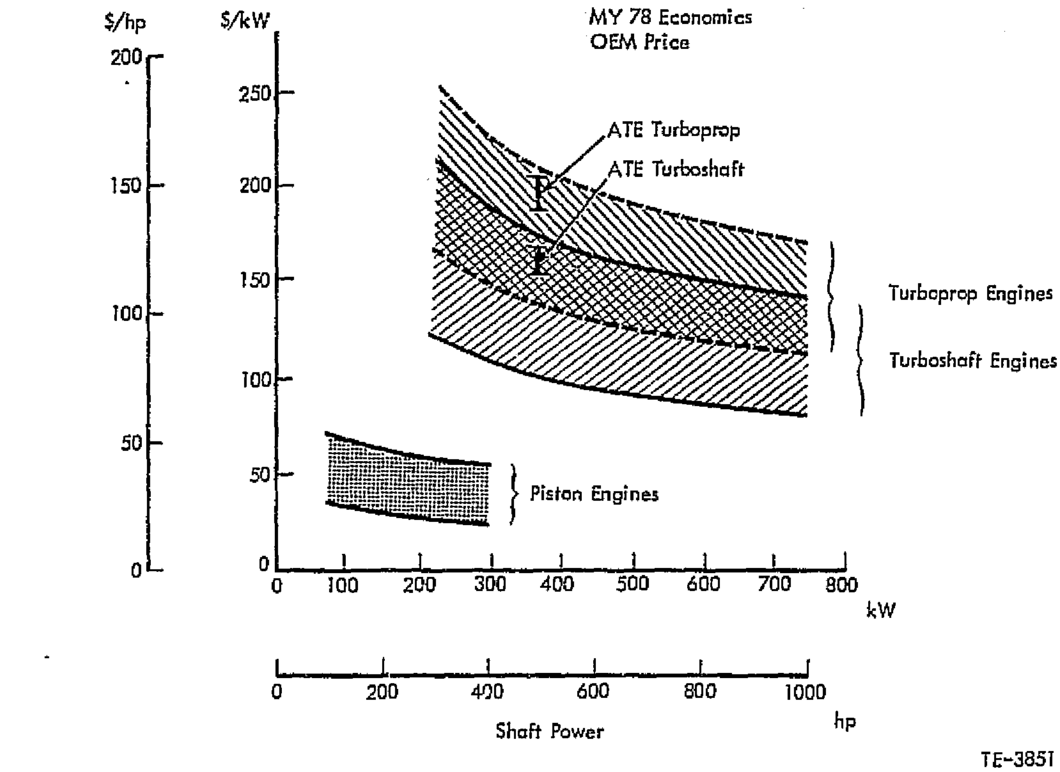

Figure 84. Specific cost trends.

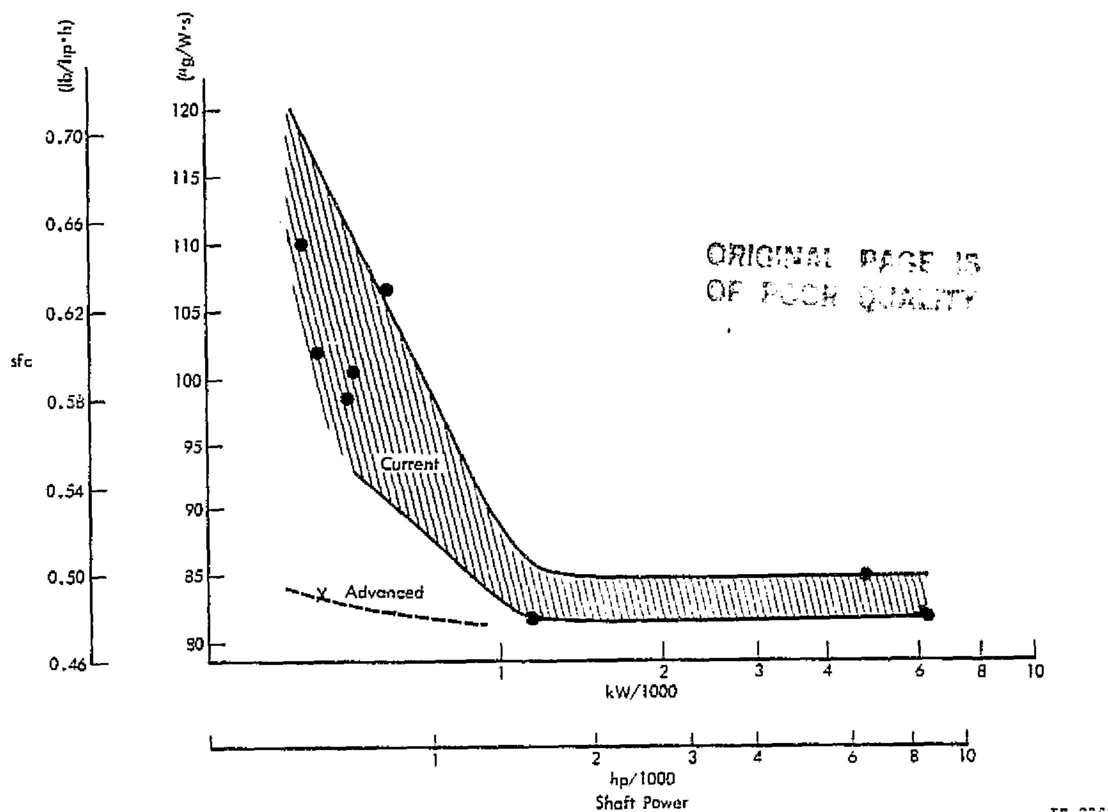

Figure 85. Small gas turbine technology lag.

