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FINAL REPORT

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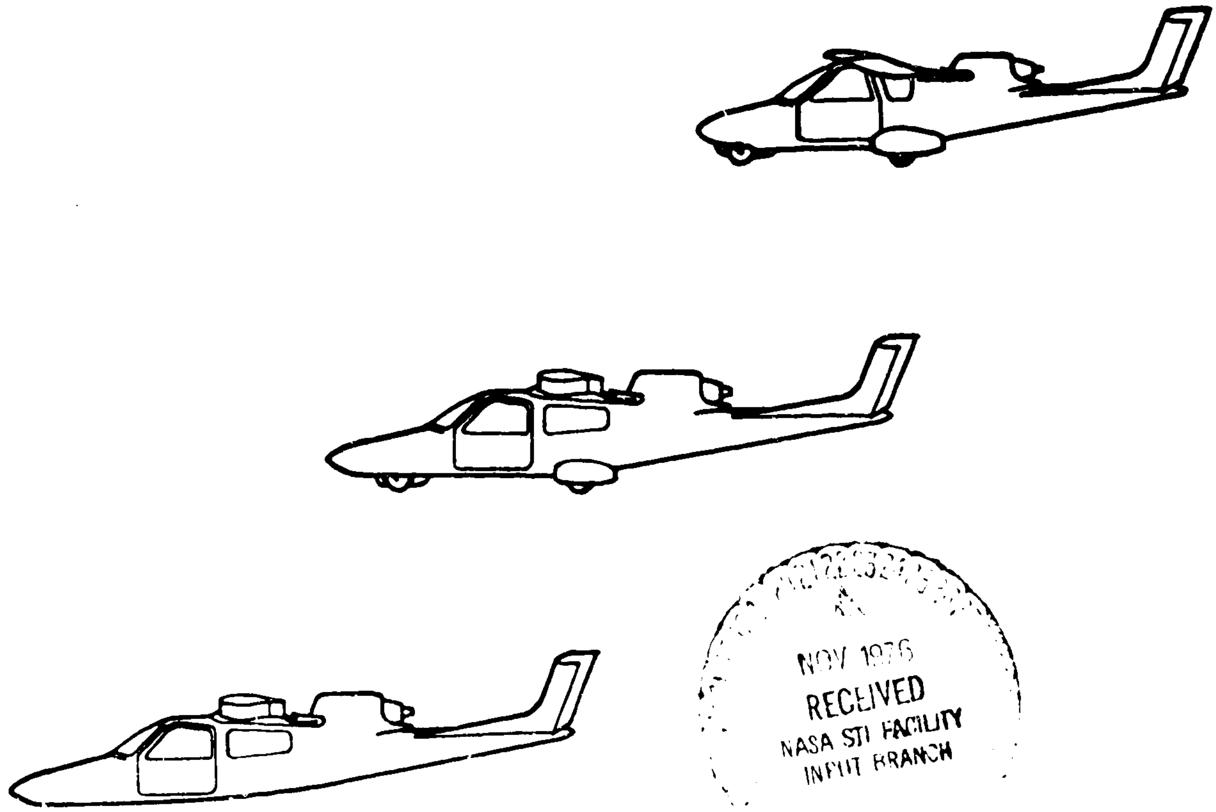

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16. Abstract

The results of a study to investigate the design, efficiency and cost factors attendant to the application of turbofan propulsion engines to single-engine, general-aviation light airplanes are presented. In addition, results of a companion study of a hypothetical engine family of a thrust range suitable to such aircraft and having a high degree of commonality of design features and parts are presented. The results indicate that future turbofan-powered light airplanes can have a lower fuel consumption, lower weight, reduced airframe maintenance requirements and improved engine overhaul periods as compared to current piston-engined powered airplanes. Achievement of compliance with noise and chemical emission regulations is expected without impairing performance, operating cost or safety. It is recommended that evaluation of the turbofan-powered light airplane be continued and that an engine component research and experimental program be undertaken.

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STUDY OF SMALL TURBOFAN ENGINES APPLICABLE TO SINGLE-ENGINE LIGHT AIRPLANES

SUMMARY

This report presents the results of a study sponsored by NASA Ames Research Center, Systems Studies Division, and conducted under Contract NAS2-3582. The purpose of the study was to investigate the design, efficiency, and cost factors which affect the applicability of turbofan engines to single-engine light airplanes.

In recent years, the turbofan engine has been selected for prime propulsion of nearly all new, high-performance airplanes. The light weight, low installed drag and low fuel consumption of modern turbofans contribute significantly to the performance capabilities and cost-effectiveness of the new airplanes. Low noise levels, smoke emissions below the visibility threshold, and the potential for very low exhaust emissions characterize the environmental qualities of high-bypass-ratio turbofans. Research and development of modern turbofans is continually expanded to assure that the most efficient and environmentally compatible propulsion systems will be available to aviation when they are needed.

The general-aviation light-airplane is the only air-transport class remaining that does not enjoy the benefits of turbofan propulsion. Therefore, a series of three studies have been conducted to investigate the applicability of small turbofans to smaller, lower-performance airplanes. In the first study, a six-seat, light twin was the subject of extensive parametric analysis. It was demonstrated that modern optimization analysis, advanced wing technology, and a high-quality turbofan could be combined to yield a very efficient and light airplane having low predicted ownership costs. In the second study, it was shown that military primary trainers could similarly benefit from turbofan propulsion. In turn, the trainer engines would have civil airplane applicability. Thus, if research and development programs were undertaken by the military on engines in this class, it could hasten their availability to general-aviation.

In this, the third study in the series, light singles were chosen for examination. In addition, an engine-family concept was investigated. Together, these study tasks constitute an approach to the solution of the cost problem that has inhibited turbofan propulsion for light airplanes. The three single-engine airplane categories studied comprise the bulk of the light airplane market, and thus, reflect the very large production base

required for economical manufacture of small turbofans. A family of engines, having a high degree of design and parts commonality, can dramatically reduce manufacturing costs.

The study has demonstrated that future turbofan-powered airplanes can be designed to have up to 20 percent lower fuel consumption than current propeller-driven light airplanes. More than 30-percent lower airframe structural weight can result from the use of light-weight turbofans and an advanced wing configuration. Thus, there is also a potential for some reduction of airframe manufacturing costs. Lower operating costs will most likely occur due to 25- to 45-percent lower fuel expenses, greater engine overhaul periods, and reduced airframe maintenance requirements as a result of lower vibration levels.

Turbofans can be developed to meet noise and chemical emissions regulations without impairing performance, operating cost, or safety. Numerous safety-oriented advantages have been identified that are inherent to turbofan propulsion systems. In addition, product enhancement that will result from low cabin noise and vibration levels and simple power management procedures is very desirable.

Investigation of the engine-family concept has shown that a comparatively small ten-engine family, having high commonality, can adequately cover the requirements for light-airplane propulsion. Such a family is projected to have a 1990 market potential of 30,000 units per year. The three engines evaluated in this study would, alone, have a market potential of 20,000 units-per-year.

For turbofan engines to be viable contenders, it must be shown conclusively that they can be both technically and economically responsive to market demands. Therefore, recommendations are made for continued development of the light-airplane turbofan concept. Specifically, the airplanes that were the subject of this study should be evaluated and redefined by the manufacturers of general-aviation aircraft. It is further recommended that an engine component research and experimental program be undertaken. This important step is required for final validation of the concept.

INTRODUCTION

Three studies have been conducted for the application of modern turbofan engines to smaller, lower performance airplanes than those in current manufacture. With completion of the study described in this report, a large amount of data is available for evaluating small turbofan applicability across a broad spectrum of airplane size and performance classes, both civil and military. The studies have stressed the need for timely solution of the propulsion-oriented problems faced by both aircraft manufacturers and operators of the airplane types studied. Originally, emphasis was placed on achieving low levels of noise and airplane operating cost. Later, with the impact of the energy crisis, low fuel consumption was given high priority. Throughout the studies, the consideration of overall propulsion system efficiency and cost-effectiveness of the total aircraft were of primary concern.

In the first study (ref. 1), methods were formulated whereby engine and airplane conceptual baseline designs of high relevance could be defined quickly and economically. For the first time, an aircraft synthesis computer program was used in the definition and evaluation of a light airplane preliminary design. This program, the General Aviation Synthesis Program (GASP) (ref. 2), was developed by NASA to provide a tool for in-depth analysis of the complex interrelationships between propulsion, aerodynamics, structures, performance, mission, and costs. The program permitted extensive parametric sensitivity and trade-off analyses of a six-seat, 648 km/h (350 kt) business-type airplane. Five candidate engine designs that resulted from manufacturing cost reduction studies were evaluated for the study airplane, and a "best" engine that minimized the cost of ownership was identified. Using a comprehensive noise-prediction computer program, a 95 EPNdB 500-foot sideline noise level was calculated for the airplane. This noise level required minimal acoustic attenuation treatment of the engines, and is well below the proposed values of future regulations. It was concluded from the study results that turbofan propulsion could be very responsive to the needs of general aviation in the lower-performance class of business aircraft represented by the study airplane.

Following a review of the study results, it was reasoned that turbofans in this class would be applicable to future military primary trainers. Furthermore, military sponsorship of small turbofan development could hasten their availability to general aviation. Therefore, a follow-on study (ref. 3) was formulated to investigate turbofan-powered primary trainer designs for future military undergraduate pilot training. Again, extensive parametric analyses were performed for four candidate airplane configurations. The airplanes were designed to provide performance that is superior to existing primary trainers in the military fleets, and other conceptual designs that had been reported. Of the several advantages of turbofan propulsion evidenced in this study, the potential savings in fuel were thought to be most important. A reduction in cruise fuel consumption of about 80 percent was predicted for the most efficient of the four trainer designs over the current USAF turbojet-powered primary trainer. In addition, the designs addressed a comprehensive list of mission, performance, configuration, and equipment requirements that would make the new trainer substantially more versatile than the current trainer. Despite these improvements, the gross weight of the smallest of the conceptual designs was about half that of the current trainer.

This trainer size solution confirmed the potential for high commonality between civil and military variants of small turbofans. The turbofan for a single-engine trainer was only negligibly different in thrust level and core size from the civil engine solution in the first study. "Best" cycle quality solutions for each application were essentially the same. For the twin-engine trainer, the engine size was appropriate for use on smaller civil twins or single-engine light airplanes.

Synthesis sensitivity and trade-off analyses were used to optimize the trainer designs, and Cessna Aircraft Company was engaged under subcontract to provide design review and consultation services. With the design credibility thus enhanced, and significant advantages identified for turbofan propulsion, the applicability of small civil turbofans to military airplanes was substantially confirmed.

With the encouraging results of the first two studies in hand, it remained to be shown that turbofan propulsion was technically responsive to the lowest size and performance classes of general aviation airplanes. It was also thought necessary that the gas turbine cost problem be resolved. Therefore, additional studies were conducted of the lowest cost and performance (but highest production) general-aviation single-engine aircraft. If these airplanes could achieve a good balance of performance qualities with operating cost characteristics commensurate with current piston-engine airplanes, the potential for high-production would exist. If this concept were to include engines and airplanes over a broad range of size and performance classes, cost benefits could be identified that may eventually place turbofan costs on a par with piston engine costs. Finally, with the improvements in social qualities and safety-oriented factors, together with readily identifiable product enhancement features, turbofans are indeed attractive candidates for light airplane propulsion.

The study results presented in this report show that, when combined with a high quality wing, turbofan propulsion can yield lighter and more efficient airplanes at overall performance levels comparable to existing piston-powered airplanes. The initial task in the study was first, to quantify the acceptable performance level of each airplane type examined. Recognizing that price and performance are bound together, the best balance is determined by acceptance in the marketplace. The best sellers in each class are those which have achieved the best balance. Therefore, the method employed for selecting performance and utility parameters for the study airplanes was to identify the values that characterize the most popular airplanes in each class.

