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EVALUATION OF PROPFAN PROPULSION APPLIED TO GENERAL AVIATION

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by

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BEECH AIRCRAFT CORPORATION
WICHITA, KANSAS

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Lewis Research Center
Cleveland, Ohio 44135

Contract NAS3-24349

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FORWARD

This report presents the results of a study conducted by The Beech Aircraft Corporation with support from Hamilton Standard Division of United Technologies Corporation (UTC) and Pratt and Whitney, Canada Division of United Technologies Corporation (UTC) for the National Aeronautics and Space Administration, Lewis Research Center (NASA-LeRC) under NASA contract NAS3-24349, "Multiple Application Propfan Studies (MAPS) Category One (1)". The study was conducted from August, 1984 to June, 1985. The Study Manager for Beech was Randal W. Awker. The NASA Contract Manager for the study was Susan M. Johnson, NASA-LeRC, Cleveland, Ohio.

The author wishes to express special thanks to the following UTC personel who provided valuable technical assistance and propulsion system data that made this report possible.

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1.0 SUMMARY

This study examined the potential application and benefits of propfan propulsion for General Aviation aircraft. The study's objective was to examine various candidate aircraft configurations for propfan propulsion and select a configuration which would allow a good comparison of propfan propulsion to conventional propulsion for a similar mission cruise speed of .7 to .8 Mach. The selected configuration was then used to compare the environmental impact, cost, performance, and market potential of propfan propulsion against conventional turbofan propulsion.

A generic, small turbofan designed with characteristics similar to those of current aircraft in today's General Aviation fleet was chosen as the basis for the propulsion system comparison in the study. To provide a common configurational basis for comparison, four similar aircraft were designed, each with the same basic aerodynamic characteristics but with four different propulsion systems. The four propulsion systems consisted of a current technology turbofan engine, an advanced 1988 technology turbofan engine, and an advanced 1988 turboprop engine combined with both a pusher and a tractor propfan installation. Each aircraft examined was designed for eight passengers with 1800 NM NBAA IFR range.

Comparison of the propulsion systems in these four similar business class aircraft shows that the single-rotation (SR) propfans evaluated in this study can provide a 33% reduction in fuel consumption compared to current day small turbofans and a 14% reduction compared to equivalent technology turbofans.

The study showed, however, different cost trends than previous studies of similar propulsion systems in large transport aircraft applications. The propfan propulsion system (engine and propeller) utilized in this study had a 35% higher acquisition cost than an equivalent turbofan. This resulted in a significantly higher total aircraft selling price for the propfan. Because of lower utilization rates, the total cost of operating General Aviation aircraft was shown in this study to be more sensitive to change in aircraft acquisition cost (or airplane selling price) than to a change in fuel costs due to a change in fuel consumption. Thus the higher price of the propfan in this study overshadowed the considerable improvement in fuel consumption and resulted in the propfan having a 4% higher total cost of operation than the current technology turbofan and a 10% higher cost of operation compared to an equivalent technology turbofan.

2.0 INTRODUCTION

Advanced, high speed propeller systems or propfans have been under development since before 1976, primarily due to the fuel crisis in mid-1974. Propulsion systems utilizing propellers can show significant benefits in fuel consumption over current turbofan aircraft. The main problem in the past is that these propeller driven aircraft could not compete with the mission capability or the passenger comfort and appeal of the turbofans. Prior to the fuel crisis in 1974, fuel was not of major concern in the overall cost of operation of most U.S. aircraft and, therefore, there was little incentive to design competitive, high speed turboprops. However, after the 1974 fuel crisis with the substantial increase in fuel prices and the spectre of fuel shortages, fuel conservation became of major public interest. Fuel costs soared to over 50% of the total cost of operation (Reference 1) for large commercial and military transports.

In response to the concern from the Senate Committee on Aeronautical and Space Sciences, NASA implemented in 1975 the Aircraft Energy Efficiency (ACEE) program to investigate areas of technology that could conserve the fuel used by U.S. aircraft. Propulsion system technology was among those areas identified for investigation, and consisted of three general programs.

- Energy Component Improvement (ECI)
- Energy Efficient Engine (E^3)
- Advanced Turboprop Program (ATP)

The high speed propeller technology utilized in this study developed out of the Advanced Turboprop Program. The Advanced Turboprop Program, begun in 1978, was designed to be a three phase effort (Reference 2). Phase I was to develop a fundamental data base using small scale models and to establish the concept feasibility. Phase II was to establish the design, fabrication, and ground testing of a Large-Scale Advanced Propeller (LAP) with a nine-foot diameter. Finally, Phase III was to complete the necessary system integration to perform a flight research program on a commercial-type aircraft (a Gulfstream G-II was selected) and was referred to as the Propfan Test Assessment (PTA) (Reference 1).

The majority of effort in Phase I has been directed towards large commercial and military transport class aircraft. Many of these studies have indicated possible 15% to 30% reduction in fuel use for these aircraft by using propfan propulsion instead of conventional turbofans. These studies have also shown that the propfan propulsion system has only slightly higher (+3%) acquisition cost. This, combined with the significant fuel savings shown, results in a 6% to 10% lower direct operating cost (DOC) for these transports.

To identify other potential areas of application for this high speed propeller technology NASA initiated the Multiple Application Propfan Studies (MAPS) program. Under the MAPS program six potential aircraft categories of interest were identified.

(1) Business Aircraft

(2) Military Light or Heavy Attack Aircraft

(3) Long Endurance Aircraft

(4) VTOL, STOVL, or STOL Aircraft

(5) Unpiloted or Remote Piloted Aircraft

(6) Unique/Other

This study addressed the potential application of propfan propulsion for the first category, business aircraft. This study was performed as part of the MAPS program under the NASA contract NAS3-24349.

The objectives of this study were to:

- Assess the potential of propfan propulsion for business class aircraft.

- Compare propfan propulsion to conventional propulsion for an aircraft performing the same mission.

- Identify areas requiring further development.

- Recommend application of the promising technology.

The Beech MAPS study was divided into four tasks to accomplish these goals.

Task I - Definition of Study Evaluation Procedures and Assumptions

Based on a preliminary configuration evaluation, the study ground rules, design approach, and aircraft configuration were selected.

Task II - Conceptual Design

Four aircraft were conceptually designed. The four aircraft are shown in Figure 1. Two of these aircraft utilized conventional propulsion systems and two utilized propfans. One conventional system was designed to current technology practices while the other conventional system and both propfan systems were designed utilizing 1988 propulsion technology. An artist's conception of the pusher propfan installation is shown in Figure 2.

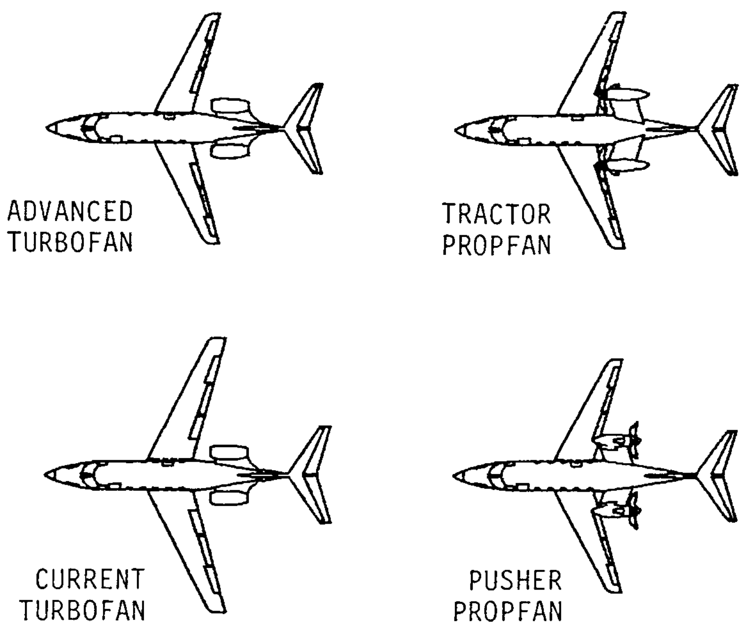

FIGURE 1. The Four Aircraft Used to Evaluate Propfan Propulsion

FIGURE 2. The Pusher Propfan Configuration

Task III - Mission Evaluation

The four aircraft designed in Task II were then evaluated for the same mission to determine cost and mission performance.

Task IV - Conclusions and Recommendations

The study results were summarized in Task IV. Also, specific areas requiring further research identified in Task III were presented and summarized in Task IV.

3.0 DESIGN APPROACH

This section presents the ground rules and design approach for the study. The ground rules were established after a preliminary configuration evaluation. A detailed discussion of the preliminary evaluation is given in Section 4. The four aircraft evaluated in this study were all sized and optimized for minimum fuel burn utilizing the following design and mission ground rules.

3.1 DESIGN GROUND RULES

In the preliminary evaluation phase of the study both current turboprops and turbofans were examined as potential candidates for the study's baseline current technology propulsion system. As can be seen in Figure 3, for a given engine size (or horsepower level) propfans begin to show an advantage over turboprops only at speeds higher than .65 Mach. Figure 3

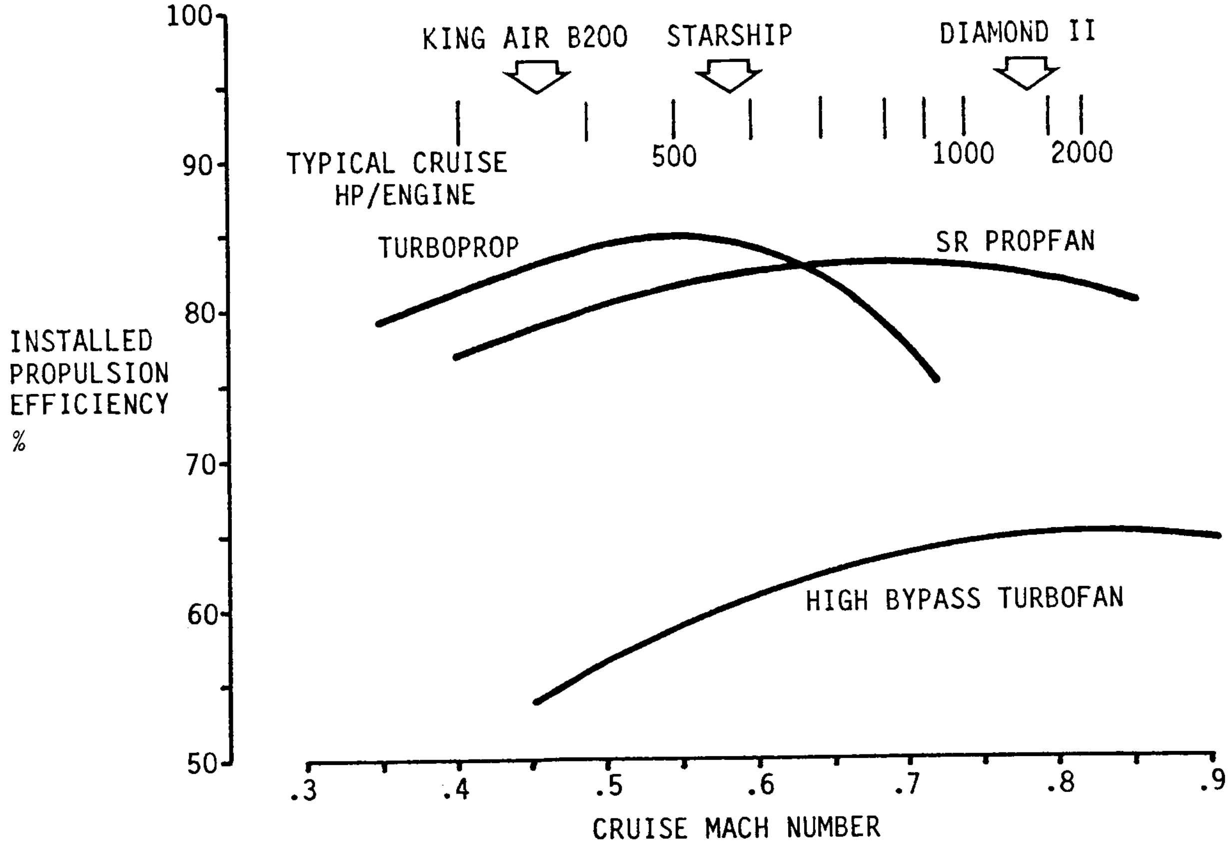

FIGURE 3. Comparison of Propulsive Efficiency

shows a typical turboprop, propfan, and turbofan propulsion system compared at each system's design cruise altitude. Figure 3 illustrates the effect of cruise speed on propulsive efficiency for the chosen propulsion systems. It does not, however, represent the envelope of optimum design for all propellers. Further, Figure 3 illustrates how the required engine size must increase for increased cruise speed capability, for the class of aircraft examined in this study, regardless of the propulsion system. Since it was desired to have a current technology aircraft performing the same mission as the propfan aircraft in this study for comparison, the turboprop was eliminated as a candidate primarily because there are no current general aviation turboprop aircraft which cruise in the .7 to .8 Mach speed range. There are, however, several small business turbofans which do cruise in this range, as shown in Table 1. These were chosen to provide a basis for establishing the ground rules of the study. All the performance characteristics of these turbofans are achievable using propfan

TABLE 1. Current Small Turbofan Business Aircraft Characteristics

ITEM		FALCON 100	LEAR 35	CITATION SII	DIAMOND II
PASSENGER CAPACITY		7	8	10	9
MAX CRUISE SPEED	MACH	.84	.80	.70	.77
VFR RANGE	NM	1880	2289	1800	1810
TAKEOFF FIELD LENGTH @ S.L., STD	FT	4200	4224	3240	3950
MAX TAKEOFF WEIGHT	LB	19300	17000	14700	15780
FUEL WEIGHT	LB	5909	6237	5777	4904
WING LOADING	LB/FT^2	74.4	67.1	42.9	63.3
THRUST LOADING	LBT/LBM	.33	.41	.34	.37
SPAN LOADING	LB/FT	450	430	282	363

propulsion. Additionally, the small business jet aircraft also provides a good baseline for comparison because it represents a large part of the business market (in terms of units) and provides the greatest spread from the current transport class aircraft being evaluated for propfan propulsion. The results of the preliminary configuration evaluation and selection are discussed further in Section 4.

The design ground rules for the study were selected, using the small turbofan market as a basis, to provide a good comparison between three propulsion systems: a current technology turbofan, a 1988 technology level turbofan, and a 1988 technology level propfan. Later in the study the propfan propulsion system was split into two installations, a pusher and a tractor, and a total of four propulsion systems were compared. Further, the design ground rules were selected so that a potential flight prototype would be feasible by the 1990 time frame. These ground rules were then used to design the four aircraft utilizing the four propulsion systems examined in this study. These ground rules were submitted to and approved by NASA in the initial phase of the study.

The design ground rules for the study were:

(1) TECHNOLOGY READINESS DATE

A 1990 aircraft technology readiness date was selected. Aircraft technology readiness, as used in this study, is defined to be the date at which a prototype would be ready for initial flight test. The 1990 date was based on information from Hamilton Standard indicating, for airline class propfans, the earliest operational readiness date would be 1987 for a prototype propulsion system. It was anticipated that an additional year and one half would be required by both engine and propfan manufacturers for development of a propfan/engine installation for use on a general aviation aircraft. This resulted in a propulsion technology readiness date of mid-1988. Subsequently, an additional year and one half for design and construction of a flying prototype would be required by the airframe manufacturer, thus yielding a 1990 aircraft technology readiness date.

(2) AIRCRAFT AERODYNAMIC TECHNOLOGY

All of the study aircraft were designed to have comparable aerodynamics. Each incorporated a wing design which allowed a significant amount of laminar flow. The wing configuration was selected to optimize cruise performance and to prevent any adverse shock effects. The high lift system design was sufficient to provide the necessary capability to achieve the desired 4000 FT takeoff field length at sea level. The tail sizing accounted for differences necessary to maintain directional control and sufficient static stability for a typical business aircraft center of gravity travel.

(3) AIRFRAME STRUCTURAL TECHNOLOGY

The structural design of the current technology aircraft incorporated conventional aluminum construction techniques. The structural design of the 1990 technology level aircraft incorporated advanced composite materials and advanced aluminum-lithium alloys. The fuselage design of the advanced aircraft utilized filament wound graphite epoxy with a Kevlar based core and integrally woven metal wire for lightning protection. The wing utilized a combination of advanced aluminum alloys and advanced composite materials. Although the scope of this study did not warrant a detailed structural analysis, the airframe weights and cost estimates discussed in Section 5 reflect the effects of these current and 1990 level structural design approaches.

(4) PROPULSION TECHNOLOGY

To meet a total aircraft technology readiness date of 1990 requires an engine technology readiness of 1988, as previously stated in (1). The engine for the propfan aircraft consisted of a Pratt and Whitney, Canada PT6A cycle scaled to the necessary horsepower level to meet the mission requirements with weight and fuel consumption adjusted to be consistent with the 1988 propulsion technology readiness. The turbofan aircraft utilized a JT15D-5 cycle also adjusted to the 1988 technology level. The 1988 level engine technology for both utilized advanced material technology (single crystal turbine blades) and advanced air flow technology (improved gas path in compressor, combustor, and exhaust). Engine data and technical assistance was provided by Pratt and Whitney, Canada to assure consistent levels of technology for the current day and 1988 engines.

The study utilized a propfan designed for General Aviation application by Hamilton Standard with a sweep distribution and diameter selected based on the study's performance, cost, and noise goals. Propfan performance, cost, and noise were evaluated using methods supplied by Hamilton Standard.

(5) CERTIFICATION REQUIREMENTS

Both study aircraft were designed to FAR 25 (Airworthiness Standards: Transport Category Airplanes) requirements. Both aircraft were anticipated to be over 12,500 LB and therefore, required FAR 25 certification. In particular, there were two areas which impacted the aircraft design for this study resulting from FAR 25 certification:

(1) Hot day, high altitude climb capability

(2) Engine out control (V_{MC})

(6) ENVIRONMENTAL NOISE

Both near field and far field noise were considered in this study. The preliminary evaluation indicated that small business jet interior noise levels range between 78 dBA and 85 dBA. A value of 82 dBA was chosen for the cabin noise level target in this study. Each design incorporated the acoustical treatment and associated weight penalty to achieve this maximum 82 dBA noise level for both the propfan and turbofan designs. For far field, all aircraft were required to meet FAR 36 (Noise Standards: Aircraft Type and Airworthiness Certification) Stage III noise requirements.

(7) AIRCRAFT PAYLOAD

Each of the configurations was designed to provide a cabin with seating for a maximum of 8 passengers or a maximum payload with full fuel of 1200 LB. The assumed weight for each passenger and crew was 200 LB including baggage.

(8) MISSION PROFILES

The mission analysis for this study was done using two missions. The first mission, shown in Figure 4, was used to size each aircraft and is referred to as the design mission. The second mission, Figure 5, was used to evaluate the operating costs using the direct operating cost methods discussed in the Appendix and is referred to as the cost mission. The cost mission represents a weighted average of actual missions being flown by owners/operators of turbofan and turboprop aircraft based on current industry experience. Over 50% of General Aviation missions flown are less than 400 NM. Only 15% of the missions flown today require the aircraft's maximum design range capability.

(9) TAKEOFF FIELD LENGTH

The design takeoff field length was selected to be 4000 FT at sea level, standard day. This field length allowed the design of a configuration with the high speed capabilities required to provide a valid comparison between propulsion systems without over penalizing the design for takeoff field length.

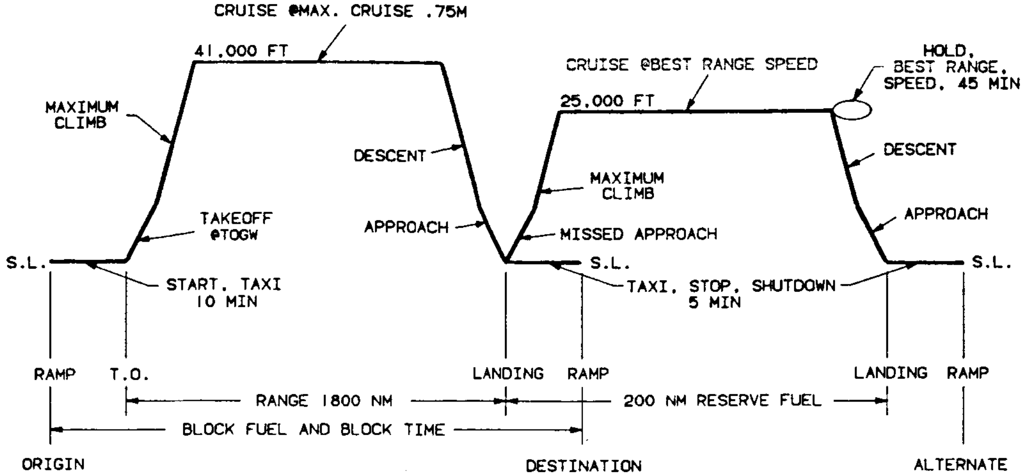

FIGURE 4. Design Mission

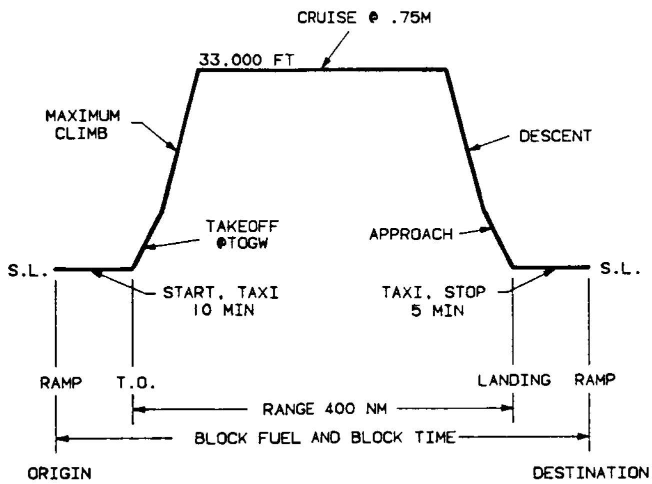

FIGURE 5. Cost Mission

3.2 AIRCRAFT SYNTHESIS

The aircraft synthesis technique used in this study is a multi-mission parametric optimization method which utilizes several steps in the synthesis process. This allows the flexibility of interfacing with the system at various key points in the design process to allow custom tailoring of the process to fit a specific class of aircraft or a specific set of mission requirements.

3.2.1 CARPET PLOTS

As part of this process, the aircraft synthesis technique utilizes carpet plots as a means of multiple dimensional parametric selection and optimization. In Figure 6, each intersection on the carpet represents an individual aircraft design (or point design). As shown in Figure 6, each point design is characterized on the plot by a unique combination of wing area and engine size, as indicated by the static sea level thermodynamic thrust. Each point design is sized to meet the design mission which was specified in the ground rules, and thus the weight and usable fuel varies for each point design. All 16 point designs in Figure 6 are for the same wing geometry such as aspect ratio, sweep, taper ratio, and wing thickness

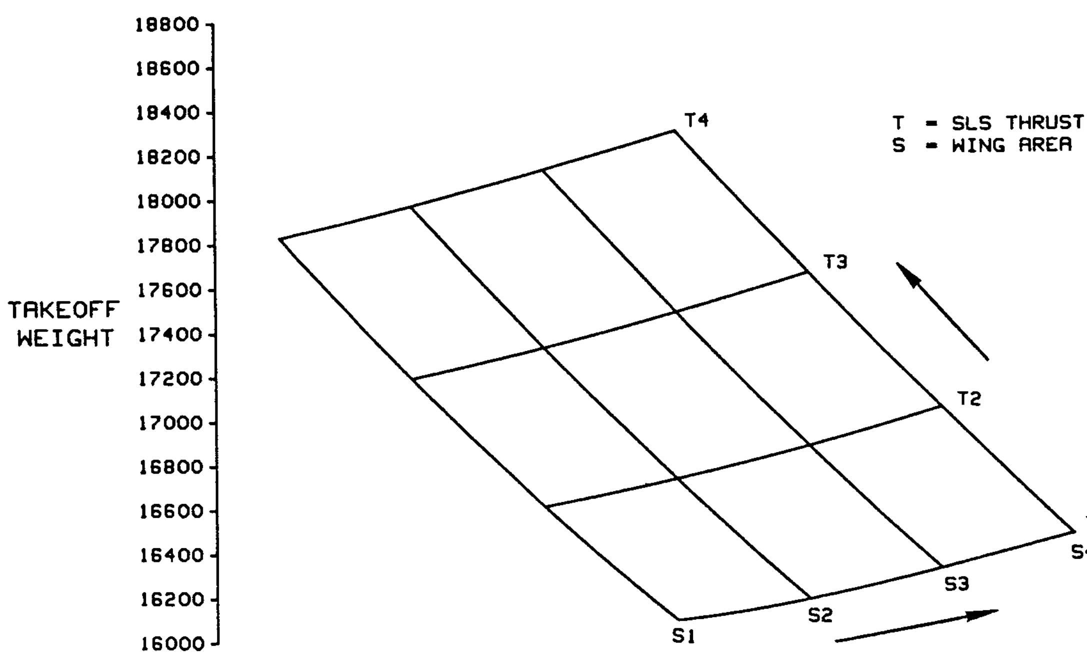

FIGURE 6. Typical Carpet Plot with 16 Individual Aircraft Point Designs

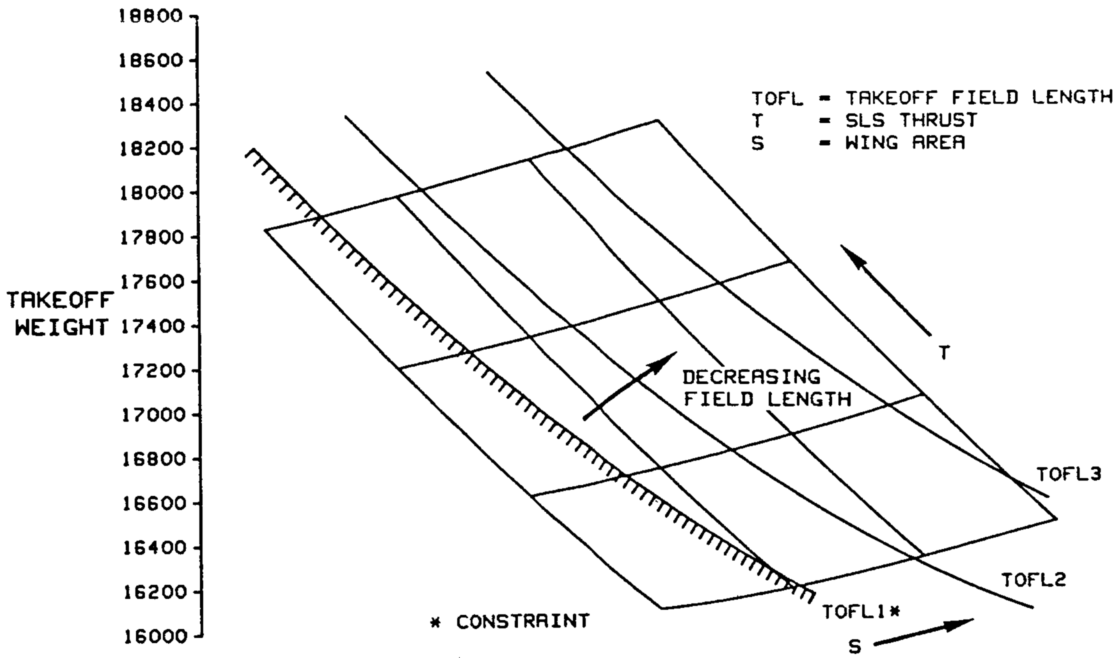

FIGURE 7. Carpet Plot with Lines of Constant Takeoff Field Performance

ratio. Additionally, each point design has an individual set of performance capabilities. The performance characteristics of each point design, such as takeoff field length shown in Figure 7, can be interpolated to yield lines of constant performance. Performance constraints are minimum or maximum design requirements and are indicated by lines with cross-hatching, as in Figure 7. The process can be repeated for each design constraint, such as cruise speed, shown in Figure 8. Finally, as in Figure 9, all of the design requirements can be applied to define the design region, shown unshaded, in which any combination of engine and wing area satisfies both the design mission requirements and the required performance capabilities. Also, the sensitivity of other cost or mission parameters, such as mission block fuel in Figure 9, can be examined.

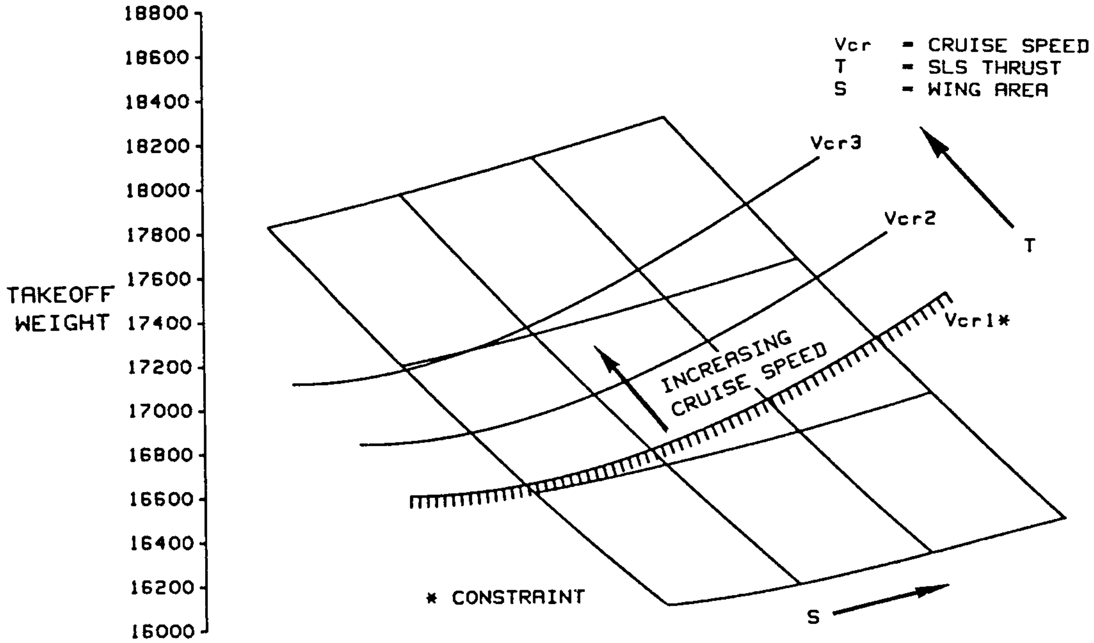

FIGURE 8. Carpet Plot with Lines of Constant Cruise Speed

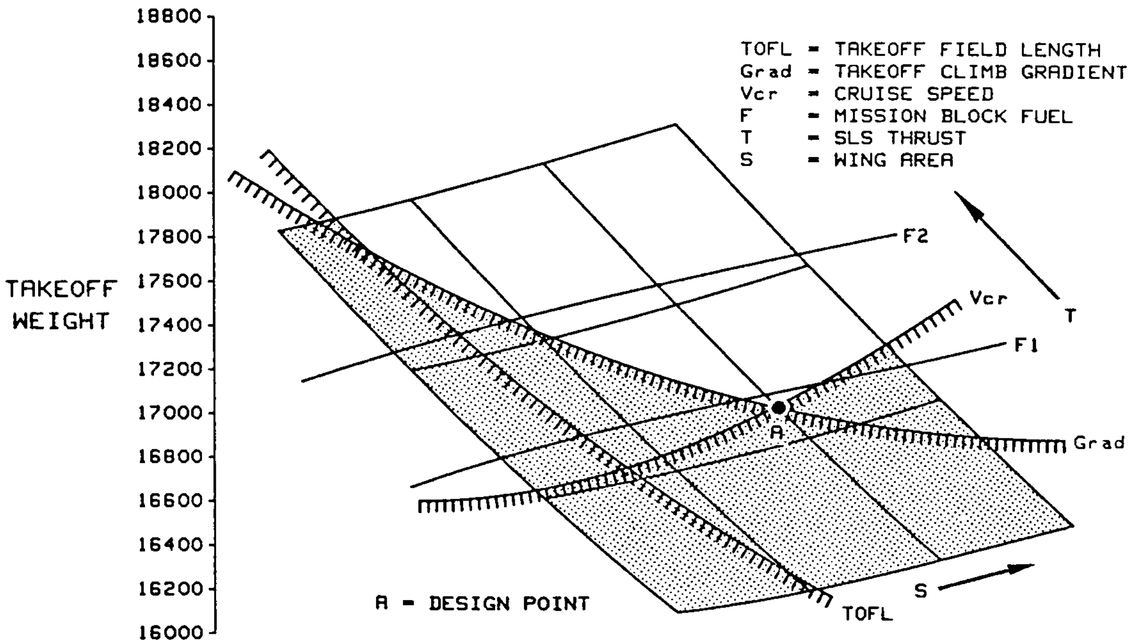

FIGURE 9. A Design Carpet Plot

3.2.2 OPTIMIZATION

In Figure 9, all the point designs in the unshaded area satisfy the design requirements but do not necessarily yield the most optimum design. Once the design region is defined, then the optimization can be accomplished by finding the point which provides the maximum or minimum value or values of a given figure or figures of merit. For example, in Figure 9, Point A represents the design which satisfies all the mission requirements, all performance constraints, and provides minimum mission fuel burn.

Point A, in Figure 9, then is the optimized point design for a specific set of propulsion system characteristics and aircraft geometry. The next step in the process is to modify the aircraft geometry and/or the propulsion system, repeat the carpet selection process, and obtain a new optimized point design for the new characteristics. As shown in Figure 10, this process is repeated, varying each of these characteristics until an overall

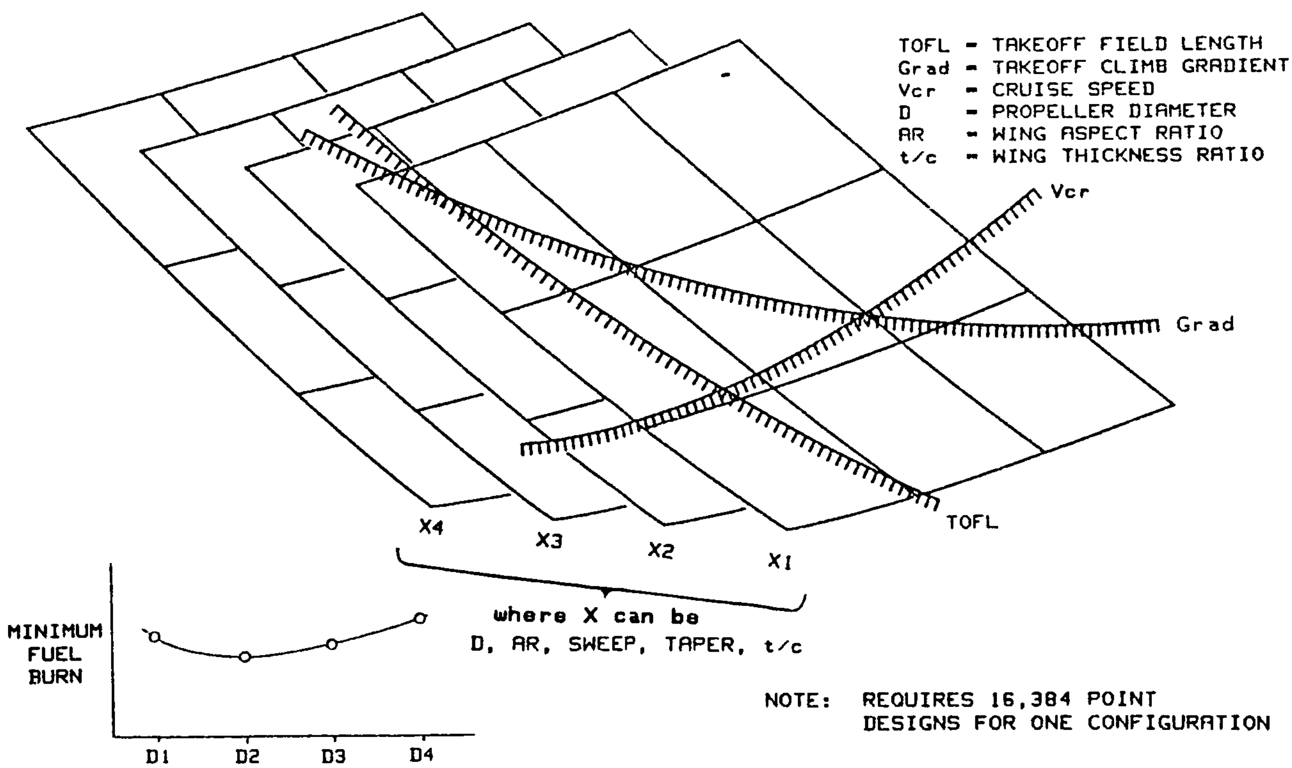

FIGURE 10. Configuration Optimization

optimum is obtained, or until a constrained design region is defined. For this study the parameters indicated in Figure 10 were considered. However, as will be discussed in Section 6.1, not all the parameters have a major impact on the design selection.

Figure 11 shows the top level flow diagram of the synthesis process. The baseline aircraft characteristics used as a point of departure by the synthesis method is typically defined in a preliminary evaluation phase which yields an aircraft with approximately similar characteristics to those of interest.

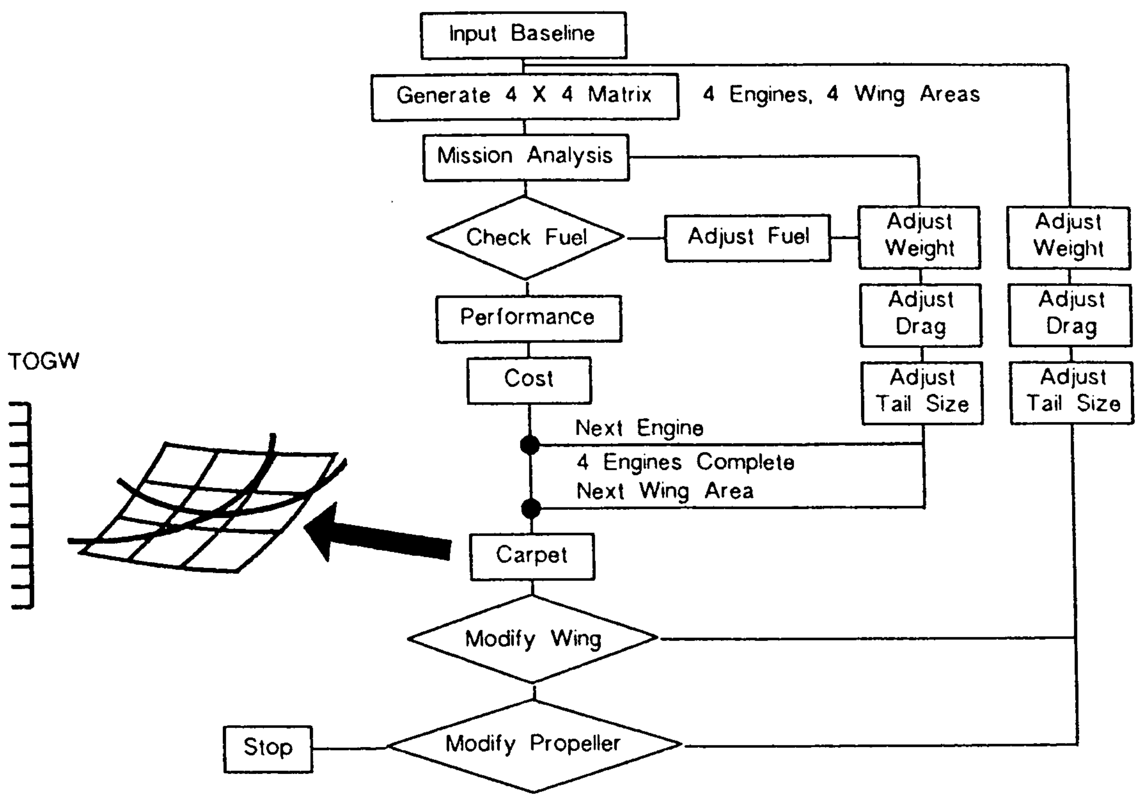

FIGURE 11. **Aircraft Computer Synthesis Flow Diagram**

3.3 COST MODELS AND AIRCRAFT PRICING

Two separate cost models were used to evaluate the cost factors for this study. One cost model was based on the Air Transport Association of America (ATA) 1967 cost model modified to reflect General Aviation experience. The other was developed specifically for this study to better model the cost environment experienced by most of today's business aircraft owners. It was felt that utilizing both cost models would provide a better understanding of the commuter aircraft market and the corporate aircraft market combined. Thus, in the study, the modified ATA cost model is used to represent commuter airline class General Aviation aircraft, and the Corporate cost model is used to represent the typical business owned aircraft. A complete, detailed description of both cost models is contained in the Appendix.