The role recommended for NASA was one of active accomplishment and support of meaningful basic component research in compressors, combustors, turbines, seals, controls, gearboxes, and shafting including on-going efforts in materials and engine/airframe integration. It was also recommended that NASA serve as the catalyst to encourage the introduction of useful new technology into engine designs through application studies and core demonstrators as component R & D work matures. Engine development and certification programs, however, should be user sponsored based on market needs.

Twenty-four suggested program plans were described and provided to NASA in support of the recommended role.

APPENDIX

GATE Cost Analysis Computer Program

Note: This computer program was devised in customary units only; thus, only the customary units are used in the description of the program and the sample problem.

INTRODUCTION

The cost analysis program developed for the NASA General Aviation Turbine Engine (GATE) study provides the following cost information for fixed as well as rotary-wing aircraft:

- Total aircraft acquisition cost, dollars
- Direct operating cost, dollars/$fl h
- Total cost of ownership, dollars
- Cash flow analysis, dollars

This appendix is a presentation of the methodology used in the DDA cost analysis program. It begins with a description of the input data required. Discussions of the total aircraft cost, direct operating cost, total cost of ownership, and cash flow analysis follow. Finally, a sample problem illustrating the cost analysis computer program input and output is presented.

INPUT DATA

The input data required by the cost program comprise the mission and aircraft/engine sizing results obtained from the DDA Mission Analysis Computer Program. They also serve to establish a number of cost parameters.

Mission and Aircraft/Engine Sizing Results

The following is a list of mission and aircraft/engine information communicated to the cost routine:

Symbol	
TB	Block time--total mission time, h
D	Block distance, statute miles (SM)
VB	Block velocity, statute miles per hour (mph)
FB	Block fuel, lb
TF	Flight time--block time less ground maneuvering time including T.O., h
GWE	Aircraft design gross weight, lb
WME	Aircraft empty weight, lb
WENGI	Engine weight, lb

Engine price (Original Equipment Manufacturer), dollars

Engine maintenance cost, dollars/flight hour ($/fl hr)

Cost Parameters

The cost parameters listed in Table LIII were established to complete the cost analysis routine input data for fixed, as well as rotary-wing aircraft. These values reflect 1978 base year economics. A second fuel cost and utilization (shown in parentheses) were used in the cost calculations to obtain sensitivity data. An inflation factor of 0.0% was observed throughout this cost analysis.

TABLE LIII.—COST PARAMETERS

Cost parameter	Symbol	Fixed wing	Helicopter
Fuel cost, $/gal	CFT(CFTI)	0.83(1.24)	0.83(1.24)
Oil cost, $/gal	COT	9.50	9.50
Depreciation period, yr	DR	8	8
Aircraft less engine spares, %	SPA	0	0
Engine spares, %	SPE	0	0
Labor rate (including burden), $/h	RL	20	20
Annual utilization, h/yr	U(UI)	600(900)	360(600)
Annual insurance rate, %	XIRA	1	5
Annual rate of depreciation, %	ARD	25	25
Annual interest rate, %	AIR	10	10
Down payment rate, %	DPP	10	10
Resale value, %	RSV	40	40
Rate of tax saving, %	RTS	52	52
Residual value, %	RV	20	20
Hangar rental, $/yr	HRY	3540	--
Aircraft registration, $ + $/lb	IC+(CPP)	25 + (0.035)	--

TOTAL AIRCRAFT COST

The total aircraft acquisition cost was calculated by summing the engine and the aircraft-less-engine costs as follows:

TAC = (CE*ECOSTX) + (EWLE*ACQS)

where

TAC	=	total aircraft cost, $
EWLE	=	aircraft empty weight less basic engine weight, lbm
ACQS	=	aircraft cost, $/lb
CE	=	number of engines
ECOSTX	=	list price of single engine, $
ECOSTX	=	1.5*OEM

where

OEM = Original Equipment Manufacturer's price, $

The Original Equipment Manufacturer's (OEM) price is calculated by multiplying the specific cost for the scaled engine (in OEM dollars per shp) by the scaled engine shp rating.

The specific cost for the scaled engine is established by multiplying the unity engine specific cost by the engine scaling effect.

The specific cost for the unity engine is supplied by DDA's Value Engineering Department as input data to the cost analysis program. The engine scaling effect is established by using Figure 86.

The aircraft costs listed in Table LIV were used in the GATE study (11).