Conceptual designs were evaluated for three light singles in the classes that experience highest production: a two-seat utility/trainer, a four-seat utility airplane, and a four-seat high performance type. Each design was subjected to parametric analysis to define the interrelationships between propulsion, aerodynamics, structures, performance, and operating cost. The judging criteria for selecting the final design parameters was a combination of performance capabilities, engine size, airframe weight, and cruise fuel consumption.

The final results showed more attractive values than were initially anticipated. For example, the engine needed for the two-seat trainer, which was expected to be in the 1334 to 1779 N (300 to 400 lb) sea level static thrust range, was only 961 N (216 lb) in the best solution airplane. Similarly, empty and gross weights and cruise fuel consumption had lower values for each airplane solution than was expected.

Commonality investigations conducted in the final phase of the study confirmed that a family of engines could be defined that is technically responsive to light airplane power and performance requirements. The concept visualizes an engine line that is derived by successive scaling and uprating of a basic design in increments appropriate to the size and performance levels required by the projected airplanes. The many potential cost benefits that this concept yields were readily identified, but could only be partly quantified within the limited scope of this study.

When the study of light single-engine airplanes and commonality benefits was completed, conclusions and recommendations were drawn from the results of all three studies in the series. The potential utility of modern turbofans was examined across a broad range of power requirements for general aviation airplanes. Throughout the studies, comprehensive synthesis analyses were performed to identify the best design parameter values. These parametrics not only aided the propulsion studies, but illustrated the significant advantages of new wing concepts investigated in other

NASA programs. The investigations also benefited from the encouragement and technical assistance provided by light airplane manufacturers, notably Cessna Aircraft Company.

In concluding that turbofans are technically applicable to general aviation classes where they are not now available, specific recommendations are made for go-forward programs. Necessary investigative, research, and experimental programs are recommended that would identify, develop, and demonstrate the required technology. The intended goal is to extend to future light airplanes, the benefits that have accrued from the near-universal adoption of turbofan propulsion for military, commercial, and high-performance business aircraft.

SYMBOLS

AR	Aspect ratio
BPR	Bypass ratio
Btu	British thermal unit
°C	Degrees Celsius
C_D	Drag coefficient
C_{Di}	Induced drag coefficient
$C_{D\ wet}$	Drag coefficient referenced to the wetted area
C_L	Lift coefficient
$C_{L\ MAX}$	Maximum airplane lift coefficient
c_l	Section lift coefficient
$c_{l\ max}$	Maximum section lift coefficient
c_l/c_d	Section lift-to-drag ratio
c_p	Specific heat of air at constant pressure
CU	Customary units
EPNdB	Effective perceived noise level
e	Oswald efficiency factor
°F	Degrees Fahrenheit
F	Engine thrust, N (lbf)
f/a	Fuel-air ratio
FAR	Federal Aviation Regulations
F_n	Net thrust, N (lbf)
fpm	Feet per minute
ft	Feet
F_{sls}	Sea level static thrust, N (lbf)

SYMBOLS (NTD)

F/W_a	Engine specific thrust per unit airflow, N-s/kg [lbf/(lbm/sec)]
g	Acceleration of gravity
gal	Gallon
hp	Horsepower
hr	Hour
J	Joules and work conversion factor 778
°K	Degrees Kelvin
k	Thousand
kg	Kilogram
km/h	Kilometers per hour
kt	Knot
L	Length
lbf	Pound(s) force
lbm	Pound(s) mass
m	Meter
MAC	Mean Aerodynamic Chord
min	Minute
mm	Millimeter
mpg	Miles per gallon
mph	Miles per hour
N	Newton
N_g	Gas generator rotational speed, rpm
n. mi.	Nautical miles
P	Pressure, lb per sq ft

SYMBOLS (CONTD)

PR	Pressure ratio
psf	Pounds per square foot
psi	Pounds per square inch
q	Dynamic pressure
°R	Degrees Rankine
R	Reynolds number
S	Wing area, sq m (sq ft)
sm	Statute mile
sls	Sea level static
sec	Second
S_{wet}	Wetted area, sq m (sq ft)
T	Temperature, °K (°F or °R)
TIT	Turbine Inlet Temperature
TAS	True airspeed, knots
TSFC	Thrust specific fuel consumption, kg/N-hr [(lbm/hr)/lbf)]
ΔT	Temperature change
U	Rotational velocity, m/sec, (fps)
V_a	Axial velocity
V_s	Airplane stall speed, km/h (mph)
W	Weight, kg (lbm)
W	Watt
W/S	Wing loading, kg/m^2 (lbm/ft^2)
η	Efficiency (actual work/ideal work)
η_p	Propulsive efficiency

SYMBOLS (CONTD)

λ	Turbine work factor $(gJc_p\Delta T/U^2)$
Φ	Flow coefficient (V_a/U)
Ψ	Compressor work coefficient $(gJc_p\Delta T/U^2)$

ACRONYMS

ADF	Automatic Direction Finder
GASP	General Aviation Synthesis (Computer) Program
IFR	Instrument Flight Rules
ISA	International Standard Atmosphere
NAVCOM	Navigation and Communication Radio
SI	Systeme Internationale d' Unites
VFR	Visual Flight Rules

PHASE I - PRELIMINARY EVALUATION OF CIVIL LIGHT AIRPLANES

It was demonstrated in the work conducted under NASA Contract NAS2-6799 that small turbofan engines can provide efficient and cost-effective propulsion for both high performance civil light twins and military primary trainers. It was found for these classes of airplanes that mission-optimized turbofan engines, with relatively high cost, will pay for themselves in terms of life-cycle costs because of their low weight, low installed drag, and low fuel consumption. The purpose of this study was to determine if this trend exists for smaller and slower single turbofan-powered airplanes. Two- and four-seat airplanes in trainer, utility, and high-performance classes were selected for study. The general characteristics specified at the beginning of the program for the study airplanes are given in Table 1. However, more specific guidelines were developed early in the program by reviewing the performance capabilities of the popular light singles in current production.

Design-point performance goals for the three study airplanes were derived in the following manner. Pertinent performance data was plotted from a source (ref. 4) that annually publishes reliable data on size, power, price, and performance characteristics for current production airplanes. The parameters chosen for these plots yielded information that permitted the selection of performance design points that would be responsive to market demands. Data that is applicable to the selection of design cruise speed is illustrated in Figure 1. In the plot of cruise speed versus number of seats, the lower speed points characteristically represent low-priced, fixed landing gear, utility airplanes. The higher speed points are of airplanes with retractable gear, high power, turbochargers, and inevitably, higher price tags. As shown, the speeds selected for the study airplanes are representative of speeds in their intended classes: two-seat trainer, 201 km/h (125 mph); four-seat utility, 241 km/h (150 mph); four-seat high-performance, 322 km/h (200 mph).

In the plot of speed versus range for light airplanes shown in Figure 2, both maximum fuel range and maximum cabin-load range were plotted for each airplane. A high degree of range/payload tradeoff is typical of light airplane designs. Some of the airplanes plotted spanned the full width of the envelope, with full cabins and reduced fuel loads at the left of the envelope, and full fuel and reduced cabin loads at the right. The range chosen for each study airplane represents the design-payload range, and it was assumed that sufficient fuel capacity would be available to provide maximum-fuel ranges comparable to those of current airplanes in each class.

TABLE 1. GENERAL CHARACTERISTICS ESTABLISHED FOR SINGLE ENGINE STUDY AIRPLANES

	Two-Seat Trainer	Four-Seat Utility	Four-Seat High Performance
Payload/crew, kg (lb)	181 (400)	363 (800)	363 (800)
Endurance at cruise, hrs	4	4	4
Cruise speed, km/h (mph)	161-241 (100-150)	209-290 (130-180)	362-483 (225-300)
Altitude, m (ft)	<3048 (10,000)	<3048 (10,000)	4572-7315 (15,000-24,000)
Field length, m (ft)	610 (2000)	610 (2000)	762 (2500)
Climb requirements, m/min (fpm)	229 (750)	229 (750)	--

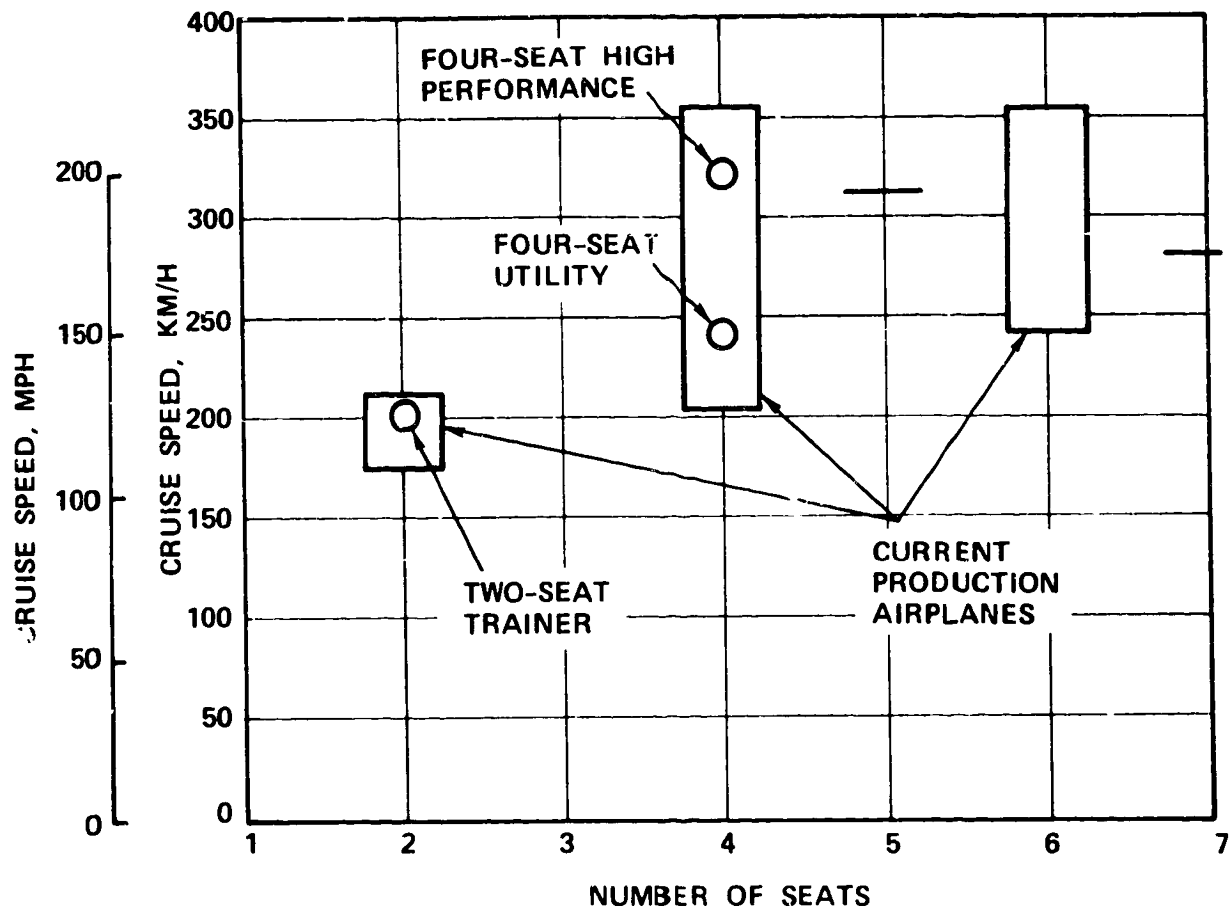


Figure 1. - Cruise speed versus seating capacity of single-engine light airplanes selected for study.