4.0 CONFIGURATION DEFINITION

A preliminary configuration analysis was performed as part of the study to select a suitable configuration to use for evaluation of propfan propulsion. This section presents the results of this preliminary evaluation and discusses the details of the configuration selected for the propulsion system comparison.

4.1 CONFIGURATION SELECTION

As part of the preliminary evaluation, various configurations were initially considered for the evaluation of propfan propulsion for this study. Each configuration in Figure 12 was evaluated in terms of weight and balance, mission capability, installation feasibility, stability and control, and acoustic impact to confirm that propfan propulsion was feasible for each of them. Each configuration layout used a similar passenger cabin, discussed in Section 4.2. The .75 Mach cruise speed requirement specified in the design ground rules required an engine that was significantly larger than is currently available for General Aviation class turboprops. As discussed in Section 4.3, a scaled PT6A engine was selected. This larger engine, then, had a significant impact on achieving a balanced configuration as well as increasing the basic operating weight. Configurations 2 and 3 were similar aircraft configurations with different engine installations. In Configuration 2, a pusher propfan was evaluated, whereas in Configuration 3 a tractor propfan installation was evaluated. Configurations 4 and 5 also utilized a common configuration with two different propulsion system installations. Both configurations 4 and 5 were pusher installations. Configuration 5 had a straight-forward propfan attachment to the engine/gearbox. Because of the engine weight and subsequent balance requirements, the installation only allowed approximately a 10 inch clearance between the wing trailing edge and the propeller plane. This eliminated the possibility of having flaps on Configuration 5, thus impacting the takeoff and landing field performance. Configuration 4, on the other hand, had an engine installation which incorporated a shaft between the gearbox and propfan, allowing an aft extension of the propeller plane. With the propeller plane extended aft, a flap system was incorporated and resulted in an improvement of field performance.

As stated, each configuration was examined in sufficient detail to establish that propfan propulsion was feasible in each case for the

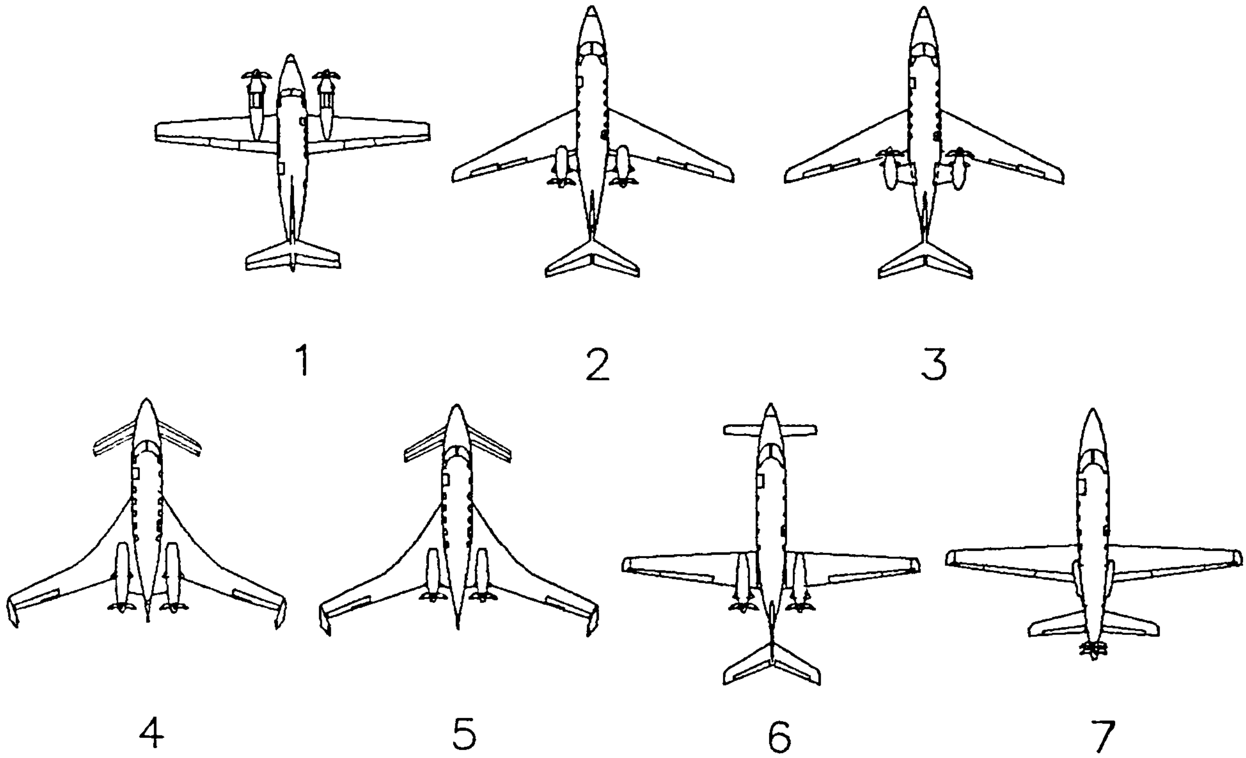

FIGURE 12. Configurations Examined

selected mission. However, the following two requirements established by NASA to provide a good propulsion system comparison narrowed the choice of configurations which could be selected:

1. The requirement to assess the potential application of propfan propulsion for business aircraft at .7 to .8 Mach cruise speed.

2. The requirement to compare the selected configuration to a current day technology aircraft performing the same mission.

The only configurations with current day counterparts capable of those speeds were Configurations 2 and 3. Thus, Configurations 2 and 3 were selected for those two reasons. Further, by selecting Configurations 2 and 3 the flexibility exists to compare current propulsion to both pusher and tractor propfan installations without clouding the comparison by variation of configuration. Also, the selection provides a basis of comparison which is representative of the currently established General Aviation fleet.

4.2 CABIN SELECTION

Based on the preliminary evalation, a typical small business jet cabin was selected. It was designed using the configuration ground rules in Table 2.

Figure 13 shows the selected cabin features. The double club arrangement shown does not provide the maximum seating capacity but, rather, provides a typical comfort level which is representative of how most business aircraft are configured. Special regulations under FAR 25 allow aircraft of this class to have aisle widths between 9" and 12"; 11" was selected as typical.

TABLE 2. Cabin Design Criteria

- 57" Aisle Height
- 11" Aisle Width
- Flat Floor
- Lavatory
- Desired 56 Cubic Foot Baggage Volume
- Circular Cross Section on Fuselage Pressure Vessel
- Seating for Eight Passengers in a Double Club Arrangement
- 55" Between Seats
- 19" Seat Width
- Small Beverage Service Area
- All Fuel in the Wings
- Two Pilot Cockpit with Dual Instrumentation

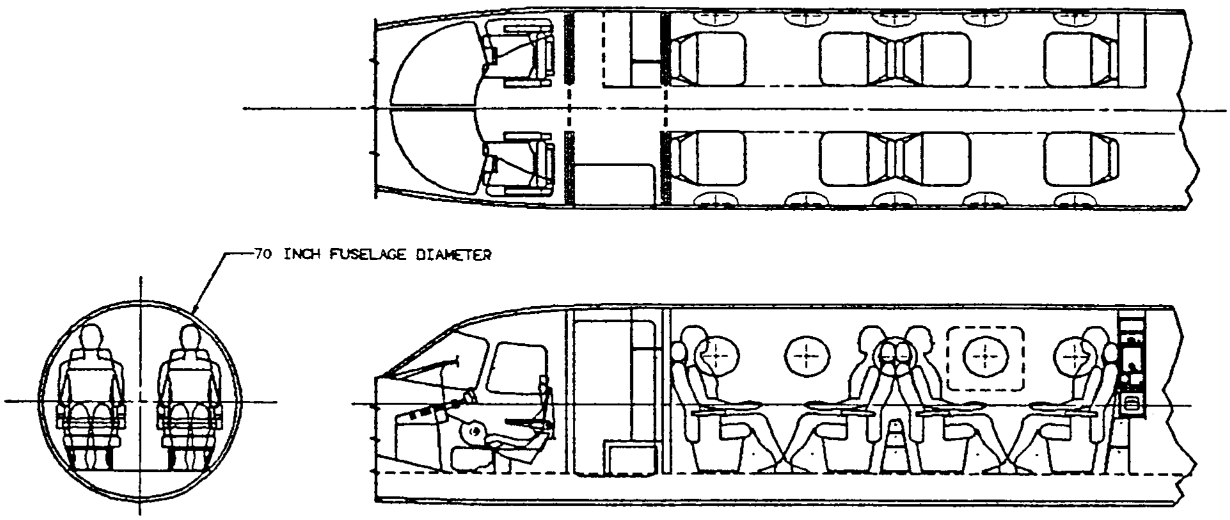

FIGURE 13. Selected Cabin Layout

In Figure 13, the entry door is shown just aft of the cockpit with a small baggage area across from the door. Some of the configurations required that the door and baggage compartment be moved aft to facilitate wing and propulsion system location. The head clearance, sidewall clearance, and seat separation of the passengers are all shown for a 97.5 percentile man (Reference 3), i.e. a height of 74".

4.3 ENGINE SELECTION

Pratt and Whitney, Canada (P&WC) developed three conceptual engine designs in support of this study. Pratt and Whitney, Canada is a major engine manufacturer of small General Aviation engines, such as those in this study, and provides both turboprop and turbofan engines for numerous aircraft in the General Aviation market (both business aircraft and commuter airlines). This provided a single source of engine definition assuring a consistent comparison of technology levels in this study. The three baseline conceptual designs, a current technology turbofan, an advanced technology turbofan, and an advanced turboprop for propfan propulsion, were selected based on the following ground rules utilizing P&WC's experience with this class of engines.

1. Each reference engine was sized to yield 650 LB of installed thrust at .75 Mach and 41,000 FT altitude. The propfan efficiency for this initial sizing was assumed to be 79%.

2. The current day turbofan was to utilize 1984 level engine technology.

3. The advanced engines were to incorporate technology consistent with a 1988 propulsion readiness date.

4. The advanced engines were to have equivalent technology to provide a valid comparison between propfan propulsion and conventional propulsion.

5. An engine scaling scheme was to be provided to allow each engine to be sized for each study aircraft.

Because of the near term technology readiness date, P&WC did not expect a radical departure from the current small, General Aviation engine design practice. Rather, application of currently available technology would be utilized and combined with the flexibility of optimizing the cycle on a new design to yield substantial performance benefits while still achieving reasonable cost levels.

Pratt and Whitney, Canada chose as a point of departure for the conceptual designs the JT15D cycle for the turbofan engines and the PT6 cycle for the propfan engine. The engine designs did not include the use of ceramics, composites, or variable geometry because of the near-term technology readiness date. However, key technologies that were considered in these designs were:

1. Use of advanced single crystal turbine blades permitting increased cycle temperatures.

2. Use of three-dimensional aerodynamic design methods yielding improved pressure ratios, reduced pressure losses, and improved component efficiencies.

3. Use of advanced mechanical design technology giving a high degree of structural optimization for minimum weight and complexity, more efficient use of secondary air, better sealing techniques, and improved tip clearance control.

4. Use of computer automated manufacturing technology to ensure repeatability and improve cost.

4.3.1 TURBOFAN ENGINES

The 1988 turbofan engine selected was an advanced version of the JT15D engine. A schematic is shown in Figure 14. The engine was a two spool configuration similar to the JT15D-5 engine. The high pressure spool consisted of a single stage centrifugal compressor driven by a single stage uncooled axial turbine with the advanced single crystal blades. The centrifugal compressor had a pressure ratio of 6.5:1 at 7.2 LB/SEC air flow

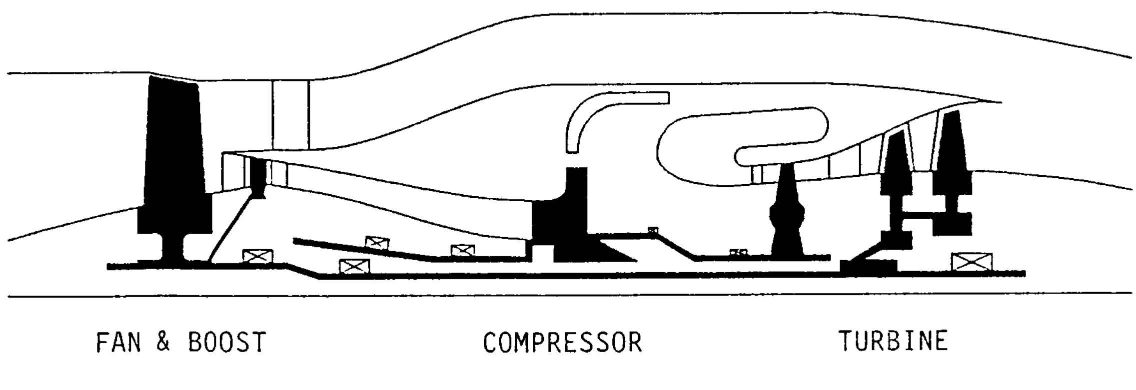

FIGURE 14. 1988 Technology Turbofan Schematic

with a rotor speed of 30,385 RPM. A reverse flow annular combustor, designed for high efficiency (99%) and low emissions, was utilized. The low pressure spool consisted of a high pressure ratio, high tip speed single stage axial fan plus a core boost stage both driven by a two stage fan turbine. The fan and core boost provided a pressure ratio of 2.73:1 to the core at a rotor speed of 14,385 RPM. This resulted in a total compressor pressure ratio of 17.8:1. The bypass ratio was 3.5 with a bypass air flow of 25.3 LB/SEC at a pressure ratio of 1.88:1. The engine also utilized a simple exhaust mixer so that core and bypass flows would pass through a single nozzle thus providing an improvement in cruise performance and reducing jet noise. The engine was 64 inches long with a fan diameter of 24 inches. The engine weight was 695 LB.

The schematic in Figure 14 is also representative of the 1984 technology turbofan used in this study. This current day engine was similar to the JT15D-5. The single stage centrifugal compressor had a rotor speed of 30,041 RPM and was driven by a single stage turbine. The core mass flow was 9.1 LB/SEC. The fan was driven by a two-stage turbine at 16,104 RPM. The combined compressor and fan pressure ratio was 16.5:1. The fan bypass ratio was 1.93 with a bypass airflow of 17.5 LB/SEC. The 1984 turbofan length was 63 inches long with a fan diameter of 21 inches and a weight of 650 LB.

Comparing the current and 1988 turbofan engine at the design point gives the following: for the advanced engine, the bypass ratio is higher, the pressure ratio is higher, the core air flow is lower, and the turbine inlet temperature is higher. These were a direct result of the single crystal blades and higher component efficiencies, which produced the same thrust but at significantly improved SFC.

4.3.2 TURBOPROP ENGINE

The design of the 1988 propfan engine was based on the PT6 turboprop configuration, upgraded with the new technology items, and reoptimized for high altitude, high speed flight conditions. A schematic is shown in Figure 15. The PT6 cycle was chosen, rather than the newer PW100 series, because it was felt that this cycle was better suited for high altitude optimization. Further, the PT6 configuration easily facilitates either tractor or pusher installation with very little modification. The engine utilizes a free power turbine approach. The gas generator consists of a single spool compressor with three axial stages and one centrifugal stage, driven by a single stage axial turbine with advanced single crystal

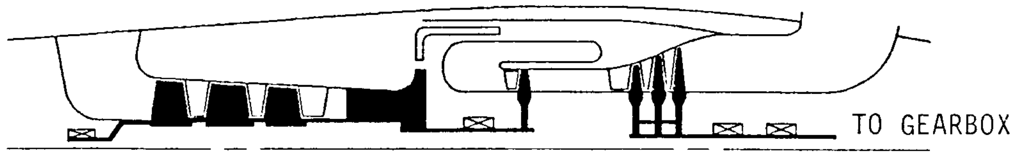

FIGURE 15. 1988 Technology Turboprop Schematic

uncooled blades. It utilized a reverse flow, fully annular combustor for high efficiency (99%) and low emissions.

The 1988 propfan engine was chosen to have a similar technology level to the 1988 turbofan engine but was optimized slightly different. Because of the additional compressor boost stage on the low pressure fan spool, the turbofan provided a higher overall pressure ratio than did the single-spool, multi-stage compressor design in the propfan engine. To achieve a similar high pressure ratio in the propfan engine would have required a two-spool design incorporating variable geometry due to turbine loading and engine control requirements. This would have substantially increased the cost and weight of the propfan engine as well as increasing its technology level above the turbofan. As a result of the lower pressure ratio of the propfan engine combined with its lower required rotor speed, the propfan engine also provided the additional benefits of lower turbine stresses and subsequent higher permissible turbine entry temperature.

The power section was comprised of a three stage axial power turbine which drove the gearbox and a low pressure ratio exhaust nozzle. The gearbox designed for the turboprop engine took into consideration the heavy flat rating (sea level thermodynamic power of 2970 SHP flat rated to 1500 SHP). This allowed a much lighter gearbox and gearing system to handle the torque and SHP loads. The flat rating was selected for several reasons, as stated in Section 5.1.1. The gear system was a growth step from the standard PT6 gearing, and utilized a two-stage, in-line planetary reduction geartrain to give an output RPM of 1800.

The air flow of the 1988 turboprop engine was 5.8 LB/SEC at a pressure ratio of 14.5:1 and a rotor speed of 28,136 RPM. The power turbine rotated at 17,000 RPM and drove a gearbox which provided the 1800 RPM to the propfan. The engine was 86 inches long (including accessories) and 26 inches in diameter. The engine weight was 725 LB including gearbox.

4.3.3 SUMMARY OF ENGINE CHARACTERISTICS

Table 3 summarizes the characteristics of the engines selected for this study. Tables 3 provides both the charactistics at the design point (41,000 FT altitude and .75 Mach cruise speed) and the maximum thermodynamic characteristics at the sea level, static condition. Each of

TABLE 3. Engine Characteristics Summary

FLIGHT CONDITION S.L, STATIC, STD DAY				
ITEM		1984 TURBOFAN	1988 TURBOFAN	1988 PROPFAN
FAN				
FAN AIRFLOW (W_A)	LB/SEC	59.4	78.7	--
FAN BYPASS RATIO		2.09	3.7	--
FAN SPEED	RPM	15,896	13,480	--
FAN THRUST	LB	1756(53%)	2393(73%)	--
COMPRESSOR				
CORE AIRFLOW (W_A)	LB/SEC	28.4	21.4	18.1
CORE THRUST	LB	1533(47%)	887(27%)	317
TURBINE INLET TEMPERATURE	°F	1900	2005	2062
TOTAL AIRFLOW (W_A)	LB/SEC	87.8	100.1	18.1
UNINSTALLED THRUST	LB	3289	3280	--
UNINSTALLED POWER*	SHP	--	--	2970*

*Flat Rated to 1500 SHP installed

TABLE 3. Engine Characteristics Summary (cont'd.)

DESIGN POINT FLIGHT CONDITION .75M, 41,000 FT, STD DAY				
ITEM		1984 TURBOFAN	1988 TURBOFAN	1988 PROPFAN
FAN				
FAN AIRFLOW (W_A)	LB/SEC	17.5	25.3	--
FAN BYPASS RATIO		1.93	3.5	--
FAN SPEED	RPM	16,104	14,385	--
FAN THRUST	LB	236(35%)	356(51%)	--
COMPRESSOR				
CORE AIRFLOW (W_A)	LB/SEC	9.1	7.2	5.8
PRESSURE RATIO-TOTAL		16.5:1	17.8:1	14.5:1
CORE THRUST	LB	445(65%)	343(49%)	23
COMPRESSOR TURBINE				
PRESSURE RATIO		3.03	2.82	3.52
ROTOR SPEED	RPM	30,041	30,385	28,136
INLET TEMPERATURE	^{o}F	1820	1905	1962
HORSEPOWER		1,608	1532	1243
POWER TURBINE				
PRESSURE RATIO		2.30	3.56	4.61
ROTOR SPEED	RPM	16,104	14,385	17,000
HORSEPOWER		1,062	882	1170
TOTAL AIRFLOW (W_A)	LB/SEC	26.6	32.5	5.8
UNINSTALLED				
THRUST	LB	681	699	722*
TSFC	LB/LB/HR	.862	.714	.605
FUEL FLOW	LB/HR	588	499	438
INSTALLED				
THRUST	LB	650	650	650*
TSFC	LB/LB/HR	.882	.736	.634
FUEL FLOW	LB/HR	573	479	412

*NOTE: Assumes 79% propeller efficiency at 41,000 FT, .75 Mach and includes effects of exhaust thrust these engines has been sized to produce the desired 650 LB installed thrust necessary at the 41,000 FT, .75 Mach cruise condition as shown in Table 3. Table 3 also shows the uninstalled thrust levels. The assumed installation losses were as follows:

- 8 LB/MIN bleed air flow
- 8 HP accessory loss
- 0.4% inlet total pressure loss for the turbofan engines
- 3.0% inlet total pressure loss for the turboprop engine

Comparison of the installed fuel consumption of each engine, in Table 3 indicates a 28% reduction for the propfan engine compared to a current turbofan and a 14% reduction when compared to an equivalent technology turbofan. Once again, these engines are matched to give the same thrust at the design point. As the engines were scaled to meet the design mission for each aircraft, the reduction in fuel consumption of the propfan relative to the turbofan improves slightly. This is detailed in Sections 4.5, 5.1.1, and 5.7

4.4 PROPFAN SELECTION

Hamilton Standard provided the basic propfan parametric data for the study, References 4 and 5. Previous propfan blade designs developed by Hamilton Standard for single-rotation (SR) applications are given in Table 4. The propfan blade selected for this study is illustrated in Figure 16 and is described in Table 4. It was a six-bladed, 8 FT diameter, single-rotation (SR) propfan. In the preliminary evaluation of the study it was apparent that General Aviation propfans would be highly sensitive to propulsion system acquisition cost. Because of this, every attempt was made to select the propfan design which would provide the lowest possible cost without compromising the design goals. Only six-bladed propfans were examined in this study. Eight and ten-bladed propfans, as well as counter-rotation propfans, were not examined due to their much higher acquisition cost. Additionally, on the recommendation of Hamilton Standard, the blade sweep was reduced from 35^{o} to 15^{o} to further lower the propfan acquisition cost while not significantly impacting the performance.

TABLE 4. Hamilton Standard Propfan Blade Designations

SR-1	a first cut design, 8 blades, 22° sweep at the tip, AF of 204, 37.5 SHP/D^2, .8M, 800 FPS tip speed, 35,000 FT.
SR-2	a rectangular shaped, straight blade with 0° sweep, AF of 203, 8 blades, designed for 37.5 SHP/D^2, .8M, 800 FPS tip speed, 35,000 FT.
SR-3	33° sweep, AF of 235, 8 blades, designed for 37.5 SHP/D^2, 800 FPS tip speed, .8M, 35,000 FT.
SR-4	new airfoil design/dropped by NASA.
SR-5	acoustic design, 10 blades, AF of 210, 46.5° sweep, designed for 35,000 FT, 26 SHP/D^2, .8M, 600 FPS tip speed.
SR-6	designed by NASA, similar to SR-1 with a larger hub, 10 blades, AF of 204, 39° sweep, 30 SHP/D^2, 700 FPS, .8M, 35,000 FT.
SR-7	blade design for the Large-Scale Advanced Propeller (LAP) for flight test on the Propfan Test Assessment (PTA) Gulfstream II jet aircraft; 9 ft diameter, 8 blades, AF of 227, 36° sweep, 800 FPS tip speed, 32 SHP/D^2, .8M, 35,000 FT.
SR-8	blade design that incorporates new, thicker airfoil sections; designed for .8M, 35,000 FT, 31 SHP/D^2, 850 FPS tip speed; 9 blades, AF of 195, 43° sweep.
GA STUDY PROPFAN	blade design for General Aviation applications; designed for .75M, 41,000 FT, 16 SHP/D^2, 750 FPS, 6 blades, AF 180, 15° sweep.

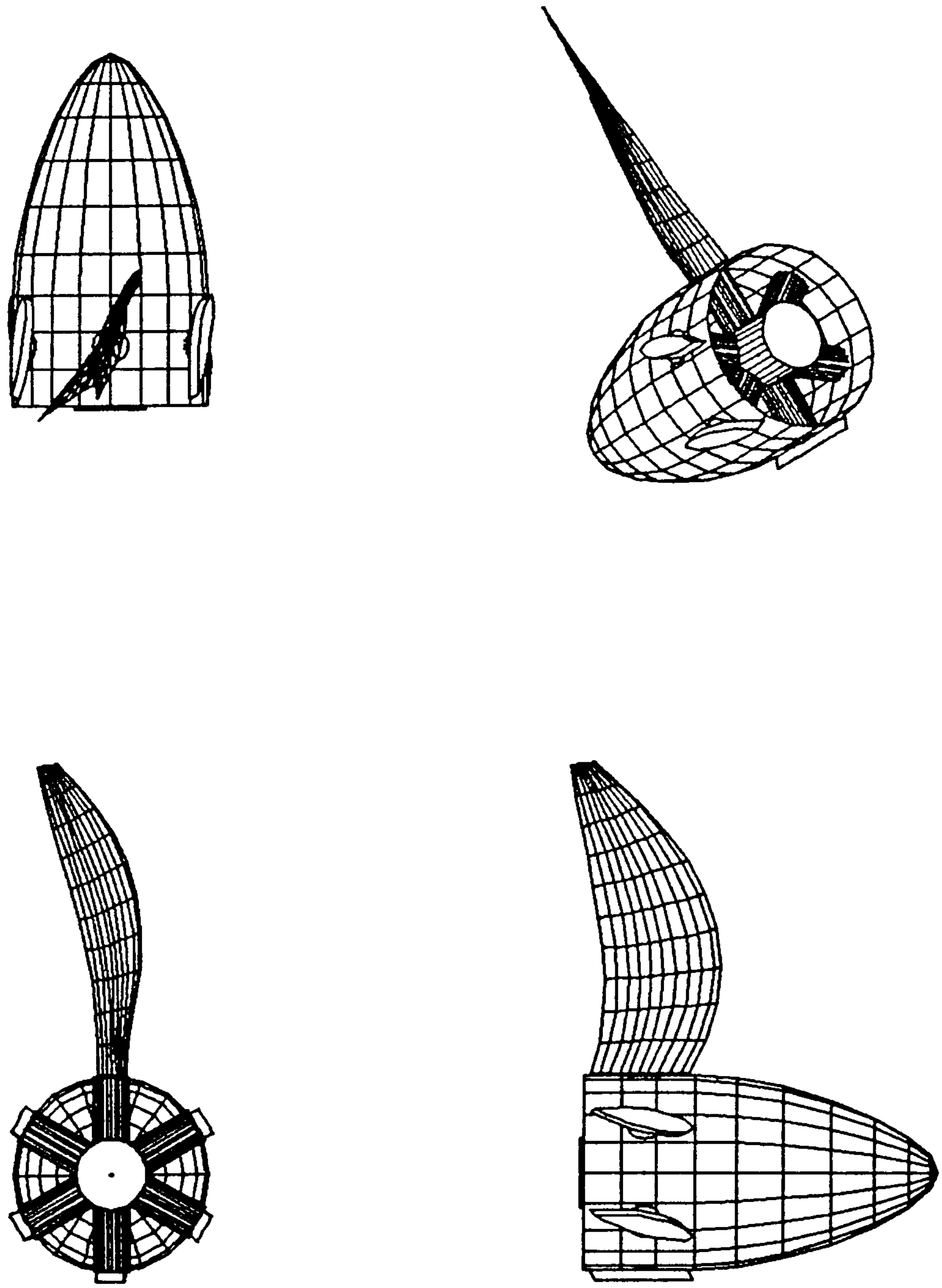

FIGURE 16. ISO-Views of the Selected Propfan

The performance was estimated utilizing the data package from Reference 5. The data in Reference 5 represents an SR-3, ten-bladed propfan and was used to approximate the performance of the selected six-bladed propfan. Several check cases were made by Hamilton Standard for key flight conditions to assure that this approach would yield valid results for the six-bladed propfan used in this study. Table 5 shows that the data package generated slightly higher propeller efficiency in the climb condition and slightly lower efficiency in the cruise condition. The higher propeller efficiency in climb resulted in slightly lower estimated fuel use in climb. This was compensated, however, by the slightly higher estimated fuel use in cruise due to the lower cruise efficiency such that, overall, the data package of Reference 5 gave a valid fuel utilization estimate for the six-bladed propfan.

The propfan disk loading and tip speed were selected based on the study's mission requirements and ground rules. Hamilton Standard provided propfan information for the study for tip speeds from 600 FPS to 800 FPS. As stated previously, the 82 dBA goal was expected to be difficult to achieve for the propfan. Propfan noise is reduced as the tip speed is reduced, but with a subsequent increased cost and weight of the gearbox. On the other hand, higher tip speeds allow a reduction in gearbox weight and cost plus improved aerodynamic performance, but with significantly increased noise levels. The minimum cost and highest performance would be achieved

TABLE 5. Comparison of Propfan Performance Estimates

FLIGHT CONDITION			PROPFAN EFFICIENCY	
SEGMENT	ALTITUDE (FT)	SPEED (MACH)	SP07A82 DATA PACK	SELECTED SIX BLADE PROPFAN
CLIMB	15,000	.40	.81	.80
CRUISE	30,000	.70	.83	.84
CRUISE	41,000	.80	.82	.83

utilizing an 800 FPS tip speed. At this tip speed, however, the cruise noise levels were potentially high enough that the airframe structure would be subject to significant sonic fatigue. Due to the uncertainty of the noise calculations, a tip speed design margin was introduced. A tip speed of 750 FPS was selected as a compromise to lower the potential of sonic fatigue problems while still providing the higher performance and lower cost of a high tip speed design.

The propfan disk loading (or propeller diameter) was selected for minimum block fuel for the cost mission, Figure 17. Figure 18 shows the performance of the selected propfan for the cruise condition design point. It is interesting to note that the minimum mission fuel burn occurs near the maximum efficiency of the propeller at about an equivalent disk loading (SHP/D^2). Other studies have indicated much higher disk loadings for propfans. This is discussed further in Section 6.1.

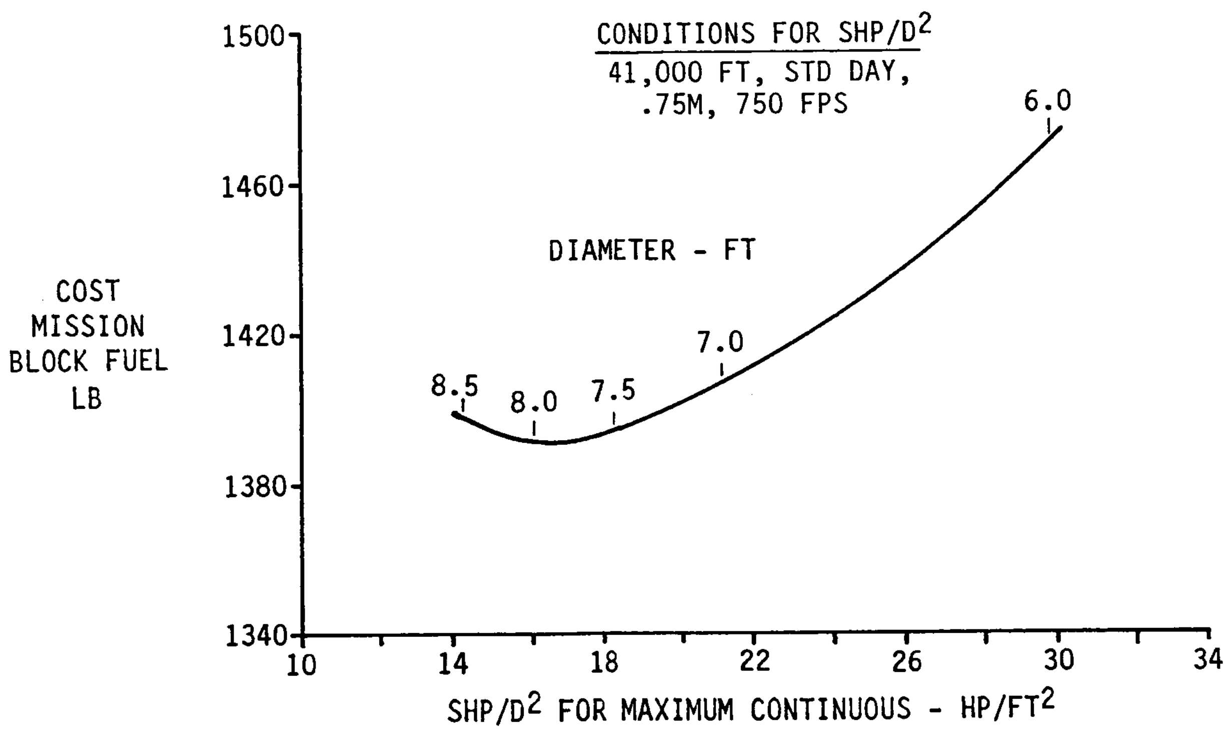

FIGURE 17. **Effect of Propfan Disk Loading on Fuel Burn**

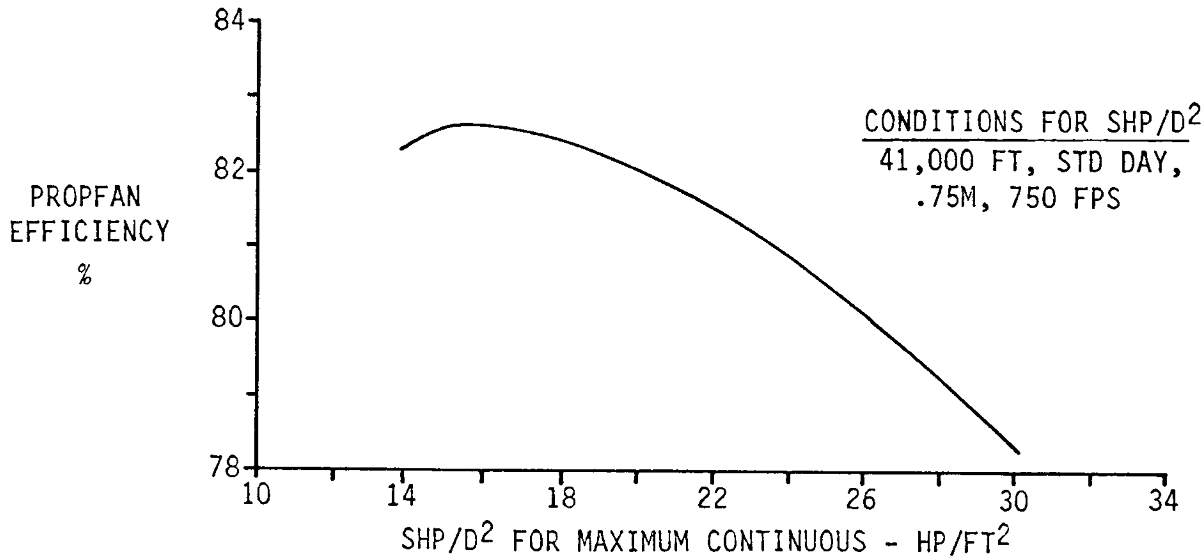

FIGURE 18. **Effect of Propfan Disk Loading on Efficiency**

4.5 PROPULSION SYSTEM SCALING

Propulsion system weight data provided by Pratt and Whitney, Canada and Hamilton Standard was used to develop the propulsion system weight scaling shown in Figures 19 through 23. The propulsion system weight includes the weight of the engines, gearboxes, and props. Figure 19 shows the relative weight effects of engine size for both the current technology and 1988 technology turbofans. Figure 20 shows the relative weight effects of engine size for the 1988 technology turboprop at a gearbox output speed of 1800 RPM. The weight effect of change of RPM and impact of flat rating is given in Figures 21 and 22. The propulsion system weight in Figures 19 through 22 assumes a constant propfan diameter. Figure 23 shows the effect of propfan diameter change on propfan propeller weight.

The RPM of the propfan was selected to yield the chosen rotational blade tip speed of 750 FPS. The optimum blade diameter selected as discussed in Section 4.4, was eight feet and the RPM required to achieve the 750 FPS tip speed was roughly 1800 RPM.