TABLE LIV. - AIRCRAFT SPECIFIC COSTS (Includes Avionics)

Aircraft	Specific cost, $/lb
Unpressurized twin	50.30
Light twin	56.50
Heavy twin	85.00
Light agricultural	20.00
Light single helicopter	60.00
Light twin helicopter	120.00

The fixed-wing aircraft cost curve (Figure 87) supplies the specific costs for the light, heavy, and unpressurized fixed-wing aircraft. The light twin was assigned a specific cost value based on the Beech Baron 58P and Cessna 414 aircraft plots. The Piper Cheyenne provided the data for the heavy twin air-

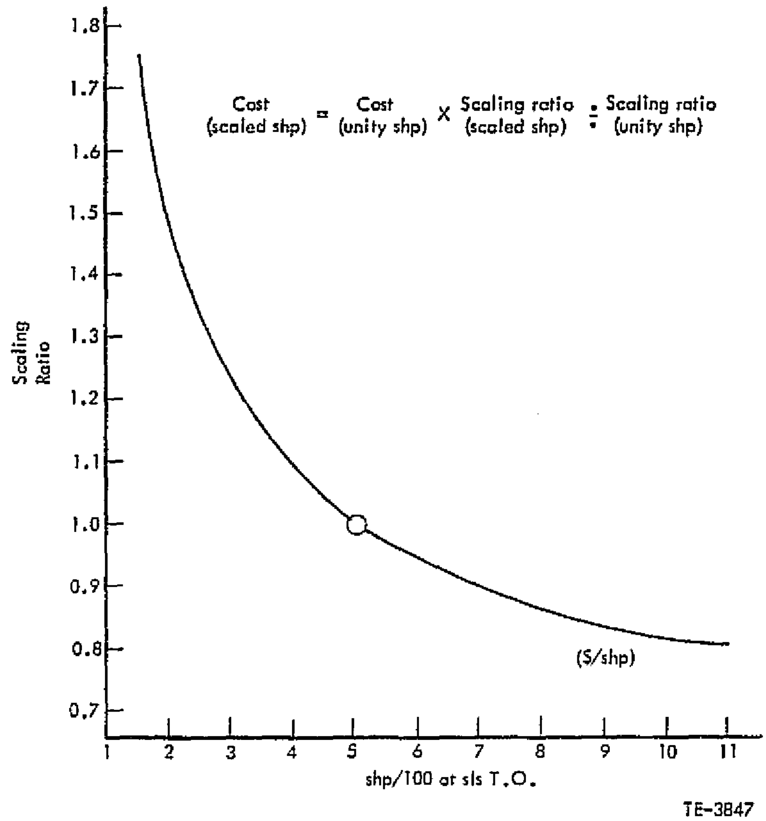

Figure 86. GATE turboshaft and turboprop engine sealing ratios for engine-specific and maintenance costs.

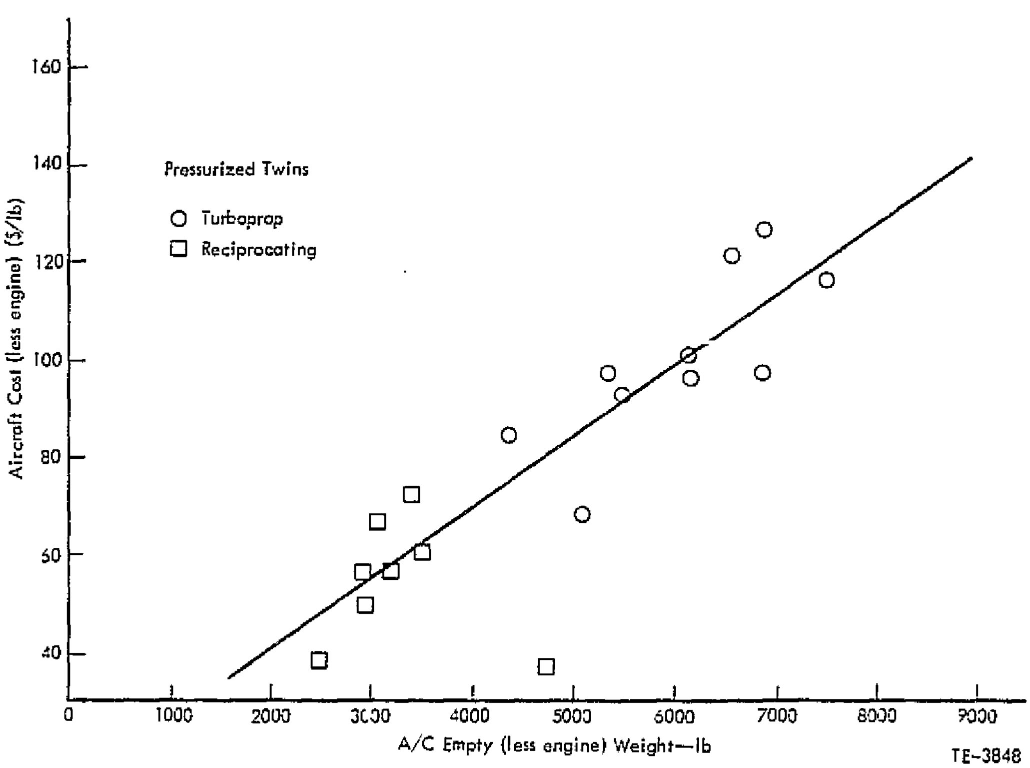

Figure 87. Cost curve--fixed-wing aircraft.

craft specific cost. The cost relationship between the pressurized (Cessna 414) and unpressuriz i (Cessna 402B) twin aircraft applied to the light twin specific cost results in the specific cost for the unpressurized twin.

The specific cost for the light agricultural aircraft was based on the Rockwell Thrush Commander aircraft (12). The Bell Helicopter acquisition costs curve (Figure 88) provided the specific cost for the light twin helicopter. DDA assumptions formed the basis for the specific cost assigned to the light single helicopter.