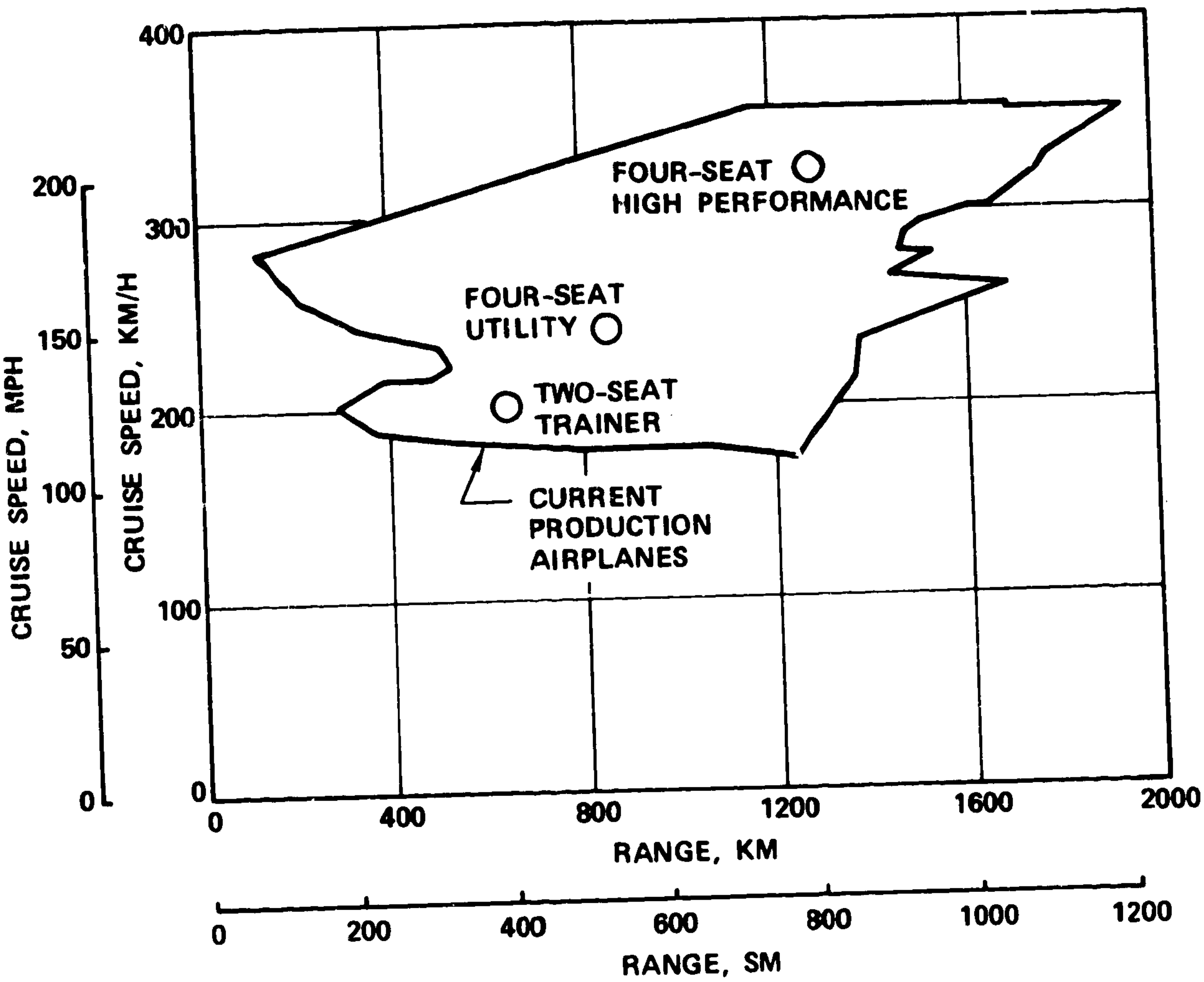


Figure 2. - Cruise speed versus range of single-engine light airplanes selected for study.

Preliminary analysis indicated that airfield performance would have a fundamental effect on several basic engine and airplane design considerations, as well as on factors affecting airplane size and cost. The analysis showed that at reasonable takeoff distance, wing loading, and wing aspect ratio, the engine would be sized by the takeoff power required. Furthermore, it would be essential to define a best balance of the design factors; otherwise, high cruise fuel consumption could be expected. Currently produced light singles have minimum field length requirements from about 427 m (1400 ft) to about 671 m (2000 ft) for takeoff over a 15 m (50 ft) obstacle. The landing distance is usually shorter. Based on these considerations, the initial field length requirement of 610 m (2000 ft) was considered reasonable for all three study airplanes. Sensitivities to field length was then examined in the study.

Similar considerations attended the selection of initial rate-of-climb criteria. At low wing loadings and greater takeoff distances, engines could be sized by high rate-of-climb requirements, with consequences similar to those found in the study of airfield requirements. Typical rate-of-climb values are between 183 and 366 m/min (600 and 1200 ft/min) for light singles and appear to be strictly fallout values that resulted from other performance requirements. Again, it was determined that the study airplanes should exhibit rate-of-climb performance similar to the current airplanes in their respective classes.

Finally, it is useful to identify power and price classes for which the study airplanes were intended. When these two important parameters are plotted, current light singles fall in the envelope illustrated in Figure 3. While the prices designated for the study airplanes are viable, the location on the power axis of the figure is academic; they only imply the performance levels conferred on the airplanes by the thrust-rated turbofan engines.

The final performance and design criteria established for the three study airplanes are listed in Table 2. It should be pointed out that these values are not goals. In the study, they are treated as requirements with attractive values of solution airplane sizes and predicted costs being the actual goals.

Baseline Two-Seat Utility/Trainer Airplane

In the past, two-seat airplanes were popularly associated with sport flying or low-cost VFR touring. They were rarely considered as appropriate business transportation, and their significance as tools for flight instruction was more or less incidental in their initial design and early development. These concepts of what a two-seat airplane is or can be are now being revised. Most two-seaters, and many four-seaters are being sold to flying

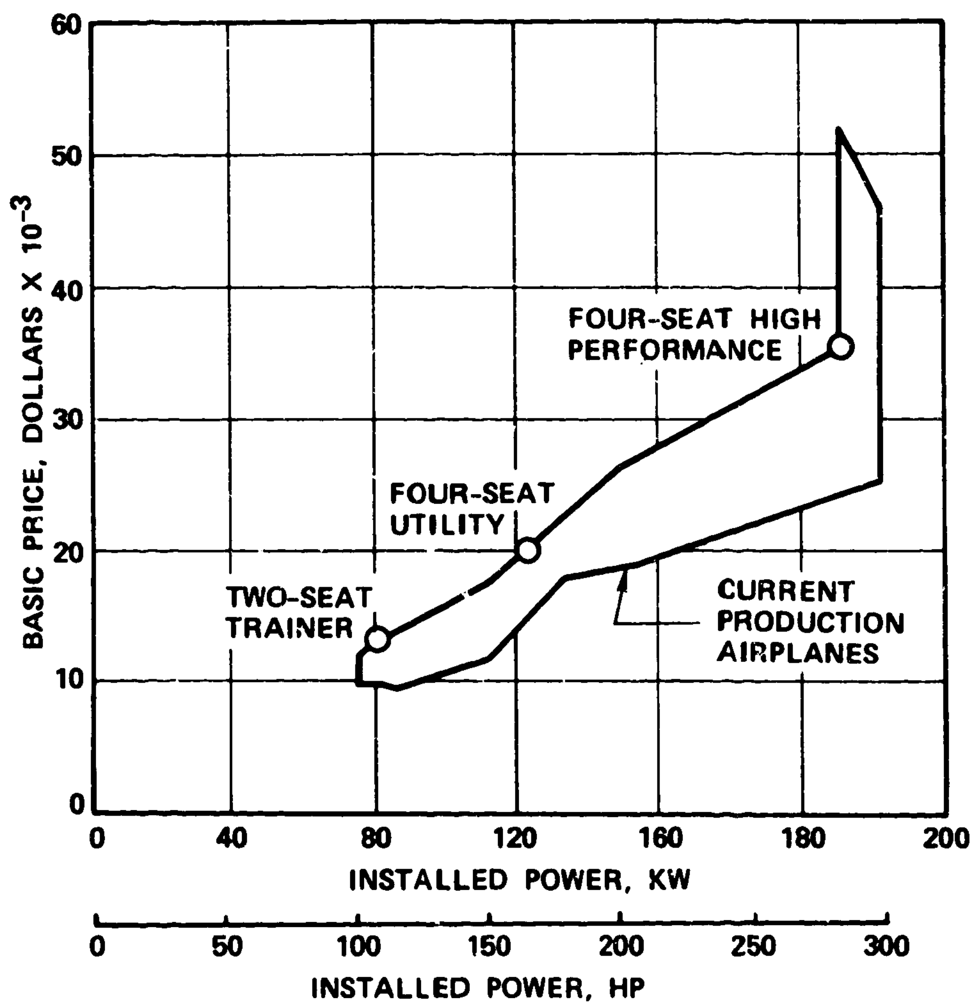


Figure 3. - Basic price versus installed power for single-engine light airplanes selected for study.

TABLE 2. FINAL PERFORMANCE AND DESIGN CRITERIA ESTABLISHED FOR STUDY AIRPLANES

	Two-Seat Trainer	Four-Seat Utility	Four-Seat High Performance
Design payload, kg (lb)	181 (400)	272 (600)	272 (600)
Maximum payload, kg (lb)	181 (400)	363 (800)	363 (800)
Design cruise speed, km/h (mph)	201 (125)	241 (150)	322 (200)
Design cruise altitude, m (ft)	2286 (7500)	3048 (10,000)	3048 (10,000)
Design range, km (sm)	643 (400)	885 (550)	1287 (800)
Takeoff distance to 15 m (50 ft), m (ft)	<610 (<2000)	610 (2000)	610 (2000)
Sea level rate of climb, m/min (fpm)	>204 (>670)	>256 (>840)	>335 (>1100)

schools, where they are flown as many as 1200 demanding hours per year. Many are now purchased by businessmen who recognize the time-value factor and actual fuel savings (versus automobiles) on business trips of a few hundred miles. Few airplanes are purchased primarily for sport flying. In recognition of these marketing factors, the study airplanes were addressed to utilitarian roles where the advantages of turbofan propulsion weigh heavily.

In view of its use, the modern airplane should be rugged, easily serviced and maintained, and capable of carrying an adequate complement of IFR instrumentation and avionics without impairing range and payload. Configuration aspects such as cabin size and visibility should enhance function and utility rather than style. The engine should have minimal servicing requirements and the potential for high overhaul time, or should utilize "on-condition" maintenance to minimize the engine-reserves operating cost increment. Engine size and resultant airplane performance should be restrained to just adequate values, recognizing that fuel consumption will be a large cost factor in high-utilization-rate operations. These considerations influenced the initial definition work in the following ways. Care was taken in airframe structural weight calibrations to assure that weight was available for appropriately "ruggedized" components. A "standard" equipment weight was specified that included dual controls, and basic IFR equipment such as full instrumentation, gyros, transponder and nav-com radio. A 114 cm (45 in.) width side-by-side cabin was stipulated for ample elbow room as well as for handling and stowing charts and manuals. A design range was specified so that with a full cabin and adequate equipment, meaningful IFR cross-country training could be done. A modest engine cycle was chosen to permit conservative long-life mechanical design without significantly penalizing weight. Reasonable takeoff and climb performance targets were established to minimize engine size and fuel consumption.

Airplane configuration and synthesis modeling. - The General Aviation Synthesis Program (GASP) was an invaluable tool throughout the turbofan study. The function of GASP is to synthesize a "solution" airplane that incorporates all design data inputs and satisfies all performance and mission stipulations. It permits the synergistic or compounding effects of a large number of variables to be examined, thus making sensitivity and tradeoff analyses economical. In turn, it makes identification of "best" design parameters possible. The program was designed to be both comprehensive and flexible, with provisions for extensive modeling and "calibration" inputs. Although the program can synthesize a solution airplane from a very sketchy model, the better defined the model is, the better the designer's intent is reflected in the solution. In the case of the two-seat trainer, particular qualities were sought that required a well defined model and care in selection of program inputs. Thus, in several cases, use of built-in program values based on generalized correlation data was avoided while values reflecting more specific design criteria were adopted.