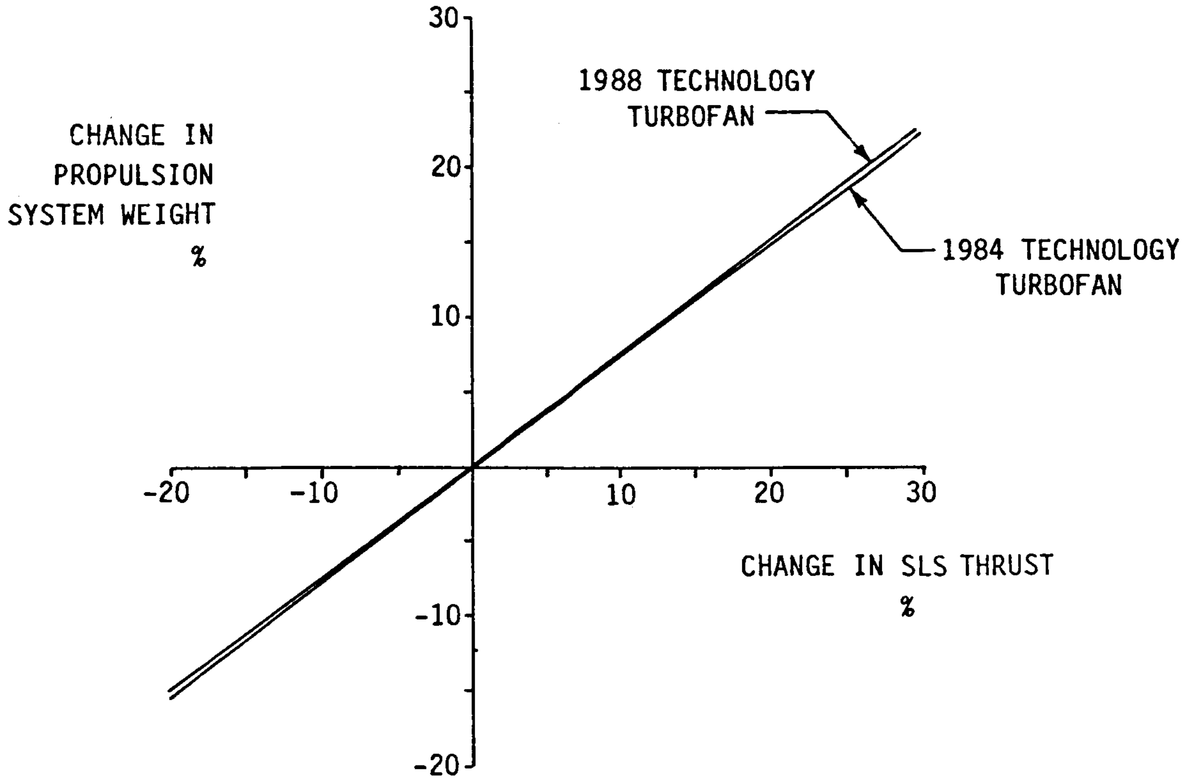

FIGURE 19. Turbofan Engine Size Effect on Propulsion System Weight

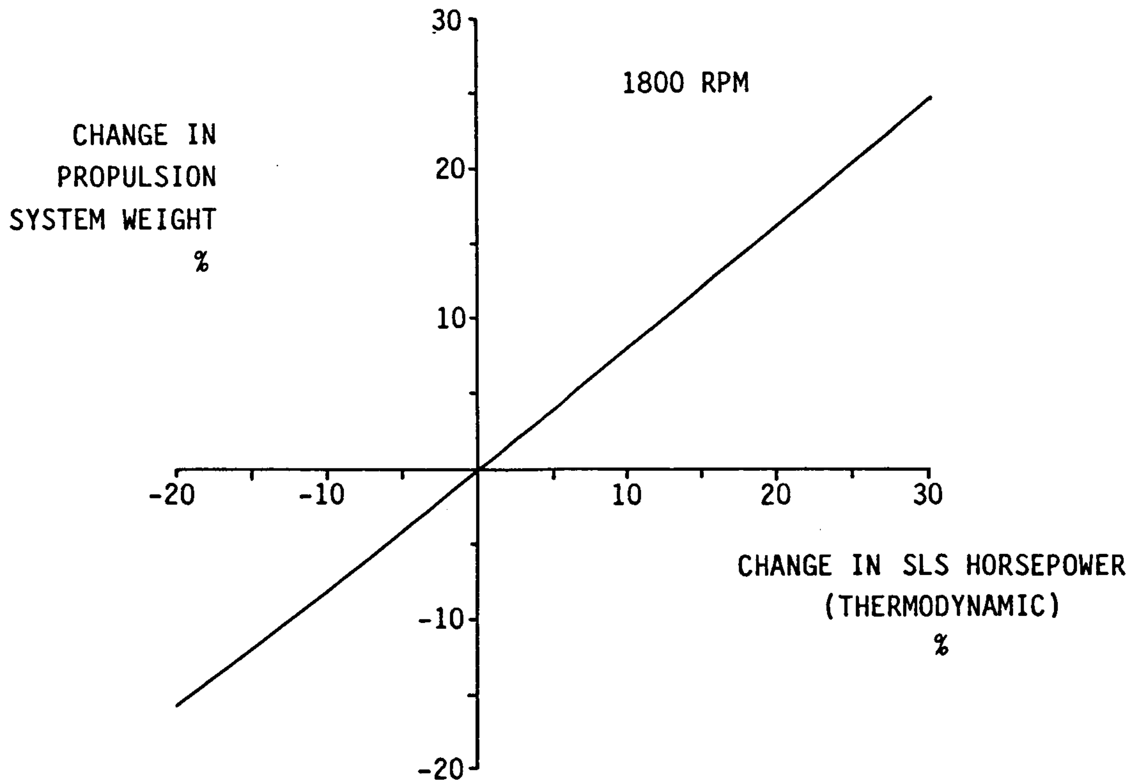

FIGURE 20. Turboprop Engine Size Effect on Propulsion System Weight

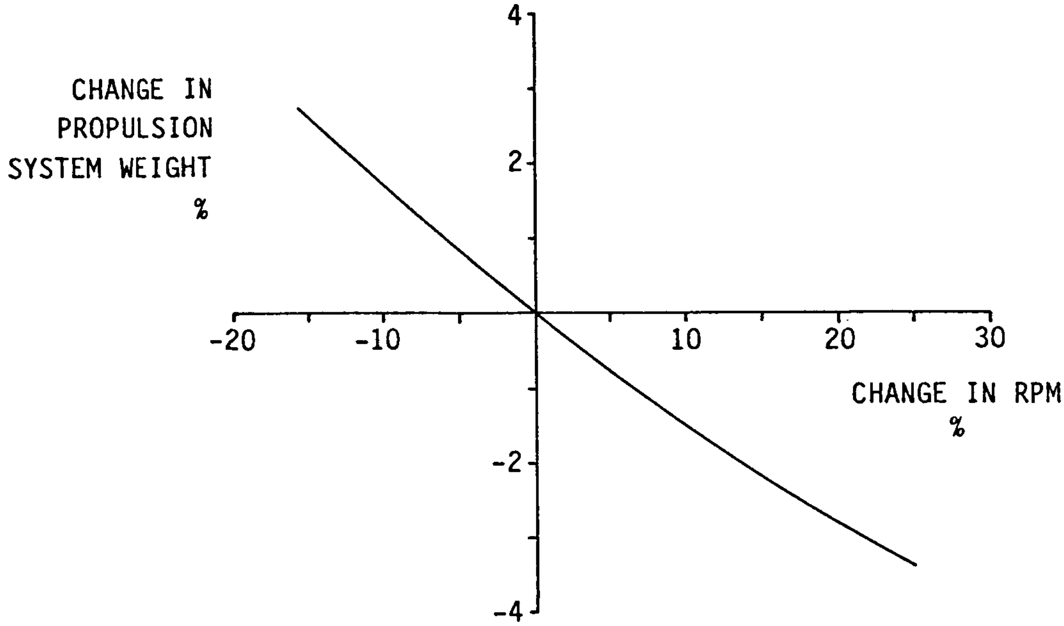

FIGURE 21. RPM Effect on Turboprop Propulsion System Weight

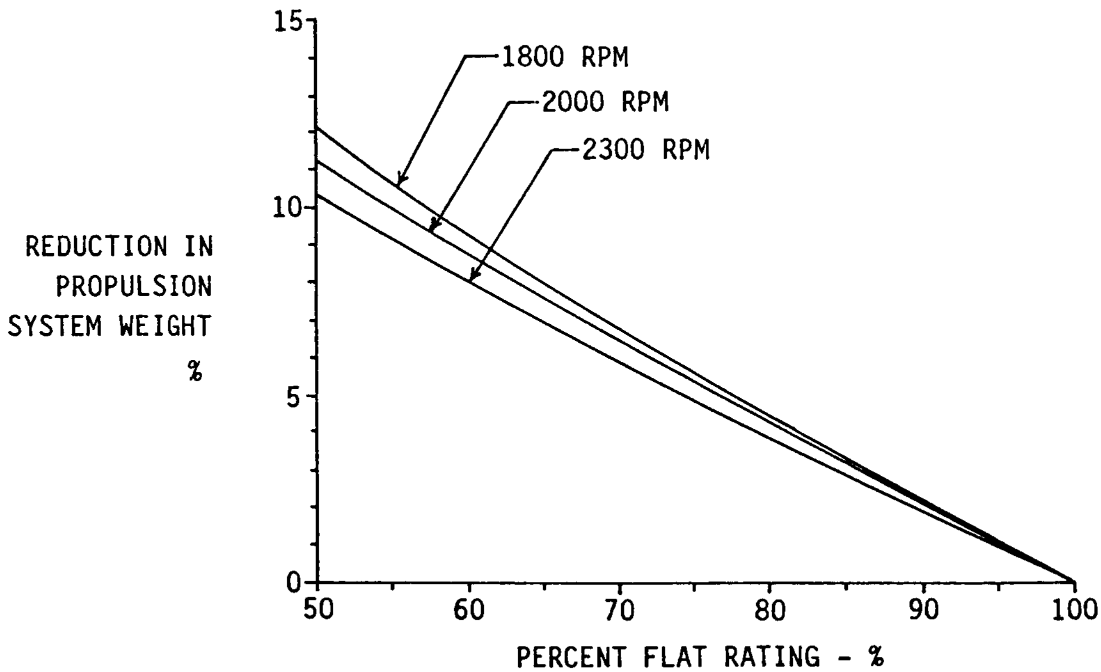

FIGURE 22. Flat Rating Effect on Turboprop Propulsion System Weight

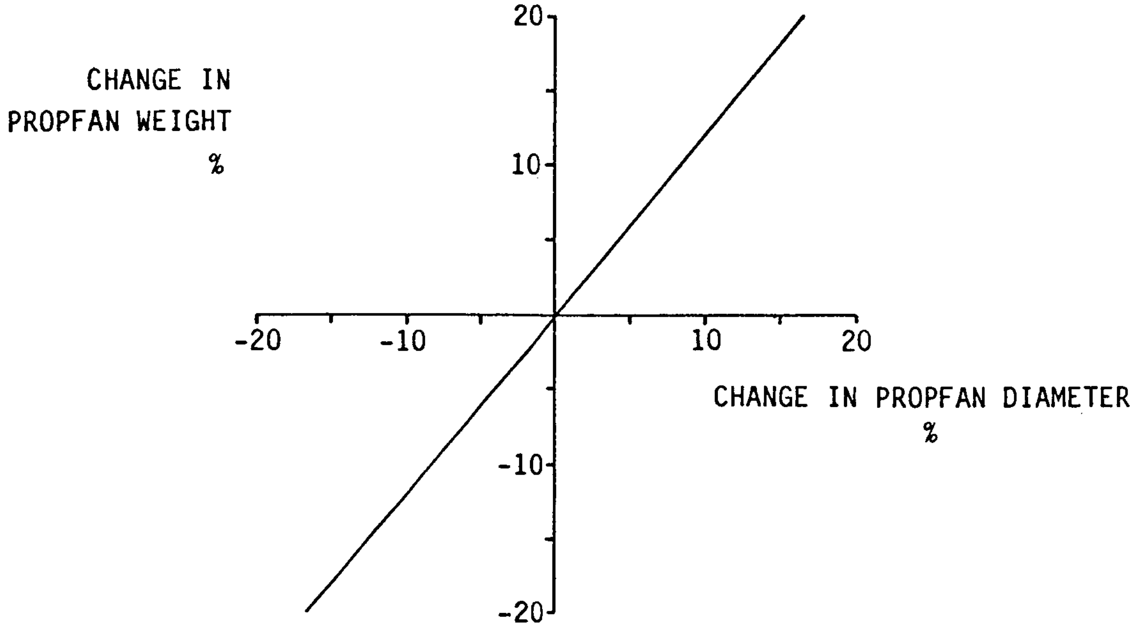

FIGURE 23. **Propfan Diameter Effect on Propeller Weight**

It was assumed that the engine envelope dimensions of the baseline engines did not change with the small amount of engine scaling required for the study aircraft. A nominal length of 64 inches was used for the turbofans with a diameter of 31 inches. The turboprop engines (exclusive of the propfan itself) had a nominal length of 82 inches overall (including gearbox and accessories) and a diameter of 26 inches. These dimensions are consistent with the current PT6 and JT15D series engines.

5.0 CONFIGURATION EVALUATION

Utilizing the selected general configuration of Section 4, this section presents the detailed sizing and optimization of four aircraft; a 1984 technology turbofan aircraft, a 1990 technology turbofan aircraft, a 1990 pusher propfan aircraft, and a 1990 tractor propfan aircraft. The mission performance and cost of operation results are presented.

5.1 CONFIGURATION SIZING AND OPTIMIZATION

Figures 24 through 27 are the carpet plots that were used to size and optimize the final study configurations. The process to specify each configuration (design point A in each figure) was similar to that described in Section 3.2

Each design point was selected based on two criteria. First, the aircraft design point had to meet all the performance capabilities specified in the study ground rules. Then, second, if possible, the design point had to provide the minimum fuel burn for the cost mission described in Section 3.1.

In Figures 24 and 25, both the current turbofan and advanced turbofan were designed by performance constraints. Point A in each case was constrained by a 2.4% climb gradient and a cruise Mach number of .75 at 41,000 FT altitude. Point A, then, was the point which satisfied both design criteria.

The pusher and tractor propfans, on the other hand, were only constrained in performance by the cruise requirement. Thus the design point was the minimum fuel point along the constant cruise Mach line shown in Figures 26 and 27. Point A, in addition to meeting the required cruise speed, also exceeded all the other performance requirements while providing the minimum fuel usage for the propfans.

5.1.1 PROPULSION SYSTEM PERFORMANCE

As stated in Section 4, the Pratt and Whitney PT6 engine cycle was used as a baseline to provide scaled turboprop data for the study. The Pratt and Whitney JT15D engine cycle was used as a basis for the turbofan data. A flat rating of 1500 SHP was imposed on the turboprop engine at lower altitudes. This was done to relieve some of the installation problems

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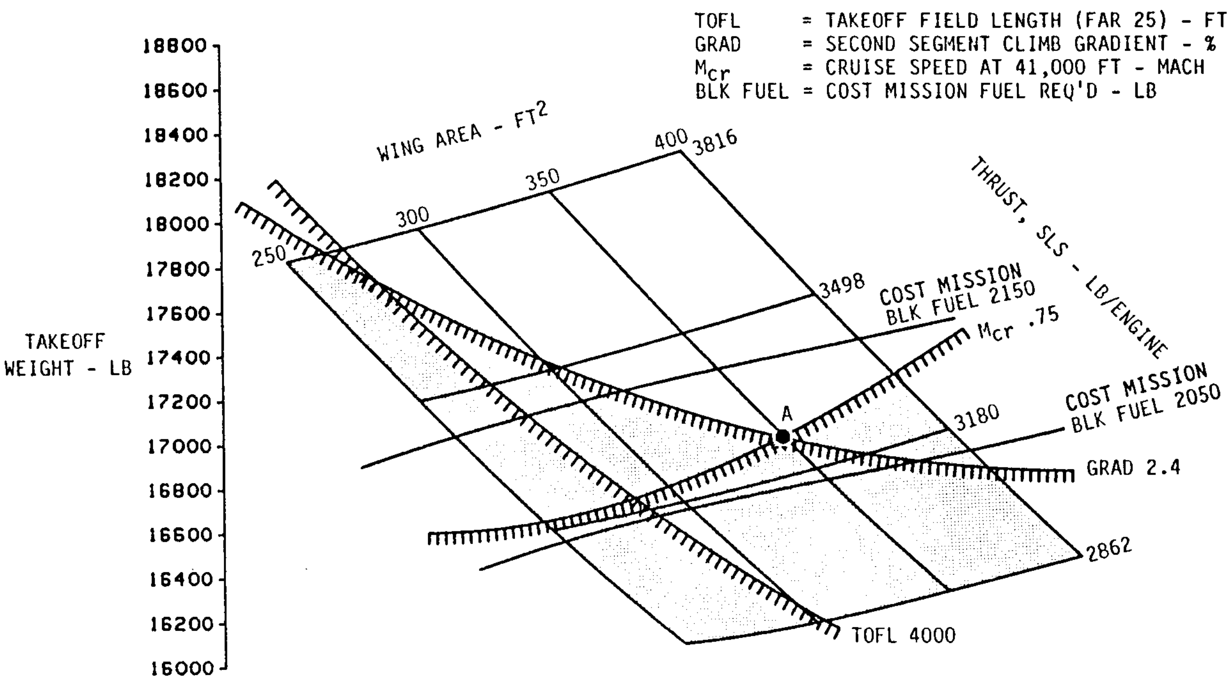

FIGURE 24. Current Turbofan Carpet Plot

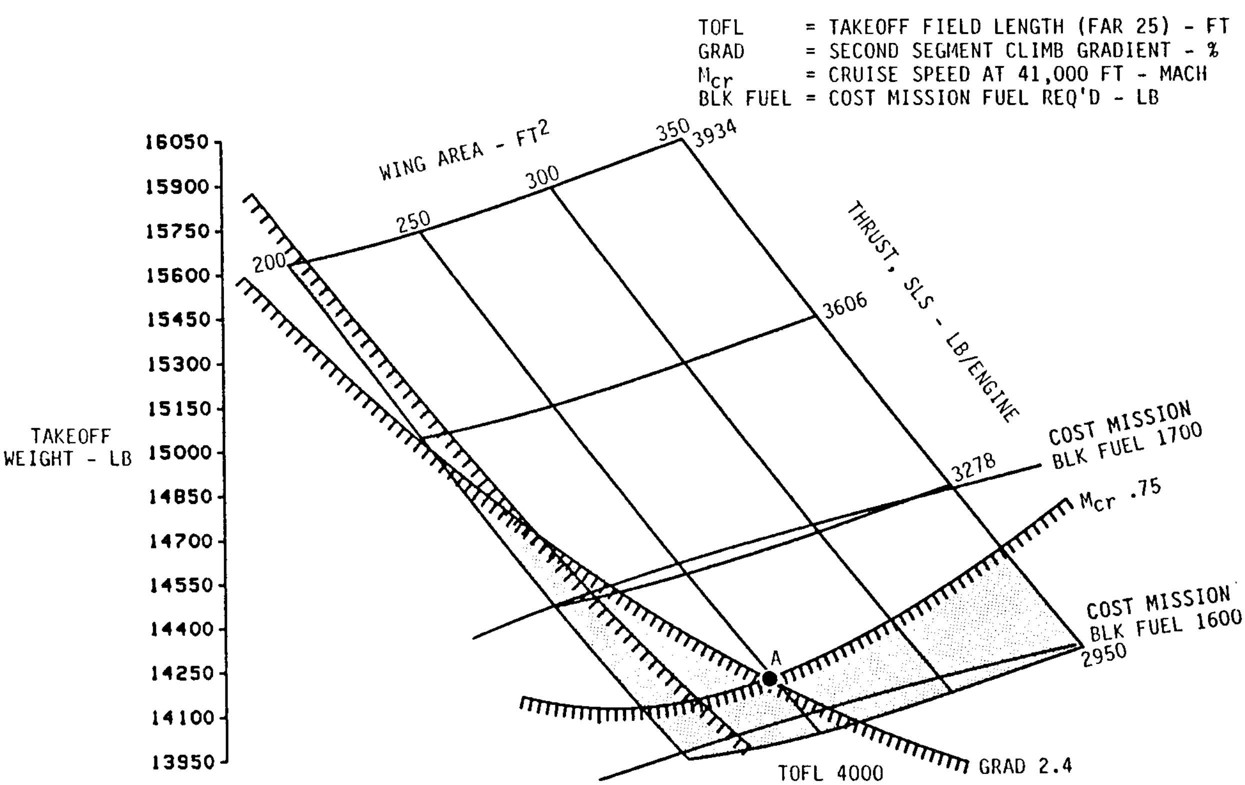

FIGURE 25. Advanced Turbofan Carpet Plot

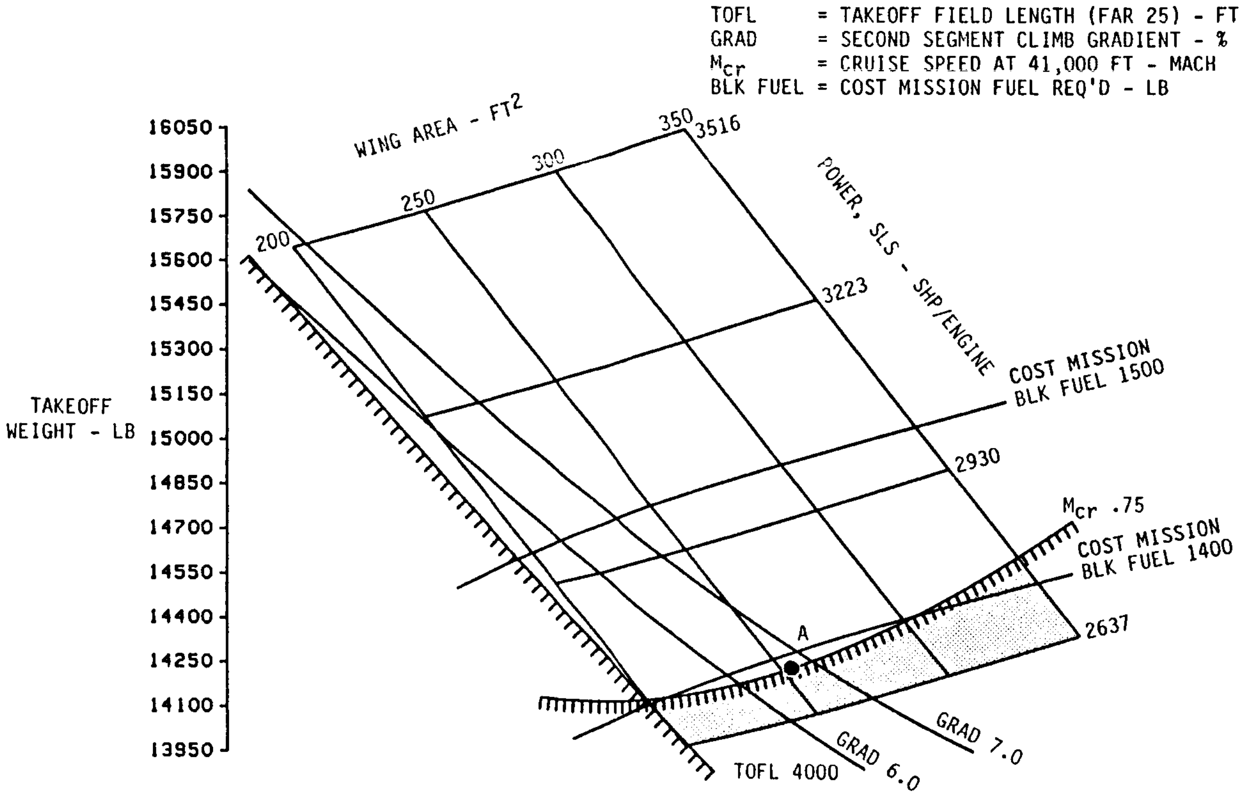

FIGURE 26. Pusher Propfan Carpet Plot

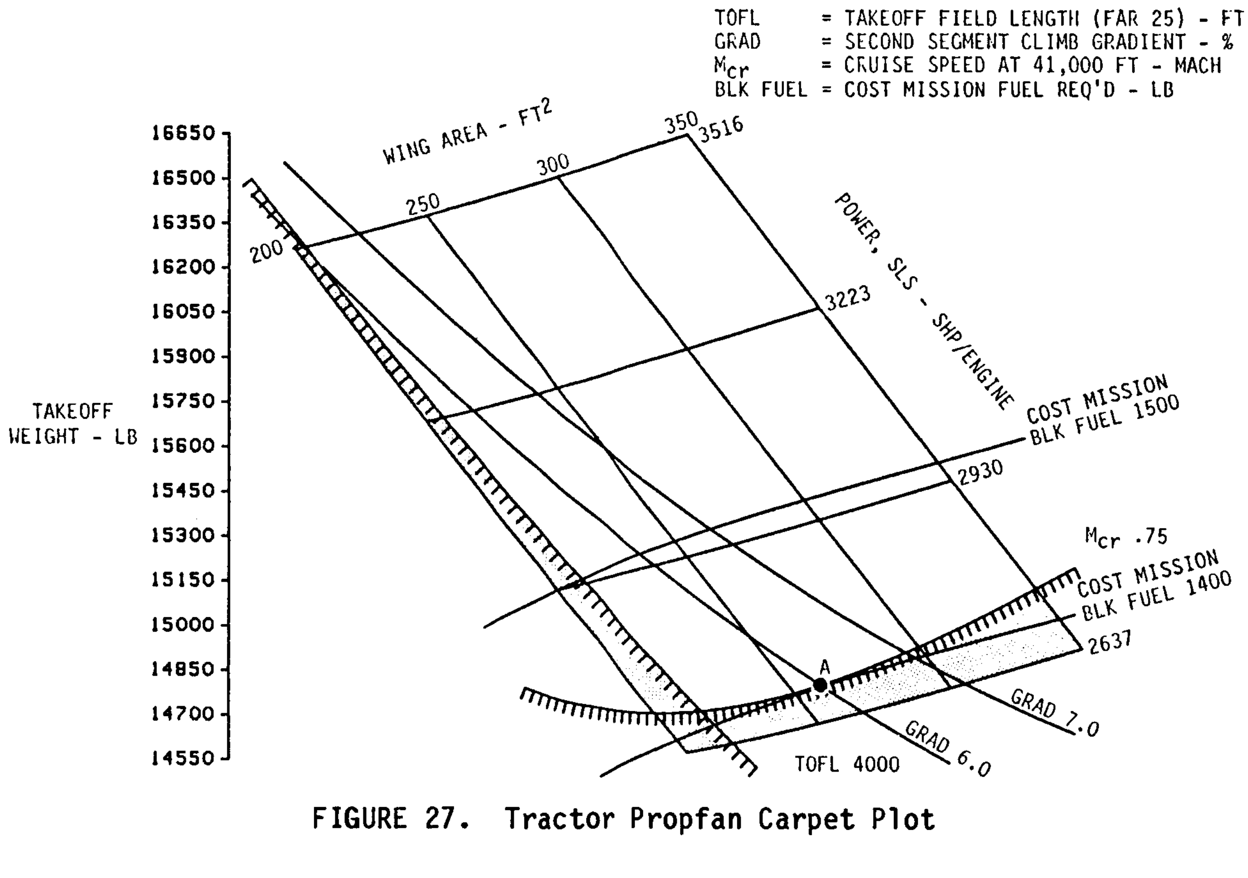

FIGURE 27. Tractor Propfan Carpet Plot

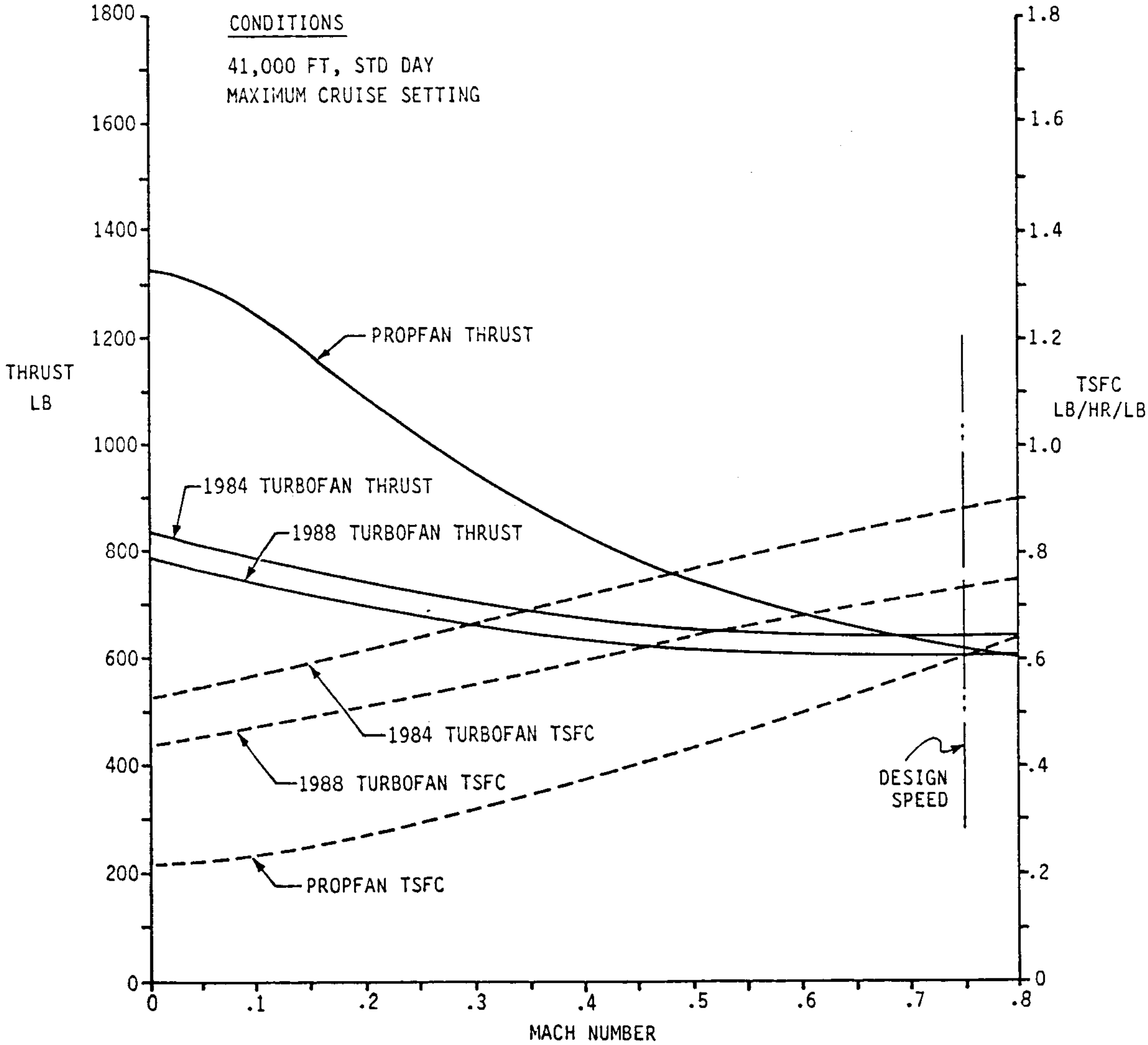

FIGURE 28. Sized Engine Characteristics

associated with the propfan such as high blade stresses, engine weight, gearbox weight, cost, airframe weight, and aircraft tail size. Figure 28 compares the current 1984 turbofan engine, the advanced 1988 turbofan engine, and the advanced 1988 propfan engine, all on a thrust basis. The propulsion systems provided by Pratt and Whitney were all sized initially to provide 650 LB of thrust at the design point. When each aircraft was then sized to meet the design mission, different thrusts were required at the design point because of configuration weight and drag differences, as shown in Figure 28. The propfan thrust shown is for the pusher installation and includes the effect of the engine exhaust thrust as well as the propeller thrust. The tractor installation is not shown, but differs only slightly from the pusher data. The thrust for the tractor installation was approximately 3% higher than that of the pusher but with the same TSFC. The TSFC curves show that, at the cruise design point of .75 Mach and 41,000 FT altitude, the propfan had 31% less fuel consumption than a current turbofan and 17% less fuel consumption than an advanced turbofan.

Propulsion system scaling utilized the baseline engine data provided by Pratt and Whitney. The baseline thrust or power data was scaled linearly while keeping the specific fuel consumption the same as the baseline. This approximation was valid over the narrow band of scaling required for this study. The weight scaling was accomplished using the methods outlined in Section 4.5.

5.1.2 CONFIGURATION THREE-VIEWS

Figures 29, 30, 31, and 32 show the 3-views for the final study aircraft. The aircraft shown represent the aircraft characteristics of Design Point A for each of their respective carpet plots in Figures 24 through 27. Each aircraft satisfied all of the initial design ground rule requirements and provided the minimum block fuel burn for the cost mission defined in Section 3.1.

TOGW	17033 LB
OEW	8676 LB
PAYLOAD	1200 LB
USABLE FUEL	7157 LB
WING AREA	349.0 FT^2
SPAN	54.5 FT
ASPECT RATIO	8.5
WING LOADING	49 LB/FT^2
THRUST/ENGINE, SLS	3257 LB

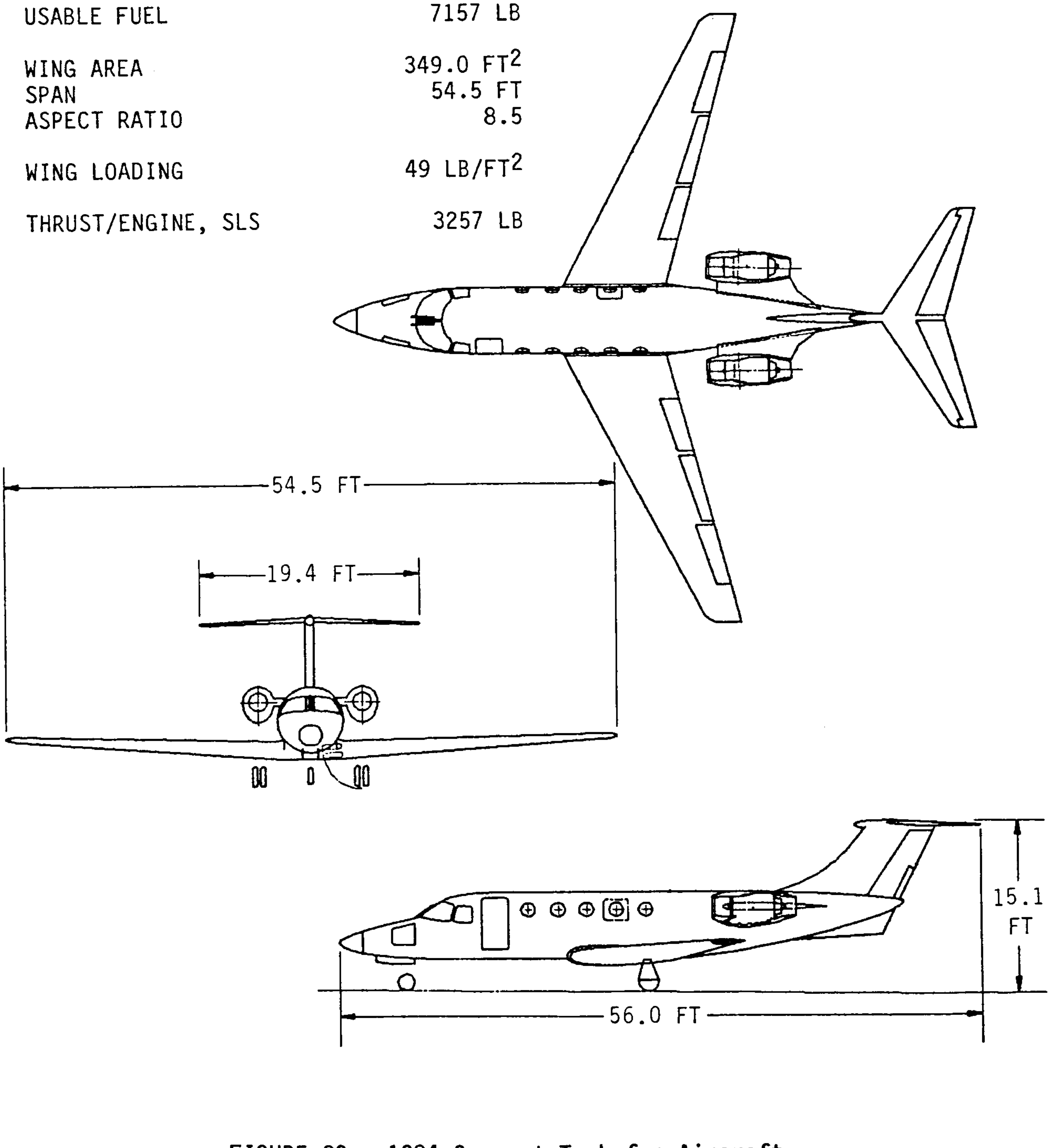

FIGURE 29. 1984 Current Turbofan Aircraft

TOGW	14234 LB
OEW	7426 LB
PAYLOAD	1200 LB
USABLE FUEL	5608 LB
WING AREA	248.1 FT^2
SPAN	45.9 FT
ASPECT RATIO	8.5
WING LOADING	57 LB/FT^2
THRUST/ENGINE, SLS	3067 LB

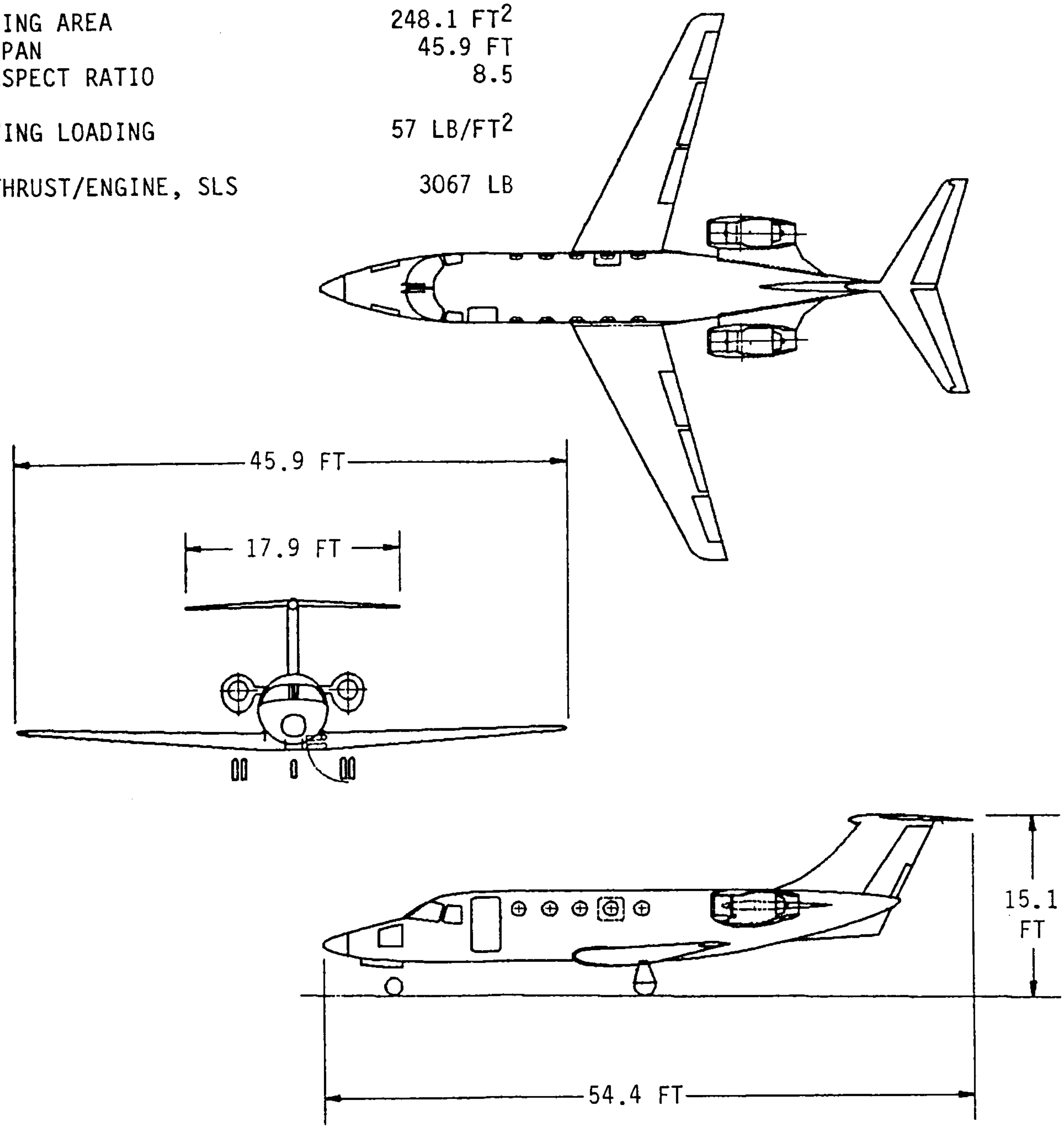

FIGURE 30. 1990 Advanced Turbofan Aircraft

TOGW	14230 LB
OEW	8274 LB
PAYLOAD	1200 LB
USABLE FUEL	4756 LB
WING AREA	252.2 FT^2
SPAN	46.3 FT
ASPECT RATIO	8.5
WING LOADING	56 LB/FT^2
SHP/ENGINE, SLS	2714 THERMODYNAMIC 1500 FLAT RATED