DIRECT OPERATING COST

Direct operating cost (DOC) is the cost of using and maintaining an aircraft. ATA DOC calculation methodology (13) was used for fixed and rotary wing aircraft unless otherwise indicated. The total DOC was determined by summing the following items:

- Fuel and oil cost
- Hull insurance
- Aircraft less engine maintenance cost
- Engine maintenance cost
- Depreciation

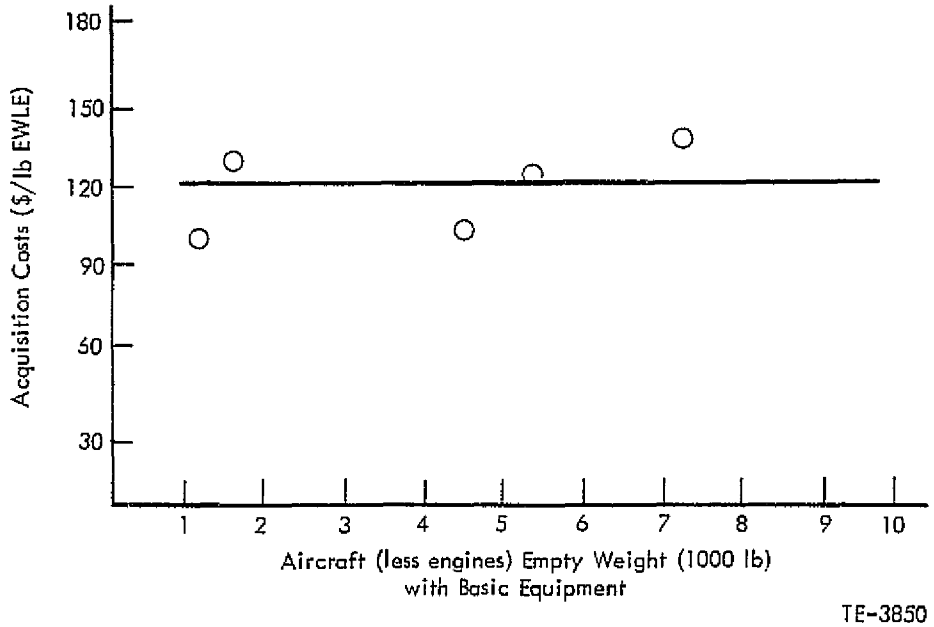

Figure 88. Helicopter acquisition cost.

o Aircraft registration fee*

o Hangar rental*

*Not included in the rotary wing DOC calculation.

Fuel and Oil Cost

FOC = 1.02*((FB*(CFT/6.5))+(CE*.135*(COT/8.1)*TB))/D

where

FOC = fuel and oil cost, $/SM

FB = block fuel, lbm

CFT = cost of fuel, $/gal (refer to Table LIII)

CE = number of engines installed

COT = cost of oil, $/gal (refer to Table LIII)

TB = block time, hr

D = block distance, SM

The rate of consumption of oil was assumed to be 0.135 lbm/hr/engine. The oil density was 8.1 lbm/gal; jet fuel (JP-5) density was 6.5 lbm/gal.

Hull Insurance

HI = (XIRA*TAC)/(U*VB)

where

HI = hull insurance, $/SM

XIRA = annual insurance rate, % (refer to Table LIII)

U = annual utilization, hr/yr (refer to Table LIII)

VB = block velocity, mph

Aircraft Less Engine Maintenance Cost--Fixed and Rotary Wing Aircraft

Fixed Wing

Aircraft less engine maintenance labor and material cost for the fixed-wing aircraft was calculated per Ref. 13.

Labor Cost

AFMLF = ((XKFCA+(XKFHA*TF))/(VB*TB))*RL

where

AFMLF = aircraft less engine maintenance labor cost, \$/SM

XKFCA = labor man-hours/flight cycle

XKFCA = 0.05*(EWLE/1000)+6-(630/((EWLE/1000)+120))

where

EWLE = aircraft empty weight less basic engine weight, lbm

XKFHA = labor man-hours/flight hour = 0.59*XKFCA

TF = flight time, hr

RL = labor rate, \$/hr (refer to Table LIII)

Material Cost

AFMMF = ((CFHA*TF)+CFCA)/(VB*TB)

where

AFMMF = Aircraft less engine maintenance material cost, \$/SM

CFHA = material cost, \$/flt hr = 3.08*TAC/10^6

CFCA = material cost, \$/flight cycle = 6.24*TAC/10^6

<u>Rotary Wing</u>

Aircraft less engine maintenance labor and material costs for the rotary wing aircraft were calculated using the following equations derived from Bell Helicopter data (14).

Labor Cost

AFML = (((2.345*10^{-8})*EWLE-(2.729*10^{-5}))*EWLE*RL+3.506)/VB

where

AFML = Aircraft less engine maintenance labor cost, \$/SM

Material Cost

AFMM = ((7.338*(2.718**((2.633*10^4)*EWLE)))/VB*APCOST

where

AFMM = aircraft less engine maintenance material cost, \$/SM

APCOST = aircraft less engine material cost adjustment factor

where	Helicopter	Adjustment Factor
	Light single	0.5
	Light twin	1.0

Engine Maintenance Cost

Unity engine maintenance labor and material costs were obtained from the DDA Operation and Support Cost Program (OS590) (15). Scaled engine maintenance costs were obtained by using engine scaling effect in a manner similar to engine acquisition cost adjustment (refer to "Total Aircraft Cost" heading in this appendix).