In modeling the two-seat design, many detailed configuration-oriented evaluations were performed. These included layouts, sketches and calculations. The basic configuration evolved from this work; e.g., the single-engine, high-wing, monoplane with a "V" tail. This configuration was selected in order to place the engine at a best location on the airplane. To maximize installed efficiency and performance, the engine should be located above and midway along the fuselage tail cone with the inlet occurring approximately in the plane of the wing trailing edge. This will permit the exhaust to pass between the "V" tail members. Because the engine thrust axis is above the airplane center of pressure, the pitching moment trim drag and trim change with power level is minimized by a high wing configuration. This yields a center of pressure nearest the high thrust axis. In the case of a fixed landing gear configuration, with the high drag component occurring low on the airplane, the high wing location is considered essential. Two additional considerations attend this choice. They are visibility and center of gravity shift with cabin load variation. Trainers that spend significant portions of their flight time in VFR airport traffic patterns must have good visibility.

In typical two-seaters, with the wing leading edge forward of the pilot's eyes, both low and high wing locations compromize visibility; high wings in in-bound pattern turns, and low wings on straight and level pattern legs. The forward wing location is necessitated by the center of gravity shift that occurs when the wing center of lift is substantially offset from the center of gravity of the cabin occupants. The criterion selected for the study airplane was that the aft center of gravity shift be no greater than 10 percent of MAC when occupant load is reduced from 136 kg (300 lb) to 45 kg (100 lb). This would eliminate the need for a nose-down trim change when a heavy instructor turned an airplane over to a light student for a solo flight. It is accomplished by limiting the offset between occupant cg and the 25 percent of MAC point to 25.4 cm (10 in.). The configuration that best meets all requirements is a forward-swept wing, with an eye-level vertical location, where only wing thickness subtends visibility, and the thickness may be made to "disappear" by raising or lowering eye level. With fixed eye position, the wing root thickness was calculated to subtend a visual arc of about 15 degrees, and the tip thickness less than 2 degrees. A desirable feature of the forward-swept wing is that the wing spar can pass through the cabin well aft of the occupants, which would permit the reduction of customary fuselage depth and frontal area. Several recently designed aircraft incorporate an eye-level, forward-swept wing configuration. These include the Bell XV-15, Saab MFI-15, the Flugzeugbau AWI-2 Fantrainer, and a number of high performance sailplanes.

A 10 aspect ratio constant chord wing was selected for the baseline model, using the NASA GA(W)-1 section described in References 5 and 6. This section has a 17-percent thickness/chord ratio, a large leading edge "radius", and high camber in the leading edge region that contributes to the section's high c_{lmax} property. A desirable performance feature of this section is its high c_l/c_d, or lift/drag ratio, in the $c_l = 1.0$ region of the polar. While single-engine climb performance of a twin-engine airplane can be greatly improved with this section, it can also be beneficial to a single turbofan engine airplane by significantly reducing engine size for a specified climb performance capability.

It was confirmed in initial synthesis analysis that, with the engine sized for adequate takeoff and climb performance, a substantially reduced power setting was required for 201 km/h (125 mph) cruise, resulting in a high value of specific fuel consumption. Thus, the smallest possible engine size for takeoff and climb would result in a higher cruise power setting and lower fuel consumption.

Consistent with the earlier studies, full span Fowler flaps were chosen for the model. This requires that spoilers be used for roll control. Since this combination has not been used on light aircraft together with the GA(W)-1 section, it is the subject of analytical and flight research programs conducted by NASA. The higher C_{Lmax} afforded by this wing formula permits a large reduction in wing area for a desired stalling speed. This in turn permits optimization of wing loading for maximum cruise efficiency. As demonstrated in previous turbofan studies, the synergistic effects of this optimization results in remarkably reduced values of solution airplane size and fuel consumption.

In the initial configuration analysis, it was found that the conventional 6.00 X 6 landing gear wheel would create excessive drag. With fixed landing gear, it would account for more than 25 percent of the total airplane cruise drag. In order to reduce frontal area without appreciably reducing the rolling radius, the 15.24 cm (6 in.) rim diameter can be retained, and the width reduced to 11.18 cm (4.4 in.). The lighter gross weight anticipated for the turbofan airplane would then result in footprint pressure equal to current airplanes of similar capability. In addition, nose gear drag can be substantially reduced by partially recessing the nose gear in the fuselage. This can easily be accomplished on a turbofan airplane since there is no need to maintain propeller-to-ground clearance. Lighter gear, better ground handling, and stepless cabin access are additional benefits provided by the reduced height. To reduce drag further, it was assumed that both the nose and main wheels were closely faired with a damage resistant material such as the high-impact polypropylene plastic currently used in motorcycle fenders and automobile wheel wells. The combined effect of these drag reduction efforts was to reduce gear drag to about 10 percent of the total profile drag of the airplane.

One further drag reduction stipulation was made that would provide a small but useful advantage. It is generally conceded that normal light aircraft design and manufacturing practice precludes the attainment of laminar flow over airfoil surfaces. Although the GA(W)-1 section was not intentionally designed for it, test data indicates that at low Reynolds number a large amount of laminar flow did exist on the smooth test section. In fact, test data taken at $R \approx 2 \times 10^6$ showed that at the design lift coefficient, the drag coefficient for the smooth (natural boundary layer transition) section test was about half that obtained with an artificial roughness strip applied at eight percent of the chord. By coincidence, the study airplane's wing Reynolds number is 2 million at the design cruise point, with a 67 cm (2.2 ft) chord. This potential for useful drag reduction should not be ignored. Furthermore, in the absence of turbulent propeller wake, the tail surfaces and portions of the fuselage could have some laminar flow if the surfaces were smooth. It was determined that a modest drag reduction increment of about 15 percent could be given to the study airplane if it were assumed that relatively smooth construction was possible. Anticipating that the solution airplane would have a wing chord of about 61 cm (2 ft) and tail surface chords even less, it can be assumed that relatively thick aluminum skins can be employed without a great weight penalty. With closely spaced, adhesive bonded rib construction, the use of spanwise stiffeners and rivets can be avoided. Thus, a smooth wave-free surface should be possible from the leading edge to the main spar. References 7 and 8 contain descriptions of the methods employed and results obtained with this configuration in one light airplane design. Photographs in these references show the prototype to have wave-free mirror-like surfaces.

Aside from the relatively novel construction employed to assure comparatively smooth skins, no further deviations from conventional light aircraft practice were assumed. GASP weight calibrations were taken from a typical, high production, two-seat light airplane. A normal turbofan installation weight factor was used, with no airframe structural weight advantage assumed for decreased torque and vibration. The wing weight calibration was checked with use of several preliminary wing weight formulas to assure accuracy. This included the effect of 10 degrees of forward sweep. As described previously, a dual control, IFR "standard" equipment weight was selected, and a pilot, passenger, and baggage weight of 181 kg (400 lb) was specified. With this initial definition of the two-seat trainer model completed, the turbofan engine performance model was prepared.

<u>Baseline engine definition and performance analysis</u>. - The definition of a "best" or most responsive modern aircraft propulsion system has become an extremely technical, highly competitive, expensive, time-consuming task. This description applies, of course, to the definition of both military and commercial transport engines. For these applications, the interrelationships between the propulsion system and the aircraft are determined through extensive analyses as the synergistic and compounding effects of the propulsion system become known. In nearly all military and commercial applications, the modern turbofan engine in an appropriate design and cycle has been found to have the highest overall propulsion system efficiency, and the greatest cost-effectiveness.

In the initial phase of these general aviation turbofan studies, work was done to show why this superiority has come about. The elements of overall propulsion system efficiency were identified, and methods were developed that permitted the elements to be quantified. It was shown that by properly selecting fan and core jet pressure ratios, a maximum net propulsive efficiency may be obtained for any flight speed. It was also shown that relatively modest gas turbine cycles can provide net thermal efficiencies equal to those of light airplane piston engines. It was ascertained that gas turbines do not suffer the drag penalties attendant to cooling piston engines. Although the aircraft gas turbine was described as the smallest and lightest heat engine, proof of the effects of this attribute was left to aircraft synthesis analysis. Additional analysis has shown that, although the propulsion system weight of a typical piston-powered light airplane constitutes only about one-fifth of the airplane gross weight, through synergistic effects about one-third of the total airplane drag can be charged to lifting and propelling the propulsion system "weight". With an equivalent-power, lightweight turbofan, this penalty falls to less than 10 percent of total air-plane drag.

The foregoing brief perspective is given to ensure that the principles employed in defining the baseline two-seat trainer engine are understood. From this, it should be apparent that high technology in the normal gas turbine context is not necessarily required to assure a superior propulsion system for light airplanes. For example, a high, state-of-the-art turbine inlet temperature, that would shrink the core engine, would yield little additional benefit when the core will weigh only about 11.3 kg (25 lb), with a modest temperature. Similarly, a high cycle pressure ratio would yield little additional benefit, when this 201 km/h (125 mph) airplane would achieve nearly 8502 km/m^3 (20 mpg) with a low pressure ratio. Every engine design parameter was considered in this context when formulating the baseline. Initial cost, overhaul life, maintainability, and reliability were additional factors given qualitative consideration in defining the baseline cycle.

The initial design point cycle selected for the baseline engine is listed in Table 3. Of the parameters listed, selection of a best fan pressure ratio is perhaps most important, although it is most difficult to prove why it is best. With respect to the engine itself, the fan has the following significance. If the engine had no fan at all (i.e., if the engine were a turbojet having the same thrust level), it would be lightest, least costly and have the least installed drag. But of course, propulsive efficiency at 201 km/h (125 mph) would be so low that cruise fuel consumption would be unsatisfactory. When a fan is added, the lower the fan pressure ratio the higher the bypass ratio becomes, resulting in greater weight, cost, and installed drag. However, propulsive efficiency improves, which reduces fuel consumption. Obviously, a best fan pressure ratio is a compromise between these extremes. A pressure ratio of 1.15 was chosen in deference to engine weight, cost, and drag as the highest value that would yield a satisfactory cruise fuel consumption. It must be pointed out that the resultant propulsive efficiency is only about 50 percent. It should also be noted that this value differs very little from the "net" propulsive efficiency of a light airplane propeller.

Propeller efficiency is not propulsive efficiency, nor is propulsive efficiency, as applicable to airplane performance analysis, defined by the momentum derived equation, $\eta_p = \frac{V}{V + \Delta V}$. The only propulsive efficiency that is meaningful in performance analysis is that given by dividing the net work supplied to the airplane in flight by the work supplied to the propulsor, whether propeller, jet nozzle, or both. In the case of turbojets, net propulsive efficiency is easily calculated, whereas for propellers it is nearly impossible.

The efflux from a propeller is not the homogeneous stream tube visualized in momentum or actuator disk theory of propeller action. As blade-element and vortex theories clearly show, the wake consists of flow having high pressure and velocity gradients, accompanied by swirl and vorticity. The non-uniformities existing in propeller-wake flow are described by theoretical analyses and photographic illustrations in a recent paper discussing contemporary propeller theory (Ref. 9). These non-uniformities give propellers their characteristic beat and snarl noise signatures. A large part of a single engine light airplane "flys" in this pulsing, swirling, turbulent wake, which increases not only profile drag, but induced drag as well. The mass average "q" increase implied by the thrust generated is comparatively small. The swirl

TABLE 3. DESIGN POINT CYCLE SELECTED FOR BASELINE TWO-SEAT TRAINER ENGINE

At design point: 201 km/h - 2286 m (125 mph - 7500 ft)	
Initial size 400N (90 lb thrust at 90-percent power setting)	
Fan pressure ratio	1.15
Core pressure ratio	4.00
Cruise turbine inlet temperature	815.6°C (1500°F)
Takeoff turbine inlet temperature	954.4°C (1750°F)
Bypass ratio	Optimum for minimum TSFC (approx.. 10)

and vorticity effects generate adverse flow circulations and sepa-
rations. Those separations occuring in the area of wing roots cause adverse lift and drag increments due to span loading changes outside the wake, thereby decreasing the airplane (or Oswald) efficiency factor "e", and increasing induced drag. In addition, propeller normal forces that develop when the propeller is operating at an effective angle of attack produce a drag force component. If the propeller is driven by a piston engine, the power required and drag incurred to cool the engine must also be accounted for. In order to have a useful value of propeller or propulsive efficiency, these effects must be acknowledged and subtracted from the apparent propeller efficiency, yielding a "net" propulsive efficiency. First, of course, the effects must be quantified. The work of August Raspet, who quantified the resultant total effects on one representative light airplane, was cited in the initial general aviation turbofan study report. The losses accounted for were shown to debase propeller efficiency from over 80 percent to approximately 50 percent.