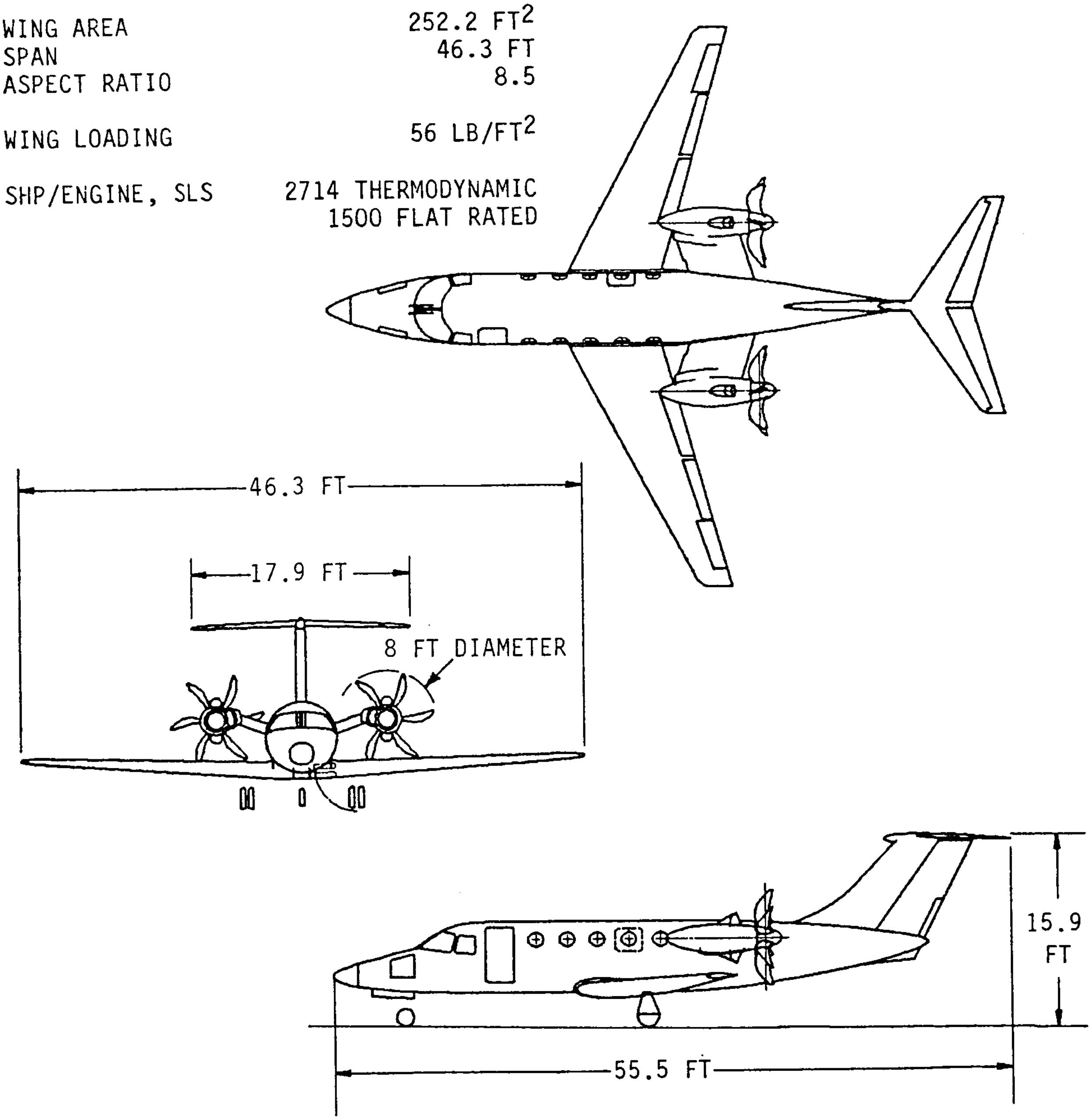

FIGURE 31. 1990 Pusher Propfan Aircraft

TOGW	14805 LB
OEW	8802 LB
PAYLOAD	1200 LB
USABLE FUEL	4803 LB
WING AREA	260.8 FT^2
SPAN	47.1 FT
ASPECT RATIO	8.5
WING LOADING	57 LB/FT^2
SHP/ENGINE, SLS	2693 THERMODYNAMIC 1500 FLAT RATED

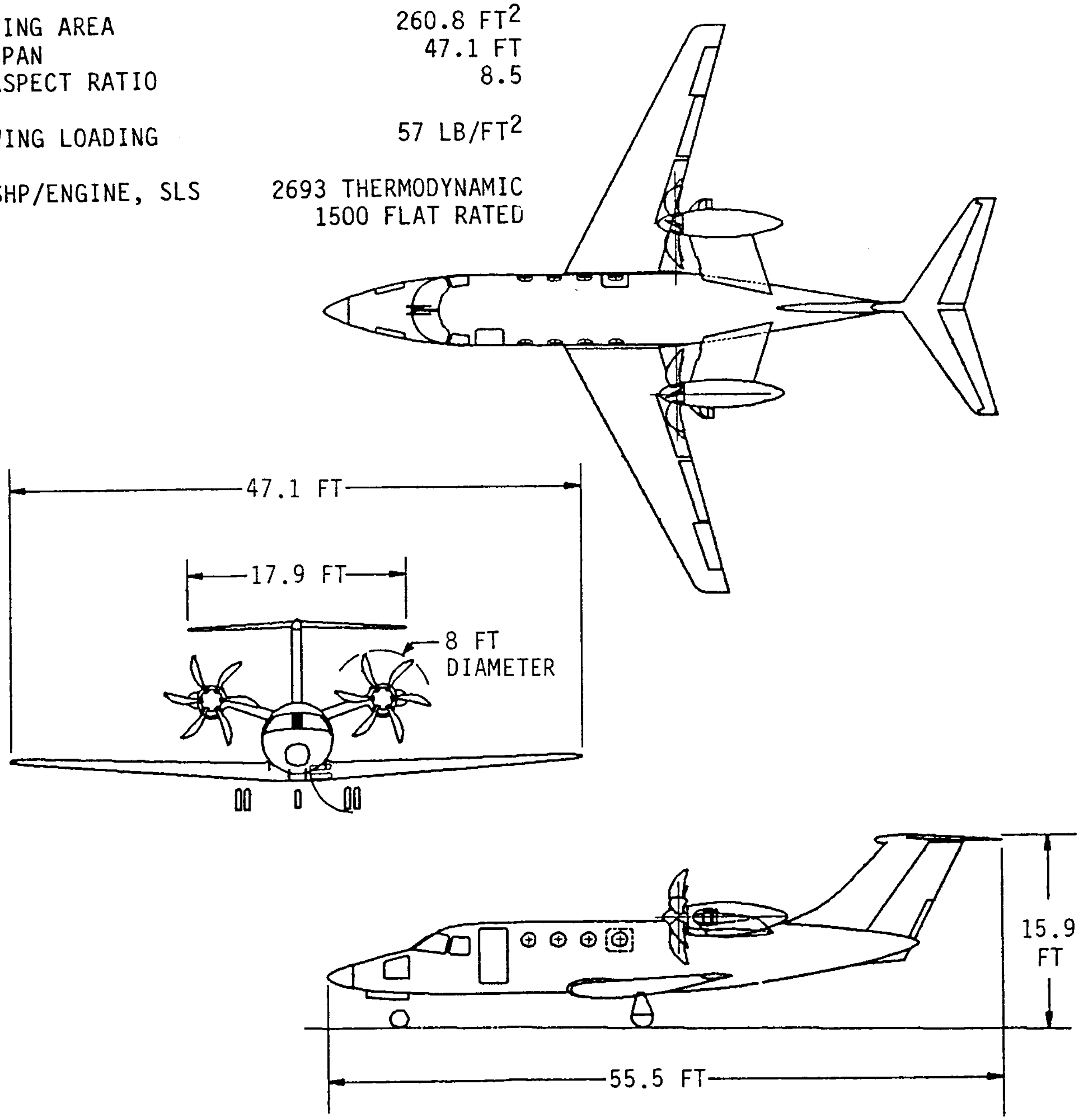

FIGURE 32. 1990 Tractor Propfan Aircraft

5.2 INSTALLATION CONCEPTS

Since the study goal was to provide a good comparison between conventional propulsion and propfan propulsion, an attempt was made to select similar installation concepts. Figure 33 shows a typical conventional turbofan installation for a Pratt and Whitney JT15D class engine. The major loads were carried by the engine mount support beam. The engine was stabilized by a "steady-rest" support tied to the aft portion of the engine. The accessories were provided cooling air through a small duct and were mounted below the engine.

Figure 34 shows the installation for the tractor version of the propfan using a Pratt and Whitney PT6 engine. Figure 35 shows the pusher version installation. Similar to the turbofan, the major loads were carried by the mount support beam for both propfan versions. However, because of the higher propulsion system weight and slightly modified geometry, the support beam for the propfan versions was larger than the beam required for the turbofan. The propfan propulsion system weight was roughly 30% more than the turbofan and was located further from the fuselage for propeller clearance. To carry the additional loads, the propfan installation required a spar cap of roughly twice the area of that required for the turbofan. The larger spar, combined with the effect of a longer length pylon, resulted in a significant pylon weight increase over the turbofan installation. Combining this with the structural requirements for gyroscopic loads, whirl induced loads, and sudden prop stoppage (FAR 25.361(b)(1)) resulted in a pylon/nacelle weight increase of roughly 34% for the pusher installation and 78% for the tractor installation, as compared to the turbofan installations.

The engine in both the pusher and tractor versions was stabilized by a "steady-rest." This steady-rest had to be capable of handling whirl induced loads. Also, the engine case itself required additional strength to handle the additional propfan loads.

De-ice was accomplished using engine bleed air on the engine inlet lips for the turbofan. De-ice was also provided on the inlet lips for both turboprop installations. Also, as illustrated in Figures 34 and 35, anti-ice protection for the engine intake screen was provided by the inertial separators. The inertial separators are a mechanical vane and bypass duct arrangement which forces the heavier, super-cooled water and ice particles to bypass the inlet plenum and thus prevents the engine inlet

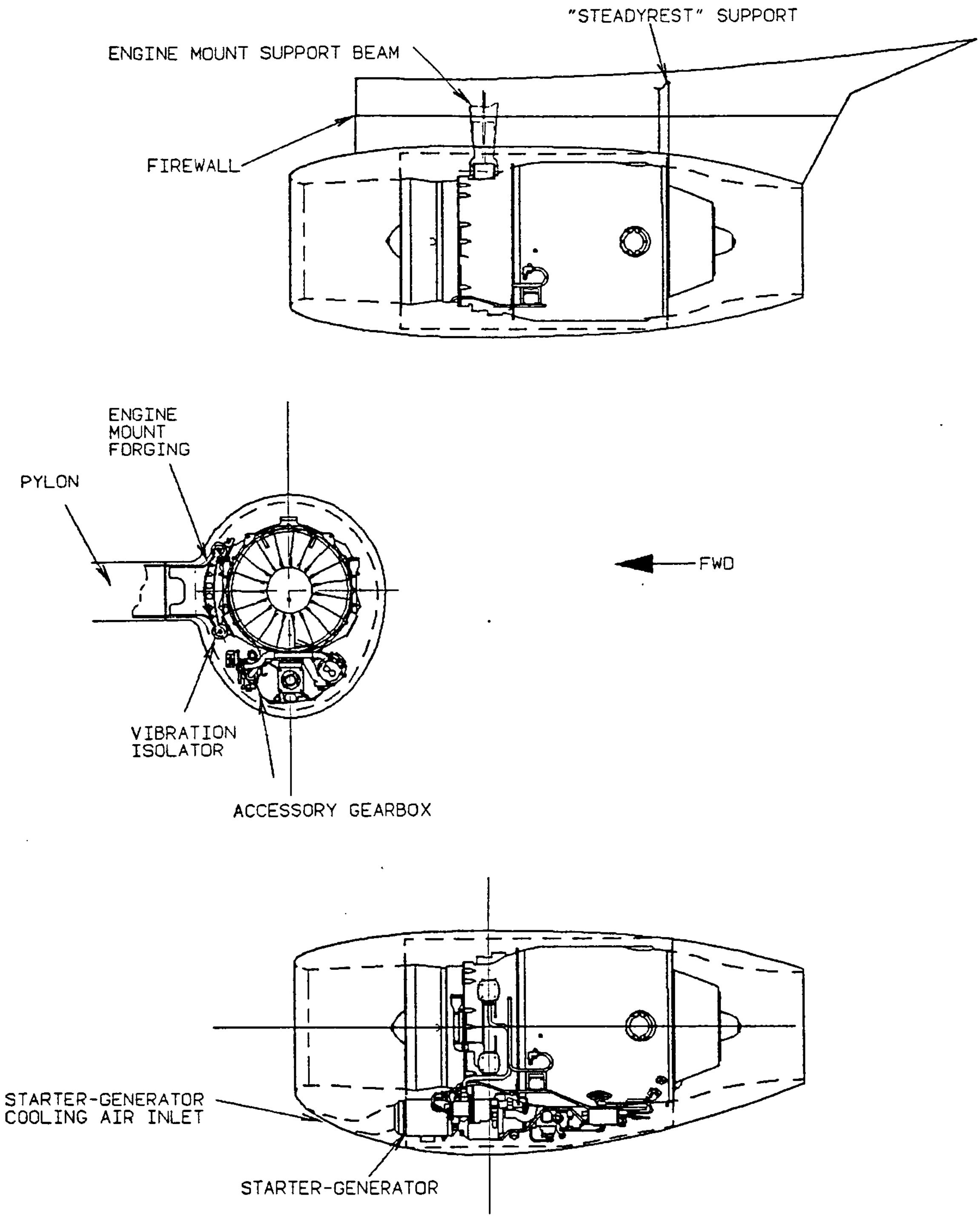

FIGURE 33. Turbofan Installation Concept

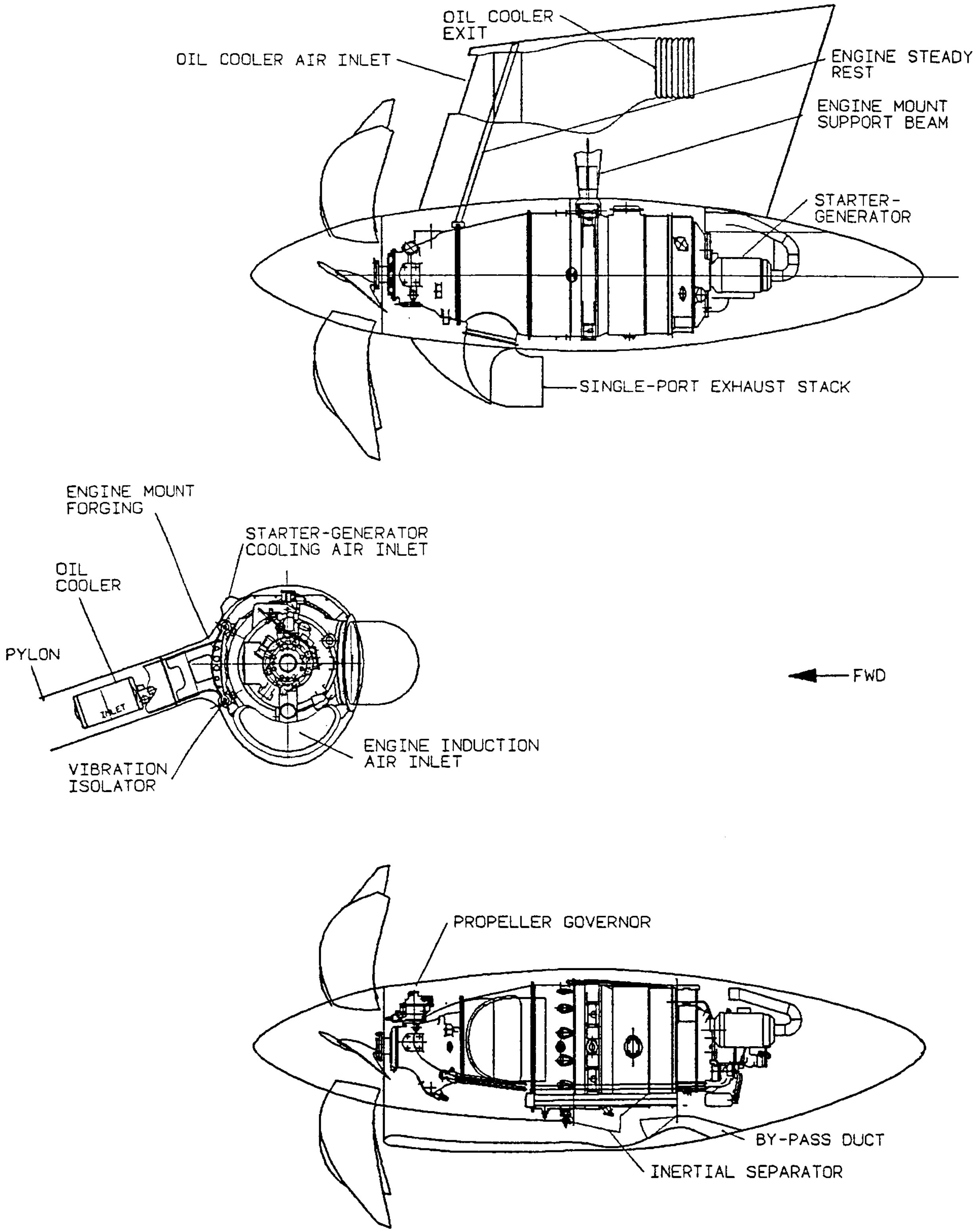

FIGURE 34. Tractor Propfan Installation Concept

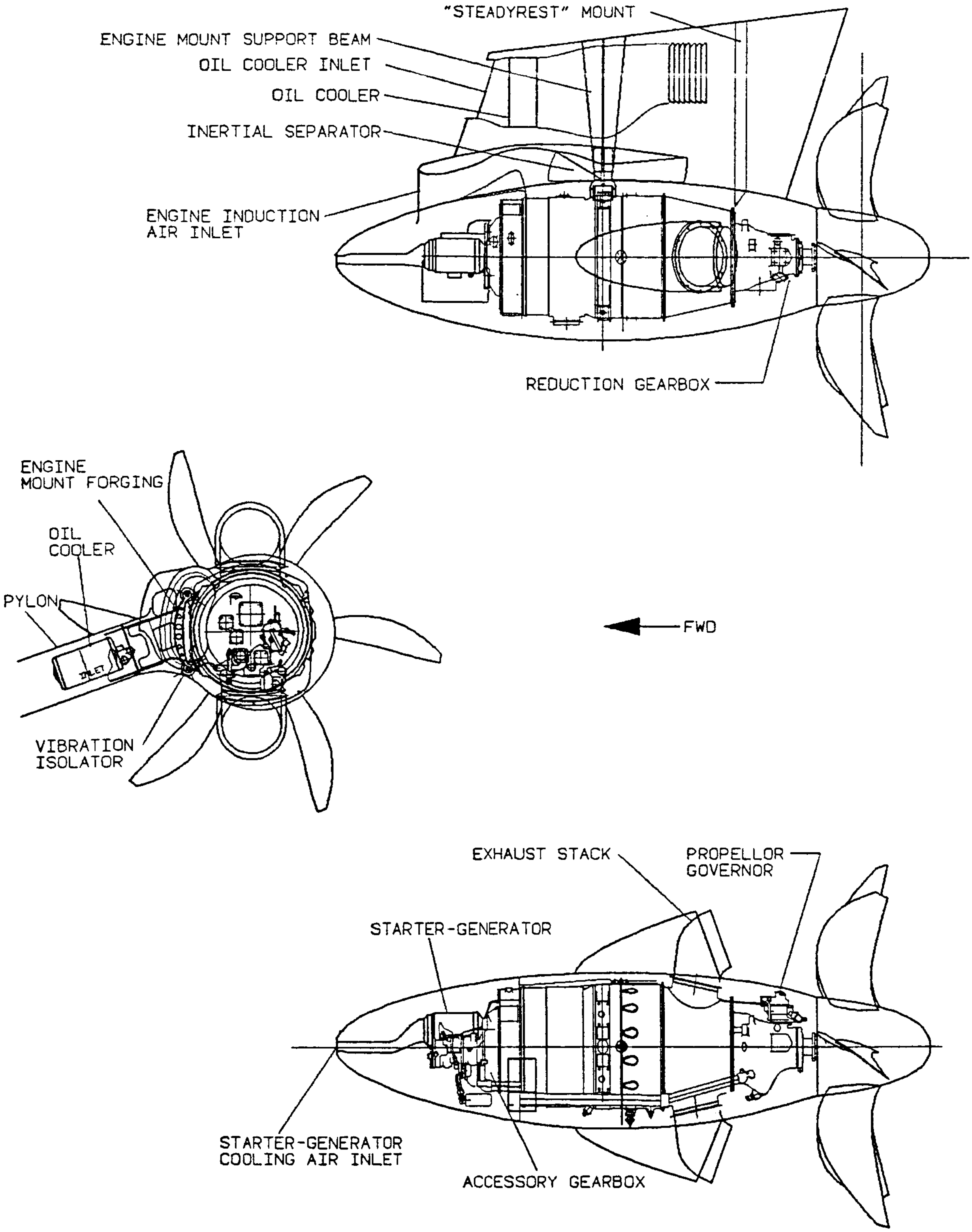

FIGURE 35. Pusher Propfan Installation Concept

screen from becoming blocked. It was assumed that the propfan blades in the pusher installation would not require any ice protection because of the hot exhaust gas flowing into the blades. Ice protection for the propfan blades in the tractor installation was not examined in this study.

Two different exhaust stack concepts are illustrated in Figures 34 and 35. The tractor version utilized a single port exhaust and an under nacelle "smile" type inlet. The pusher version used a bifurcated inlet located in the pylon and dual exhaust ports. It was felt that either of these inlet and exhaust concepts could have been used interchangeably with either the pusher or tractor installations. However, the dual exhaust port had several advantages over the single port exhaust. The large single port exhaust presented a much larger base drag than the dual port. Also, with the larger exposed area, the single port exhaust's potential for shocking was greater. In a pusher installation, the formation of shocks, in addition to an increase in drag, could result in significant cyclic loads on the propfan blades. Additionally, in the pusher configuration, the dual port would provide better hot exhaust gas mixing and thus lower temperatures prior to entering the prop plane. Detailed analysis of the exhaust stack impact on the flow field was beyond the scope of this study. However, a simplified potential flow model, Figure 36, was constructed to verify that a fairing could be designed which would prevent shock formation. Figure 36 shows a fairing which remains just slightly subsonic for the design cruise condition, as illustrated in the graph in Figure 36. This fairing was a rough cut, first attempt design for the pusher installation. It was felt that with further analysis and tailoring a fairing could easily be designed which would remain well below sonic and thus yield a shock-free design.

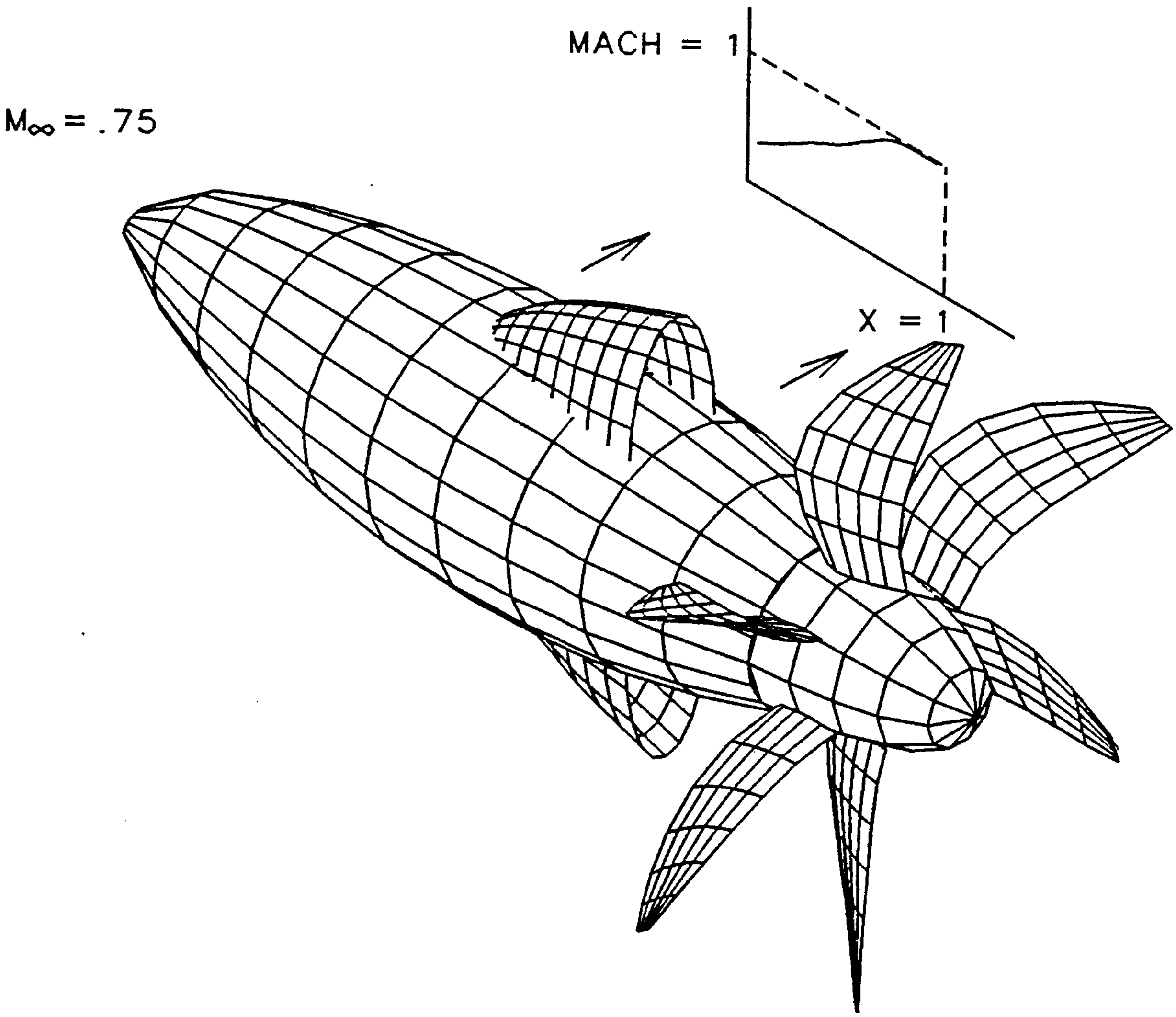

FIGURE 36. Effect of Exhaust Stack in the Propfan Flow Field

5.3 AERODYNAMIC CHARACTERISTICS

The selected configurations utilized conventional aerodynamic design. The wing plan form for each was chosen based on the results from the aircraft synthesis programs. The wing section for each design was based on an airfoil section which eliminated any transonic effects for the aircraft's mission requirements. The airfoil section at the root was 18% thick. The airfoil section at the tip was 15% thick.

5.3.1 LOW SPEED DRAG CHARACTERISTICS

The low speed drag polars for each configuration are shown in Figures 37 through 40. Each includes the effects of propulsion system installation. The high speed Mach effects are minimal and are discussed in Section 5.3.3. The drag shown is for twin engine cruise and takeoff. Single engine (engine-out) takeoff drag is 3% higher for the turbofan installations and 9% higher for the propfan installations than the twin engine takeoff drag. The higher single engine drag accounts for the effects of yaw, trim, feathered propeller, and windmilling turbine. Taking into account the

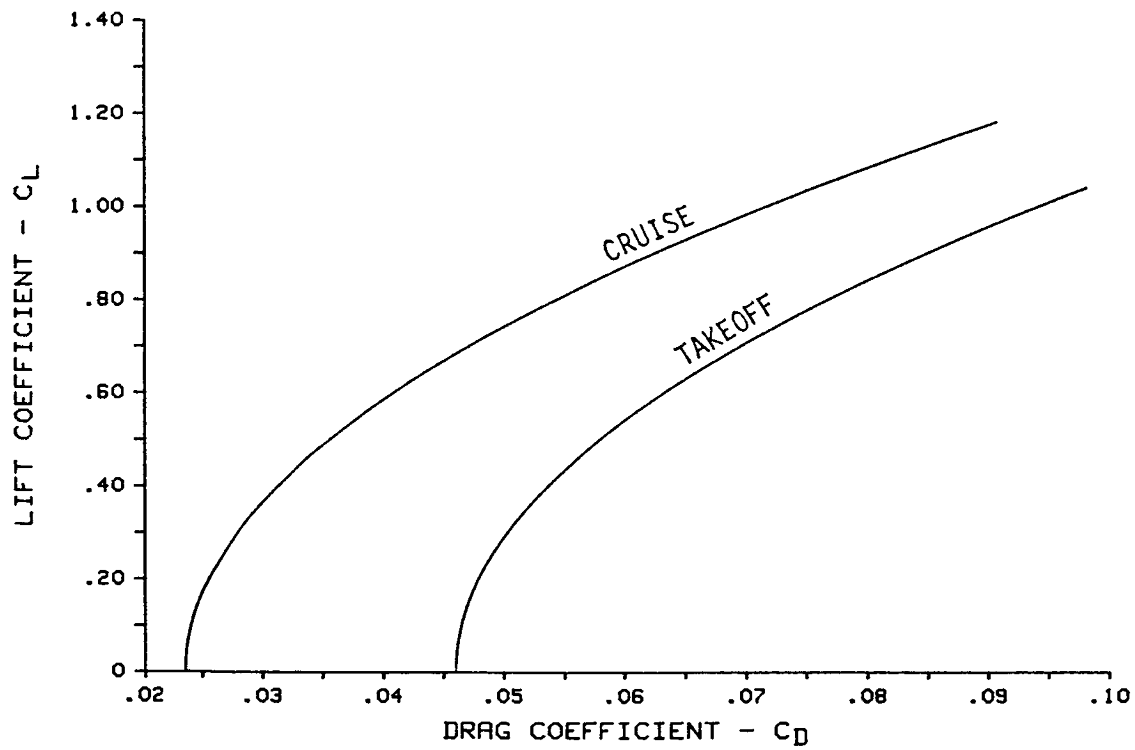

FIGURE 37. Current Turbofan Low Speed Drag Characteristics

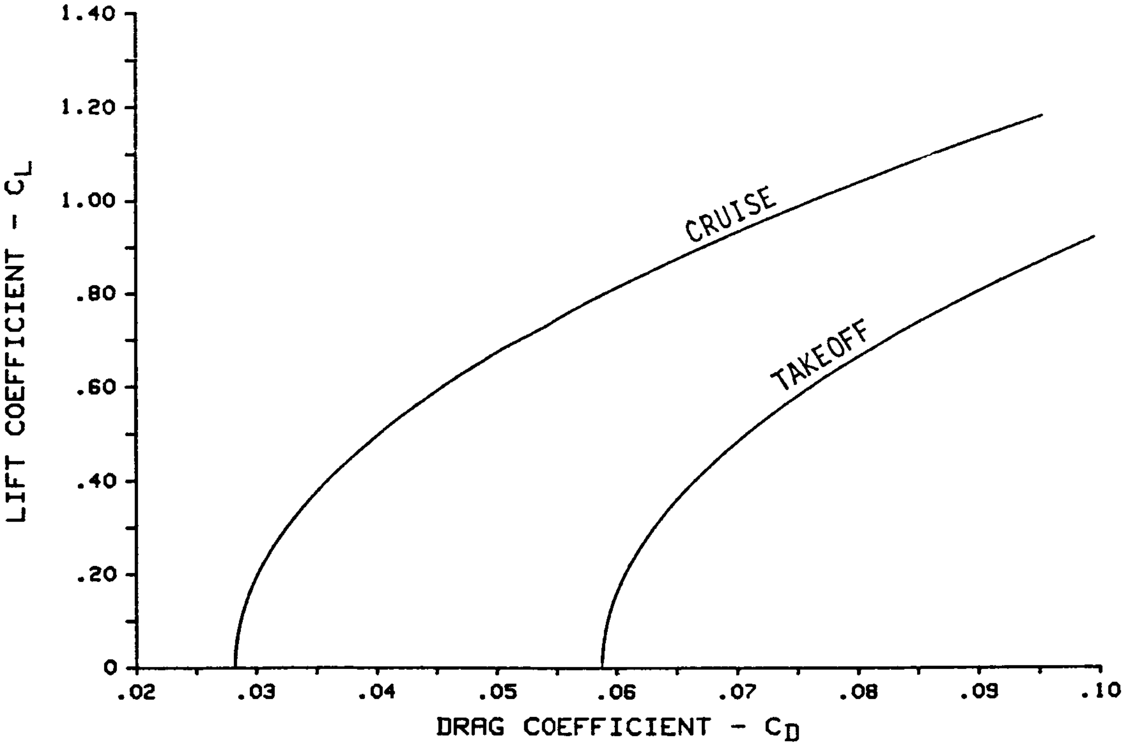

FIGURE 38. Advanced Turbofan Low Speed Drag Characteristics

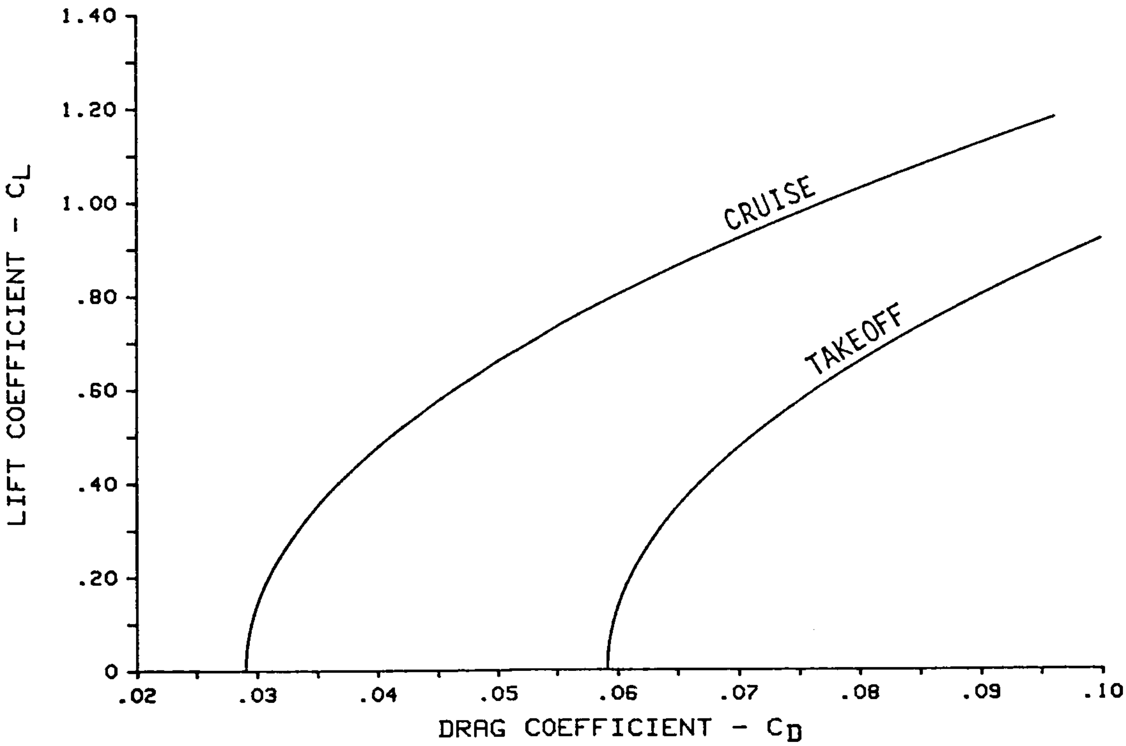

FIGURE 39. Pusher Propfan Low Speed Drag Characteristics

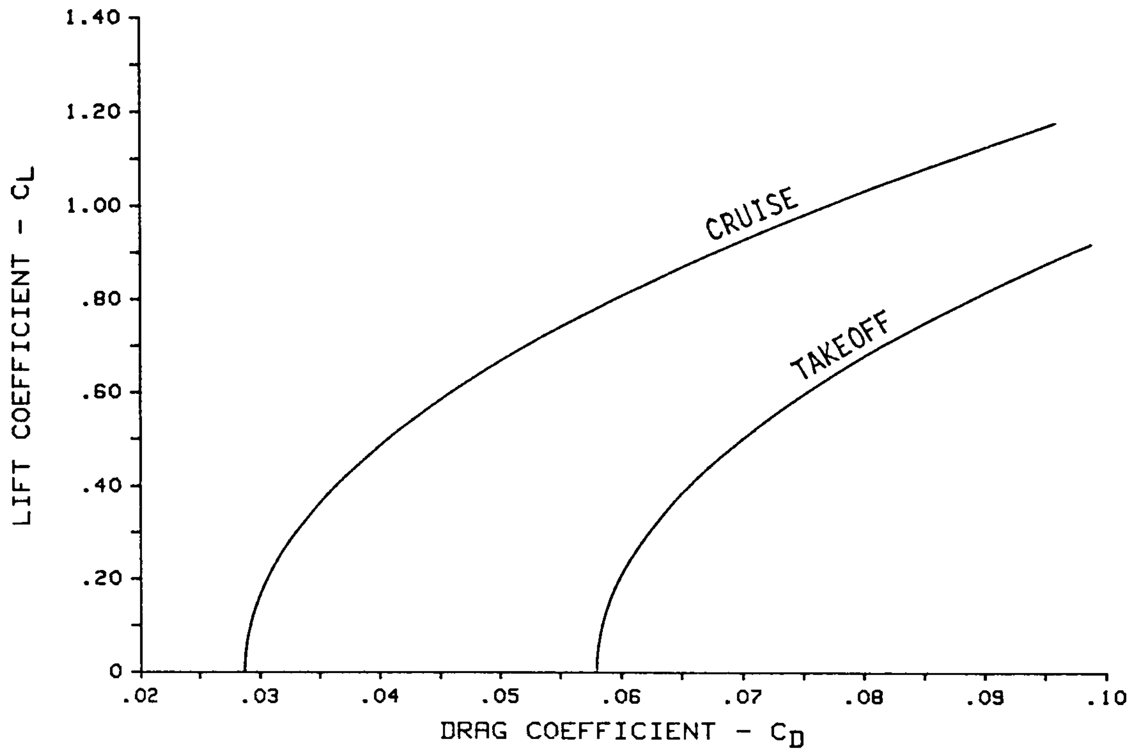

FIGURE 40. Tractor Propfan Low Speed Drag Characteristics

differences in reference wing area, the pusher propfan showed a 4.7% higher drag than the advanced turbofan. Also, the tractor installation was 2% higher drag than the pusher installation, due to the larger pylon required and the effect of the prop wash.

5.3.2 STABILITY AND CONTROL CONSIDERATIONS

The horizontal tail of each study aircraft was designed to provide adequate center of gravity range for typical business aircraft payloads. Each design incorporated a variable incidence horizontal tail. Because of the aft fuselage mounted arrangement of the propfan configurations, the propfan propellers provided additional longitudinal stability when compared to the turbofans. At first glance this would seem desirable. However, the stabilizing effects of the larger pylons, as well as the stabilizing effects of the propellers, shifts the usable CG range aft with the same horizontal tail as the turbofan. Further, the increased stability makes the nose wheel liftoff the limiting factor rather than the stall in ground effect or approach trim condition. This new aft limit is aft of the main landing gear tip-back limit for the propfans, making some of the CG range unusable. It was not possible to move the landing gear any farther aft and remain in the structure. Also, lengthening of the fuselage was not an option because a common cabin configuration was desired. Therefore, a larger horizontal tail was utilized for the propfans for increased control power. This provided a CG limit far enough forward to give the desired CG range while providing the required nose wheel liftoff capability.

Table 6 shows the horizontal tail characteristics for each configuration.

TABLE 6. Horizontal Tail Characteristics

CONFIGURATION	CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
C.G. RANGE %	14.0	18.5	15.0	15.0
TAIL VOLUME	.78	1.00	1.11	1.05
TAIL AREA FT^2	74.9	61.2	63.4	63.4

The larger vertical tail size of the propfan configurations resulted primarily due to the requirement for engine-out control. The vertical tail characteristics are shown in Table 7. Several steps were taken to reduce the impact of the propfan installation on the vertical tail size. First, a flat rating of 1500 SHP was chosen to help reduce the thrust available for the engine-out case. Second, the vertical position of the thrust centerline was adjusted separately for the pusher and tractor versions so that the thrust line's horizontal position remained in the same position. Third, a larger, more effective rudder was incorporated in the propfans' vertical tails.

TABLE 7. Vertical Tail Characteristics

CONFIGURATION		CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
THRUST MOMENT ARM	IN	55	55	84	84
VERTICAL TAIL VOLUME		.06	.09	.12	.11
VERTICAL TAIL AREA	FT^2	60.8	60.8	71.1	71.1
RUDDER SIZE	(c_r/c_v)	.35	.35	.45	.45

5.3.3 HIGH SPEED CONSIDERATIONS

The design cruise speed for the study aircraft was .75 Mach. This speed was well below speeds in which significant transonic drag interference effects are typically encountered, provided the designs are relatively clean. The conventional configurations selected for this study could easily be tailored to prevent these undesirable drag effects. The turboprop engine exhaust stacks were of particular concern. To verify that it was possible to tailor the stacks to prevent shock formation, the installation was examined in Section 5.2 . The potential flow analysis indicated that no shock effects were present. The wing plan form sweep was chosen to prevent any possibility of shock formation which would affect the flow field into the propfan blades. The high speed drag characteristics for each aircraft are shown in Figures 41 through 44.