Depreciation

Depreciation was figured as follows:

DEPR = (1/VB)*((TAC+SPA*(TAC-(CE*ECOSTX))+SPE*CE*ECOSTX)/(DR*U))

where

DEPR = depreciation over U hours, $/SM

SPA = aircraft less engine spares, % (refer to Table LIII)

SPE = engine spares, % (refer to Table LIII)

DR = depreciation period or years of ownership (refer to Table LIII)

Aircraft Registration Fee and Hangar Rental

Aircraft registration and hangar rental were not included in ATA's report (13). They were included in the DDA general aviation fixed-wing aircraft DOC but not in the rotary-wing DOC calculation.

Registration

Aircraft registration fee varies with the level of use and was calculated as follows:

R = IC+((CPP*GW)/(U*VB))

where

R = registration fee, $/SM

IC = initial charge, $(refer to Table LIII)

CPP = charge per pound, $/lb (refer to Table LIII)

GW = gross weight of aircraft, lbm

Hangar Rental

Hangar rental also varies with the level of use and was calculated as follows:

HR = HRY/(U*VB)

where

HR = hangar rental, $/SM

HRY = annual hangar rental, $/yr (refer to Table LIII)

Crew costs were not included in this cost analysis for general aviation aircraft. A breakdown of DOC was included to identify the components that make up the DOC and their relative significance with respect to total operating costs. The following equation was used to convert DOC units of dollars per statute mile to dollars per flight hour:

DOCH = DOCM*VB

where

DOCH = direct operating cost, $/fl h

DOCM = direct operating cost, $/SM

TOTAL COST OF OWNERSHIP

Total cost of ownership (TCO) is an indication of the cost to purchase and operate the aircraft over a specific period of ownership. As defined by DDA, TCO includes the following cost items:

- Total aircraft cost
- Fuel and oil cost
- Aircraft less engine maintenance cost
- Engine maintenance cost

TCO was calculated as follows:

TCO=TAC+((FOC+AFML+AFMM+ENML+ENMM)*VB*U*DR)

where

TCO = total cost of ownership, $

ENML = engine maintenance labor cost, $/SM

ENMM = engine maintenance material cost, $/SM

CASH FLOW ANALYSIS

The cash flow analysis consisted of two components—cash outflow and cash inflow—both in terms of dollars per year over a specific period of operation.

The constants defined in the following paragraphs are assumed to be valid for rotary and fixed-wing aircraft unless otherwise stated (16, 17).

Cash Outflow

The cash outflow is composed of cost elements which were "paid out." The cash outflow includes the down payment, an annual payment on the aircraft loan, and the cost of operating the aircraft.

Down Payment

The down payment is required only in the first year of ownership and is calculated as follows:

DPY(1) = TAC*DPP

where

DPY(1) = down payment, $ for year 1

DPP = down payment rate, % (refer to Table LIII)

Annual Payment

The annual payment on the aircraft loan decreases as the time of ownership increases and is calculated as follows:

AP(M) = 12*XMLP+XIN(M)

where

AP(M) = annual payment, $ for year M

M = indication of year, (1 through DR years)

XMLP = monthly level payments, $/mo

XMLP = (TAC-(TAC*DPP))/(12*DR)

XIN(M) = annual interest, $ for year M (refer to Table LIII)

XIN(M) = (B1-((M-1)*12*XMLP)-(XMLP*66)/12)*AIR

where

B1 = first unpaid balance, $

B1 = TAC-(TAC*DPP)

AIR = annual interest rate, % (refer to Table LIII)

Note that the monthly level payments do not include interest. Annual interest is the sum of the monthly interest based on the monthly balance and one-twelfth of the annual interest rate.

Operating Costs

The total annual operating cost was determined by summing the variable and fixed costs.

Variable Costs

Variable costs are those items which are influenced by use and/or fuel costs. The variable costs include:

- Fuel and oil
- Aircraft less engine maintenance labor and material
- Engine maintenance labor and material

Fixed Costs

Fixed costs are those items which are unaffected by use and fuel costs. The fixed costs include:

- Hangar rental
- Insurance
- Aircraft registration fee

The total cash outflow is obtained by summing the previously described yearly cost elements over M years.

Cash Inflow

The cash inflow was composed of items considered as "income" with respect to current corporation income tax procedures. These included an investment tax credit, a tax saving, and a cash sale.

Investment Tax Credit

The investment tax credit was applicable only in the first year of ownership and was equal to the down payment.

Total Tax Saving

The total tax saving was found by using the following equation:

TS(M) = (D(M)+XIN(M)+TAOC(M)+BA(M))*RTS

where

TS(M) = tax savings, $ for year M

D(M) = depreciation, $ for year M

Depreciation — Declining Balance Method for N Years

N = number of years declining balance method is used

N = LOG(RV)/LOG(1.0-ARD)

where

RV = residual value, % (refer to Table LIII)

ARD = annual rate of depreciation, % (refer to Table LIII)

D(M) = (1.0-ARD)**(M-1)*TAC*ARD

The declining balance method of depreciation used during the first N years of ownership applies a constant rate each year to the book value of the asset at the beginning of the year (18).