In a properly executed turbofan installation, the wake effects that penalize a propeller do not exist. The only analogous losses are the inlet and exhaust duct internal pressure losses, which are fully accounted for in engine performance analysis and are reflected in specific thrust and specific fuel consumption values. Thus, while the fan pressure ratio chosen for the baseline engine results in substantial loss of jet kinetic energy and lower than attainable propulsive efficiency, the penalty is not extraordinary when the comparison is made with "net" propeller efficiency.

The baseline engine aerodynamic component design and efficiency assessments were iterated a number of times with design point cycle analysis and initial airplane thrust requirements. At a design point cruise thrust requirement of only 356 to 400 N (80 to 90 lb), the engine components are comparatively small, and the component efficiencies are very size-sensitive over small ranges of corrected flow. The design point cycle analyses were in the form of parametrics, wherein the effects of design parameter variations on component sizes and engine performance specifics were evaluated. The design point was taken as the airplane design cruise condition, 201 km/h (125 mph) at 2286 m (7500 ft) altitude. A design point thrust of 400 N (90 lb) at 90 percent power level was chosen. Taken from parametric analysis results, Figure 4 shows the effects of bypass ratio and turbine inlet temperature on engine specific thrust and specific fuel consumption. With the fan pressure ratio constant at 1.15, the bottom or zero slope points on the TSFC curves are considered optimum bypass ratios at each turbine inlet temperature. By projecting these minimum TSFC points, it can be seen that specific thrust is nearly constant. It follows then that specific thrust of an optimized engine is a function of fan pressure ratio, not turbine inlet temperature. The effect of fan pressure ratio on TSFC and optimum bypass ratio

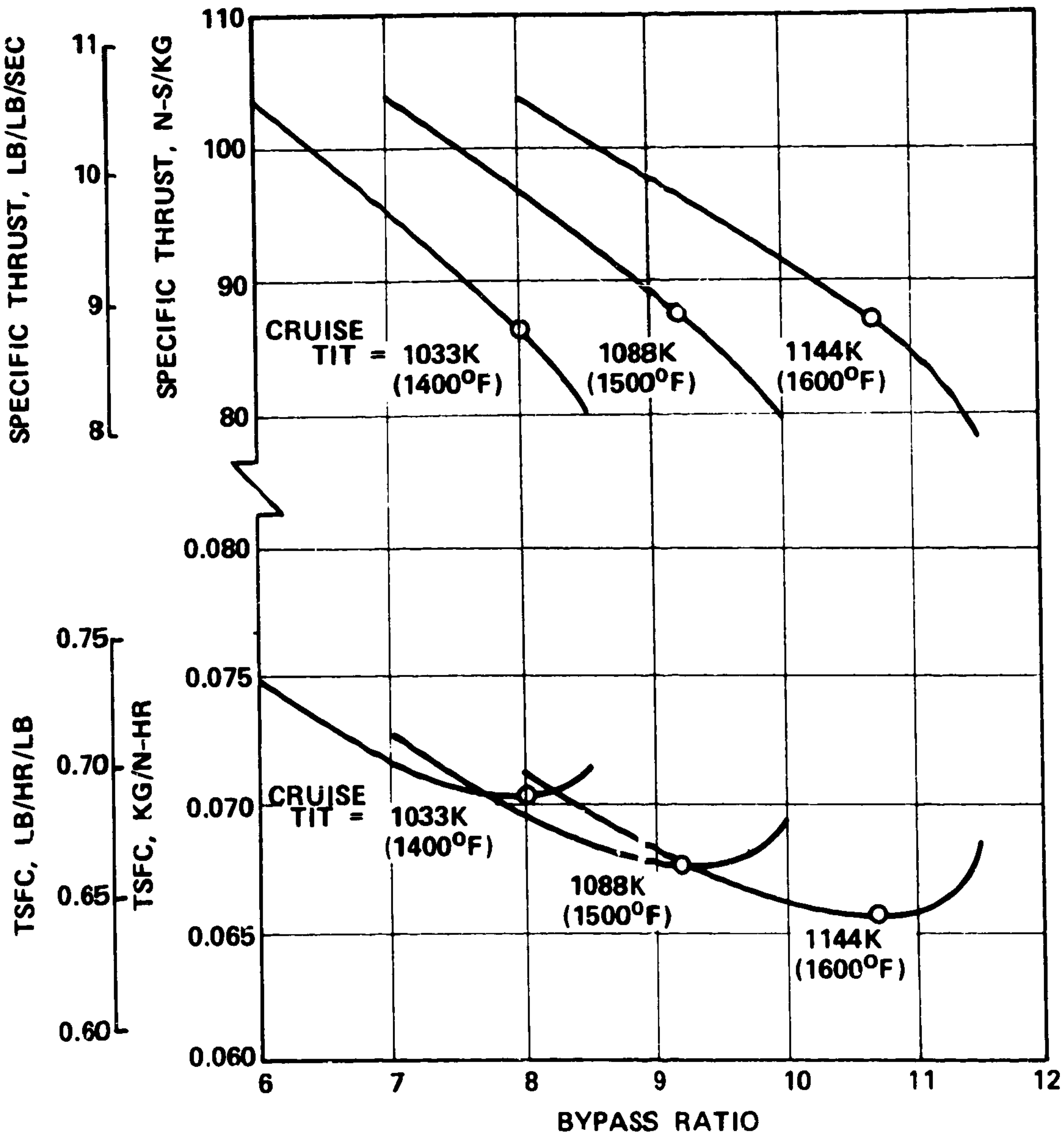


Figure 4. - TSFC and specific thrust versus turbine inlet temperature and bypass ratio at a fan pressure ratio of 1.15.

at the zero-slope point with turbine inlet temperature constant at 815.6°C (1500°F) is shown in Figure 5. Also illustrated in this figure is the comparatively small improvement in TSFC that results from improved propulsive efficiency as fan pressure ratio is reduced. The 2.5 percent improvement offered by reducing the baseline design to 1.10 pressure ratio would drive the optimum bypass ratio from 9.5 to about 14, and would result in a larger, heavier engine. The greatest effect, however, would be on engine complexity and cost. At 14 bypass ratio, the number of fan-driving turbine stages would be doubled, or a reduction gear system would be required between the fan and its turbine. Figure 6 shows that the lower fan pressure ratio would have little effect on core corrected airflow and its physical size, but the fan would be about 20 percent larger due to the 30 percent reduction in specific thrust. It has been shown in the previous small turbofan study reports that the principle effect of turbine inlet temperature on a turbofan cycle is to "size" the core. (Ref. 1 and 3). Figure 7 again illustrates this effect. With fan pressure ratio constant at 1.15, the core inlet corrected airflow is shown to vary significantly with turbine inlet temperature. The zero slope points on these curves are nearly coincident in bypass ratio with minimum TSFC points and therefore, represent the best energy split between the fan and core jets.

With component efficiencies sensitive to size, several analyses were performed to evaluate efficiency effects on performance and matching. Figure 8 shows various effects of core compressor efficiency. For maximum benefit from two points of efficiency improvement, the best match point occurs at higher bypass ratio. In this case, specific thrust would remain constant and the core would be smaller.

Following parametric cycle analysis, initial airplane drag analyses were completed. It was determined that the engine would be sized by the requirements of takeoff distance and rate-of-climb. The solution engine size was expected to be between 890 and 1112 N (200 and 250 lb) thrust at sea-level static conditions. This, together with design point cycle analysis, permitted a finalization of component preliminary designs, efficiency and loss assessments, and the preparation of the off-design performance model.

The component designs selected for the baseline engine are entirely state-of-the-art with respect to configurations, loading criteria, and estimated efficiencies. The small size, in terms of corrected airflow, is the most notable characteristic of each component. Each component was tailored to achieve a best balance of spool efficiency and attendant cost-driving factors.

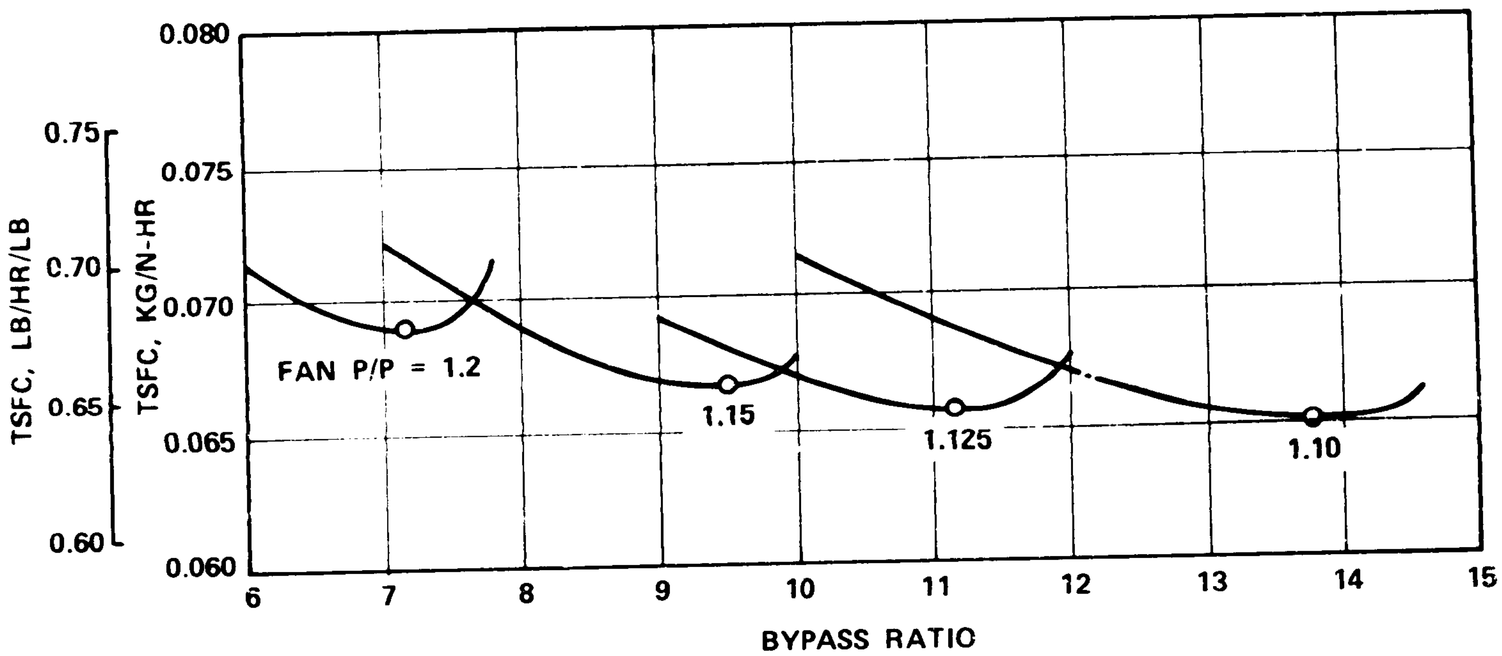


Figure 5. - TSFC versus fan pressure ratio and bypass ratio at a cruise turbine inlet temperature of 1500°F.