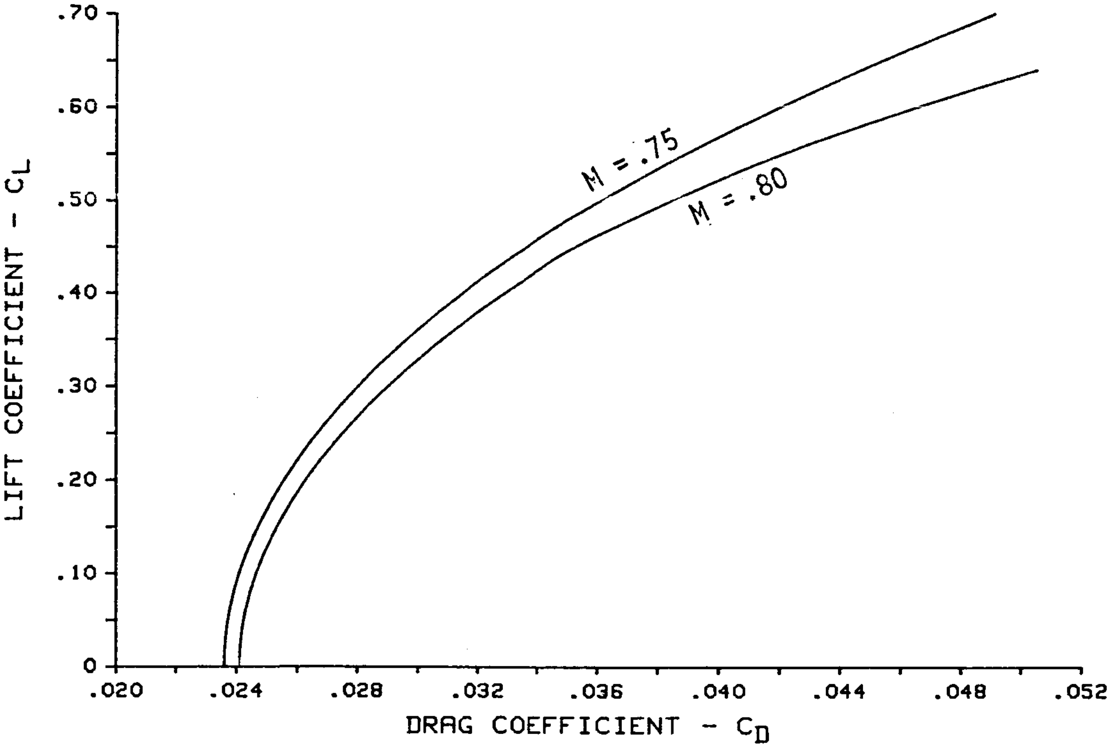

FIGURE 41. Current Turbofan High Speed Drag Characteristics

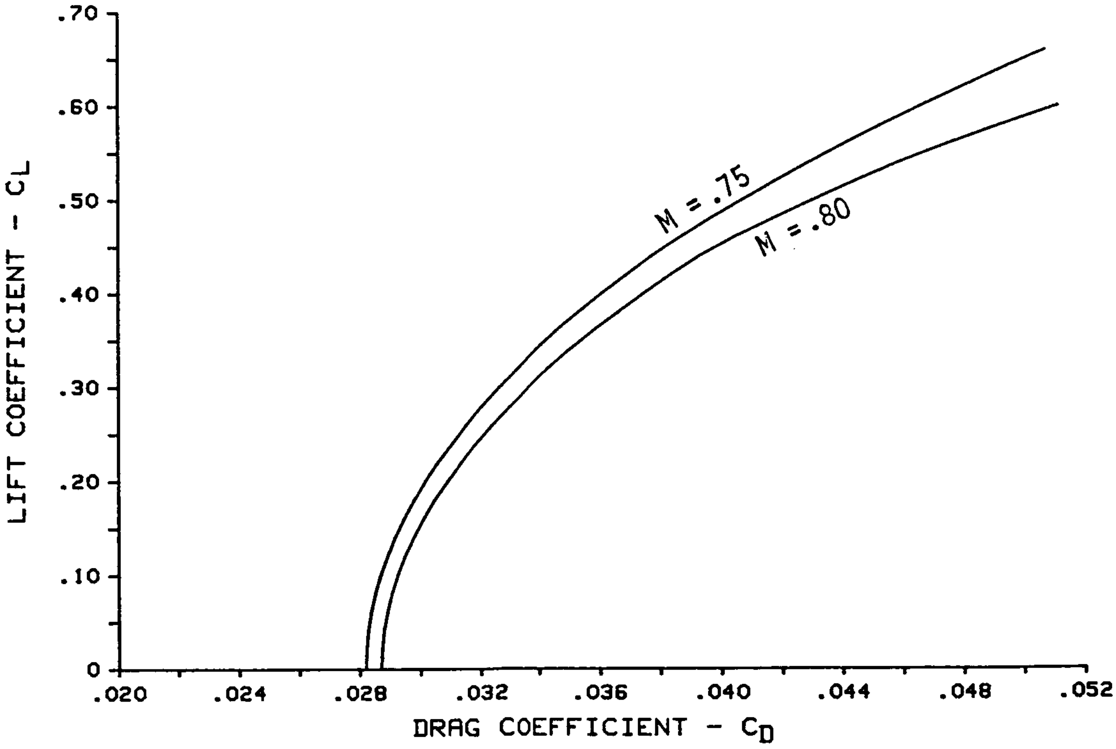

FIGURE 42. Advanced Turbofan High Speed Drag Characteristics

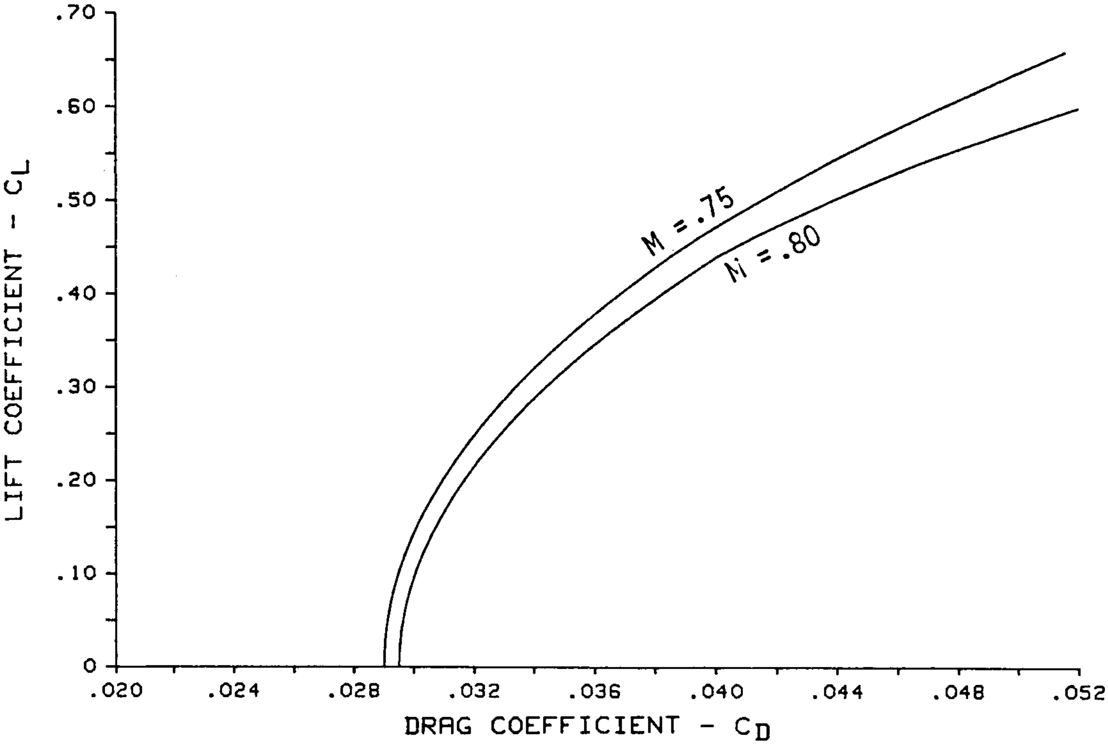

FIGURE 43. Pusher Propfan High Speed Drag Characteristics

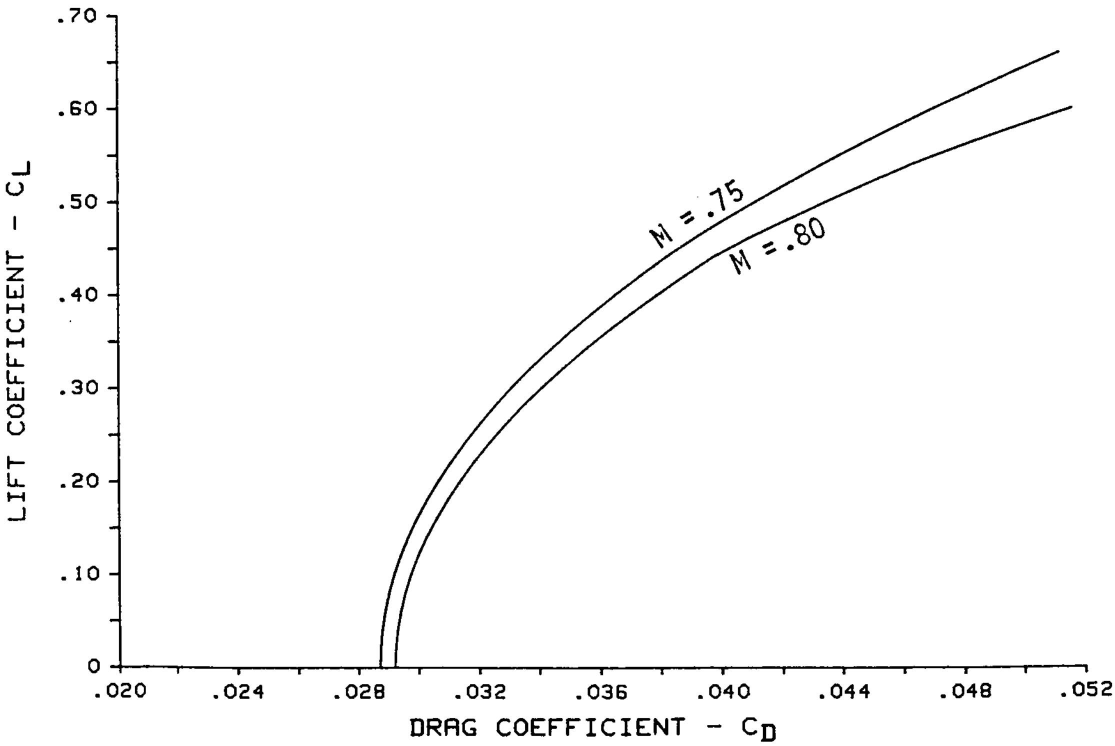

FIGURE 44. Tractor Propfan High Speed Drag Characteristics

5.4 WEIGHT AND BALANCE

A weight summary is given in Table 8 for each of the configurations. The propulsion system group total is shown in parentheses and a breakdown of the major elements are given below. All of the configurations studied were twin engine aircraft, and the propulsion system elements shown are the totals for both propulsion units on each aircraft. Since both propfans were assumed to have full reverse capability for landing, thrust reversers were incorporated on the turbofans to provide equivalent capability. Gearbox and engine weights were provided by Pratt and Whitney, Canada. Propfan weights were provided by Hamilton Standard. More discussion of the propulsion system weights and installation can be found in Sections 4.3 and 5.2.

The current turbofan aircraft represents current technology aluminum construction. The 1990 technology level turbofan and propfan aircraft reflect the application of advanced materials. As discussed in Section 5.5, advanced airframe materials and construction represent a 26% reduction in airframe structural weights (References 6, 7, and 8). The turbofan aircraft had sufficient fuselage structural damping material and insulation to achieve the required 82 dBA cabin noise level. The propfans required additional acoustic treatment to achieve this level. The weight of this additional material is shown as a separate item in Table 8. This material for the pusher propfan is 1.5% of the gross weight; 4% of the gross weight for the tractor propfan. Further discussion of these numbers and acoustic effects can be found in Section 5.6.

The loading diagrams for each study aircraft are shown in Figures 45 to 48. A typical loading for both a maximum forward CG and a maximum aft CG at maximum gross weight is shown. The envelope limits were set by the criteria discussed in Section 5.3.2.

TABLE 8. Configuration Weight Summary
(LB)

GROUP	CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
WING	1569	927	910	944
TAIL	391	288	318	318
BODY	1165	806	844	824
GEAR	681	600	600	622
NACELLE	254	189	267	343
PROPULSION	(1901)	(1902)	(2412)	(2412)
ENGINE (2)	1299	1300	1221	1221
GEARBOX (2)	--	--	232	232
PROPELLERS (2)	--	--	478	478
SYSTEMS (2)	402	402	481	481
THRUST REVERSERS (2)	200	200	--	--
FLIGHT CONTROLS	293	293	274	274
INSTRUMENTS	135	135	135	135
HYDRAULICS	121	121	121	121
ELECTRICAL	366	366	366	366
AVIONICS	484	484	484	484
FURNISHINGS	883	883	883	883
ADDITIONAL ACOUSTIC MATERIAL	--	--	210	625
ENVIRONMENTAL/ANTI-ICE	359	356	357	357
OTHER/MISC.	74	76	93	94
EMPTY WEIGHT	8676	7426	8274	8802
FULL FUEL	7157	5608	4756	4803
PAYLOAD	1200	1200	1200	1200
GROSS WEIGHT	17033	14234	14230	14805

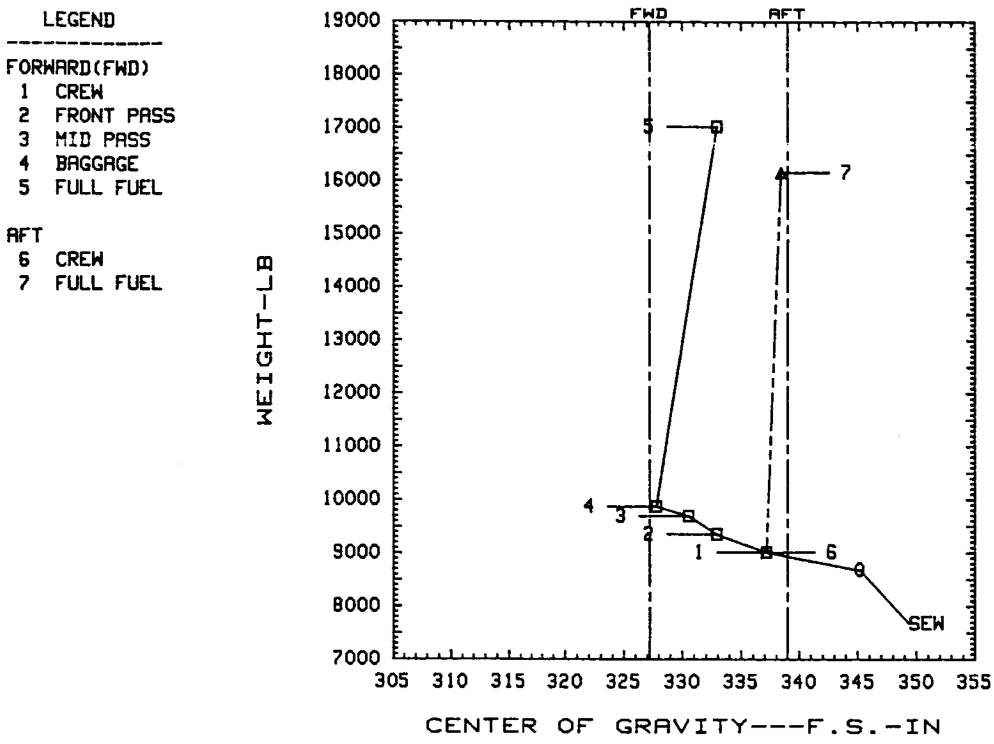

FIGURE 45. Current Turbofan Loading Diagram

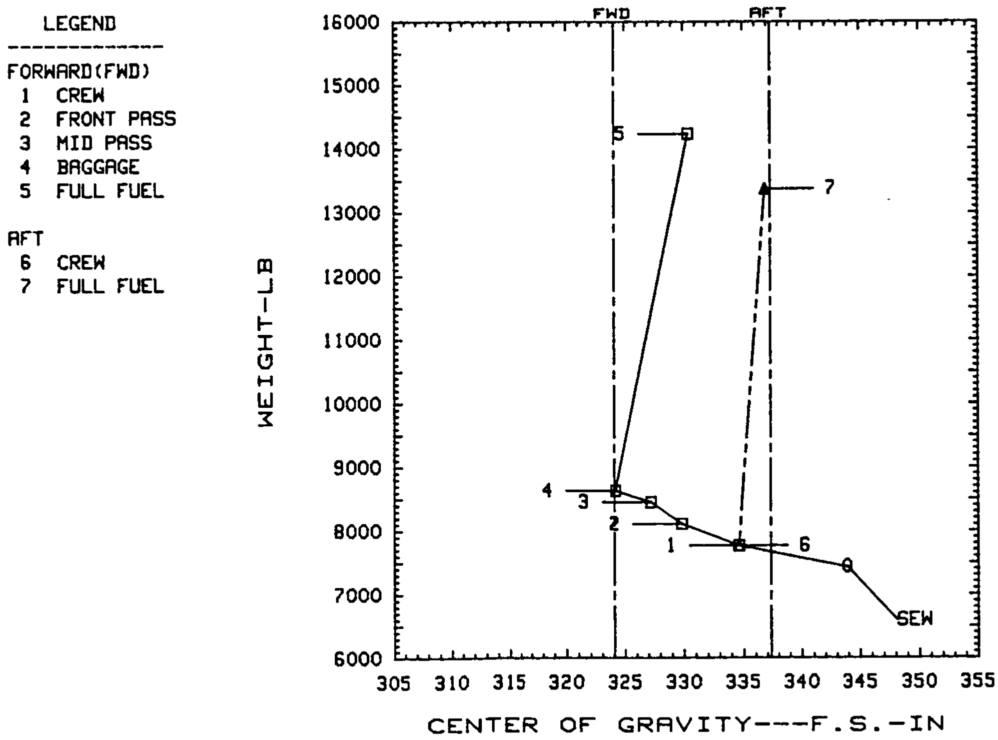

FIGURE 46. Advanced Turbofan Loading Diagram

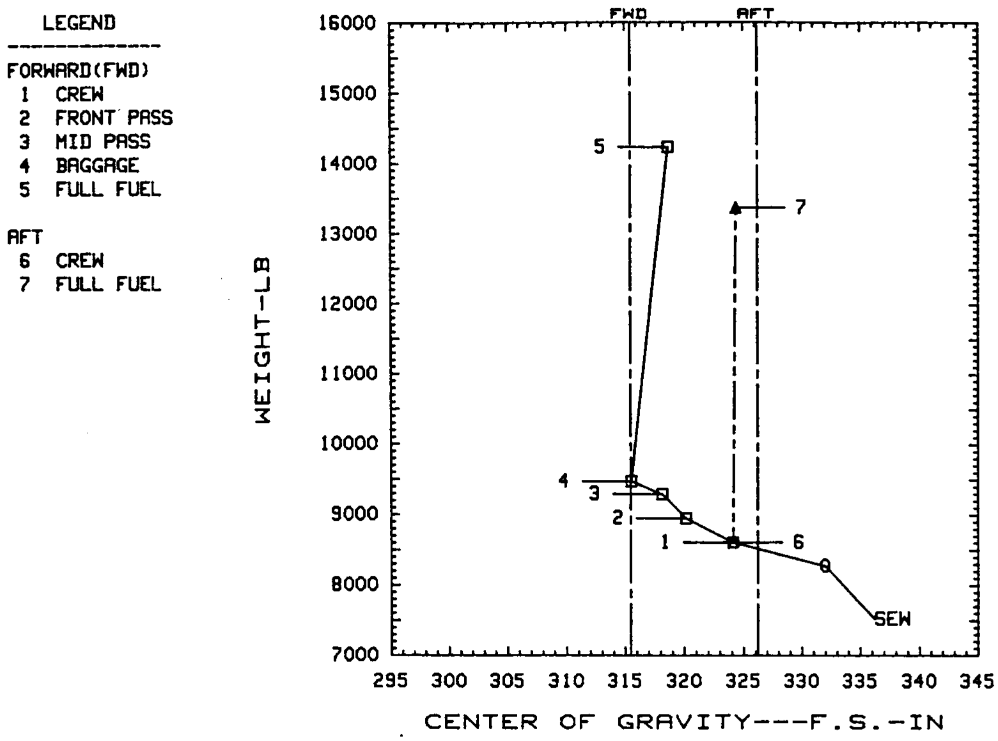

FIGURE 47. Pusher Propfan Loading Diagram

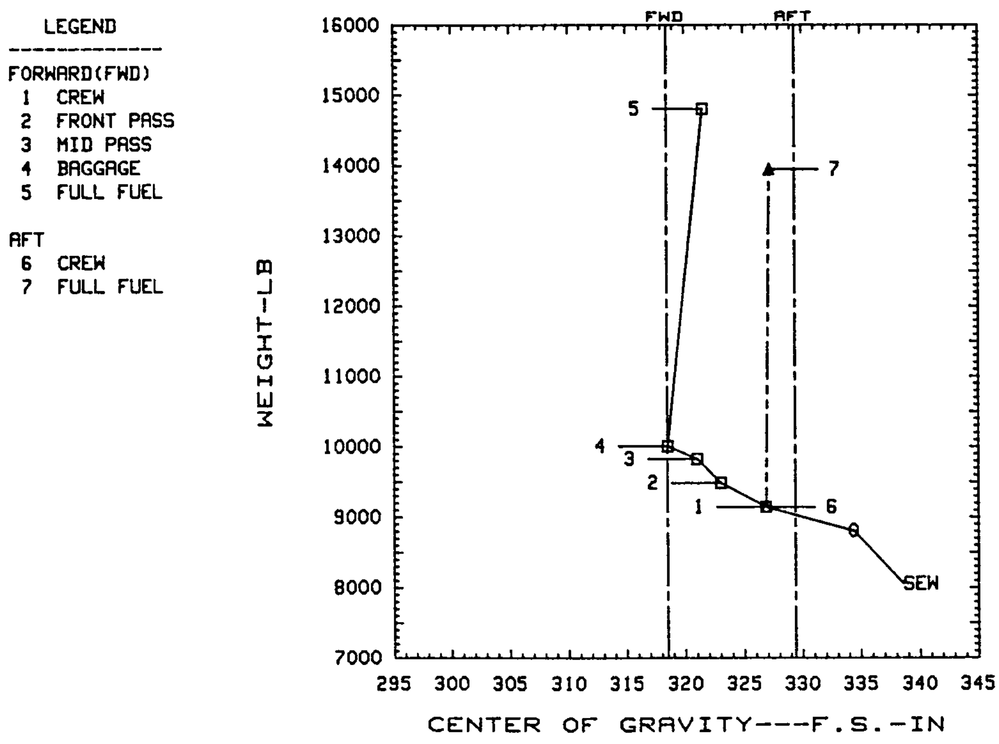

FIGURE 48. Tractor Propfan Loading Diagram

5.5 STRUCTURAL DESIGN

The weight and cost estimates for the study were based on the use of two levels of material technology. The structural design criteria for all the study aircraft was based on FAR 25.

5.5.1 STRUCTURAL MATERIAL

The current technology turbofan's airframe utilized an all aluminum construction. The advanced 1990 level technology aircraft assumed the use of aluminum, aluminum-lithium alloys, and composite materials to acheive the best possible weight reduction. A detailed structural analysis was beyond the scope of this study. However, based on current NASA and industry understanding (References 6, 7, and 8) weight reductions of up to 30% (Reference 8) are possible on major structural components. It was assumed, for this study, that utilizing these advanced materials in the structural design would provide a 26% reduction in airframe weight. For this class of aircraft, the airframe structural weight ranges between 38% to 42% of the total aircraft empty weight. Thus the resultant improvement due to this 26% reduction in airframe weight would be approximately, a 10% reduction in total un-resized empty weight.

The propfan installations required additional structural beef-up to carry the higher loads and prop effects. The installations shown in Section 5.2 all have a similar mount designs. However, the higher propfan loads required a spar cap with roughly twice the area of that required for the turbofan installations. The fuselage frames also required strengthening to handle the additional loads, and the fuselage skin was thickened for protection from possible sonic fatigue in the region of the prop plane.

5.5.2 FAR 25 SAFELIFE REQUIREMENTS

An area of concern which was not evaluated in this study was the potential structural hazard of catastrophic failure of the propfan propulsion system. Hamilton Standard's structural criteria for both the propfan blade spars and hub is to design for infinite component life, but work needs to be done relative to shed blade damage to the aircraft structure. Recently certified General Aviation turbofans, certified under FAR 25, have had to meet a special rotor burst condition. This condition states that a projectile from a rotor burst traveling forward at a 5 degree angle relative to the rotor face cannot penetrate either the fuselage pressure vessel or aircraft fuel tank. Additionally, FAR 25.901 requires that no single failure or malfunction can jeopardize the safe operation of the aircraft, including potential structural damage from shed propfan blades. FAR 23 (Airworthiness Standards: Normal, Utility, and Acrobatic Category Airplanes) does not include this structural provision. Rather, it only requires that a propulsion system failure be isolated from the other propulsion systems of the aircraft so that it will not prevent the continued safe operation of the remaining engines. This is an area which requires further work before propfan propulsion can be implemented on General Aviation aircraft.

5.6 ACOUSTIC EFFECTS

In the initial phase of the study it was clear that, for propfan propulsion to be competitive with turbofan propulsion, the propfan powered aircraft would have to provide an equivalent level of comfort in the cabin and cockpit. The interior noise level significantly impacts the perceived level of comfort, and thus, the propfan interior noise level would need to be as close as possible to the level of comfort of the turbofan. Recent work indicated that the annoyance threshold of passengers to noise due to the boundary layer occurs at 82 dBA (Reference 9). The annoyance threshold, as defined in Reference 9, is the A-weighted level at which 50% of the cabin occupants were annoyed. This annoyance threshold level of 82 dBA was chosen as the maximum acoustic level design point for this study. Additionally, 82 dBA is a typical interior noise level for this class of small turbofans. All of the aircraft interior and structural weights were estimated based on this average cabin noise level.

Two primary sources of aircraft interior noise were considered in this study; the propulsion system and boundary layer. The fuselage structural treatment was based on the mass law technique of Reference 10. The boundary layer noise was estimated using the method defined in Reference 11. The propfan external noise distribution was predicted using the methods contained in Reference 4 and 5.

Figures 49 and 50 show the predicted external sound pressure levels for the propfan aircraft as a function of fuselage station. The blade passage frequency for the 8 FT diameter propfan examined in this study was 179 HZ. The boundary layer noise shown in these figures is for the design cruise point of .75 Mach at 41,000 FT. Cabin interior noise data available on the Beech Model FJ400 test vehicle (an experimental prototype turbofan tested by Beech in 1974) was used, combined with the method of Reference 11, to predict the dominant boundary layer effect and the resultant exterior

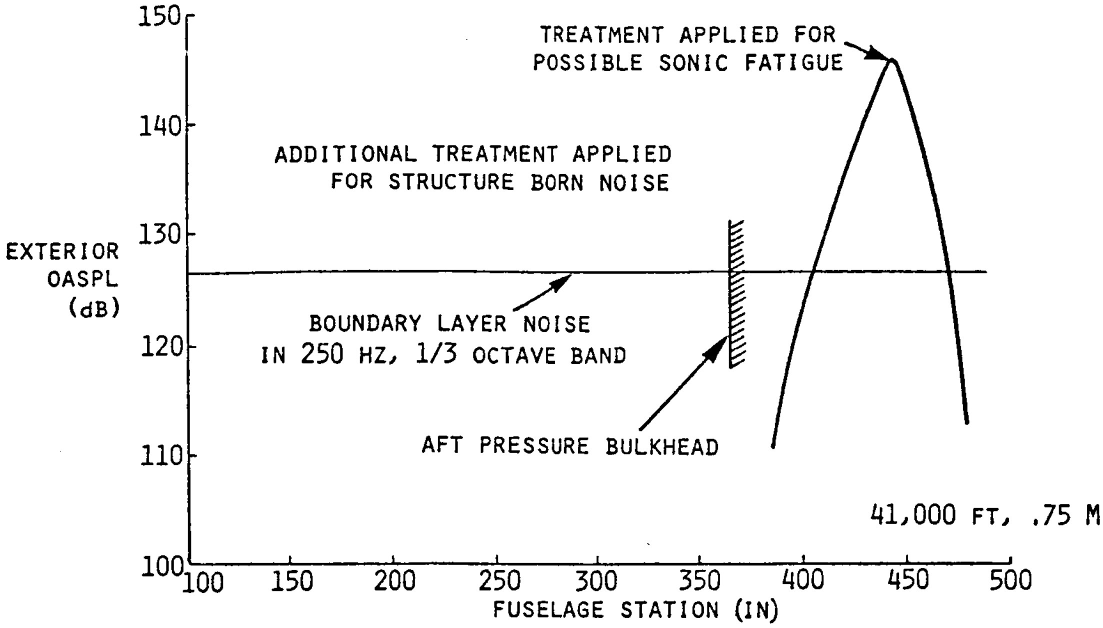

FIGURE 49. Pusher Propfan Installation Acoustic Loading

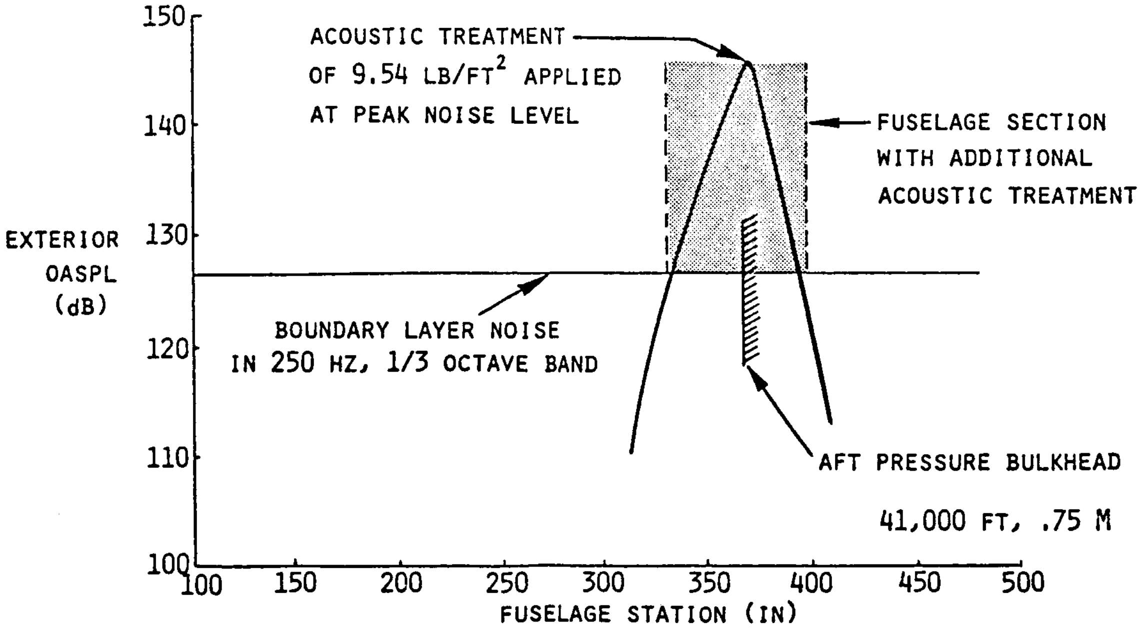

FIGURE 50. Tractor Propfan Installation Acoustic Loading

boundary layer sound pressure levels, as shown. The boundary layer noise, together with the propeller noise first harmonic, was then plotted versus fuselage station in Figures 49 and 50. Figure 49 shows the acoustic loading for the pusher propfan installation. The location of the prop plane in this installation lies well aft of the cabin pressure vessel bulkhead. The passenger cabin environment receives no directly radiated exterior noise input from the propfan blades. The only acoustic treatment necessary then, is that required to damp out the boundary layer noise and the additional structural born noise generated by the propfan and engine. Both the turbofan and propfan fuselage furnishing weight estimates shown in Section 5.4 incorporate the necessary acoustic treatment to reduce the boundary layer noise level and structure born noise of the turbofan to achieve the 82 dBA goal. The additional weight required for the pusher propfan's additional structure born noise was estimated using Reference 10 and data from the FJ400 test to be 210 LB or 1.5% of the maximum gross weight. This weight also incorporated the treatment for protection from sonic fatigue in the region of the prop plane.

The tractor version of the propfan required much more cabin treatment than the pusher. The prop plane in this installation was farther forward and was located at the pressure bulkhead. Because of this the passenger cabin exterior was exposed to higher noise levels and more treatment was necessary. The fuselage location requiring additional treatment is illustrated in Figure 50 by the shaded area. Figure 51 shows that a maximum of 9.54 LB/FT^2 was required for this installation. The additional acoustic treatment required for the tractor propfan installation was 625 LB or 4% of the maximum gross weight.

The directivity of the propfan noise was predicted using the methods of Reference 4 and 5. These methods are based on data for tractor propfans. Other methods such as Reference 12 and work done at NASA-Langley (References 13 and 14) indicate that the shape of the directivity curve for pusher propellers could be much different than tractor propellers. The difference is illustrated in the sketch in Figure 52. If this is indeed correct it would mean significantly higher noise treatment for pushers than is currently indicated in this study. However, the directivity of noise for pushers has not been sufficiently examined at this time to provide a reliable noise distribution estimate. More work needs to be done in this area. Therefore, for this study, the methods in Reference 4 and 5 were assumed valid for both tractors and pushers.

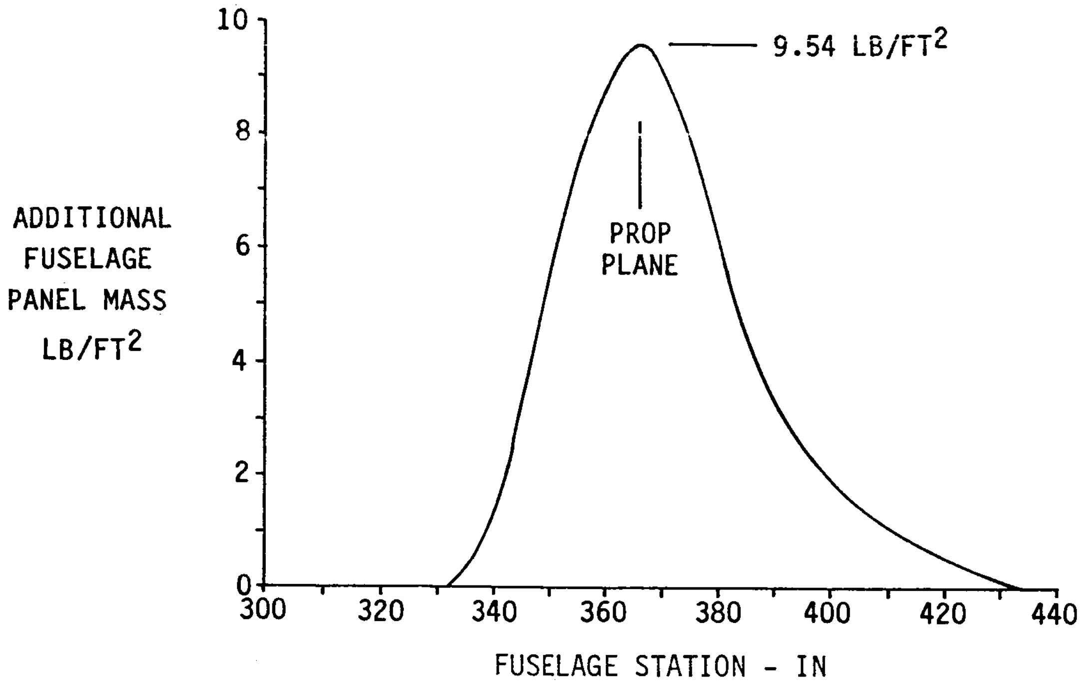

FIGURE 51. Additional Acoustic Mass Treatment for Tractor Installation

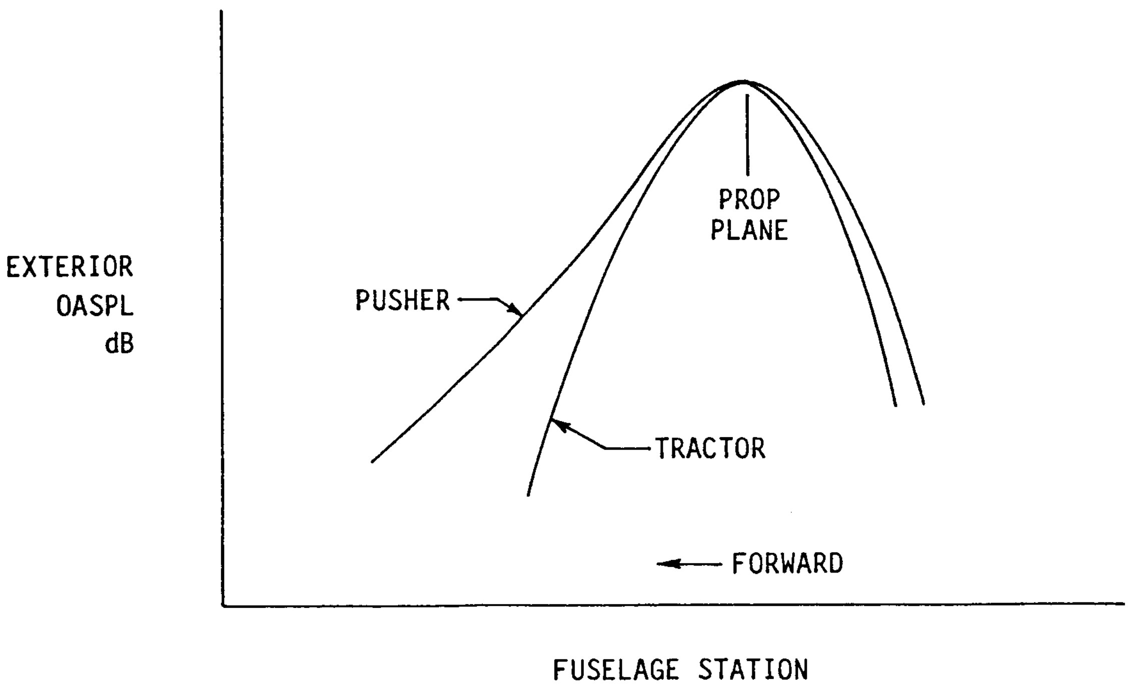

FIGURE 52. Uncertainty in Noise Directivity

The far field noise estimates are given in Table 9. Table 9 shows the community noise at the three standard certification locations (as defined in FAR 36, Appendix C: Noise Levels for Transport Category and Turbojet Powered Airplanes Under FAR 36.201):

- Takeoff Flyover - beneath the flight path 21,325 FT from start of takeoff roll;
- Takeoff Sideline - peak noise level at a lateral distance of 1,476 FT;
- Landing Approach - beneath aircraft when at an altitude of 394 FT on a three-degree glide slope, 6,562 FT from the touchdown point.

The propfan noise levels shown are for the pusher configuration with the 8 FT diameter prop and are estimated using Hamilton Standard's computer method from Reference 5. Examination of these noise levels shows that the pusher propfan meets all of the required FAR 36 Stage 3 noise requirements. This is achieved without the need for a power cutback after takeoff.