Depreciation — Straight-Line Method for Remaining Years of Ownership (N1)

N1 = number of years straight-line method is used

N1 = DR-N

D(M) = YD

where

YD = yearly depreciation, $

= RD*TAC

where

RD = annual straight-line depreciation rate, %
= ((1.0-ARD)**N-RV)/N1

The straight-line method of depreciation results in a constant depreciation charge each year and is used during the last years (N1) of ownership.

TAOC(M) = total annual operating cost, $ for year M

BA(DR) = book adjustment, $ for year DR

= -(TAC*RV)

where

RTS = rate of tax savings, % (refer to Table LIII)

The book adjustment was considered a negative inflow in the last year of ownership.

Cash Sale

The cash sale was applicable only in the last year of ownership and was equal to the estimated resale value. The cash sale was figured as follows:

CS(DR) = TAC*RSV

where

CS(DR) = cash sale, $ for year DR

RSV = resale value, % (refer to Table LIII)

The total cash inflow was obtained by summing the previous yearly values through DR years.

Net Cash Outflow

The yearly net cash outflow was equal to the yearly cash outflow less the yearly cash inflow. Summing these yearly net cash outflow figures over the period of ownership resulted in a net cash outflow for the entire ownership cycle.

SAMPLE PROBLEM

A typical set of the input and output data follows.

Input Data

The cost parameters (refer to Table LIII) and the data in Table LV complete the input to this sample problem.

TABLE LV. - SAMPLE PROBLEM INPUT

Variable	Value used
Block time	4.62 h
Block distance	1151.60 SM
Block Velocity	249.23 mph
Block fuel	1420.82 lb
Flight time	4.59 h
Aircraft design gross weight	7425.0 lb
Aircraft less engine empty weight	3570.9 lb
Engine weight	186.2 lb
Number of engines	2
Engine price (list)	$109,278.93
Engine maintenance cost	30.73(29.19)$/fl h
Aircraft cost	50.30 $/lb

Output Data

The input data are converted to the printed output, as shown in the following pages, when the computer cost analysis program is executed. Note that four separate printed outputs of the direct operating cost breakdown, the operating cost summary, and the cash flow analysis tables are delivered for each aircraft/engine design studied. These are organized as represented in Table LVI.

TABLE LVI. - COMPUTER OUTPUT ORDER

Output number	Fixed-Wing aircraft		Rotary-wing aircraft	
	Fuel cost, $/gal	Utilization h/yr	Fuel cost, $/gal	Utilization, h/yr
1	0.83	600	0.83	360
2	0.83	900	0.83	600
3	1.24	600	1.24	360
4	1.24	900	1.24	600

GATE COST ANALYSIS
DIRECT OPERATING COSTS

AIRFRAME COST=	160884.500	ENGINE COST=	109278.937	AIRCRAFT COST=	379442.375				
FUEL COST=	0.1575	FUEL COST=	0.2354	OIL COST=	0.0013	INSURANCE=	0.0254	INSURANCE=	0.0189
A/F LABOR COST=	0.0674	A/F MATERIAL COST=	0.0028	ENG LABOR COST=	0.0494	ENG LABOR COST=	0.0469		
ENG MATERIAL COST=	0.1972	ENG MATERIAL COST=	0.1874	DEPRECIATION=	0.3172	DEPRECIATION=	0.2115		
REGISTRATION=	0.0019	REGISTRATION=	0.0013	HANGAR RENTAL=	0.0237	HANGAR RENTAL=	0.0156		

DIRECT OPERATING COSTS= 210.30
DIRECT OPERATING COSTS= 176.63
DIRECT OPERATING COSTS= 229.69
DIRECT OPERATING COSTS= 196.03

TOTAL COST OF OWNERSHIP

TOTAL COST OF OWNERSHIP= 948459.37 1210791.00 1041559.37 1350441.00

DIRECT OPERATING COST RESULTS
* DOC AND TCO *
TOTAL COST OF OWNERSHIP RESULTS

FUEL COST * $/GAL *	UTILIZATION * HRS/YR *	DOC * $/F HR *	TCO *** $ **
0.83	600.00	210.30	948459.37
0.83	900.00	176.63	1210791.00
1.24	600.00	229.69	1041559.37
1.24	900.00	196.03	1350441.00

DIRECT OPERATING COST BREAKDOWN

FUEL = 0.83$/GALLON UTILIZATION= 600.00HRS/YR

	$/SM A/C	$/SM ENGINES	$/FLT HR A/C	$/FLT HR ENGINES
FUEL & OIL	----	0.16	----	39.58
INSURANCE	0.01	0.01	2.69	3.64
MNT LBR & MAT	0.07	0.25	17.50	61.46
DEPRECIATION	0.13	0.16	23.52	45.57
REGISTRATION	0.00	----	0.47	----
HANGAR RENTAL	0.02	----	5.96	----
TOTAL *	0.24	0.60	60.08	150.22
A/C + ENGS TOTAL	0.84		210.30	