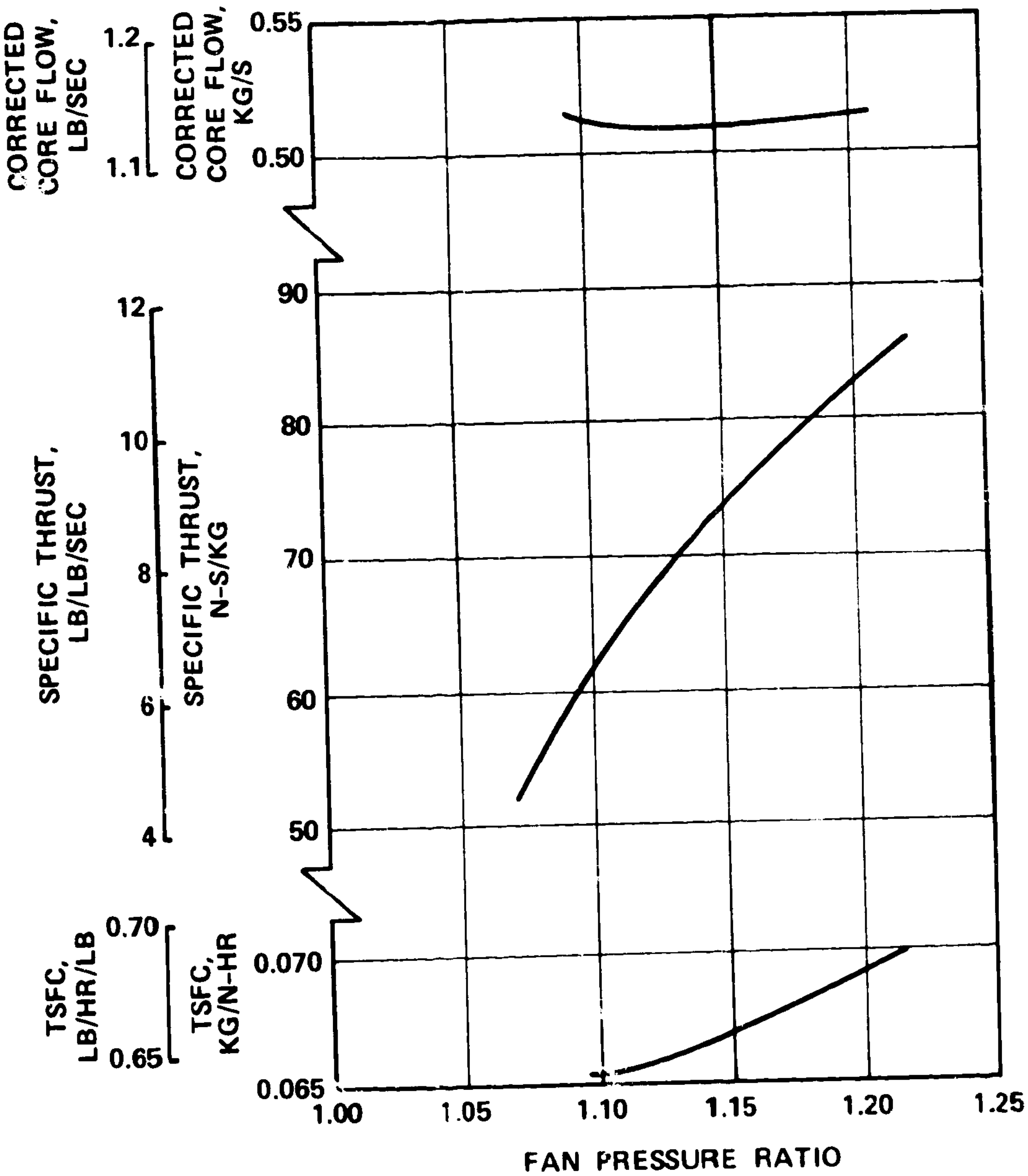


Figure 6. - TSFC, specific thrust, and core corrected flow versus fan pressure ratio at a cruise turbine inlet of 1500°F and optimum bypass ratio.

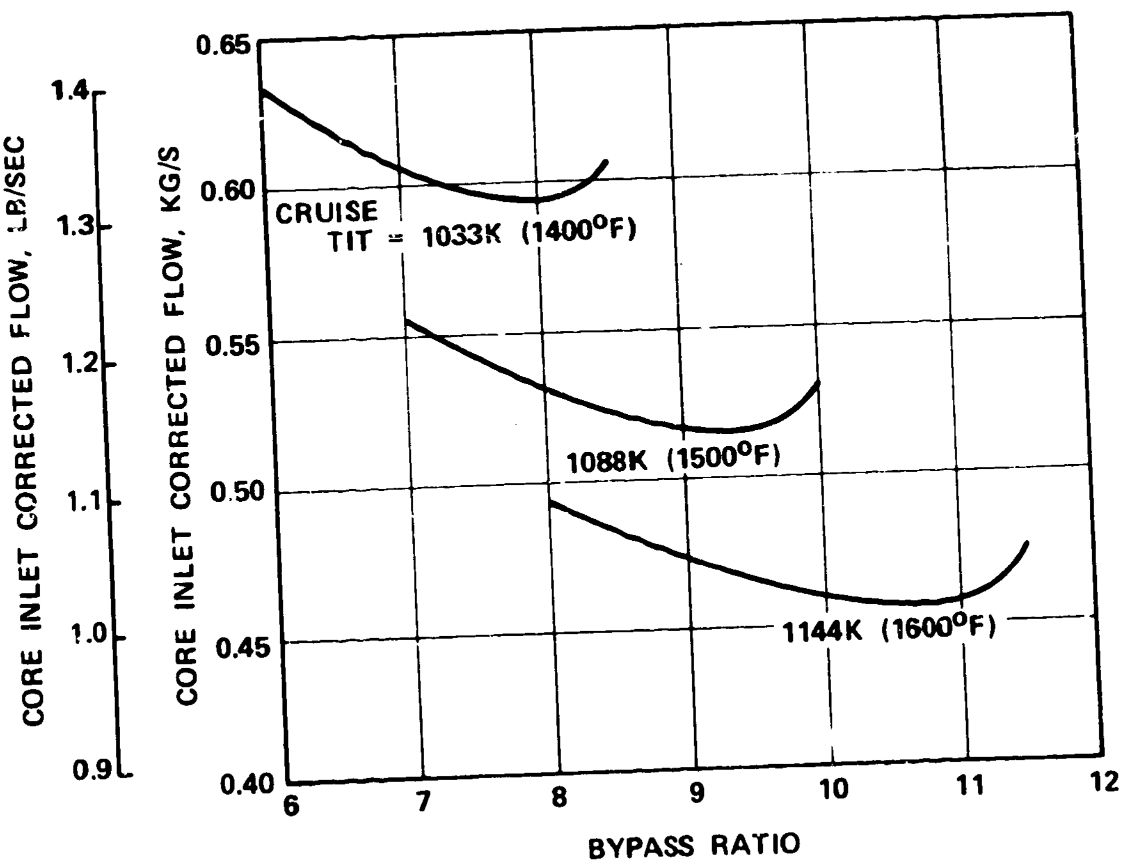


Figure 7. - Core inlet corrected flow versus turbine inlet temperature and bypass ratio at a fan pressure ratio of 1.15.

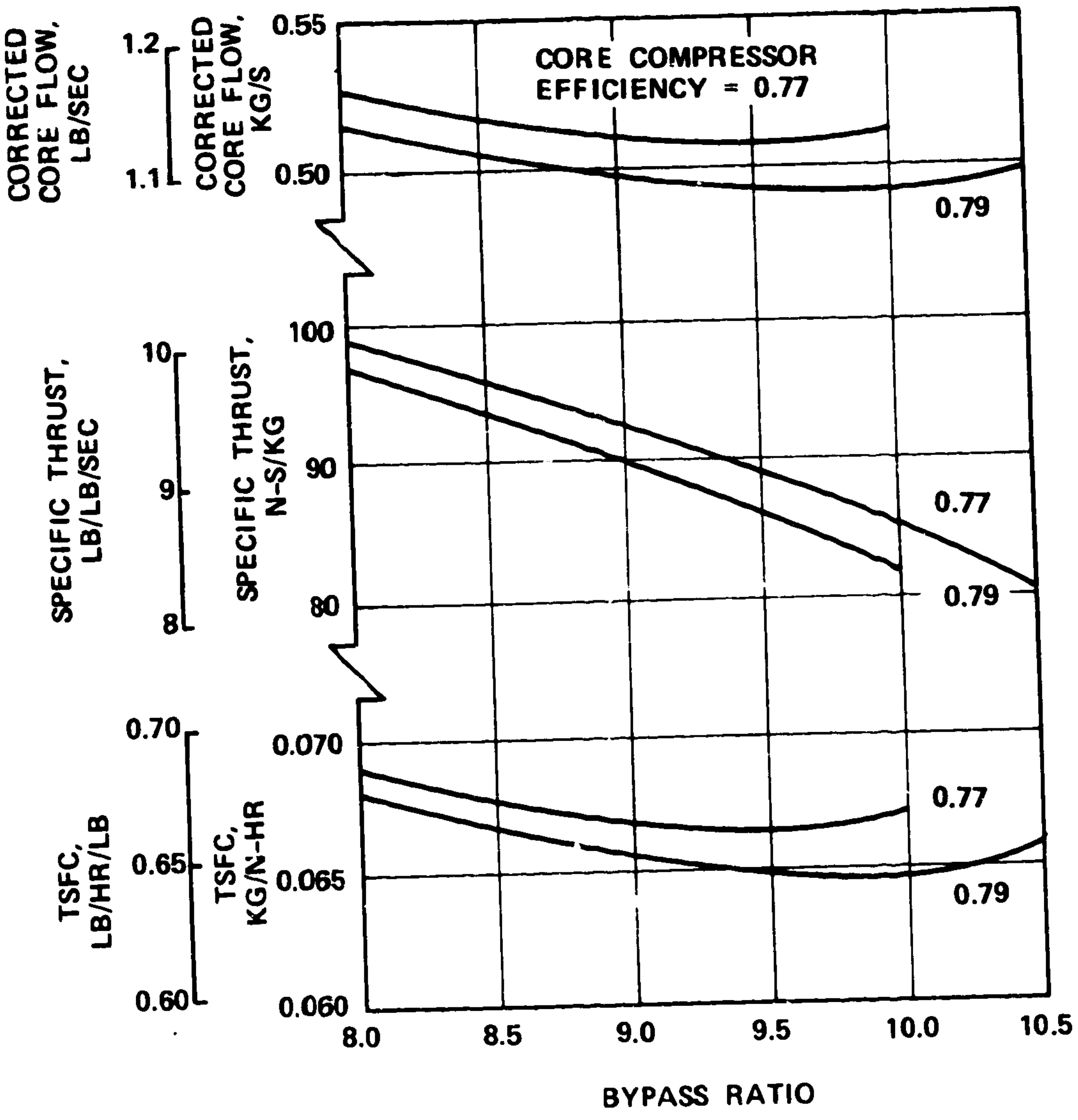


Figure 8. - TSFC, specific thrust, and core corrected flow versus bypass ratio at a turbine inlet temperature of 1500°F and a fan pressure ratio of 1.15.

The fan spool consists of the fan and a three-stage turbine. The principle design problem in this spool was achieving the minimum number of turbine stages, while retaining high component efficiencies. It was also desirable to avoid the use of speed-reduction gearing. At a bypass ratio of 9.5, the problem is extremely difficult since the turbine must be close-coupled to the core turbine exit in order to avoid inter-turbine ducting. The resulting small turbine diameter provides a low rotational velocity, thus, requiring either a large number of stages or high turbine work factors. It was found that by designing the fan for higher than optimum speed, an efficient three-stage turbine design was possible. Lower hub/tip ratio, higher tip speed, and higher axial velocity are fan design compromises. For the combination of values chosen, the penalty to fan efficiency was judged to be small, and spool efficiency and cost-effectiveness was thought to be near optimum.

The core spool consists of a four-stage compressor and a tip-shrouded, single-stage turbine. Again, maximizing the efficiency and cost-effectiveness of the spool was given top priority. The multi-stage compressor, while providing little efficiency advantage over a single centrifugal stage, does however, yield a substantially lower rotor speed. This, in turn, permits incorporation of a turbine tip shroud that significantly improves turbine efficiency. A further benefit of the lower speed is the easing of mechanical design difficulties attendant to achieving the desired two-frame, four-bearing engine configuration. With larger bearing, seal, and disk bore diameters, the fan-spool shaft is sufficiently large and stiff to be carried on two bearings while maintaining the required critical speed margins. In addition, uprating of the core spool can be accomplished by zero staging and increasing rotor speed up to the higher limits imposed by the mechanical design constraints. This is an important factor in the high-commonality family concept addressed in the final phase of the study.