TABLE 9. Community Noise Estimates

ITEM	NOISE LEVEL - EPNdB		
	TAKEOFF	APPROACH	SIDELINE
FAR 36 REQUIREMENT	89	98	94
PUSHER PROPFAN	85.5	94.6	89

5.7 PERFORMANCE

Table 10 presents a summary of the performance capabilities of each study aircraft. Table 10 presents the design requirements established for the study and then shows how each aircraft satisfied those requirements. All of the aircraft were specifically sized to meet the design mission which had a range requirement of 1800 NM plus 200 NM IFR alternate and a cruise speed capability of .75 Mach at 41,000 FT altitude.

The field length goal selected was 4,000 FT. But because each of the designs was constrained by other requirements, the field length for each design was less than required. As discussed in Section 5.1, both turbofan designs were constrained by the hot day takeoff climb (second segment climb gradient). Both propfan configurations were not constrained by either field length or climb gradient. Therefore, these were selected on the basis of minimum fuel burn capability using the costing mission.

TABLE 10. Performance Summary

ITEM		DESIGN RQMTS	CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
RANGE + ALTERNATE @ 41,000 FT	NM	1800+200	1800+200	1800+200	1800+200	1800+200
CRUISE SPEED @ 41,000 FT	MACH	.75	.75	.75	.75	.75
TAKEOFF FIELD LENGTH* S.L., STD DAY	FT	4000	3260	3520	2980	3140
SECOND SEGMENT* CLIMB GRADIENT @ 5,000 FT, ISA+25^{o}C	%	2.4	2.4	2.4	6.7	6.0

*FAR 25

The time, rate of climb, maximum cruise speed, and VFR range performance for each of the study aircraft are given in Figures 53 through 56. (Note: VFR range is with only a 45 minute fuel reserve, i.e., no alternate capability.) The effect of the flat rating on the propfan engines can be seen in Figures 54, 55, and 56. The point at which both the maximum continuous and maximum cruise power settings come off the flat rating occurs roughly around 30,000 FT. There is an additional break, as with most turbofan engines, at the iso-thermal break, roughly 36,000 FT. The range shown in Figure 56 is a maximum VFR range with no alternate capability and is basically a climb - cruise to destination - hold 45 minutes mission. The maximum cruise speed shown in Figure 55 is for a mid-cruise weight.

The rate of climb curves in Figure 54 show that at low altitude the propfan has less maximum rate of climb than the advanced turbofan. This was due to the effect of the flat rating. The speed for the maximum rate was approximately 220 KTAS for the turbofan and 170 KTAS for the propfan. When the speed was reduced to the second segment climb speed for both aircraft (roughly 130 KTAS) there was a significant relative increase in thrust for the propfan because of the different thrust lapse rates with speed between

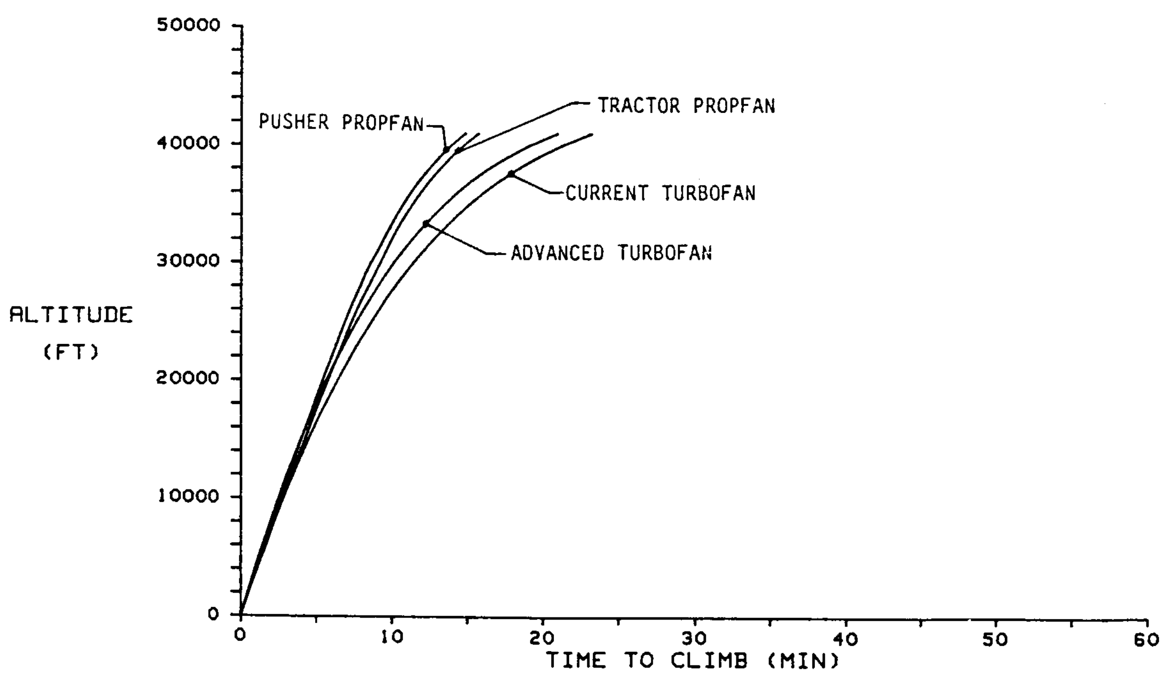

FIGURE 53. Time to Climb

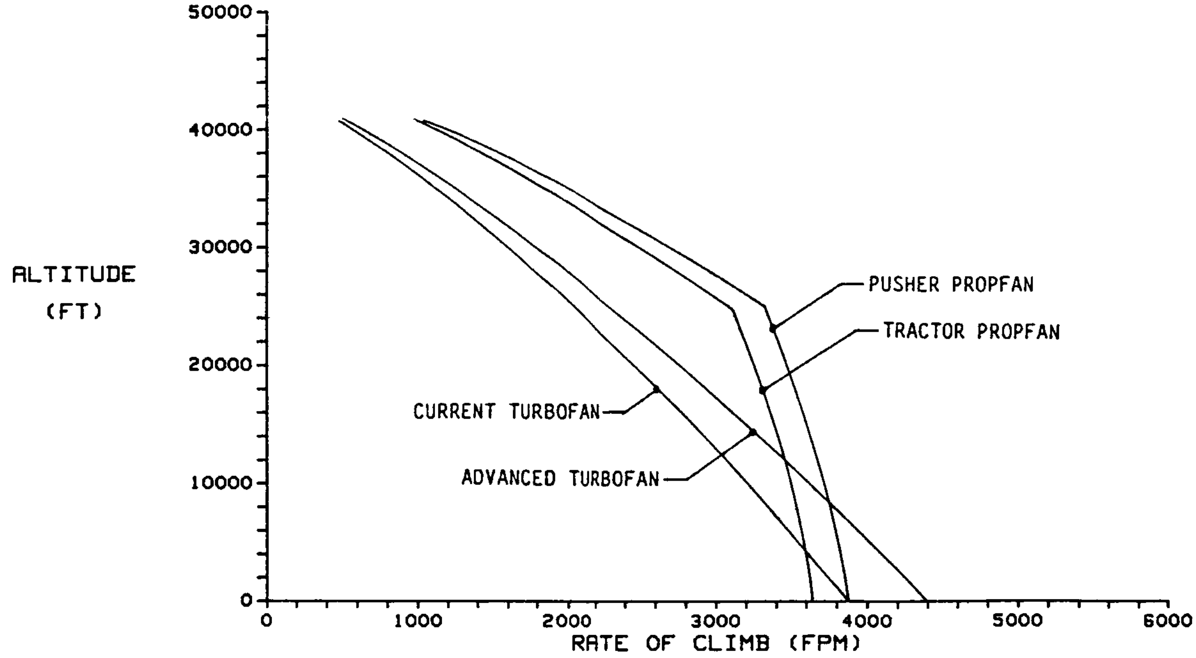

FIGURE 54. Rate of Climb

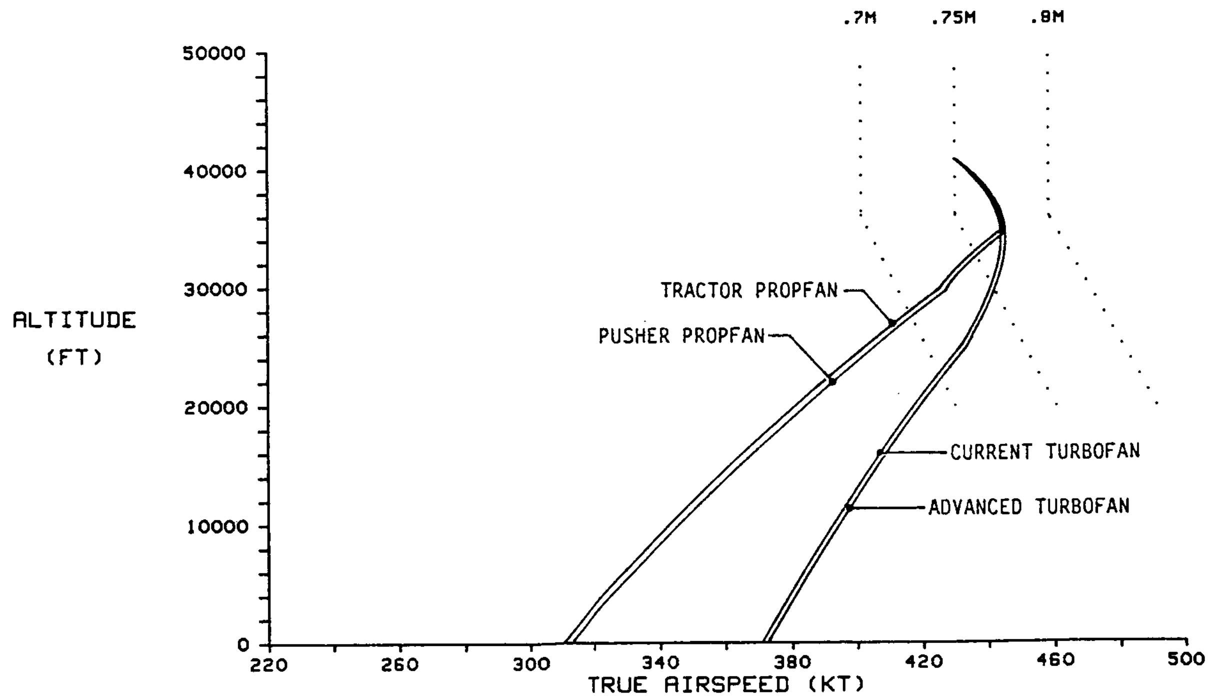

FIGURE 55. Cruise Speed

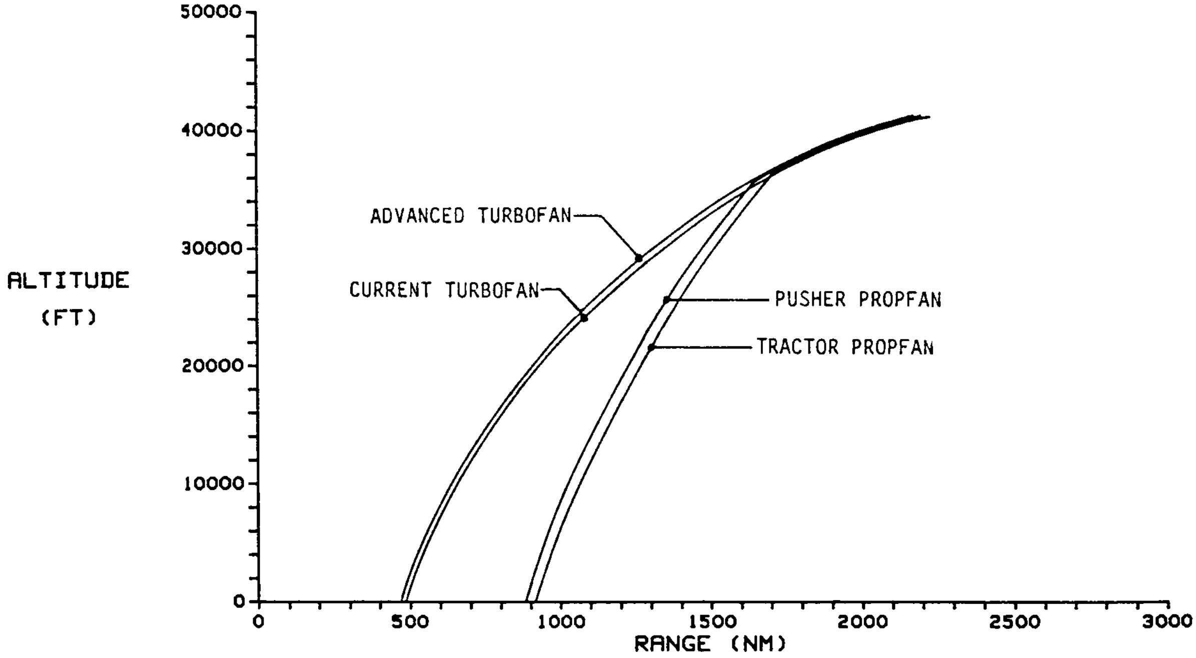

FIGURE 56. VFR Range

the turbofan and propfan. This difference in thrust, then, yielded the higher second segment climb gradients shown in Table 10 for the propfans.

The mission performance is presented in Tables 11 and 12. Fuel required for each segment is given. Figures 57 and 58 depict each numbered element of the design and cost mission as they relate to Tables 11 and 12 respectively. The design mission, once again, was used to size each of the aircraft. Subsequently, the required total mission fuel in Table 11 was also the maximum usable fuel capacity for each of the study aircraft. Table 12 shows both the fuel required for each segment and its relative percentage to the total required mission fuel for the 400 NM cost mission. It is interesting to note that the descent, landing, and taxi elements for the propfans show a higher percentage of the total fuel burn than the corresponding elements for the turbofans. This was caused by a higher fuel flow at idle for the propfan engine data provided by Pratt and Whitney. The reason for this was that the turboprop engines assumed for this study required higher RPM's for minimum (idle) operation than did the turbofans and thus used more fuel at idle. This effect of higher idle fuel flow was, however, minimal on the total fuel consumption results.

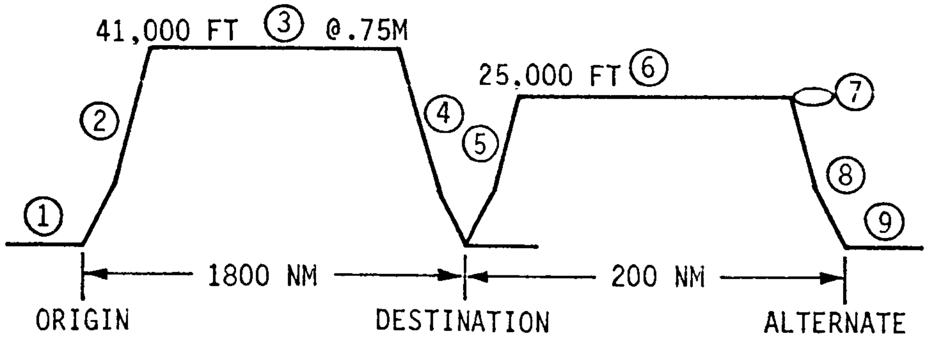

FIGURE 57. Design Mission Elements

TABLE 11. Design Mission Fuel Summary

MISSION ELEMENT		CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
TO DESTINATION (1800 NM)					
1. START, TAXI, TAKEOFF	LB	230	180	169	169
2. CLIMB	LB	692	493	259	272
3. CRUISE	LB	4321	3426	2953	2968
4. DESCENT/APPROACH	LB	276	212	231	239
TO ALTERNATE (200 NM)					
5. MISSED APPROACH/CLIMB	LB	288	210	121	127
6. CRUISE	LB	663	534	411	402
7. 45 MINUTE HOLD	LB	414	340	363	370
8. DESCENT/APPROACH	LB	217	169	187	193
9. LANDING, TAXI, STOP	LB	56	44	62	63
TOTAL MISSION FUEL	LB	7157	5608	4756	4803

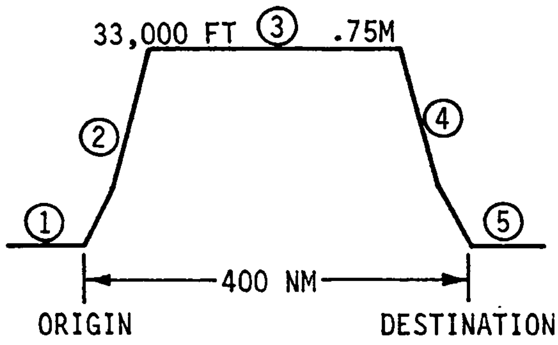

FIGURE 58. Cost Mission Elements

TABLE 12. Cost Mission Fuel Summary

MISSION ELEMENT		CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
TO DESTINATION (400 NM)					
1. START, TAXI, TAKEOFF	LB (%)	230 (11.0)	180 (11.1)	169 (12.1)	169 (12.0)
2. CLIMB	LB (%)	497 (23.8)	349 (21.5)	194 (13.9)	203 (14.5)
3. CRUISE	LB (%)	1017 (48.7)	834 (51.3)	736 (52.9)	727 (51.9)
4. DESCENT/APPROACH	LB (%)	289 (13.8)	218 (13.4)	231 (16.6)	239 (17.1)
5. LANDING, TAXI, STOP	LB (%)	56 (2.7)	44 (2.7)	62 (4.5)	63 (4.5)
TOTAL MISSION FUEL	LB (%)	2089 (100)	1625 (100)	1392 (100)	1401 (100)

The cost mission fuel burn data for the pusher propfan is summarized in Figure 59. The General Aviation propfan shows a 33% reduction in fuel burn over the current turbofan for the cost mission and a 14% reduction in fuel when compared to the equivalent 1990 technology turbofan. As mission range increases, such as in the design mission, the relative fuel burn improves slightly. The propfan design mission fuel burn is 16% less than the equivalent technology turbofan and 34% less than the current day turbofan.

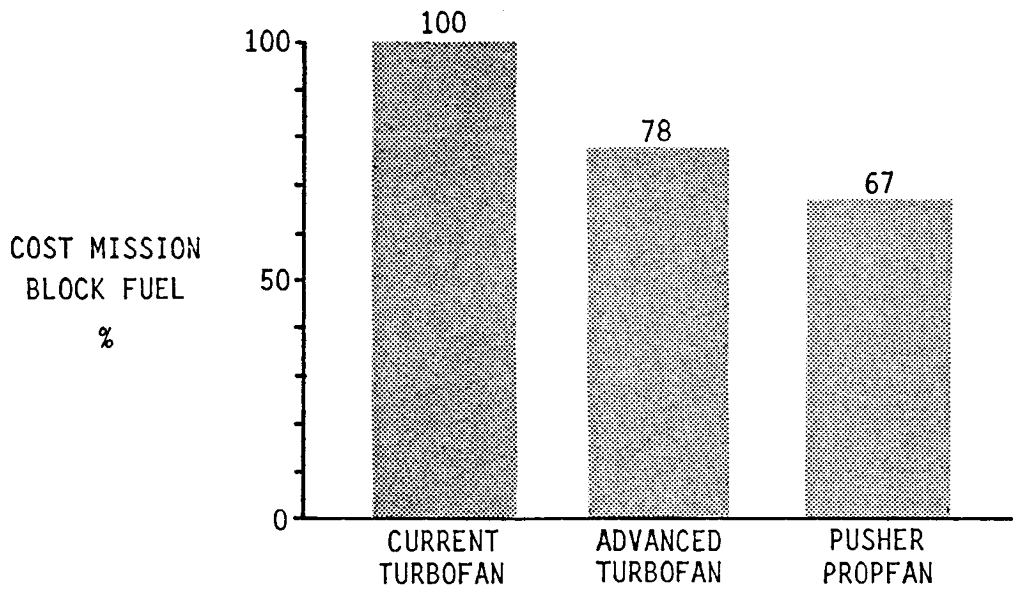

FIGURE 59. Cost Mission Fuel Burn Comparison

5.8 COST

The total aircraft price for each airplane, as discussed in the Appendix, was evaluated using the same formulation to provide an equal basis of comparison. The pricing formulation does not yield the exact price of any particular aircraft in the market today, but rather, gives an estimate based on a correlation of published pricing information for various aircraft which is typically within 5% to 7% of the published price data. Pricing strategy or market fluctuation can induce similar variations in price. Thus, the formulation yields a simplified yet relatively good approximation of actual acquisition cost while also providing a consistent method for price comparison in this study.

A similar method was utilized by Pratt and Whitney to estimate the engine acquisition cost. The only disadvantage of this approach for the engines is that it requires a considerable extrapolation of the turboprop cost data from current market prices, since there are no General Aviation engines in this horsepower class (2900 SHP). The propeller and speed control pricing provided by Hamilton Standard was based on scaled data which was available for the airline class propfans. Unlike the airline class studies, there was no propfan design tailoring done for this preliminary study. Thus the cost and performance of the propfans represent the large, transport propfan data scaled to meet the General Aviation mission requirements. This is an area where further study could help reduce the acquisition cost while still maintaining the propfan performance levels.

The acquisition cost for both the propulsion system and total aircraft is given in Table 13 for each of the study aircraft. As discussed in the Appendix, the airplane price consisted of three elements; an airframe weight related price, a propulsion system price, and a fixed avionics cost. As shown in Table 13, even with a 10% higher propulsion price and a higher cost for the use of advanced materials, the reduction in airframe weight due to the advanced materials and improved engine SFC resulted in an overall 1% reduction in total acquisition cost of the advanced turbofan compared to the current turbofan. On the other hand, the pusher propfan acquisition cost was 18% higher than the equivalent technology advanced turbofan. The primary cause of this was that the pusher propfan propulsion system cost was 35% higher than the advanced turbofan. Also a factor in the higher cost was the additional weight of the structure required to carry the propfan loads. The tractor installation, requiring even more structural weight for acoustical treatment, had a 21% higher acquisition cost compared to the advanced turbofan.

TABLE 13. Acquisition Costs

COST ITEM		COST			
		CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
TOTAL AIRCRAFT	$(MILLION)	3.60	3.58	4.22	4.33
PROPULSION SYSTEM	$(MILLION)	.455	.464	.625	.621

A comparison of the propulsion system cost, given in Table 14, showed a significant disadvantage for propfans. When compared on an equivalent thrust basis, the propfan propulsion system was 33% higher cost than the equivalent technology turbofan. Compared to the current technology turbofan the propfan system was almost 45% higher cost. The propfan propeller and speed control alone was 22% the cost of the current turbofan. When the propulsion systems were then sized to meet the design mission requirements, this cost disadvantage increased to 35%, shown in Table 13.

TABLE 14. Relative Propulsion System Acquisition Cost

ELEMENT		RELATIVE COST		
		CURRENT TURBOFAN	ADVANCED TURBOFAN	PROPFAN
ENGINE	%	100	109	122.7
PROPELLER	%	--	--	22.2
TOTAL	%	100	109	144.9

NOTE: Propulsion systems matched for equivalent thrust
@ 41,000 FT, .75M.

The effect of the higher aircraft price on the total cost of operation for these General Aviation propfans overcomes the cost improvement which normally could be anticipated with a 15-30% improvement in fuel consumption. The pusher propfan showed an 11% higher cost of operation, utilizing the Corporate Cost model, compared to the advanced turbofan, Table 15, for typical General Aviation annual utilization. On the other hand, the ATA method showed a 10% cost disadvantage for the propfan. The modified ATA method is less sensitive to aircraft acquisition cost than the Corporate model. It is more representative of commuter airline aircraft and is provided for comparison to other studies. A breakdown of the variable and fixed elements of the annual operational costs are given in Tables 16 and 17. The fuel costs utilized in this study were based on a typical average 1984 retail price of $1.90 per gallon (see Appendix, Section A2.0 for further discussion of fuel price). Table 16 shows that the cost of fuel was reduced 15% by using a propfan while the overall maintenance cost only increased by 11%. This would have provided a definite cost advantage for the propfan if the propulsion system acquisition cost of the propfans were

TABLE 15. Total Cost of Operation for 400 Hours Annual Utilization

COST MODEL		COST			
		CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
MODIFIED ATA	$/SEAT-NM	.857	.797	.878	.899
CORPORATE	$/SEAT-NM	.484	.453	.501	.514

TABLE 16. Variable Operating Costs - Corporated Model

ELEMENT		COST			
		CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
FUEL @ $1.90/GAL	$/HR	392.84	309.28	264.04	264.51
AIRCRAFT MAINTENANCE					
LABOR	$/HR	61.98	57.20	58.36	60.08
MATERIAL	$/HR	60.39	48.12	52.59	59.62
PROPULSION SYSTEM MAINTENACE					
LABOR	$/HR	22.37	22.36	33.59	33.60
MATERIAL	$/HR	102.64	99.80	107.35	106.92

TABLE 17. Fixed Operating Costs - Corporate Model

ELEMENT		COST			
		CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
CREW	$(THOUSAND)	76.8	76.8	76.8	76.8
INSURANCE	$(THOUSAND)	36.0	35.8	42.2	43.3
TOTAL	$(THOUSAND)	112.8	112.6	119.0	120.0

similar to the turbofans. This was, however, not the case. Figure 60 summarizes each configuration's cost element utilizing the Corporate cost model and graphically illustrates the impact of the propfan's higher price on depreciation and interest costs.

It is important to note, also, in this study, that there was no cost added, based on information from Hamilton Standard, for propeller system overhaul. Hamilton Standard's current design philosophy for blade spars and hub is for infinite life components and thus the maintenance costs for the propfan blades and hub were for scheduled inspections, and on-condition repairs only. This corresponded to only about 1% of the total propulsion system cost shown in Table 16. There were anticipated to be no life limited parts and thus replacement would be required only for accident or significant foreign object damage. If this infinite design life can not be achieved, however, an additional maintenance cost penalty for prop overhaul would be required for propfans, thus making the propfan maintenance cost higher than shown. The maintenance costs shown in Table 16 do include an allowance for engine overhaul based on an average expected engine life of 3000 hours before overhaul.

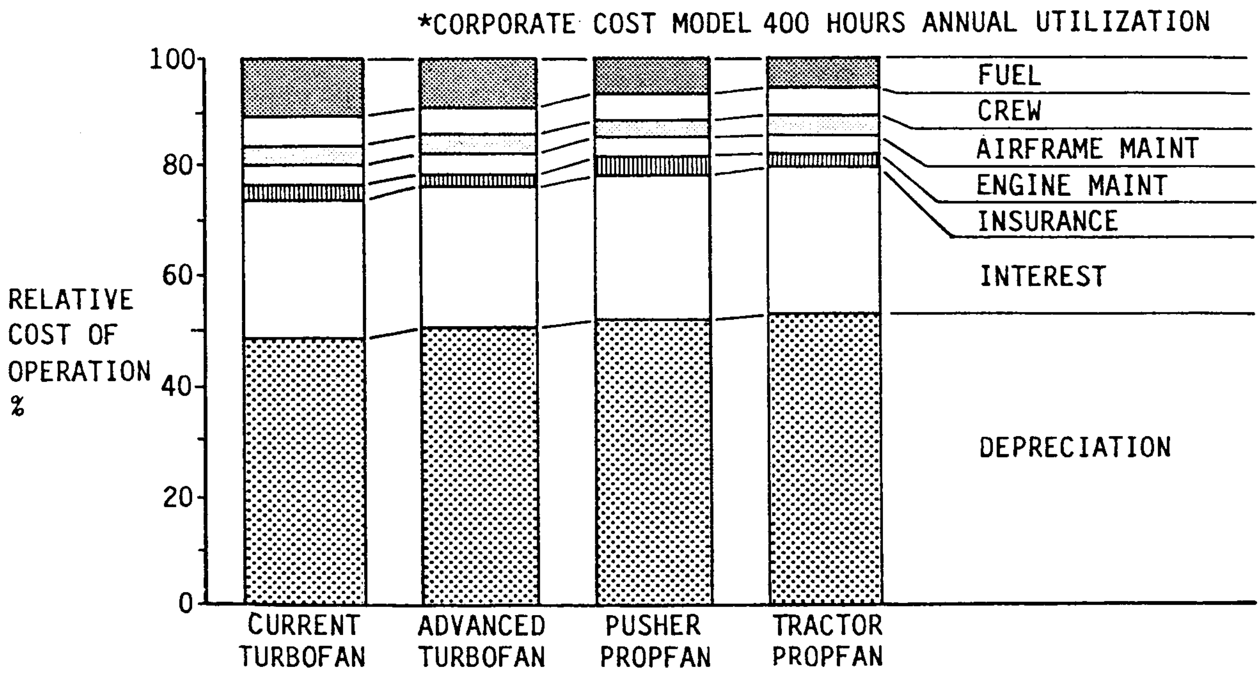

FIGURE 60. **Relative Cost Summary for the Study Configurations**

The depreciation effects and cost of capital significantly affect the total cost of operation values. A complete breakdown of the costs and depreciation effects are given in the Appendix. For comparison, the modified ATA cost model results for 400 hours annual utilization are given in Table 18, and the results for 3000 hours annual utilization are given in Table 19. The variable elements, given in Table 16, in the Corporate model are the same as those used in the ATA model. Additionally, the fixed elements of the Corporate model and the depreciation effects were evaluated on an hourly basis in the ATA model. The ATA model, unlike the Corporate model, does not provide a cost of capital element (interest cost). At 400 hours utilization the propfan's reduction in the cost of fuel when compared to the advanced turbofan was still 15% and the increase in overall maintenance was 11%, similar to the Corporate model results. The hourly cost of depreciation and insurance, however, can be seen directly using the ATA model. In Table 18, the pusher propfan shows a 19% increase for depreciation and insurance costs over an equivalent advanced turbofan. Figure 60 shows a similar effect for depreciation and insurance using the Corporate model. At 3000 hours utilization, as shown in Table 19, the propfan's relative reduction in fuel cost and relative increase in maintenance, depreciation, and insurance costs from the advanced turbofan were the same as at 400 hours utilization. However, the depreciation and insurance costs' percentage of the total cost of operation was significantly less than at 400 hours. Because of this, the cost of fuel exerts more influence on the total cost of operation at 3000 hours, whereas at 400 hours the aircraft price related items such as depreciation and insurance predominate the cost of operation.

TABLE 18. Modified ATA Costs for 400 Hours Utilization

COST ELEMENT		COST			
		CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
CREW	$/HR	192.00	192.00	192.00	192.00
FUEL @ $1.90/GAL	$/HR	392.84	309.28	264.04	264.51
INSURANCE	$/HR	89.91	89.47	105.60	108.36
DEPRECIATION	$/HR	895.40	892.72	1065.29	1090.00
AIRCRAFT MAINTENANCE					
LABOR	$/HR	61.98	57.20	58.36	60.08
MATERIAL	$/HR	60.39	48.12	52.59	59.62
PROPULSION SYSTEM MAINTENANCE					
LABOR	$/HR	22.37	22.36	33.59	33.60
MATERIAL	$/HR	102.64	99.80	107.35	106.92
TOTAL	$/HR	1817.53	1710.95	1878.82	1915.09

TABLE 19. Modified ATA Costs for 3000 Hours Utilization

COST ELEMENT		COST			
		CURRENT TURBOFAN	ADVANCED TURBOFAN	PUSHER PROPFAN	TRACTOR PROPFAN
CREW	$/HR	192.00	192.00	192.00	192.00
FUEL @ $1.90/GAL	$/HR	392.84	309.28	264.04	264.51
INSURANCE	$/HR	11.99	11.93	14.07	14.45
DEPRECIATION	$/HR	119.39	119.02	142.05	145.33
AIRCRAFT MAINTENANCE					
LABOR	$/HR	61.98	57.20	58.36	60.08
MATERIAL	$/HR	60.39	48.12	52.59	59.62
PROPULSION SYSTEM MAINTENANCE					
LABOR	$/HR	22.37	22.36	33.59	33.60
MATERIAL	$/HR	102.64	99.80	107.35	106.92
TOTAL	$/HR	963.60	859.71	864.05	876.52

6.0 DESIGN SENSITIVITIES

Several design sensitivities were examined in this study to enhance the comparison of propfan propulsion to turbofan propulsion. These sensitivities can be grouped into two categories; configuration sensitivity factors and cost sensitivity factors.

6.1 CONFIGURATION FACTORS

Several important design sensitivities were examined which impact the overall definition of the configuration. As discussed in Section 3.2.2, variations in aircraft and propulsion system parameters such as wing aspect ratio, wing sweep, wing taper ratio, wing thickness, propeller diameter, or number of propeller blades can significantly affect the selection of an optimum design depending on the criteria for optimization being used. The configurations in this study were selected for minimum fuel where possible. Minimum fuel burn was selected as a design criteria rather than minimum cost of operation for two reasons. First, the study utilized two cost methods both of which were valid for specific types of utilization but yielded different levels of answers. Second, because of the high cost of the propfan propulsion systems compared to turbofans there was concern that using cost of operation as the design constraint might yield unrealistic design choices considering the preliminary nature of these cost estimates for the conceptual propulsion system designs in this study.

The aircraft geometry was defined as discussed in Section 3.2.2. The parametric effect of wing taper ratio and thickness ratio were minimal on mission fuel burn. These parameters were thus selected to provide a wing design which would provide sufficient volume for the required systems and fuel for the design mission, while preventing any possible shock formation which might interfer with the flow field entering the propfan propeller. To further assure a shock free wing at the design speed the wing was swept 25^{o}. The parametric effect of aspect ratio on fuel burn was examined and is shown in Figure 61. Figure 61 shows that the minimum mission fuel burn for each design occurs above the maximum wing fuel volume capability. Each aircraft was resized for each new aspect ratio according to the method discussed in Section 3.2.2. The ground rules required all the fuel to be located in the wing to allow a common fuselage design (i.e. no additional fuselage fuel tanks) to be utilized in the study. An aspect ratio of 8.5 was chosen for all of the designs. This provided wing designs which in each case had sufficient fuel capacity to meet the design mission without

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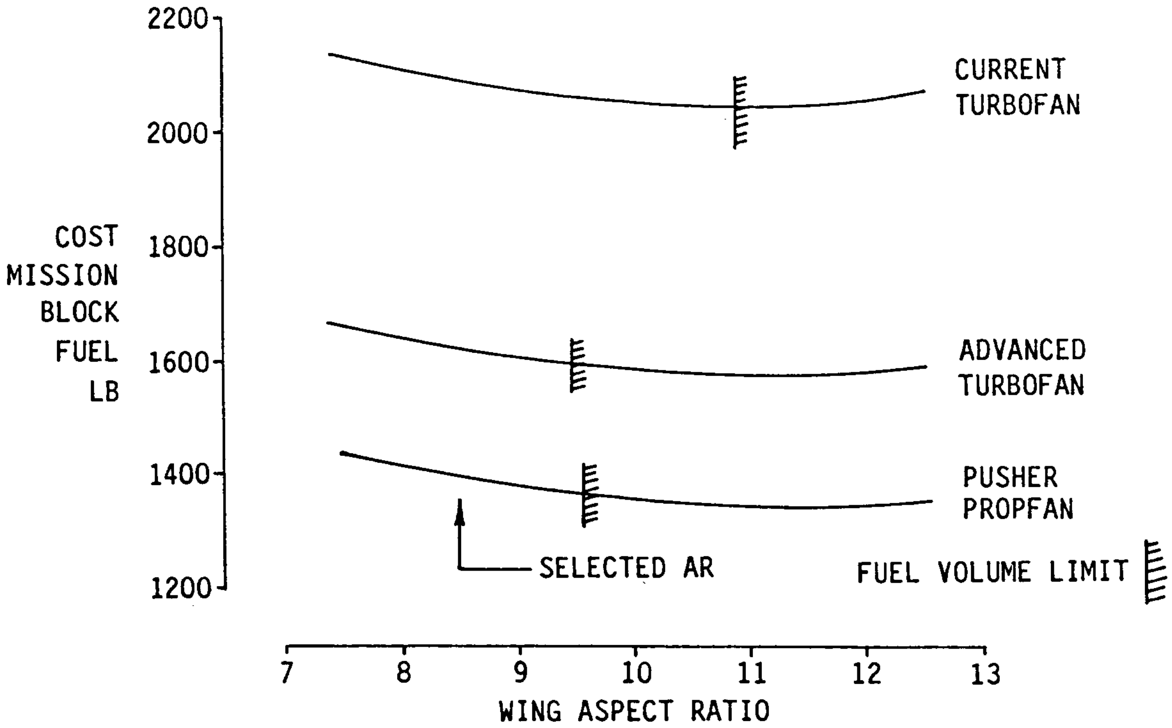

FIGURE 61. Mission Sensitivity to Design Aspect Ratio

requiring fuselage tanks. Since the relative fuel change was essentially the same for any given aspect ratio, including the minimum values, choosing 8.5 as the wing aspect ratio did not impact the relative propulsion system comparison.

In the preliminary phase of the study it was apparent that weight and, more importantly, cost were going to be major elements in the assessment of propfan propulsion. To achieve the most favorable comparison (lowest cost/weight), a six-bladed, single rotation propfan was chosen. The propeller diameter chosen, however, was selected using the minimum mission fuel criteria. It was found that variation in the design mission could result in a significant change in the propfan diameter selection. As shown in Figure 62, by changing just the design mission (1800 NM, .75 Mach, 41,000 FT) to a lower altitude and higher speed (1800 NM, .80 Mach, 35,000 FT), while leaving the costing mission used for the fuel analysis unchanged, a significant increase in design disk loading for the propfan and reduction in propeller diameter would result. This higher disk loading was similar to disk loadings seen in other studies and emphasized the sensitivity of the propfan design to the selected mission requirements.

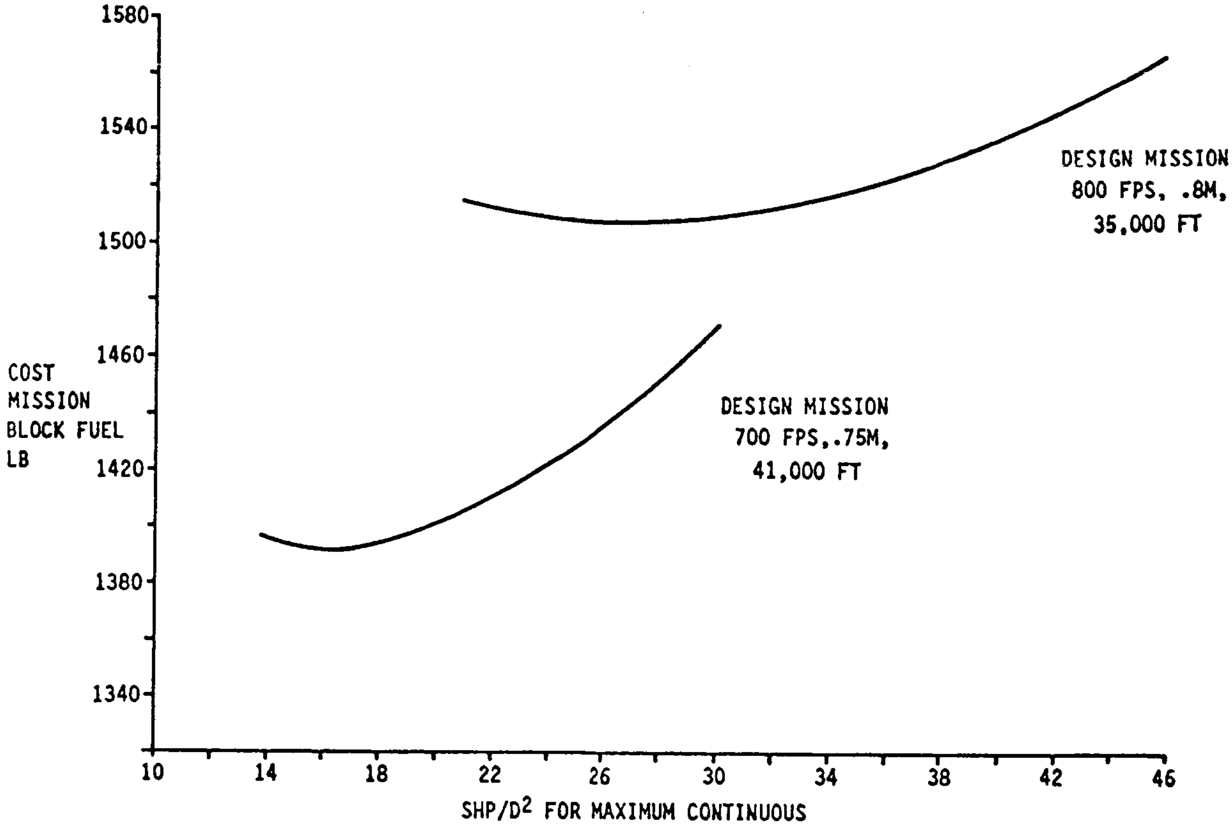

FIGURE 62. Design Mission Impact on Propfan Selection

The propfan noise estimates for the study were made utilizing the Hamilton Standard method defined in Reference 5. This method was developed based on data for tractor propfans. A pusher propfan typically operates in a significantly more disturbed flow field than a tractor propfan. As discussed in Section 5.6, recent work has been done at NASA (Reference 14) that indicates that pushers in the presence of a pylon or wing wake could have a substantially different noise directivity distribution more forward of the prop plane than that of a tractor installation. To assess the impact of the possible higher noise levels for pushers the sensitivity of the design to increased acoustic treatment weight was examined. The results are shown in Figure 63.