DIRECT OPERATING COST BREAKDOWN

FUEL = 0.83$/GALLON UTILIZATION= 900.00HRS/YR

	$/SM A/C	$/SM ENGINES	$/FLT HR A/C	$/FLT HR ENGINES
FUEL & OIL	----	0.16	----	39.58
INSURANCE	0.01	0.01	1.79	2.43
MNT LBR & MAT	0.07	0.23	17.50	58.28
DEPRECIATION	0.09	0.12	22.35	30.36
REGISTRATION	0.00	----	0.22	----
HANGAR RENTAL	0.02	----	3.93	----
TOTAL *	0.18	0.52	44.89	130.74
A/C + ENGS TOTAL	0.71		176.63	

DIRECT OPERATING COST BREAKDOWN

FUEL = 1.24$/GALLON UTILIZATION= 600.00HRS/YR

	$/SM A/C	$/SM ENGINES	$/FLT HR A/C	$/FLT HR ENGINES
FUEL & OIL	—	0.24	—	58.99
INSURANCE	0.01	0.01	2.68	3.64
MNT LBR & MAT	0.07	0.25	17.50	61.46
DEPRECIATION	0.13	0.18	33.52	45.53
REGISTRATION	0.00	—	0.47	—
HANGAR RENTAL	0.02	—	5.90	—
TOTAL *	0.24	0.68	60.08	169.61
A/C + ENGS TOTAL	0.92		229.69	

DIRECT OPERATING COST BREAKDOWN

FUEL = 1.24$/GALLON UTILIZATION= 900.00HRS/YR

	$/SM A/C	$/SM ENGINES	$/FLT HR A/C	$/FLT HR ENGINES
FUEL & OIL	—	0.16	—	39.58
INSURANCE	0.01	0.01	2.68	3.64
MNT LBR & MAT	0.07	0.25	17.50	61.46
DEPRECIATION	0.13	0.18	33.52	45.53
REGISTRATION	0.00	—	0.47	—
HANGAR RENTAL	0.02	—	5.90	—
TOTAL *	0.24	0.60	60.08	150.22
A/C + ENGS TOTAL	0.84		210.30	

CASH FLOW ANALYSIS

FUEL COST = $ 0.83 UTILIZATION =600.00 HRS/YR

YEAR	1	2	3	4	5	6	7	8	TOTAL
CASH OUTFLOW									
DOWNPAYMENT	37944.	0.	0.	0.	0.	0.	0.	0.	37944.
ANNUAL PAYMENT	74881.	70612.	66343.	62074.	57806.	53537.	49268.	44999.	479520.
OPERATING COST	78747.	78747.	78747.	78747.	78747.	78747.	78747.	78747.	629979.
TOTAL CASH OUTFLOW	191572.	149359.	145091.	140822.	13[illegible]553.	132284.	128016.	123747.	1147443.
CASH INFLOW									
INVESTMENT TAX CREDIT	37944.	0.	0.	0.	0.	0.	0.	0.	37944.
TAX SAVINGS									
DEPRECIATION	94661.	71145.	53359.	40019.	[illegible]	4718.	4718.	4718.	303554.
INTEREST	32193.	27925.	23656.	19387.	15118.	10850.	6581.	2312.	138022.
OPERATING COST	78747.	78747.	78747.	78747.	78747.	78747.	78747.	78747.	629979.
BOOK ADJUSTMENT	0.	0.	0.	0.	0.	0.	0.	-75868.	-75868.
TOTAL EXPENSE	205601.	177817.	155762.	138154.	12[illegible]80.	94315.	90047.	9889.	995666.
TAX SAVINGS AT0.52 PCT	107017.	9246[illegible].	80996.	71840.	64418.	49044.	46824.	5143.	517746.
CASH SALE	0.	0.	0.	0.	0.	0.	0.	151777.	151777.
TOTAL CASH INFLOW	144961.	92465.	80996.	71840.	64418.	49044.	46824.	156919.	707467.
NET CASH OUTFLOW	46611.	56894.	64096.	68982.	72135.	83240.	81191.	-33173.	439976.

OPERATING COST SUMMARY

FUEL COST = $ 0.83 UTILIZATION =600.00 HRS/YR

VARIABLE COSTS		FIXED COSTS	
FUEL COST	$ 23558.82	HANGAR RENTAL	$ 3541.00
OIL COST	189.97		
AIRFRAME MAINTENANCE			
LABOR	10076.63	INSURANCE	3794.42
MATERIAL	425.76		
ENGINE MAINTENANCE			
LABOR	7380.00	AIRCRAFT REGISTRATION	284.87
MATERIAL	29495.99		
TOTAL VARIABLE COSTS	71127.12	TOTAL FIXED COSTS	7620.30

TOTAL FIXED COSTS $ 7620.30 ANTICIPATED ANNUAL FLIGHT HOURS 600. = 12.70
VARIABLE COST = $ 118.55 PER HOUR
FIXED COST = $ 12.70 PER HOUR
TOTAL OPERATING COST = $ 131.25 PER HOUR
TOTAL ANNUAL OPERATING COST = $ 78747.37