The combustor design was given sufficient attention to assure that normal design loading criteria were not exceeded, and that the reverse-flow annular configuration chosen was entirely compatible with the engine configuration. In reviewing the state of combustor design and development, it was found that a high confidence level exists in the ability to achieve emission levels that meet future social requirements. Combustor technology developments, relative to emissions reduction are discussed further in the Chemical Emissions and Noise Analyses section of this report.

For the small turbofan engines defined in this study, it is expected that the EPA emission standards can be met following suitable development. Because of the very small combustor sizes, HC and CO emissions are anticipated to be a problem. However, because both cycle pressure ratios and the turbine inlet temperatures selected are low, NO_x emissions should be a lesser problem. Although a precise definition of required combustor component design is lacking, it is expected that compliance can be accomplished without impairing engine performance or operating safety.

The fan and core exhaust ducts and jet nozzles were the last engine components examined in detail. The principle loss mechanisms in turbofan exhaust systems are duct wall friction and momentum loss due to flow turning. In low bypass ratio turbofans, the annular height of the bypass duct is small, which results in low hydraulic radius and high friction losses. To minimize this effect, the fan exit flow is usually diffused to a lower Mach number, then reaccelerated at the jet nozzle. The resulting expansion and contraction losses are lower, however, than the friction losses accompanying the higher flow Mach number.

For the high bypass ratio engines of this study, it was determined that a short, annular bypass duct with no diffusion and minimal flow turning would provide minimum internal losses. A similar configuration, incorporating a center body or plug, was chosen for the core exhaust nozzle. While internal losses are small with this system, nacelle afterbody friction and pressure drag become an additive loss chargeable to the engine. Extensive analysis and model testing would be required to define optimum geometry for the configuration selected. Although engine performance was found to be very sensitive to duct losses and nozzle velocity coefficients, conservative values were used in engine performance analysis reflecting current uncertainties in low-pressure-ratio nozzle design.

Table 4 lists the design point pressure ratios, efficiencies, and losses assumed for the baseline two-seat trainer engine performance analysis. Complete off-design performance was calculated and converted to GASP input format. Representative values of thrust, specific fuel consumption, and airflow are given in Table 5, at the engine size required by the best GASP solution airplane.

A preliminary design layout that was prepared for the four-seat utility airplane engine provided the basis for the weight estimate of the trainer engine. The calculated weight of 27.7 kg (61 lb) includes, in addition to the basic engine weight, the weight of the starter-generator, the bypass duct, and the jet nozzles. The envelope dimensions of the two-seat trainer engine are given in Figure 9.

TABLE 4. DESIGN POINT PRESSURE RATIOS, EFFICIENCIES AND LOSSES ASSUMED FOR THE TWO-SEAT TRAINER TURBOFAN CYCLE

Inlet pressure recovery	0.995
Fan pressure ratio	1.150
Fan efficiency	0.885
Core compressor pressure ratio	4.000
Core compressor efficiency	0.770
Combustor pressure loss	0.040
Combustor efficiency	0.980
Core turbine efficiency	0.850
Core spool mechanical efficiency	0.980
Inter-turbine duct pressure loss	0.005
Fan turbine efficiency	0.870
Fan spool mechanical efficiency	1.000
Core exhaust pressure loss	0.015
Core jet nozzle velocity coefficient	0.970
Fan exhaust duct pressure loss	0.015
Fan jet nozzle velocity coefficient	0.970
Accessory power	745.7 w (1.0 hp)
Net thrust production margin	0.060

TABLE 5. REPRESENTATIVE PERFORMANCE VALUES FOR THE TWO-SEAT TRAINER TURBOFAN

SLS thrust (1)	N (lb)	961 (216)
SLS TSFC (1)	kg/N-h (lb/h/lb)	0.047 (0.465)
SLS airflow (1)	kg/s (lb/s)	5.94 (13.1)
Design point thrust (1, 2)	N (lb)	449 (101)
Design point TSFC (1, 2)	kg/N-h (lb/h/lb)	0.064 (0.640)
Design point airflow (1, 2)	kg/s (lb/s)	5.10 (11.25)
Design point bypass ratio (2)		9.5

(1) Standard atmosphere

(2) Design point conditions: 201 km/h, 2286 m (125 mph, 7500 ft)

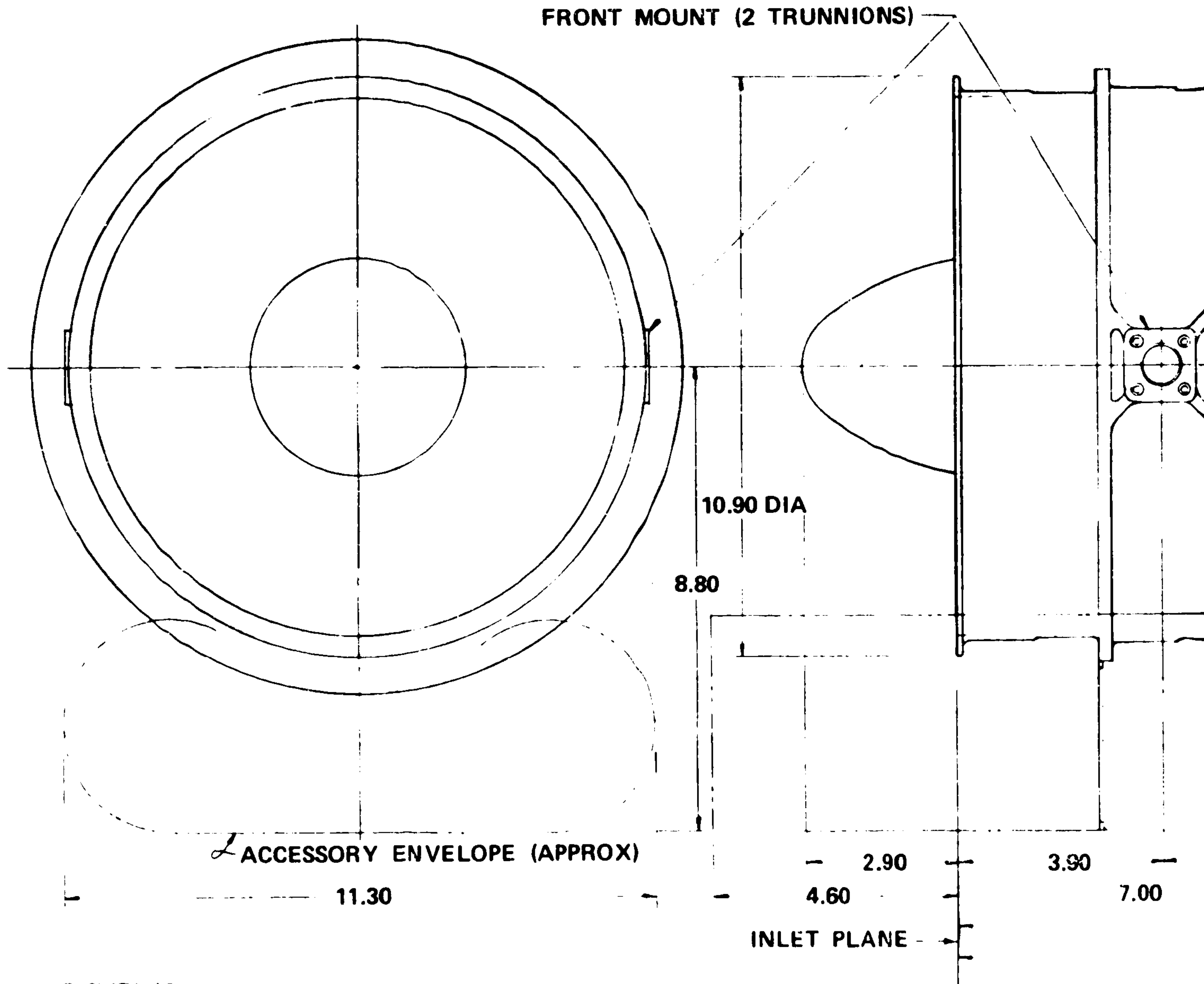
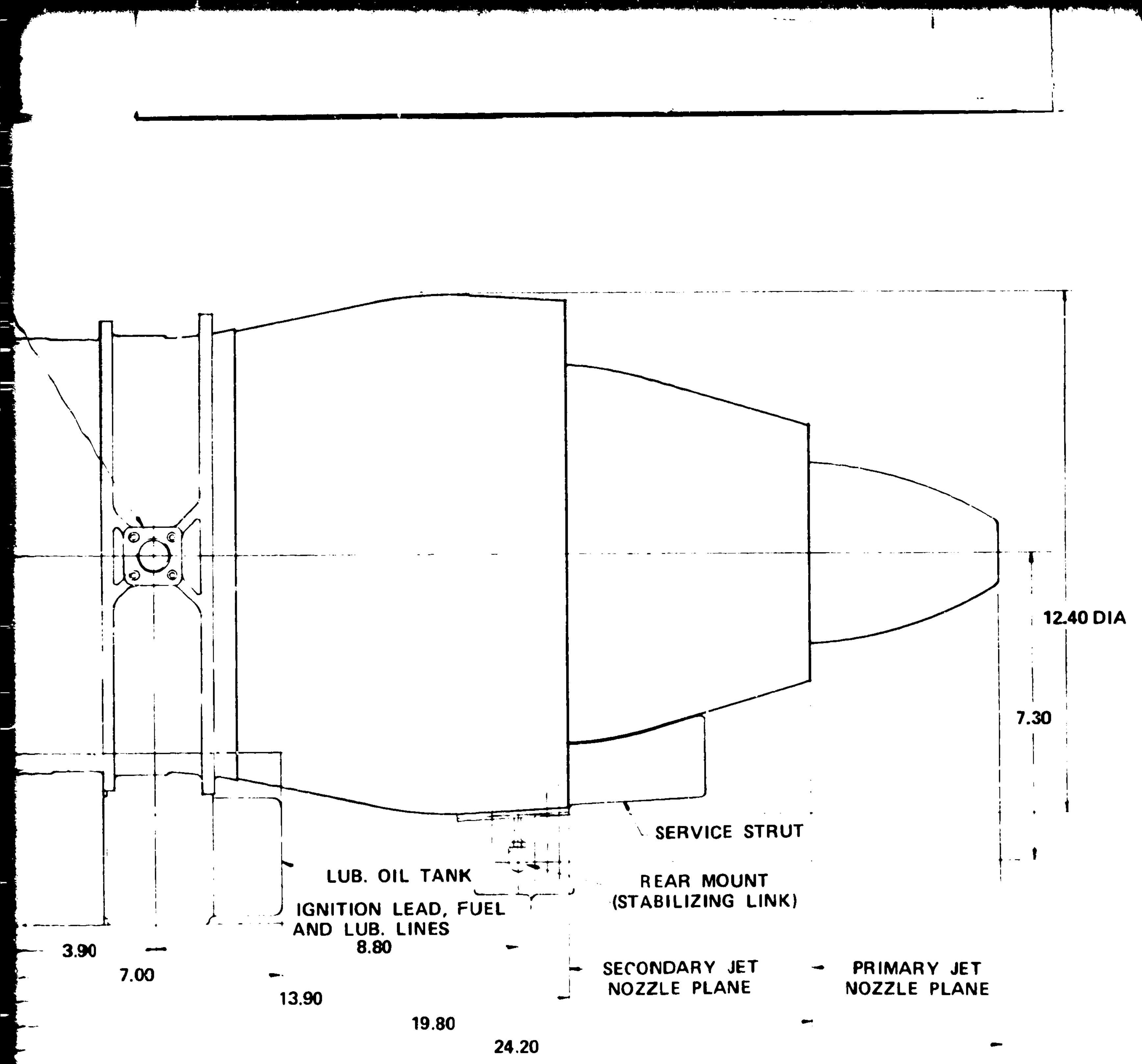


Figure 9. Two-Seat Trai

FOLDOUT FRAME



e 9. Two-Seat Trainer Engine Envelope

Baseline Four-Seat Utility Airplane

In terms of numbers sold, the four-seat utility airplane is the most popular. Over 3000 airplanes in this class were produced in the United States in 1975. In recent years, this class has outsold the two-seat utility-trainer and market analysis indicates that this trend will be permanent. Four-seat utility airplanes are analogous to the private automobile, which may account for their increasing popularity. In fact, they challenge the automobile in both utility and operating economy. Fuel mileage is directly comparable. Although their initial costs are greater than those of automobiles, depreciation rates are much less. Thus, over the useful life of the airplane, total cost of ownership is not significantly greater. For those whose travel needs justify its purchase, the payoff for airplane ownership is a reduction in travel time by a factor of two to three.