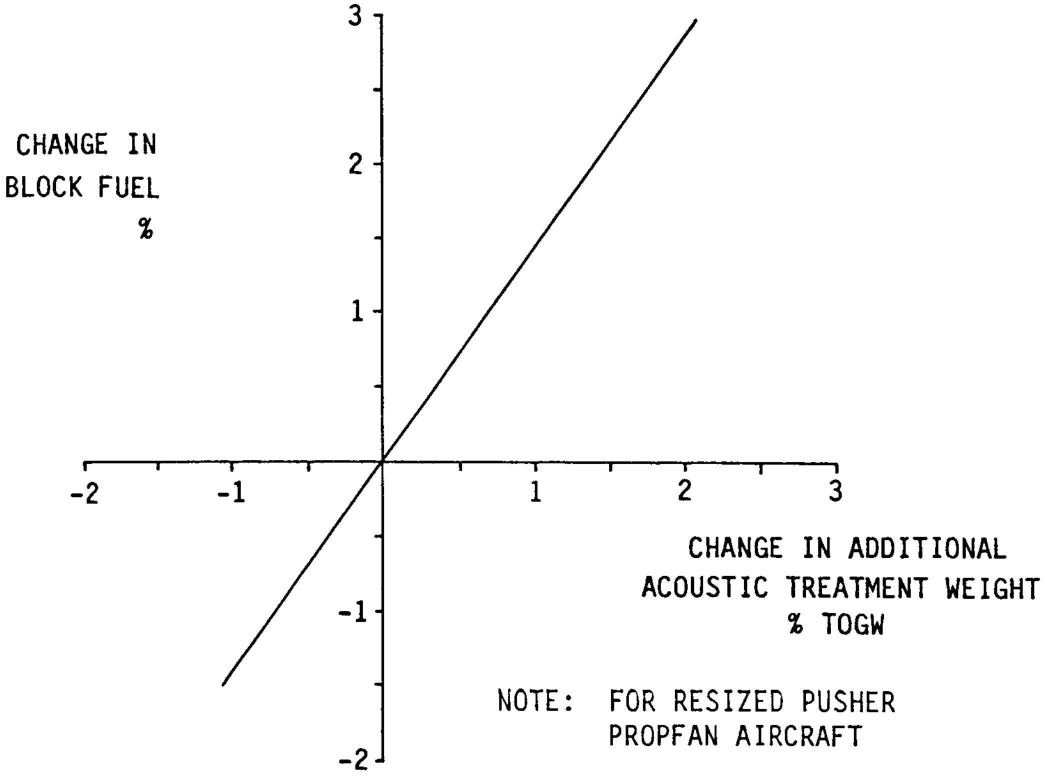

FIGURE 63. Mission Fuel Sensitivity to Acoustic Treatment Weight

6.2 COST FACTORS

The impact on the cost of operation due to variations in propulsion system cost, aircraft acquisition cost, annual aircraft utilization, and price of fuel were examined in the study. Both cost models used in this study consisted of similar operational cost elements. The ATA model's fuel cost, insurance cost, crew cost, airframe and propulsion system maintenance cost were all evaluated on a flight hour basis. The Corporate model utilized these same operational costs. It merely separated them into a set of annually fixed costs and a set of flight hour variable costs, where the crew and insurance were the fixed cost and the fuel and maintenance were the variable cost (see Appendix). The financial aspects, on the other hand, were treated differently in each model. The ATA model used a formulation for depreciation which included a 5-year residual value of the aircraft and an allowance for engine spares. The Corporate model, in addition to depreciation figured on current 1984 tax laws, also included the interest cost of borrowing capital to finance the aircraft. These differences between the models resulted in some interesting variation in sensitivity.

Both models were significantly influenced by utilization hours. With the utilization at the 400 hour level per year typical of business aircraft, the financial aspect of each model was the primary driver of the cost of operation. However, as the utilization increased up to commuter airline levels, such as 3000 hours, fuel consumption became the major influencing element in the operating cost. For example in Figure 64, using the corporate cost model for 400 hours utilization the depreciation and interest cost, which was directly influenced by the price of the aircraft, was 75.4% of the total cost of operation, whereas the fuel use represents only 9.3%. In the ATA model the influence of price was reduced because the model contains no cost of capital factor, yet, even still, the depreciation element represented 51.6% of the direct operating cost while fuel cost represented only 18.4%. On the other hand, using the ATA model at 3000 hours utilization, the depreciation only represented 13.5% of the cost of operation, whereas the fuel cost element increased to 36.1% of the cost. Similarly, fuel cost at 3000 hours for the Corporate model was 33.2% of the total cost.

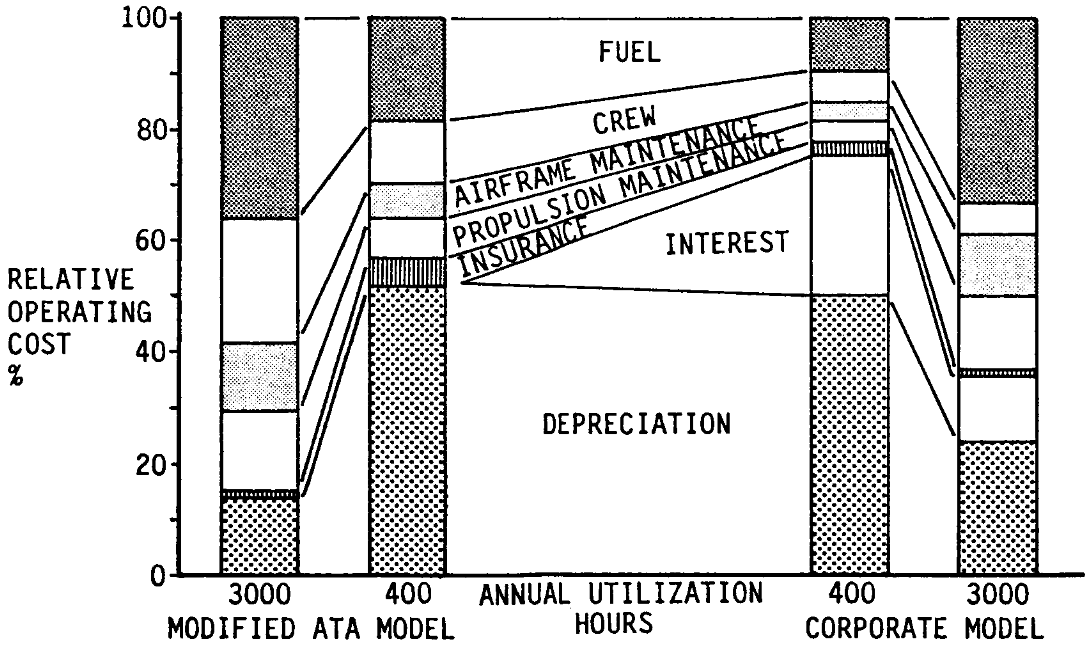

FIGURE 64. Cost Sensitivity to Chosen Cost Model and Annual Utilization

The Corporate model, with its effects of tax and cost of capital, exhibits a stronger sensitivity to aircraft purchase price than does the ATA model. This is shown in Figure 65. Aircraft purchase price affects the basis of depreciation, the amount financed and interest paid, the cost of insurance, and the tax credit received. Since the typical corporate utilization is 400 hours per year and these price related items are over 75% of the total cost of operation, the aircraft purchase price becomes the major factor in the cost analysis of a corporate aircraft.

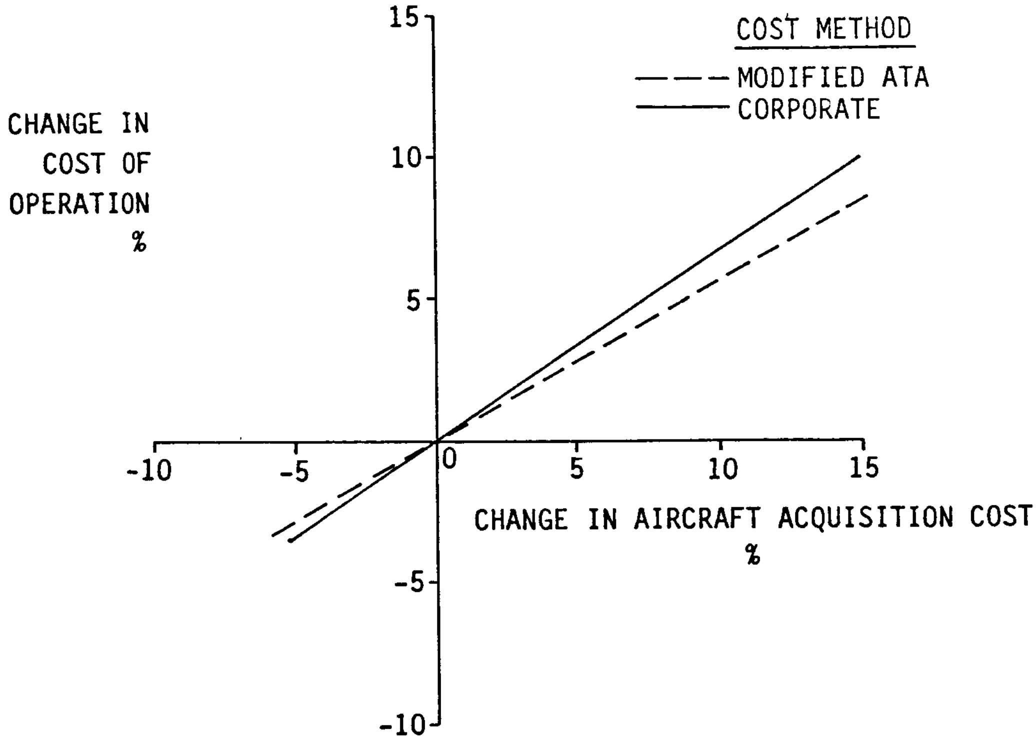

FIGURE 65. Operating Cost Sensitivity to Initial Aircraft Selling Price

The propulsion system acquisition cost has a major impact on the initial selling price of the aircraft. The propfan propulsion system alone makes up over 25% of the aircraft's empty weight (see Table 8 of Section 5.4). From a simplistic view this weight corresponds to the amount of material used which corresponds to the cost. The higher the percentage that the propulsion system's weight is of the total aircraft weight the greater the influence of the propulsion system price on the total aircraft price. As smaller aircraft designs are examined a definite scale effect becomes apparent. For example, a DC-9 airliner's propulsion system weight is approximately 10% of the total aircraft's empty weight, a Diamond I business jet's propulsion system is 15% of the total empty weight, and a King Air B200's propulsion system is roughly 22% of the aircraft empty weight.

To better understand the sensitivity to these cost factors and compare these results to other studies that have been done, a comparison was done between the factors affecting the cost in this study and a study done by the Pratt and Whitney Aircraft Group (Reference 15) on an airline class aircraft. The impact of the scale effect can be seen in Table 20. The higher weight of the propfan installation as compared to an equivalent

TABLE 20. Relative Weight of Propfans Compared to Turbofans

ITEM		GENERAL AVIATION	AIRLINE CLASS*
PROPULSION SYSTEM WEIGHT INCREASE (% OF EMPTY WEIGHT)	%	+26.8	+7.6
AIRFRAME STRUCTURAL WEIGHT INCREASE (% OF EMPTY WEIGHT)	%	+ 4.1	+4.3
ADDITIONAL ACOUSTIC TREATMENT WEIGHT (% OF TAKEOFF WEIGHT)	%	+ 1.5	+1.9

*Study by Pratt and Whitney Aircraft Group

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technology turbofan installation represented a larger percentage of the total aircraft weight than an equivalent comparison of airline class propulsion systems. The airframe and acoustic treatment were, however, similar for both the airline class design and the General Aviation design. With the higher sensitivity to propulsion system weight, the small business class aircraft exhibited more sensitivity to propulsion system cost than did the airline class aircraft. Combining this higher sensitivity to price with the higher cost of propfan propulsion resulted in a significant disadvantage for propfan propulsion, in spite of a potential 15% reduction in fuel consumption. Table 21 shows that a General Aviation propfan propulsion system had a 34.6% higher acquisition cost than a turbofan engine with equivalent mission capabilities. This combined with the higher airframe cost for propfans (due primarily to the higher weight) resulted in an overall 18% higher total aircraft selling price for a General Aviation propfan whereas an airline class propfan was only 2.2% higher than an equivalent turbofan.

TABLE 21. Relative Cost Factors of Propfans Compared to Turbofans

ITEM		GENERAL AVIATION	AIRLINE CLASS*
PROPULSION SYSTEM COST INCREASE	%	+34.6	+3.8
AIRFRAME AND AVIONICS COST INCREASE	%	+ 4.2	+1.8
TOTAL AIRCRAFT PRICE INCREASE	%	+18.0	+2.2

*Study by Pratt and Whitney Aircraft Group

The difference in operational characteristics from airline operation, as shown in Table 22, also affected the comparison of General Aviation propfans to turbofans. First, the fuel consumption reduction for this

TABLE 22. Relative Operational Factors of Propfans Compared to Turbofans

ITEM		GENERAL AVIATION	AIRLINE CLASS*
ANNUAL AIRCRAFT UTILIZATION	HR	400	3000-4000
CRUISE FUEL CONSUMPTION REDUCTION	%	15	20

*Study by Pratt and Whitney Aircraft Group

study was less aggressive than that shown for the airline study. However, more reduction than this was not believed to be realistically achievable for a General Aviation engine by 1988. Second, the cost factor differences were amplified over the fuel benefits for General Aviation because of the typically lower aircraft utilization rates as compared to airlines. A comparison of the effect of these cost factors in Table 21 on aircraft cost of operation is shown in Figures 66 and 67. Figure 66 shows that, with the cost factors determined for this study (including the benefits of the lower fuel consumption shown in Figure 59 in Section 5.7), a General Aviation propfan would have a 4% disadvantage compared to a current day turbofan capable of the same mission; an 11% disadvantage compared to an equivalent technology turbofan. If it were possible to reduce the cost differential between General Aviation propfans and turbofans such as those shown for the airline class aircraft in Table 21 a 2% advantage could be shown for propfans over turbofans with 400 hours utilization. As the utilization was increased to 3000 hours, Figure 67, this improvement would increase to 3%.

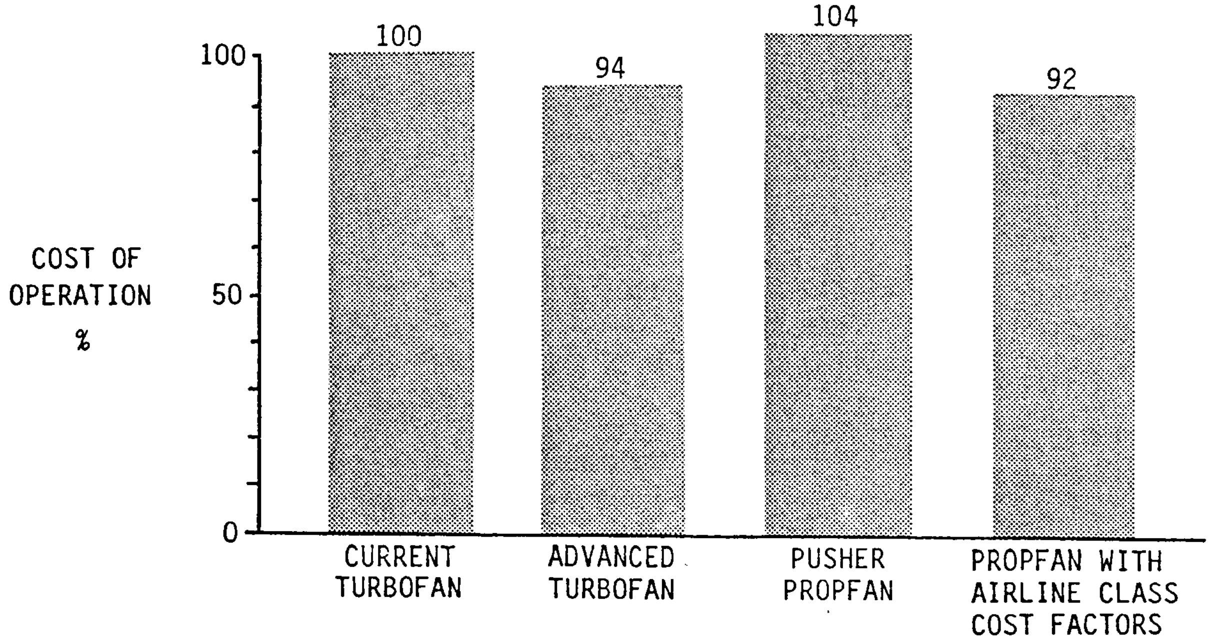

FIGURE 66. **Relative Operating Cost Comparison for 400 Hours Annual Aircraft Utilization (Corporate Model)**

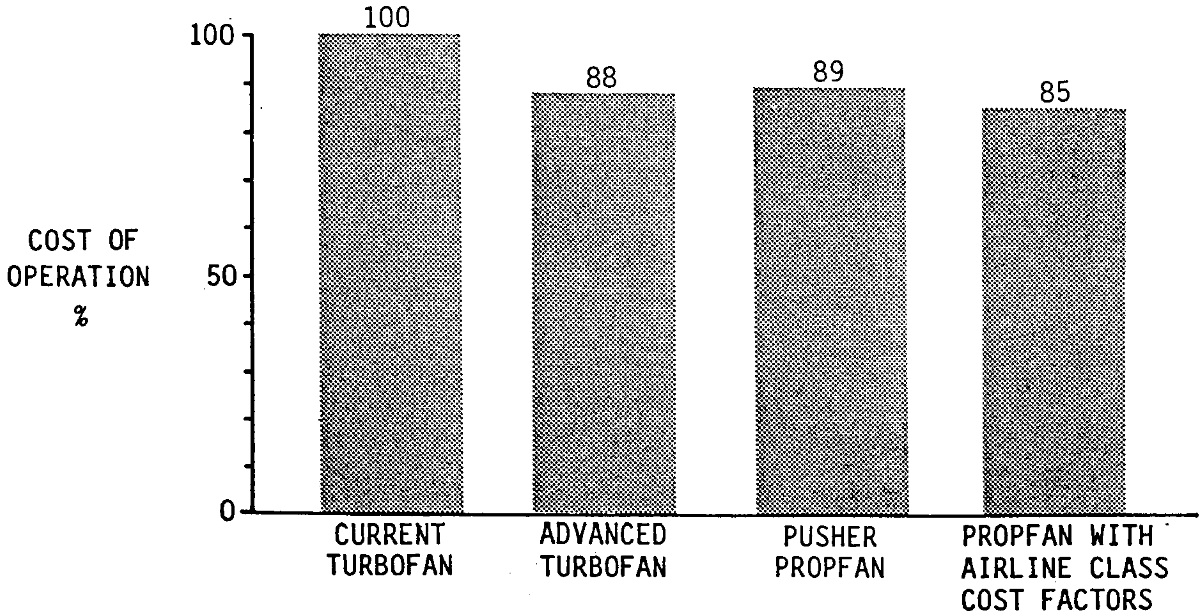

FIGURE 67. **Relative Operating Cost Comparison for 3000 Hours Annual Aircraft Utilization (ATA Model)**

The sensitivity of the cost of operation to the price of fuel is given in Figures 68 and 69. Because of higher fuel consumption the turbofan propulsion system is slightly more sensitive to change in fuel price than the propfan propulsion system as seen in Figures 68 and 69. Also, as annual utilization was increased in Figure 69, fuel use increased and both propfan and turbofan exhibited more sensitivity to change in fuel price. The base fuel price assumed for both these Figures was $1.90/gallon (see Appendix, Section A2.0 for further discussion of fuel price).

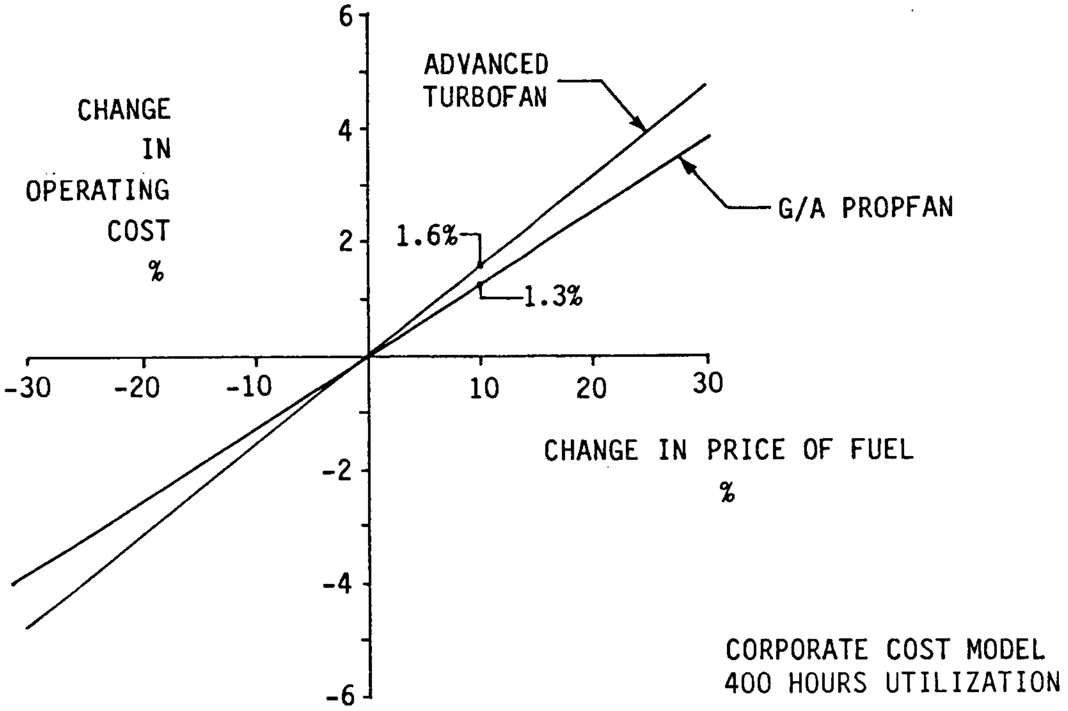

FIGURE 68. Sensitivity of Operating Cost to Fuel Price at 400 Hour Annual Aircraft Utilization

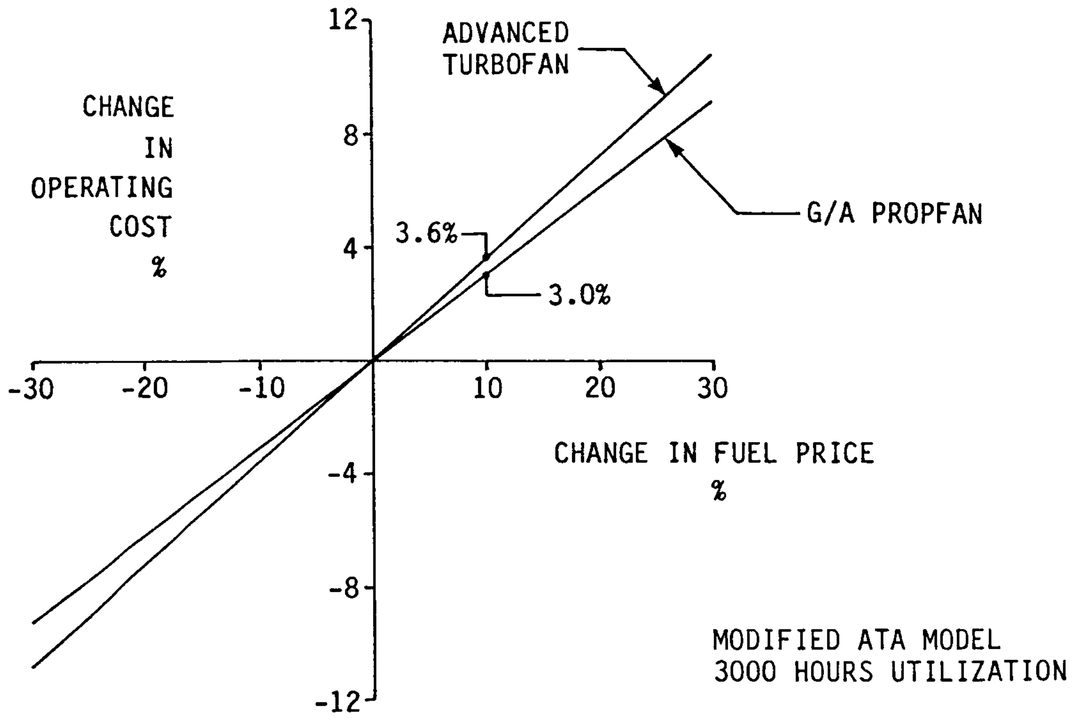

FIGURE 69. Sensitivity of Operating Cost to Fuel Price at 3000 Hour Annual Aircraft Utilization

6.3 CONFIGURATION/COST SENSITIVITY TO RETROFIT

A common practice in General Aviation (as well as other industries) is the technique of retrofitting a new system on a current design. This technique frequently results in improved design versatility at substantially lower cost. To examine the sensitivity of the designs in this study to a retrofit approach the current turbofan design was retrofit with both the advanced 1988 turbofan engine and the 1988 pusher propfan installation. The results are shown in Table 23. Both 1988 engines were sized to provide the thrust necessary to give a .75 Mach cruise at 41,000 FT. In addition to the engine retrofit, the propfan also required the changes in tail size, nacelle attachment structure, systems weight, and additional acoustic treatment to accommodate the propfan propulsion system. These changes were reflected in the propfan's increased empty weight. It was assumed that the retrofit configuration could be balanced without major problems which could resize the aircraft and diminish the potential benefits. Further, it was assumed that the takeoff weight would remain unchanged, and, therefore, the propfan had less usable fuel available. Nevertheless, the propfan still increased the range significantly from the current turbofan's range. The cost mission showed a 28.9% reduction in fuel use relative to the current day turbofan; a 15.4% reduction relative to the advanced turbofan. Once again, however, because of the much higher propulsion system acquisition cost and subsequent higher aircraft selling price the retrofit pusher propfan showed a 9.3% cost of operation disadvantage to both turbofans.

TABLE 23. Current Turbofan with Retrofit 1988 Propulsion Systems

ITEM		CURRENT TURBOFAN	RETROFIT ADVANCED TURBOFAN	RETROFIT PUSHER PROPFAN
WEIGHTS				
MAX TAKEOFF WEIGHT	LB	17033	17033	17033
USABLE FUEL	LB	7157	7157	6209
EMPTY WEIGHT	LB	8676	8676	9624
PERFORMANCE				
VFR RANGE*	NM	2175	2703	2866
CRUISE SPEED @ 41,000 FT	MACH	.75	.75	.75
COST MISSION BLOCK FUEL	LB	2089	1757	1486
*WITH 45 MIN RESERVE				
COST				
AIRCRAFT ACQUISITION COST	$ MILLIONS	3.60	3.75	4.38
PROPULSION ACQUISITION COST	$ MILLIONS	.465	.499	.651
COST OF OPERATION	$/SEAT-NM	.484	.484	.529

7.0 CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate that propfan propulsion is technically feasible for application to General Aviation. Propfan propulsion applied to General Aviation aircraft provides comparable mission capabilities to General Aviation turbofans. For the typical 400 hours annual utilization that business aircraft experience, propfans can provide the equivalent speed and payload/range capabilities of a business jet while also providing substantial fuel burn reductions. The fuel consumption benefits by utilizing propfan propulsion are:

- a 33% reduction in fuel consumption when compared to a 1984 (current) technology turbofan aircraft;
- a 14% reduction in fuel consumption when compared to a 1990 (equivalent) technology turbofan aircraft;
- a 29% reduction in fuel consumption (or 32% increase in range) using a current aircraft retrofit with propfans.

The aircraft examined in this study show that, based on current understanding, propfan propulsion can provide acceptable near field and far field noise levels similar to or better than turbofans. For far field, the propfan aircraft examined in this study achieved community noise levels below the Stage III requirements of the Federal Aviation Regulation's Part 36, Appendix C. For near field, an average cabin interior noise level of 82 dBA was selected as the design criteria. To meet this goal the General Aviation propfans examined in this study required an additional acoustic treatment above the noise treatment used in the turbofans of 1.5% of the takeoff gross weight (TOGW) for the pusher installation and 4% of TOGW for the tractor installation.

In spite of the obvious marketable benefits of reduction in fuel consumption with comparable mission capabilities to aircraft with turbofans, propfans on General Aviation aircraft have a severe cost of operation (DOC) disadvantage compared to turbofans. The General Aviation cost of operation exhibits higher sensitivity to aircraft initial selling price and the tax environment than does the cost of operation (DOC) for large transport class aircraft, while showing less sensitivity due to changes in fuel consumption. This is primarily due to the lower annual utilization rates for business aircraft.

The lower aircraft annual utilization rates for General Aviation (400 hours/year), as compared to airlines (3000-3400 hours/year), and the 18% higher aircraft acquisition cost for the propfan combine to give a cost of operation (or direct operating cost, DOC) that is much higher than a turbofan. The results showed that the cost of operation for a propfan was:

- 4% higher than a 1984 (current) technology turbofan;
- 11% higher than a 1990 (equivalent) technology turbofan.

The higher aircraft price is due primarily to the significantly higher acquisition cost for the propfan propulsion system:

- 37.4% higher price than a 1984 (current) technology turbofan engine;
- 34.7% higher price than a 1988 (equivalent) technology turbofan engine.

Propfan propulsion poses serious technical and cost challenges before it can be successfully implemented in General Aviation. The broad brush approach taken in this study indicated that several installation concepts utilizing propfans were technically feasible. However, further development in key technical and cost areas is required. Because of the smaller scale of General Aviation aircraft, as compared to transport aircraft, and the relatively large turboprop engines required for propfan propulsion to match turbofan mission capability, pusher configurations provide the best apparent installation from overall weight, balance, noise, and safelife design considerations. Analytical studies are needed, along with verification by test, to resolve the technical uncertainties for a pusher installation. In particular, the following items need further work:

- the acoustic levels for pusher propfans and their distributions/directivity for typical flight disk loadings;
- the asymmetric wake effects of a body or lifting surface in front of the prop plane on the blade structural dynamics and performance;
- the flow field shock effects on the blade dynamics;
- the exhaust flow effects on the propfan blades;

- the design and certification aspects of propfan structural failure;

- the development of design codes for the General Aviation class propfans.

Of higher priority than the technical aspects, before propfan propulsion can become marketable for General Aviation, the propulsion system cost for propfans must be competitive with turbofans. Once again, because of the broad brush aspect of this study, the costs provided by the propulsion manufacturers were based on sizable extrapolations. More work needs to be initiated by NASA to provide better definition of the propulsion cost elements involved and to study potential engine and propfan cost reductions.

APPENDIX
COST ESTIMATING MODEL

Two cost models were developed for this study to compare the propulsion system designs. The first method consists of the 1967 Air Transport Association (ATA) (Reference 16) cost model modified to reflect General Aviation. The second method takes a similar approach to operating cost, as does the ATA model, but also includes the cost of capital and tax benefits of ownership. In each case, 1984 was assumed for the dollar value and tax environment.

A1.0 MODIFIED 1967 AIR TRANSPORT ASSOCIATION (ATA) MODEL

The Direct Operating Cost (DOC) model is based on definitions provided in the 1967 ATA formulation and the approach used in Reference 17. The crew costs, fuel costs, insurance, and labor rates are based on 1984 levels typical for General Aviation. Maintenance costs contain both a cyclic and a flight hour factor. Propulsion system maintenance costs were supplied both by Pratt and Whitney, Canada and Hamilton Standard. Maintenance labor cost factors were assumed to be the same for both the current day propulsion system and the 1988 technology level propulsion systems. Variation in maintenance costs between current day and 1988-1990 level technology shown in the study occur from a difference in airframe material cost and propulsion system price.

A1.1 MODIFIED ATA COST ESTIMATING FORMULAS

The DOC model formulation used in this study is as follows:

DIRECT OPERATING COST

$$DOC = C_c + C_f + C_d + C_i + C_{al} + C_{am} + C_{pl} + C_{pm} \quad (\$/flight)$$

CREW COSTS -

$$C_c = N_c\ (K_c)\ (t_b)$$

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where

C_c = crew cost (\$/flight)
K_c = crew hourly rate (\$/HR) = \$96/HR
N_c = number of crew = 2
t_b = block time (HR)

FUEL COST -

$$C_f = F_b (P_f) / 6.7$$

where

C_f = cost of fuel (\$/flight)
F_b = block fuel (LB)
P_f = price of jet fuel (\$/GAL) = \$1.90 (Reference 18)

HULL INSURANCE COST -

$$C_i = t_b (C_t) IR / U$$

where

C_i = cost of hull insurance (\$/flight)
t_b = block time (HR)
C_t = aircraft initial selling price (\$)
IR = annual insurance rate (%) = 1%
U = annual utilization (HR) = 400 HR or 3000 HR

DEPRECIATION -

$$C_d = t_b (.46C_t + .15 C_p) / (D_a U)$$

where

C_d = cost of depreciation (\$/flight)
D_a = depreciation period (YR) = 5 YR
C_t = aircraft initial selling price (\$)
C_p = propulsion system price (\$)
U = annual utilization (HR) = 400 HR or 3000 HR
t_b = block time (HR)

AIRFRAME MAINTENANCE LABOR COST -

$$C_{al} = (K_1 (t_f) + K_2) (LR) (B)$$

where

C_{al} = airframe maintenance labor cost (\$/flight)
K_1 = labor manhours per flight hour (MHR/HR)
K_1 = $.59 K_2$
K_2 = labor manhours per flight cycle (MHR)
K_2 = $(.05 (W_a) / 1000) + 6 - 630 / ((W_a / 1000) + 120)$
t_f = flight time (HR) = $t_b - t_g$
t_b = block time (HR)
t_g = ground time (HR) = .16 HR
LR = labor rate (\$/MHR) = \$21.67/HR
B = overhead burden factor = 1.8
W_a = aircraft airframe weight (LB)

AIRFRAME MAINTENANCE MATERIAL COST -

$$C_{am} = (K_3 (t_f) + K_4) W_a/1000$$

where

C_{am} = airframe maintenance material cost (\$/flight)
K_3 = airframe material hourly factor (\$/HR/LB)
K_3 = $3.08 (C_a + C_{ae})/10^6$
K_4 = airframe material cyclic factor (\$/LB)
K_4 = $6.24 (C_a + C_{ae})/10^6$
C_a = complete airframe price (\$)
C_{ae} = price of typical optional avionics and equipment (\$)
W_a = aircraft airframe weight (LB)
t_f = flight time = $t_b - t_g$
t_b = block time (HR)
t_g = ground time (HR) = .16 HR

PROPULSION SYSTEM MAINTENANCE LABOR COST -

$$C_{pl} = N_e (K_5 (t_f) + K_6) (LR) (B)$$

where

C_{pl} = engine or engine/propeller maintenance labor cost ($/flight)
N_e = number of engines
K_5 = labor manhours per flight hour per engine (MHR/HR)
K_6 = labor manhours per flight cycle per engine (MHR)
LR = labor rate ($/MHR) = $21.67/HR
B = overhead burden factor = 1.8

for turbofans

$K_5 = .30$
$K_6 = .03$

for propfans

$K_5 = .45 + (1.57 \times 10^{-4}(N_B)(Dia) + .0045)$
$K_6 = .03$

where

N_B = number of blades
Dia = propeller diameter (FT)

PROPULSION SYSTEM MAINTENANCE MATERIAL COST -

$$C_{pm} = N_e \, (K_7 \, (t_f) + K_8)$$

where

C_{pm} = engine or engine/propeller maintenance material cost ($/flight)
N_e = number of engines
K_7 = propulsion system material cost per flight hour ($/HR)
K_8 = propulsion system material cost per flight cycle ($/flight)

for turbofans

$K_7 = .75 \, (F_N)^{.5}$
$K_8 = .35 \, (F_N)^{.5}$
F_N = thermodynamic thrust at SLS (LB)

for propfans

$K_7 = (P_t)^{.5} + (6.11 \times 10^{-3} (N_B)(Dia) + .175)$
$K_8 = .20 (P_t)^{.5}$
P_t = thermodynamic horsepower at SLS (SHP)
N_B = number of blades
Dia = propeller diameter (FT)

A1.2 DOC BREAKDOWNS

Tables 24 through 27 show the DOC element costs for the cost mission with an aircraft annual utilization of 400 hours. Tables 28 through 31 show these same elements only with an aircraft annual utilization of 3000 hours.