CASH FLOW ANALYSIS

FUEL COST = $ 0.83   UTILIZATION =900.00 HRS/YR

YEAR	1	2	3	4	5	6	7	8	TOTAL
CASH OUTFLOW									
DOWNPAYMENT	37944.	0.	0.	0.	0.	0.	0.	0.	37944.
ANNUAL PAYMENT	74881.	70612.	66343.	62074.	57806.	53537.	49268.	44999.	479520.
OPERATING COST	111539.	111539.	111539.	111539.	111539.	111539.	111539.	111539.	892312.
TOTAL CASH OUTFLOW	224364.	182151.	177882.	173613.	169345.	165076.	160807.	156538.	1409775.
CASH INFLOW									
INVESTMENT TAX CREDIT	37944.	0.	0.	0.	0.	0.	0.	0.	37944.
TAX SAVINGS									
DEPRECIATION	94861.	71145.	53359.	40019.	30014.	4718.	4718.	4718.	303554.
INTEREST	32193.	27925.	23656.	19387.	15118.	10850.	6581.	2312.	138022.
OPERATING COST	111539.	111539.	111539.	111539.	111539.	111539.	111539.	111539.	892312.
BOOK ADJUSTMENT	0.	0.	0.	0.	0.	0.	0.	-75888.	-75888.
TOTAL EXPENSE	238593.	210609.	188554.	170945.	156672.	127107.	122838.	42681.	1257990.
TAX SAVINGS AT 0.52 PCT	124068.	109517.	98048.	88892.	81469.	66096.	63876.	22194.	654159.
CASH SALE	0.	0.	0.	0.	0.	0.	0.	151777.	151777.
TOTAL CASH INFLOW	162012.	109517.	98048.	88892.	81469.	66096.	63876.	173971.	843880.
NET CASH OUTFLOW	62351.	72634.	79834.	84722.	87875.	98980.	96931.	-17433.	565895.

OPERATING COST SUMMARY

FUEL COST = $ 0.83   UTILIZATION =900.00 HRS/YR

VARIABLE COSTS		FIXED COSTS	
FUEL COST	$ 35338.22	HANGAR RENTAL	$ 3541.00
OIL COST	264.96		
AIRFRAME MAINTENANCE			
LABOR	15114.95	INSURANCE	3794.42
MATERIAL	638.64		
ENGINE MAINTENANCE			
LABOR	10512.00	AIRCRAFT REGISTRATION	284.87
MATERIAL	42029.98		
TOTAL VARIABLE COSTS	103918.69	TOTAL FIXED COSTS	7620.30

TOTAL FIXED COSTS $ 7620.30 ANTICIPATED ANNUAL FLIGHT HOURS 900. = 8.47
VARIABLE COST = $ 115.47 PER HOUR
FIXED COST = $ 8.47 PER HOUR
TOTAL OPERATING COST = $ 123.93 PER HOUR
TOTAL ANNUAL OPERATING COST = $ 111538.94

CASH FLOW ANALYSIS

FUEL COST = $ 1.24   UTILIZATION =600.00 HRS/YR

YEAR	1	2	3	4	5	6	7	8	TOTAL
CASH OUTFLOW									
DOWNPAYMENT	37944.	0.	0.	0.	0.	0.	0.	0.	37944.
ANNUAL PAYMENT	74881.	70612.	66343.	62074.	57806.	53537.	49268.	44999.	479520.
OPERATING COST	90385.	90385.	90385.	90385.	90385.	90385.	90385.	90385.	723079.
TOTAL CASH OUTFLOW	203210.	160997.	156728.	152459.	148191.	143922.	139653.	135384.	1240542.
CASH INFLOW									
INVESTMENT TAX CREDIT	37944.	0.	0.	0.	0.	0.	0.	0.	37944.
TAX SAVINGS									
DEPRECIATION	94861.	71145.	53359.	40019.	30014.	4718.	4718.	4718.	303554.
INTEREST	32193.	27925.	23656.	19387.	15118.	10850.	6581.	2312.	138022.
OPERATING COST	90385.	90385.	90385.	90385.	90385.	90385.	90385.	90385.	723079.
BOOK ADJUSTMENT	0.	0.	0.	0.	0.	0.	0.	-75888.	-75888.
TOTAL EXPENSE	217439.	189455.	167400.	149791.	135518.	105953.	101684.	21527.	1086765.
TAX SAVINGS AT 0.52 PCT	113068.	98517.	87048.	77891.	70469.	55095.	52876.	11194.	566158.
CASH SALE	0.	0.	0.	0.	0.	0.	0.	151777.	151777.
TOTAL CASH INFLOW	151012.	98517.	87048.	77891.	70469.	55095.	52876.	162971.	755879.
NET CASH OUTFLOW	52197.	62480.	69680.	74568.	77721.	88826.	86777.	-27587.	[illegible]

OPERATING COST SUMMARY

FUEL COST = $ 1.24   UTILIZATION =600.00 HRS/YR

VARIABLE COSTS		FIXED COSTS	
FUEL COST	$ 35196.29	HANGAR RENTAL	$ 3541.00
OIL COST	189.97		
AIRFRAME MAINTENANCE			
LABOR	10376.63	INSURANCE	3794.42
MATERIAL	425.76		
ENGINE MAINTENANCE			
LABOR	7380.00	AIRCRAFT REGISTRATION	284.87
MATERIAL	29495.99		
TOTAL VARIABLE COSTS	82764.62	TOTAL FIXED COSTS	7620.30

TOTAL FIXED COSTS $ 7620.30 ANTICIPATED ANNUAL FLIGHT HOURS 600. = 12.70
VARIABLE COST = $ 137.94 PER HOUR
FIXED COST = $ 12.70 PER HOUR
TOTAL OPERATING COST = $ 150.64 PER HOUR
TOTAL ANNUAL OPERATING COST = $ 90384.87

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