TABLE 24. **Current Turbofan ATA Analysis at 400 Hours Utilization**

CURRENT (1984) TURBOFAN

MISSION STAGE LENGTH = 400.0 NM YEARLY UTILIZATION = 400 HOURS
NUMBER OF PASSENGER SEATS = 8 AIRCRAFT EMPTY WEIGHT = 8676.0 LB

** TURBOFAN ENGINE **

ENGINE SL THERMODYNAMIC THRUST 3257.0 LB

BLOCK TIME = 1.508 HR
BLOCK FUEL = 2089.0 LB

MISSION ELEMENT COST BREAKDOWN:

CREW COST =	$ 289.54
FUEL COST =	$ 592.40
INSURANCE COST =	$ 135.58
DEPRECIATION COST =	$ 1350.26
AIRFRAME MAINTENANCE MATERIAL COST =	$ 91.07
AIRFRAME MAINTENANCE LABOR COST =	$ 93.47
PROPULSION MAINTENANCE MATERIAL COST =	$ 154.77
PROPULSION MAINTENANCE LABOR COST =	$ 33.73
TOTAL COST =	$ 2740.83

SUMMARY:

AIRCRAFT FIRST PRICE = $ 3596221
PROPULSION SYSTEM PRICE/ENG = $ 455134

DIRECT OPERATING COST PER HOUR = 1817.53 $/HR
COST PER SEAT MILE = .857 $/seat-nm

TABLE 25. Advanced Turbofan ATA Analysis at 400 Hours Utilization

ADVANCED (1990) TURBOFAN

MISSION STAGE LENGTH = 400.0 NM YEARLY UTILIZATION = 400 HOURS
NUMBER OF PASSENGER SEATS = 8 AIRCRAFT EMPTY WEIGHT = 7426.0 LB

** TURBOFAN ENGINE **

ENGINE SL THERMODYNAMIC THRUST 3067.0 LB

BLOCK TIME = 1.490 HR
BLOCK FUEL = 1625.0 LB

MISSION ELEMENT COST BREAKDOWN:

CREW COST = $	286.08
FUEL COST = $	460.82
INSURANCE COST = $	133.31
DEPRECIATION COST = $	1330.17
AIRFRAME MAINTENANCE MATERIAL COST = $	71.70
AIRFRAME MAINTENANCE LABOR COST = $	85.23
PROPULSION MAINTENANCE MATERIAL COST = $	148.70
PROPULSION MAINTENANCE LABOR COST = $	33.31
TOTAL COST = $	2549.32

SUMMARY:

AIRCRAFT FIRST PRICE = $ 3578783
PROPULSION SYSTEM PRICE/ENG = $ 464086

DIRECT OPERATING COST PER HOUR = 1710.95 $/HR
COST PER SEAT MILE = .797 $/seat-nm

TABLE 26. Pusher Propfan ATA Analysis at 400 Hours Utilization

ADVANCED (1990) PUSHER PROPFAN

MISSION STAGE LENGTH = 400.0 NM YEARLY UTILIZATION = 400 HOURS
NUMBER OF PASSENGER SEATS = 8 AIRCRAFT EMPTY WEIGHT = 8274.0 LB

** TURBOPROP ENGINE **

PROP DIAMETER 8.000 FT # OF BLADES = 6
ENGINE SL THERMODYNAMIC SHP 2714.0

BLOCK TIME = 1.495 HR
BLOCK FUEL = 1392.0 LB

MISSION ELEMENT COST BREAKDOWN:

CREW COST =	$ 287.04
FUEL COST =	$ 394.75
INSURANCE COST =	$ 157.88
DEPRECIATION COST =	$ 1592.60
AIRFRAME MAINTENANCE MATERIAL COST =	$ 78.62
AIRFRAME MAINTENANCE LABOR COST =	$ 87.24
PROPULSION MAINTENANCE MATERIAL COST =	$ 160.48
PROPULSION MAINTENANCE LABOR COST =	$ 50.22
TOTAL COST =	$ 2808.83

SUMMARY:

AIRCRAFT FIRST PRICE = $ 4224155
PROPULSION SYSTEM PRICE/ENG = $ 624857

DIRECT OPERATING COST PER HOUR = 1878.82 $/HR
COST PER SEAT MILE = .878 $/seat-nm

TABLE 27. Tractor Propfan ATA Analysis at 400 Hours Utilization

ADVANCED (1990) TRACTOR PROPFAN

MISSION STAGE LENGTH = 400.0 NM YEARLY UTILIZATION = 400 HOURS
NUMBER OF PASSENGER SEATS = 8 AIRCRAFT EMPTY WEIGHT = 8802.0 LB

** TURBOPROP ENGINE **

PROP DIAMETER 8.000 FT # OF BLADES = 6
ENGINE SL THERMODYNAMIC SHP 2693.0

BLOCK TIME = 1.502 HR
BLOCK FUEL = 1401.0 LB

MISSION ELEMENT COST BREAKDOWN:

CREW COST =	$ 288.38
FUEL COST =	$ 397.30
INSURANCE COST =	$ 162.75
DEPRECIATION COST =	$ 1637.17
AIRFRAME MAINTENANCE MATERIAL COST =	$ 89.54
AIRFRAME MAINTENANCE LABOR COST =	$ 90.24
PROPULSION MAINTENANCE MATERIAL COST =	$ 160.60
PROPULSION MAINTENANCE LABOR COST =	$ 50.47
TOTAL COST =	$ 2876.46

SUMMARY:

AIRCRAFT FIRST PRICE = $ 4334136
PROPULSION SYSTEM PRICE/ENG = $ 620967

DIRECT OPERATING COST PER HOUR = 1915.09 $/HR
COST PER SEAT MILE = .899 $/seat-nm

TABLE 28. Current Turbofan ATA Analysis at 3000 Hours Utilization

CURRENT (1984) TURBOFAN

MISSION STAGE LENGTH = 400.0 NM YEARLY UTILIZATION = 3000 HOURS
NUMBER OF PASSENGER SEATS = 8 AIRCRAFT EMPTY WEIGHT = 8676.0 LB

** TURBOFAN ENGINE **

ENGINE SL THERMODYNAMIC THRUST 3257.0 LB

BLOCK TIME = 1.508 HR
BLOCK FUEL = 2089.0 LB

MISSION ELEMENT COST BREAKDOWN:

CREW COST =	$ 289.54
FUEL COST =	$ 592.40
INSURANCE COST =	$ 18.08
DEPRECIATION COST =	$ 180.04
AIRFRAME MAINTENANCE MATERIAL COST =	$ 91.07
AIRFRAME MAINTENANCE LABOR COST =	$ 93.47
PROPULSION MAINTENANCE MATERIAL COST =	$ 154.77
PROPULSION MAINTENANCE LABOR COST =	$ 33.73
TOTAL COST =	$ 1453.10

SUMMARY:

AIRCRAFT FIRST PRICE = $ 3596221
PROPULSION SYSTEM PRICE/ENG = $ 455134

DIRECT OPERATING COST PER HOUR = 963.60 $/HR
COST PER SEAT MILE = .454 $/seat-nm

TABLE 29. Advanced Turbofan ATA Analysis at 3000 Hours Utilization

ADVANCED (1990) TURBOFAN

MISSION STAGE LENGTH = 400.0 NM YEARLY UTILIZATION = 3000 HOURS
NUMBER OF PASSENGER SEATS = 8 AIRCRAFT EMPTY WEIGHT = 7426.0 LB

** TURBOFAN ENGINE **

ENGINE SL THERMODYNAMIC THRUST 3067.0 LB

BLOCK TIME = 1.490 HR
BLOCK FUEL = 1625.0 LB

MISSION ELEMENT COST BREAKDOWN:

CREW COST = $	286.08
FUEL COST = $	460.82
INSURANCE COST = $	17.77
DEPRECIATION COST = $	177.36
AIRFRAME MAINTENANCE MATERIAL COST = $	71.70
AIRFRAME MAINTENANCE LABOR COST = $	85.23
PROPULSION MAINTENANCE MATERIAL COST = $	148.70
PROPULSION MAINTENANCE LABOR COST = $	33.31
TOTAL COST = $	1280.96

SUMMARY:

AIRCRAFT FIRST PRICE = $ 3578783
PROPULSION SYSTEM PRICE/ENG = $ 464086

DIRECT OPERATING COST PER HOUR = 859.71 $/HR
COST PER SEAT MILE = .400 $/seat-nm

TABLE 30. Pusher Propfan ATA Analysis at 3000 Hours Utilization

ADVANCED (1990) PUSHER PROPFAN

MISSION STAGE LENGTH = 400.0 NM YEARLY UTILIZATION = 3000 HOURS
NUMBER OF PASSENGER SEATS = 8 AIRCRAFT EMPTY WEIGHT = 8274.0 LB

** TURBOPROP ENGINE **

PROP DIAMETER 8.000 FT # OF BLADES = 6
ENGINE SL THERMODYNAMIC SHP 2714.0

BLOCK TIME = 1.495 HR
BLOCK FUEL = 1392.0 LB

MISSION ELEMENT COST BREAKDOWN:

CREW COST =	$ 287.04
FUEL COST =	$ 394.75
INSURANCE COST =	$ 21.05
DEPRECIATION COST =	$ 212.35
AIRFRAME MAINTENANCE MATERIAL COST =	$ 78.62
AIRFRAME MAINTENANCE LABOR COST =	$ 87.24
PROPULSION MAINTENANCE MATERIAL COST =	$ 160.48
PROPULSION MAINTENANCE LABOR COST =	$ 50.22
TOTAL COST =	$ 1291.75

SUMMARY:

AIRCRAFT FIRST PRICE = $ 4224155
PROPULSION SYSTEM PRICE/ENG = $ 624857

DIRECT OPERATING COST PER HOUR = 864.05 $/HR
COST PER SEAT MILE = .404 $/seat-nm

TABLE 31. Tractor Propfan ATA Analysis at 3000 Hours Utilization

```
                    ADVANCED (1990) TRACTOR PROPFAN

MISSION STAGE LENGTH =  400.0 NM  YEARLY UTILIZATION = 3000 HOURS
NUMBER OF PASSENGER SEATS =  8  AIRCRAFT EMPTY WEIGHT = 8802.0 LB

       ** TURBOPROP ENGINE **

PROP DIAMETER 8.000 FT  # OF BLADES =  6
ENGINE SL THERMODYNAMIC SHP 2693.0



BLOCK TIME =   1.502 HR
BLOCK FUEL =  1401.0 LB

                 MISSION ELEMENT COST BREAKDOWN:
                 ------------------------------

                                  CREW COST = $   288.38
                                  FUEL COST = $   397.30
                             INSURANCE COST = $    21.70
                          DEPRECIATION COST = $   218.29
     AIRFRAME MAINTENANCE MATERIAL COST = $    89.54
        AIRFRAME MAINTENANCE LABOR COST = $    90.24
   PROPULSION MAINTENANCE MATERIAL COST = $   160.60
      PROPULSION MAINTENANCE LABOR COST = $    50.47
                                            --------
                                 TOTAL COST = $ 1316.53


   SUMMARY:
   --------

AIRCRAFT FIRST PRICE = $ 4334136
PROPULSION SYSTEM PRICE/ENG = $  620967

DIRECT OPERATING COST PER HOUR =   876.52  $/HR
            COST PER SEAT MILE =     .411 $/seat-nm
```

A2.0 CORPORATE COST MODEL

The corporate model was developed for this study utilizing the cost elements of the ATA model. These elements, however, were modified somewhat to facilitate evaluation of the cost of capital and tax advantage typically experienced by business aircraft owners. Further, the depreciation formula used in the ATA model was replaced by a cash flow analysis for a five-year period to generate an overall five year cost of operation. This simple cash flow analysis provides a cost of operation analysis that is more typical of General Aviation business aircraft and provides a better understanding of the cost factors which impact the business aircraft market, particularly interest rates, insurance rates, aircraft prices, and tax law.

The operating cost was broken into fixed and variable costs as shown in Table 32. Each of the corresponding ATA elements used to calculate the fixed and variable costs are shown in Table 32. The fixed costs were assumed to include only crew cost and insurance cost determined on an annual basis. Other types of fixed costs such as hangar cost, airport use fees, aircraft cleaning cost, office supplies, charts, catering, etc., were

TABLE 32. Operating Cost Elements

OPERATING COST	
ANNUAL FIXED	VARIABLE
Crew Cost $C_c \times U/t_b$	Fuel Cost C_f/t_b
Insurance Cost $C_i \times U/t_b$	Maintenance Cost C_{pl}/t_b, C_{pm}/t_b, C_{al}/t_b, C_{am}/t_b

not considered but did not impact the relative comparison in this study. The variable costs, similar to the ATA model, were determined on a flight hour basis. The fuel cost was based on an average fuel price, as in the ATA model, of $1.90 per gallon for JET-A (Reference 18). Unlike airline operators who can obtain bulk fuel at approximately $1/gallon, business aircraft operators are forced to purchase fuel at higher retail prices that range from $1.65/gallon to $2.40/gallon depending on location. The airframe and propulsion system maintenance costs, as in the ATA model, were derived from data provided by Pratt and Whitney, Canada and Hamilton Standard and included cyclic and flight hour cost factors. Additionally, the engine cost factors also included an allowance for engine overhaul.

The cash flow analysis which yields the cost of operation for the Corporate Cost Model is broken into five steps and is illustrated in Figure 70.

Step 1. Based on the aircraft and propulsion system characteristics the aircraft acquisition cost (or aircraft first price) is determined using the method described at the end of the Appendix, Section A3.0. The tax depreciation basis and monthly loan payment are then determined for use in Steps 3 and 4.

Step 2. The yearly operating cost (or ops cost) is the next element determined. It is broken into two sub-elements: a variable cost based on flight hours and a yearly fixed cost. The yearly variable cost is determined using the aircraft annual utilization hours. The yearly ops cost is input both to Step 3 and to Step 4.

Step 3. Next the tax savings is determined for each year with the assumed 50% tax bracket. The tax savings is input into Step 4.

Step 4. The yearly net cash flow is then calculated. Negative cash flow is defined as dollars being spent by the aircraft owner.

Step 5. Finally, the sum of each year's bottom-line cash flow in Step 4 is calculated to yield the total cost of operation for 5 years. Based on the design mission's length, block time required, and the aircraft's annual utilization, the hourly cost of operation or the cost per seat per nautical mile can be calculated.

AIRCRAFT FIRST PRICE

$3,596,221.49

STEP 1

CASH FLOW ANALYSIS

CASH FLOW OUT (-)	YEARS				
	1	2	3	4	5
DOWN PAYMENT	179,811	- - - -	- - - -	- - - -	- - - -
ANNUAL PAYMENT	588,187	588,187	588,187	588,187	588,187
COST OF OPERATION	368,851	368,851	368,851	368,851	368,851
REPAY OF LOAN BAL	- - - -	- - - -	- - - -	- - - -	2,203,497
TAX ON RESALE GAIN	- - - -	- - - -	- - - -	- - - -	1,258,678
CASH FLOW IN (+)					
INVSTMT TAX CREDIT	359,622	- - - -	- - - -	- - - -	- - - -
TAX SAVINGS	640,573	748,203	717,662	702,497	685,407
RESALE	- - - -	- - - -	- - - -	- - - -	2,517,355
NET CASH FLOW					
$ OUT (-)	136,654	208,834	239,375	254,541	1,216,449

STEP 4

5 YEAR NET COST = $2,055,853

STEP 5

ANNUAL OPERATING COST

FIXED + VARIABLE

TOTAL = $368,851

STEP 2

AIRCRAFT FIRST PRICE

$3,596,221.49

STEP 1

TAX SAVINGS

	YEARS				
	1	2	3	4	5
ANNUAL OPS COST	368,851	368,851	368,851	368,851	368,851
DEPRECIATION	512,462	751,610	717,446	717,446	717,446
INTEREST	399,833	375,945	349,028	318,696	284,518
TOTAL	1,281,145	1,496,406	1,435,324	1,404,993	1,370,815
TAX SAVINGS (50%)	$640,573	$748,203	$717,662	$702,497	$685,407

STEP 3

FIGURE 70. Steps to Evaluating the Cash Flow Utilized in the Corporate Cost Model

A2.1 COST OF CAPITAL AND TAX ASPECTS

The cost of capital, for this study, was simply the interest paid each year on the loan. A value of 12% was assumed as a typical 1984 loan rate, and the loan was assumed to be a ten year direct reduction loan with a balloon payoff at the end of five years. A 5% down payment on the loan was also assumed.

The Tax Equity and Fiscal Responsibility Act of 1982 allows for two alternative methods for depreciation of capital equipment such as aircraft. The taxpayer may elect to take an investment tax credit of 8% of the initial purchase price of the aircraft for the first year, using 100% of the purchase price as the depreciation basis over five years, or he may elect to take a 10% tax credit and then use 95% of the purchase price as the depreciation basis. In the purchase of a General Aviation aircraft the option selected, of course, depends on the tax situation of the purchaser. However, the 10% option is most frequently selected and was chosen for this study as typical. Using 95% of the purchase price as a basis of depreciation, the depreciation for each year is calculated as follows: year 1 - 15% of basis, year 2 - 22% of basis, year 3, 4, and 5 - 21% of basis.

To obtain the resultant tax benefits of ownership on the overall cash flow, the annual operations cost, which is considered a deductable expense, is added to the depreciation and interest to yield the total deductions. These deductions, depending on the taxpayer's tax bracket, will result in a reduction of tax paid. Most taxpayers purchasing General Aviation aircraft of the class examined in this study are subject to a 50% tax rate. This rate was assumed for this study. Thus the resultant tax benefits of ownership on the taxpayer's overall cash flow is 50% of the allowable deductions.

A2.2 CASH FLOW ANALYSIS

The cash flow is then examined assuming ownership of the aircraft for five years. The cash flow "out" is combined with the cash flow "in" to yield the "net" cash flow, where a negative number represents dollars spent by the aircraft owner. Several assumptions were made in this cash flow model to simplify the analysis and to provide an equivalent basis of comparison for the aircraft in the study. It was assumed that the aircraft was sold at the end of five years at which time the resale value was 70% of the original purchase price. The 70% resale value is typical of the price on used General Aviation turbofan aircraft whereas turboprop aircraft have a typically lower resale value around 60% after five years. Therefore, the assumption made in this study was that propfans would behave more like turbofans in the marketplace than like turboprops. Also, it was assumed that the aircraft owner, at the end of five years, did not purchase another more expensive aircraft. Thus the dollar gain on the resale of the fully depreciated aircraft is taxable as ordinary income. This is not usually the case for a business aircraft owner. Owners typically "trade up" in equipment, thus modifying their next aircraft's depreciation basis by the sale price of their present aircraft. This significantly complicates the cash flow analysis and clouds the propulsion system comparison being made in this study. The assumption that the owner would sell the aircraft at the end of five years without a subsequent purchase of another aircraft provided a simplification to the cash flow method which still allowed a valid (yet conservative in cost per seat per nautical mile) comparison between configurations without introducing unnecessary complication.

The resultant net cash flow for each year is summed for the five year period, yielding a five year cost of operation. Then, depending on the operator's utilization, a cost per hour or a cost per seat per nautical mile can be determined.

A2.3 COST OF OPERATION BREAKDOWNS

Tables 33 through 36 show the cost spread sheets for each of the four study aircraft. These costs are evaluated for an annual utilization of 400 hours.

TABLE 33. Current Turbofan Corporate Cost Analysis

```
                              CURRENT TURBOFAN
NUMBER OF PASSENGER SEATS = 8   ENGINE SL THERMODYNAMIC THRUST 3257.0 LB
TYPICAL MISSION LENGTH =  400.0 NM       YEARLY UTILIZATION =  400.0 HR
BLOCK TIME FOR MISSION =  1.5080 HR  BLOCK FUEL FOR MISSION =  2089.0 LB
--------------------------------------------------------------------------------
  AIRCRAFT FIRST PRICE = $ 3596221.49  PROPULSION SYSTEM PRICE(EA) = $ 455134.43
ASSUMED FINANCING: 12% INTEREST, 95% FINANCED, 10% INVESTMENT TAX CREDIT
TAX DEPRECIATION BASIS = $ 3416410.41         10 YEAR LOAN
--------------------------------------------------------------------------------
   YEARLY OPERATING COST BREAK DOWN
   --------------------------------
               **VARIABLE**                                **FIXED**
                          FUEL COST = $ 392.84/HR CREW COST = $ 76800.00
  AIRFRAME MAINTENANCE MATERIAL COST = $  60.39/HR  INSURANCE = $ 35962.21
     AIRFRAME MAINTENANCE LABOR COST = $  61.98/HR
PROPULSION MAINTENANCE MATERIAL COST = $ 102.64/HR
   PROPULSION MAINTENANCE LABOR COST = $  22.37/HR
       YEARLY VARIABLE COST = $ 256088.44     YEARLY FIXED COST = $ 112762.21
--------------------------------------------------------------------------------
```

TAX SAVINGS BREAKDOWN	YEARS 1	2	3	4	5
ANNUAL OPS COST	368851	368851	368851	368851	368851
DEPRECIATION	512462	751610	717446	717446	717446
INTEREST	399833	375945	349028	318696	284518
TOTAL	1281145	1496406	1435324	1404993	1370815
TAX SAVINGS (50%)...	640573	748203	717662	702497	685407

* CASH FLOW *

CASH FLOW OUT(-)	YEARS 1	2	3	4	5
DOWNPAYMENT	179811	- - - -	- - - -	- - - -	- - - -
ANNUAL PAYMENT	588187	588187	588187	588187	588187
ANNUAL OPS COST	368851	368851	368851	368851	368851
REPAY OF LOAN BAL	- - - -	- - - -	- - - -	- - - -	2203497
TAX ON RESALE GAIN....	- - - -	- - - -	- - - -	- - - -	1258678
CASH FLOW IN(+)					
INVSTMT TAX CREDIT ...	359622	- - - -	- - - -	- - - -	- - - -
TAX SAVINGS	640573	748203	717662	702497	685407
RESALE	- - - -	- - - -	- - - -	- - - -	2517355
NET CASH FLOW					
$ OUT (-)	136654	208834	239375	254541	1216449

```
          5 YEAR COST OF OPERATION = $ 2055853.31
BASED ON THE TYPICAL MISSION:
                    ESTIMATED MILES FLOWN
                     IN 5 YEARS           = 530504.0 NM
                    ESTIMATED COST/HR     = $ 1027.93/HR
                    ESTIMATED $/SEAT-NM   =       .484
```

TABLE 34. Advanced Turbofan Corporate Cost Analysis

ADVANCED TURBOFAN

NUMBER OF PASSENGER SEATS = 8   ENGINE SL THERMODYNAMIC THRUST 3067.0 LB
TYPICAL MISSION LENGTH = 400.0 NM   YEARLY UTILIZATION = 400.0 HR
BLOCK TIME FOR MISSION = 1.4900 HR   BLOCK FUEL FOR MISSION = 1625.0 LB

AIRCRAFT FIRST PRICE = $ 3578783.17   PROPULSION SYSTEM PRICE(EA) = $ 464086.05
ASSUMED FINANCING: 12% INTEREST, 95% FINANCED, 10% INVESTMENT TAX CREDIT
TAX DEPRECIATION BASIS = $ 3399844.01   10 YEAR LOAN

YEARLY OPERATING COST BREAK DOWN

VARIABLE		**FIXED**	
FUEL COST	= $ 309.28/HR	CREW COST	= $ 76800.00
AIRFRAME MAINTENANCE MATERIAL COST	= $ 48.12/HR	INSURANCE	= $ 35787.83
AIRFRAME MAINTENANCE LABOR COST	= $ 57.20/HR		
PROPULSION MAINTENANCE MATERIAL COST	= $ 99.80/HR		
PROPULSION MAINTENANCE LABOR COST	= $ 22.36/HR		
YEARLY VARIABLE COST	= $ 214699.01	YEARLY FIXED COST	= $ 112587.83

TAX SAVINGS BREAKDOWN	YEARS 1	2	3	4	5
ANNUAL OPS COST	327287	327287	327287	327287	327287
DEPRECIATION	509977	747966	713967	713967	713967
INTEREST	397894	374122	347335	317151	283138
TOTAL	1235158	1449375	1388589	1358405	1324393
TAX SAVINGS (50%)...	617579	724687	694295	679202	662196

---

* CASH FLOW *	YEARS 1	2	3	4	5
CASH FLOW OUT(-)					
DOWNPAYMENT	178939	- - - -	- - - -	- - - -	- - - -
ANNUAL PAYMENT	585335	585335	585335	585335	585335
ANNUAL OPS COST	327287	327287	327287	327287	327287
REPAY OF LOAN BAL	- - - -	- - - -	- - - -	- - - -	2192812
TAX ON RESALE GAIN....	- - - -	- - - -	- - - -	- - - -	1252574
CASH FLOW IN(+)					
INVSTMT TAX CREDIT ...	357878	- - - -	- - - -	- - - -	- - - -
TAX SAVINGS	617579	724687	694295	679202	662196
RESALE	- - - -	- - - -	- - - -	- - - -	2505148
NET CASH FLOW					
$ OUT (-)	116103	187934	218327	233419	1190663

---

5 YEAR COST OF OPERATION = $ 1946446.26
BASED ON THE TYPICAL MISSION:
ESTIMATED MILES FLOWN
IN 5 YEARS = 536912.8 NM
ESTIMATED COST/HR = $ 973.22/HR
ESTIMATED $/SEAT-NM = .453

TABLE 35. Pusher Propfan Corporate Cost Analysis

```
                              PUSHER PROPFAN
         PROP DIAMETER =  8.000 FT              # OF BLADES =  6
NUMBER OF PASSENGER SEATS = 8  ENGINE SL THERMODYNAMIC SHP = 2714.0 ESHP
TYPICAL MISSION LENGTH =  400.0 NM       YEARLY UTILIZATION =  400.0 HR
BLOCK TIME FOR MISSION =  1.4950 HR  BLOCK FUEL FOR MISSION =  1392.0 LB
--------------------------------------------------------------------------------
  AIRCRAFT FIRST PRICE = $ 4224155.31  PROPULSION SYSTEM PRICE(EA) = $ 624857.09
ASSUMED FINANCING: 12% INTEREST, 95% FINANCED, 10% INVESTMENT TAX CREDIT
TAX DEPRECIATION BASIS = $ 4012947.54        10 YEAR LOAN
--------------------------------------------------------------------------------
   YEARLY OPERATING COST BREAK DOWN
   --------------------------------
             **VARIABLE**                                    **FIXED**
                       FUEL COST = $ 264.04/HR CREW COST = $ 76800.00
  AIRFRAME MAINTENANCE MATERIAL COST = $  52.59/HR  INSURANCE = $ 42241.55
     AIRFRAME MAINTENANCE LABOR COST = $  58.36/HR
PROPULSION MAINTENANCE MATERIAL COST = $ 107.35/HR
   PROPULSION MAINTENANCE LABOR COST = $  33.59/HR
       YEARLY VARIABLE COST = $ 206370.91     YEARLY FIXED COST = $ 119041.55
--------------------------------------------------------------------------------
```

TAX SAVINGS BREAKDOWN	YEARS 1	2	3	4	5
ANNUAL OPS COST	325412	325412	325412	325412	325412
DEPRECIATION	601942	882848	842719	842719	842719
INTEREST	469648	441589	409971	374344	334198
TOTAL	1397002	1649850	1578102	1542475	1502329
TAX SAVINGS (50%)...	698501	824925	789051	771237	751164

* CASH FLOW *

CASH FLOW OUT(-)	YEARS 1	2	3	4	5
DOWNPAYMENT	211208	- - - -	- - - -	- - - -	- - - -
ANNUAL PAYMENT	690890	690890	690890	690890	690890
ANNUAL OPS COST	325412	325412	325412	325412	325412
REPAY OF LOAN BAL	- - - -	- - - -	- - - -	- - - -	2588248
TAX ON RESALE GAIN....	- - - -	- - - -	- - - -	- - - -	1478454
CASH FLOW IN(+)					
INVSTMT TAX CREDIT ...	422416	- - - -	- - - -	- - - -	- - - -
TAX SAVINGS	698501	824925	789051	771237	751164
RESALE	- - - -	- - - -	- - - -	- - - -	2956909
NET CASH FLOW					
$ OUT (-)	106593	191377	227251	245065	1374931

```
          5 YEAR COST OF OPERATION = $ 2145217.00
BASED ON THE TYPICAL MISSION:
                    ESTIMATED MILES FLOWN
                     IN 5 YEARS            = 535117.1 NM
                    ESTIMATED COST/HR      = $ 1072.61/HR
                    ESTIMATED $/SEAT-NM    =       .501
```

TABLE 36. Tractor Propfan Corporate Cost Analysis

TRACTOR PROPFAN

PROP DIAMETER = 8.000 FT # OF BLADES = 6
NUMBER OF PASSENGER SEATS = 8 ENGINE SL THERMODYNAMIC SHP = 2693.0 ESHP
TYPICAL MISSION LENGTH = 400.0 NM YEARLY UTILIZATION = 400.0 HR
BLOCK TIME FOR MISSION = 1.5020 HR BLOCK FUEL FOR MISSION = 1401.0 LB

AIRCRAFT FIRST PRICE = $ 4334135.65 PROPULSION SYSTEM PRICE(EA) = $ 620967.04
ASSUMED FINANCING: 12% INTEREST, 95% FINANCED, 10% INVESTMENT TAX CREDIT
TAX DEPRECIATION BASIS = $ 4117428.87 10 YEAR LOAN

YEARLY OPERATING COST BREAK DOWN

VARIABLE **FIXED**

FUEL COST = $ 264.51/HR CREW COST = $ 76800.00
AIRFRAME MAINTENANCE MATERIAL COST = $ 59.62/HR INSURANCE = $ 43341.36
AIRFRAME MAINTENANCE LABOR COST = $ 60.08/HR
PROPULSION MAINTENANCE MATERIAL COST = $ 106.92/HR
PROPULSION MAINTENANCE LABOR COST = $ 33.60/HR
YEARLY VARIABLE COST = $ 209895.13 YEARLY FIXED COST = $ 120141.36

TAX SAVINGS BREAKDOWN	YEARS 1	2	3	4	5
ANNUAL OPS COST	330036	330036	330036	330036	330036
DEPRECIATION	617614	905834	864660	864660	864660
INTEREST	481875	453086	420645	384090	342899
TOTAL	1429526	1688957	1615342	1578787	1537595
TAX SAVINGS (50%)...	714763	844478	807671	789393	768798

---

* CASH FLOW *	YEARS 1	2	3	4	5
CASH FLOW OUT(-)					
DOWNPAYMENT	216707	- - - -	- - - -	- - - -	- - - -
ANNUAL PAYMENT	708878	708878	708878	708878	708878
ANNUAL OPS COST	330036	330036	330036	330036	330036
REPAY OF LOAN BAL	- - - -	- - - -	- - - -	- - - -	2655636
TAX ON RESALE GAIN....	- - - -	- - - -	- - - -	- - - -	1516947
CASH FLOW IN(+)					
INVSTMT TAX CREDIT ...	433414	- - - -	- - - -	- - - -	- - - -
TAX SAVINGS	714763	844478	807671	789393	768798
RESALE	- - - -	- - - -	- - - -	- - - -	3033895
NET CASH FLOW					
$ OUT (-)	107444	194436	231243	249521	1408805

---

5 YEAR COST OF OPERATION = $ 2191448.94
BASED ON THE TYPICAL MISSION:
ESTIMATED MILES FLOWN IN 5 YEARS = 532623.2 NM
ESTIMATED COST/HR = $ 1095.72/HR
ESTIMATED $/SEAT-NM = .514

A3.0 AIRCRAFT ACQUISITION COST

The formulation for the aircraft selling price consists of three simple elements; an airframe price, a propulsion system price, and an avionics package price. Each element includes the effects of manufacturing costs and overhead. Each is fully burdened and the airframe and propulsion systems include a price margin index. The price margin index is a statistical approach to model such items such as factory profit, liability coverage, typical option pricing, and dealer markup. The pricing method does not incorporate any discounting or pricing strategy factors and does not represent any specific manufacturers method of pricing (including Beech). Rather, because of the difficulty in accurately modeling these effects of market and pricing strategies as well as the amortization of manufacturing costs, this formulation is a statistical, rough order of magnitude (ROM) estimate of the aircraft's initial selling price. Additionally, the pricing method has been tailored for this study utilizing 1984 published price data for the class of business aircraft examined in this study and is not necessarily representative of any other class of aircraft.

The airframe pricing for current day technology represents current 1984 manufacturing processes. The airframe pricing for the 1990 level technology incorporates the higher material and manufacturing costs associated with advanced materials. The airframe price calculation, which incorporated everything except propulsion system and avionics, included all other items such as electrical equipment, environmental systems, hydraulic systems, interiors, tires, brakes, bearings, cables, etc. These have been averaged for typically equipped aircraft and are included in the airframe average price factor; $132/LB for current technology, $158/LB for 1990 technology.

The turboprop and turbofan engine pricing was provided by Pratt and Whitney, Canada. The propfan pricing was provided by Hamilton Standard. The pricing in all cases was related to propulsion system size. Maximum thermodynamic capability at sea level was used as an indicator of size in each case; static thrust for the turbofans, static horsepower for the turboprops. Figure 71 shows the functional relationship of price to thermodynamic capability. The propfan curve, in addition to engine price, also includes the price of the propfan and gear box. The avionics cost selected is representative of a typically equipped business turbofan with a single electronic flight instrument system (EFIS).

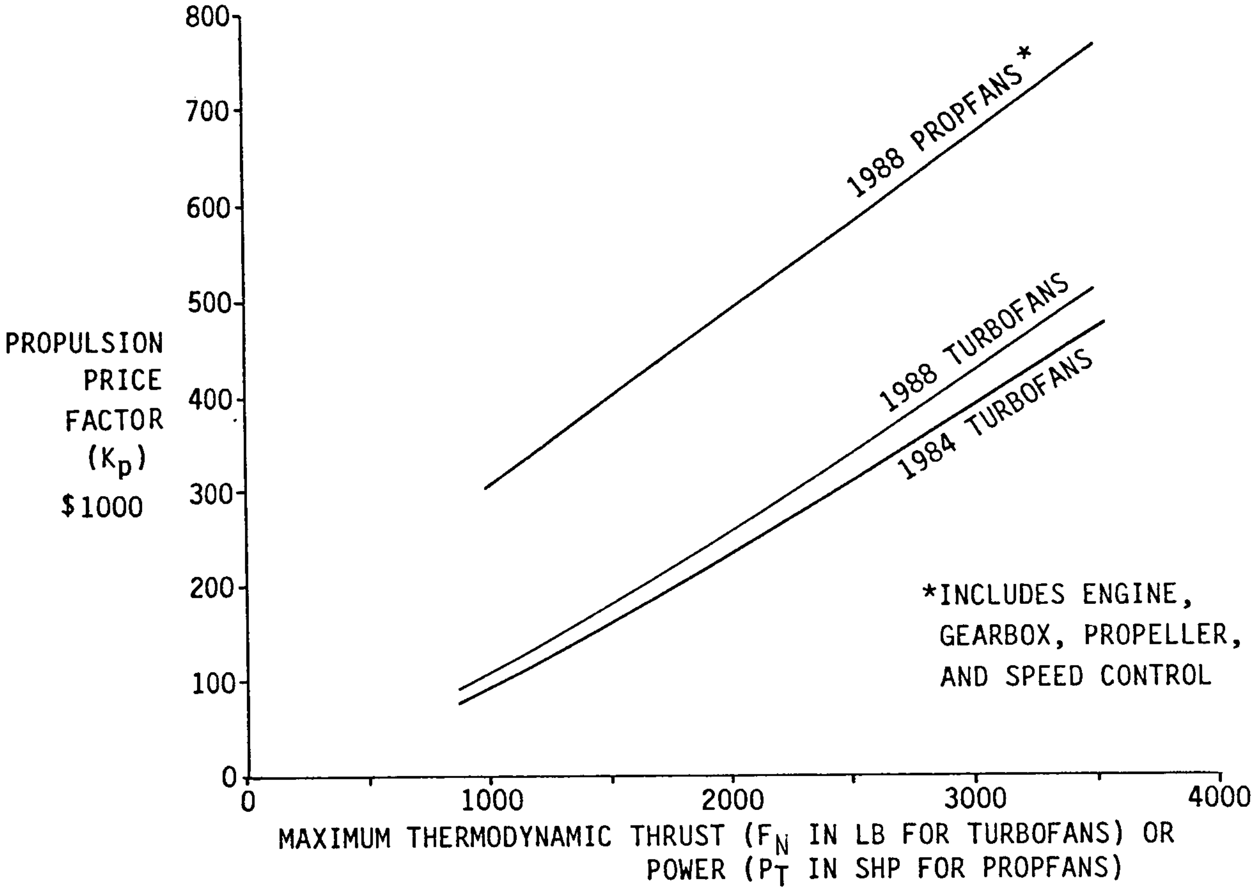

FIGURE 71. **Propulsion System Acquisition Cost Factors**

All pricing is done in 1984 dollars. The pricing formulation is as follows:

AIRCRAFT SELLING PRICE

$$C_t = C_a + C_p + C_{ae}$$

where

C_t = aircraft selling price ($)
C_a = complete airframe price ($)
C_p = total propulsion system price ($)
C_{ae} = price of typical optional avionics and equipment ($)

AIRFRAME PRICE

$$C_a = I_m K_a W_a$$

where

I_m = price margin index = 1.75
W_a = aircraft airframe weight (LB)
K_a = average airframe price factor ($/LB)

for current materials (1984)

K_a = 132

for advanced materials (1990)

K_a = 158

PROPULSION SYSTEM PRICE

for turbofans

$$C_p = I_m K_p F_N N_e$$

where

I_m = price margin index = 1.75
F_N = total maximum thermodynamic sea level static thrust (LB)
K_p = propulsion system price factor (Figure 71) ($)
N_e = number of engines

for propfans

$$C_p = I_m K_p P_t N_e$$

where

I_m = price margin index = 1.75

P_t = total maximum thermodynamic sea level static power (SHP)
K_p = propulsion system price factor (Figure 71) ($)
N_e = number of engines

AVIONICS PRICE

C_{ae} = price of typical optional avionics and equipment ($)
C_{ae} = 520,000

SYMBOLS AND ABBREVIATIONS

ACEE	Aircraft Energy Efficiency Program
AF	blade activity factor
AR	aspect ratio
ATA	Air Transport Association of America
ATP	Advanced Turboprop Program
B	overhead burden factor
BAL	balance
BLK	block
C_a	complete airframe price
C_{ae}	price of typical optional avionics and equipment
C_{al}	airframe maintenance labor cost
C_{am}	airframe maintenance material cost
C_c	crew cost
C_d	cost of depreciation
C_D	drag coefficient
C_f	cost of fuel
CG	center of gravity
C_i	cost of hull insurance
C_L	lift coefficient
C_p	propulsion system price
C_{pl}	engine or engine/propeller maintenance labor cost
C_{pm}	engine or engine/propeller maintenance material cost
c_r	rudder chord
C_t	aircraft initial selling price
c_v	vertical tail chord
D, DIA	diameter
D_a	depreciation period
dB	decibels
dBA	A-weighted decibels
DOC	direct operating cost
E^3	Energy Efficient Engine
ECI	Energy Component Improvement
EFIS	electronic flight instrument system
EPNdB	effective perceived noise level

F, F_b	block fuel
F_N	thermodynamic thrust
FAR	Federal Aviation Regulations
FPM	feet per minute
FPS	feet per second
FS	fuselage station
FT	feet
FWD	forward
GA	General Aviation
GAL	gallon
Grad	gradient
HP	horsepower
HR	hours
HSD	Hamiltion Standard Division
Hz	Hertz
IFR	Federal Aviation Regulation Instrument Flight Rules
I_m	price margin index
IN	inches
INVSTMT	investment
IR	annual insurance rate
ISA	International Standard Atmosphere
K_1	labor manhours per flight hour
K_2	labor manhours per flight cycle
K_3	airframe material hourly factor
K_4	airframe material cyclic factor
K_5	labor manhours per flight hour per engine
K_6	labor manhours per flight cycle per engine
K_7	propulsion system material cost per flight hour
K_8	propulsion system material cost per flight cycle
K_a	average airframe price factor
K_c	crew hourly rate
K_p	propulsion system price factor
KT	knots
KTAS	knots true airspeed
LAP	Large-Scale Advanced Propeller
LB	pound

LBM	pounds mass
LBT	pounds thrust
LR	labor rate
M	Mach
MAINT	maintenance
MAPS	Multiple Application Propfan Studies
MAX	maximum
M_{cr}	cruise Mach number
MIN	minute
NASA	National Aeronautics and Space Administration
N_B	number of blades
NBAA	National Business Aircraft Association
N_c	number of crew
N_e	number of engines
NM	nautical mile
OASPL	overall sound pressure level
OEW	operational empty weight
ops	operations
P&WC	Pratt & Whitney, Canada
P_f	price of fuel
P_t	thermodynamic horsepower
PTA	Propfan Test Assessment
ROM	rough order of magnitude
RPM	revolutions per minute
RQMTS	requirements
S	wing area
SEC	seconds
SFC	specific fuel consumption
SHP	shaft horsepower
SL	sea level
SLS	sea level static
SR	single rotation
STD	standard
T	thrust
t/c	thickness ratio

t_b	block time
t_f	flight time
t_g	ground time
TO	takeoff
TOFL	takeoff field length
TOGW	takeoff gross weight
TSFC	thrust specific fuel consumption
U	annual utilization
UTC	United Technologies Corporation
V_{cr}	cruise speed
VFR	Federal Aviation Regulation Visual Flight Rules
V_{MC}	minimum control airspeed
W_A	actual airflow
W_a	aircraft airframe weight
YR	year
^{o}	degrees
^{o}C	degrees Centigrade
^{o}F	degrees Fahrenheit
"	inches

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16. Abstract

This report presents the results of a study to evaluate propfan propulsion on business aircraft. Comparisons, in terms of cost and performance, were made between propfan propulsion systems and conventional turbofan propulsion systems on a typical business aircraft. In addition, configuration and cost sensitivity studies were conducted to further assess the potential of propfan propulsion.

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