By definition, four-seat utility airplanes are those currently produced with fixed landing gear and 150 to 180 horsepower engines. Cruise speeds are from 216 km/h (134 mph) to 257 km/hr (160 mph) over normal ranges of approximately 805 km (500 sm) to 1287 km (800 sm). Typical cruise fuel consumption is 0.036 m^3/h (8 gph) to 0.050 m^3/h (11 gph). With service ceilings under 4572 m (15,000 ft), normal cruise altitudes are usually less than 3048 m (10,000 ft). The sea-level rate of climb capabilities range from 197 m/min (645 fpm) to 259 m/min (850 fpm), and minimum field length requirements are from 427 m (1400 ft) to 610 m (2000 ft). Basic IFR instrumentation consisting of dual navcom radios, ADF, marker beacon receiver, transponder, and dual controls are normal equipment for this class.

Unlike trainers operated by flying schools, the annual utilization of airplanes in this class is usually very low, averaging less than 200-hours per year. Therefore, maintenance, overhaul, and reliability factors are viewed in a different perspective. Corrosion, materials aging, and similar time-related deterioration factors become more important in designing for low operating cost. Both airframe and engine design is affected. With respect to the airframe, current design practice satisfactorily addresses the exigencies of low utilization rate operation. The use of all-metal structures minimizes airframe maintenance over long periods and maximizes airframe service life.

The normal gas turbine design practice of using corrosion-resistant materials and surface coatings provides an inherent life advantage over piston engines for airplanes in this class. The crankcase corrosion problem associated with infrequent piston engine use is avoided, and in gas turbines, acid formation in lubricating oil due to combustion products contamination does not occur. Thus, the need for frequent, costly oil changes is greatly reduced.

In addition to operating economy, the four-seat utility-class airplane must have comfort, convenience, and operability qualities that are similar to those of automobiles. A spacious, quiet, and vibration-free cabin is very desirable as are ease of entry and exit. The practice of fine tuning the stability/controllability balance is essential, and uncomplicated power management must be provided. The need for elaborate loading and balancing procedures should be eliminated. Exceptional visibility is a must, since in this class, most operations are conducted under VFR conditions by owner/operator pilots.

Airplane configuration and synthesis modeling. - The baseline design established for the four-seat utility airplane addressed the foregoing considerations. The inherent qualities of turbofan propulsion assures conformance to many of the desirable characteristics identified. The general configuration was carefully selected to satisfy the remaining requirements.

The configuration is essentially a "stretched" derivative of the two-seat trainer. An additional seat row and increased baggage volume was provided by adding 1.0 m (3.3 ft) to the fuselage length at the plane of maximum cabin cross-section. A preliminary weight and balance calculation showed that the center-of-gravity gravity would be aft of the front seat row. Therefore, the forward sweep of the wing could be eliminated and a conventional high-wing configuration could be adopted. The spar carry-through structure would then pass conveniently between the seat rows as a small protruding ridge in the cabin ceiling. Pilot visibility is thus improved over that of the two-seat trainer, and wider doors could be provided for easy entry to the rear seats.

Other features selected for the two-seat trainer were retained. Engine location, wing section, flap configuration, landing gear design, and the "V" tail arrangement were features found to be satisfactory for the four-seat airplane. Structural weight and aerodynamic drag calibrations used in GASP were also retained. It was assumed that greater wing area would be required due to the substantially higher gross weight expected. The best wing area would be identified following loading and aspect ratio studies performed with use of GASP. The fixed equipment weight was increased commensurate with the requirements for added passenger accommodations and avionics.

Baseline engine definition and performance analysis. - The baseline engine for the four-seat utility airplane is a scaled derivative of the trainer engine. Although the design cruise speed of the airplane is 20-percent higher, it was determined that little benefit would be realized by adjusting the basic cycle parameters. While approximately twice as much takeoff thrust and 40-percent greater physical engine size is required, it was not deemed necessary to alter engine component configurations. However, due to the increased size of the aerodynamic components, their predicted efficiencies were found to be sufficiently greater to warrant rematching the cycle.

Direct scale-up of the aerodynamic components poses no problems. Using a linear or dimensional scale factor equal to the square root of the airflow ratio between engines, the aerodynamic flow and work coefficients remain essentially constant throughout the engine. However, the combustor loading values (based on volume) become lower when scaled by this procedure.

A detrimental effect of direct scale-up is the resulting disproportionate increase in weight due to the cube-square effect. That is, although the airflow and power increase as the square of the linear scale factor, the weight increases as the cube. This effect may be eliminated by holding one of the three dimensions describing the volume of each structural element constant while scaling the other two. It has been found that in the small engine classes this is the general result of manufacturing limitations on part thickness. Thus, it is possible to hold engine thrust-to-weight ratio nearly constant across a broad scaling range with few fundamental design changes.

The design point pressure ratios, efficiencies, and losses assumed for the baseline four-seat utility engine are listed in Table 6. The off-design performance calculated for the engine was input to GASP as a 2095 N (471 lb) thrust engine to be scaled to meet the airplane thrust requirements. Representative values of thrust, specific fuel consumption, and airflow at the size required by the best GASP solution airplane are given in Table 7.

In preparing the initial design layout of the baseline engine (see Figure 10), material selections were made and preliminary stress analysis procedures were used to define the geometry of major components. Rotating components were sized for 5-percent higher speed than was required in the initial design to permit substantial uprating. Most parts, both stationary and rotating, were designed as precision investment castings. This process was identified in previous studies as the most economical for small-engine components. Precision forgings and shell-mold castings were also incorporated in the design. The use of sheet metal was limited to the primary and bypass exhaust ducts.

The engine weight estimate of 52.6 kg (116 lb) was made from the design layout and includes the starter-generator, bypass duct, jet nozzles, and complete lubrication, ignition, and fuel systems. The engine envelope dimensions are contained in the outline drawing (Figure 11).

TABLE 6. - DESIGN POINT PRESSURE RATIOS, EFFICIENCIES AND AND LOSSES ASSUMED FOR THE FOUR-SEAT UTILITY TURBOFAN CYCLE

Inlet pressure recovery	0.995
Fan pressure ratio	1.150
Fan efficiency	0.894
Core compressor pressure ratio	4.000
Core compressor efficiency	0.787
Combustor pressure loss	0.040
Combustor efficiency	0.990
Core turbine efficiency	0.885
Core spool mechanical efficiency	0.980
Inter-turbine duct pressure loss	0.005
Fan turbine efficiency	0.877
Fan spool mechanical efficiency	1.000
Core exhaust pressure loss	0.000
Core jet nozzle velocity coefficient	0.958
Fan exhaust duct pressure loss	0.005
Fan jet nozzle velocity coefficient	0.978
Accessory power	745.7 W (1.0 hp)
Net thrust production margin	0.060

TABLE 7. - REPRESENTATIVE PERFORMANCE VALUES FOR FOUR-SEAT UTILITY AIRPLANE TURBOFAN

SLS thrust (1)	N (lb)	1797 (404)
SLS TSFC (1)	kg/N-h (lb/h/lb)	0.041 (0.402)
SLS airflow (1)	kg/s (lb/s)	11.61 (25.6)
Design point thrust (1, 2)	N (lb)	885 (199)
Design point TSFC (1, 2)	kg/N-h (lb/h/lb)	0.055 (0.540)
Design point airflow (1, 2)	kg/s (lb/s)	9.03 (19.9)
Design point bypass ratio (1, 2)		10.5

(1) Standard atmosphere

(2) Design point conditions: 201 km/h, 2286 m (125 mph, 7500 ft)

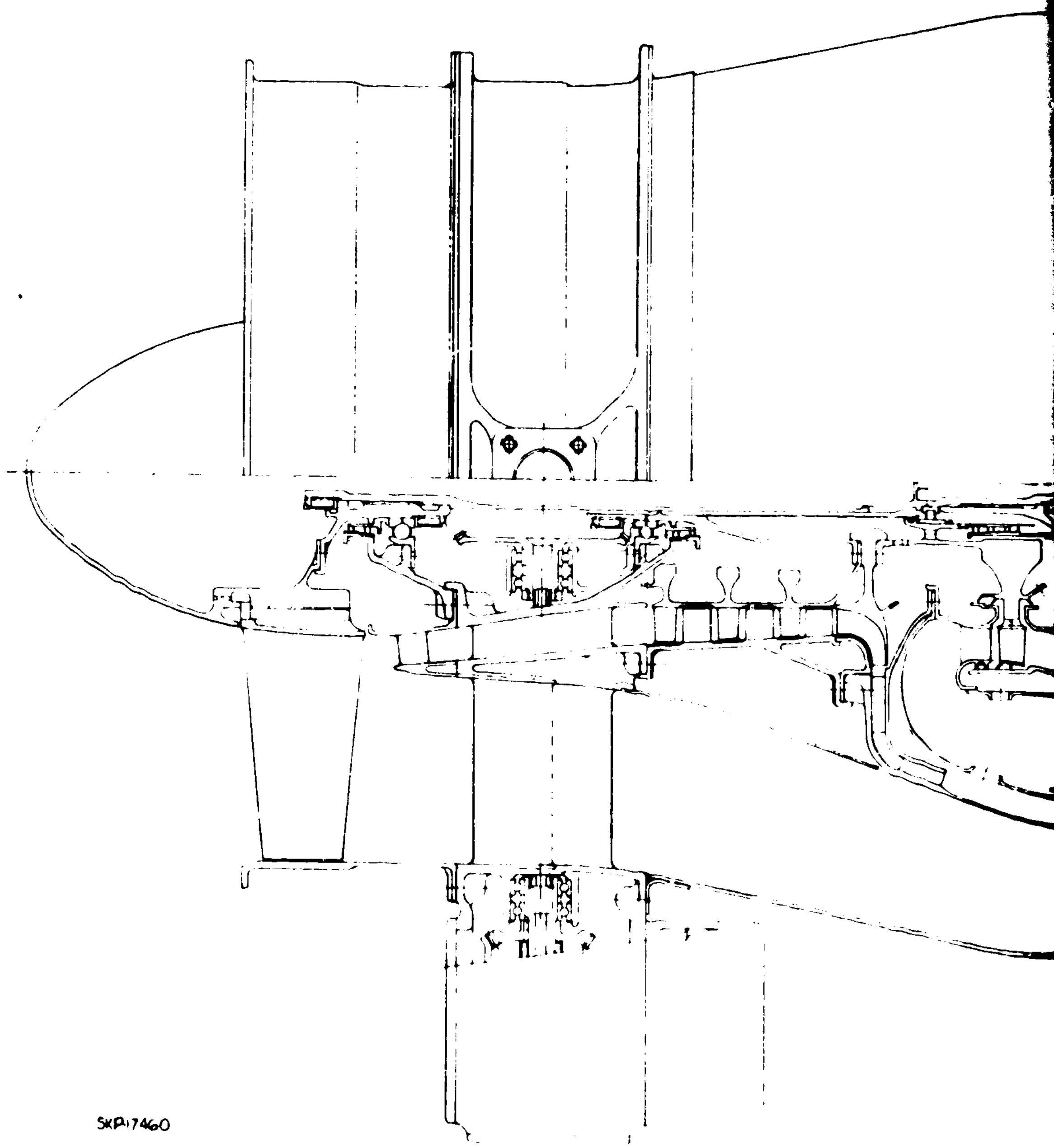


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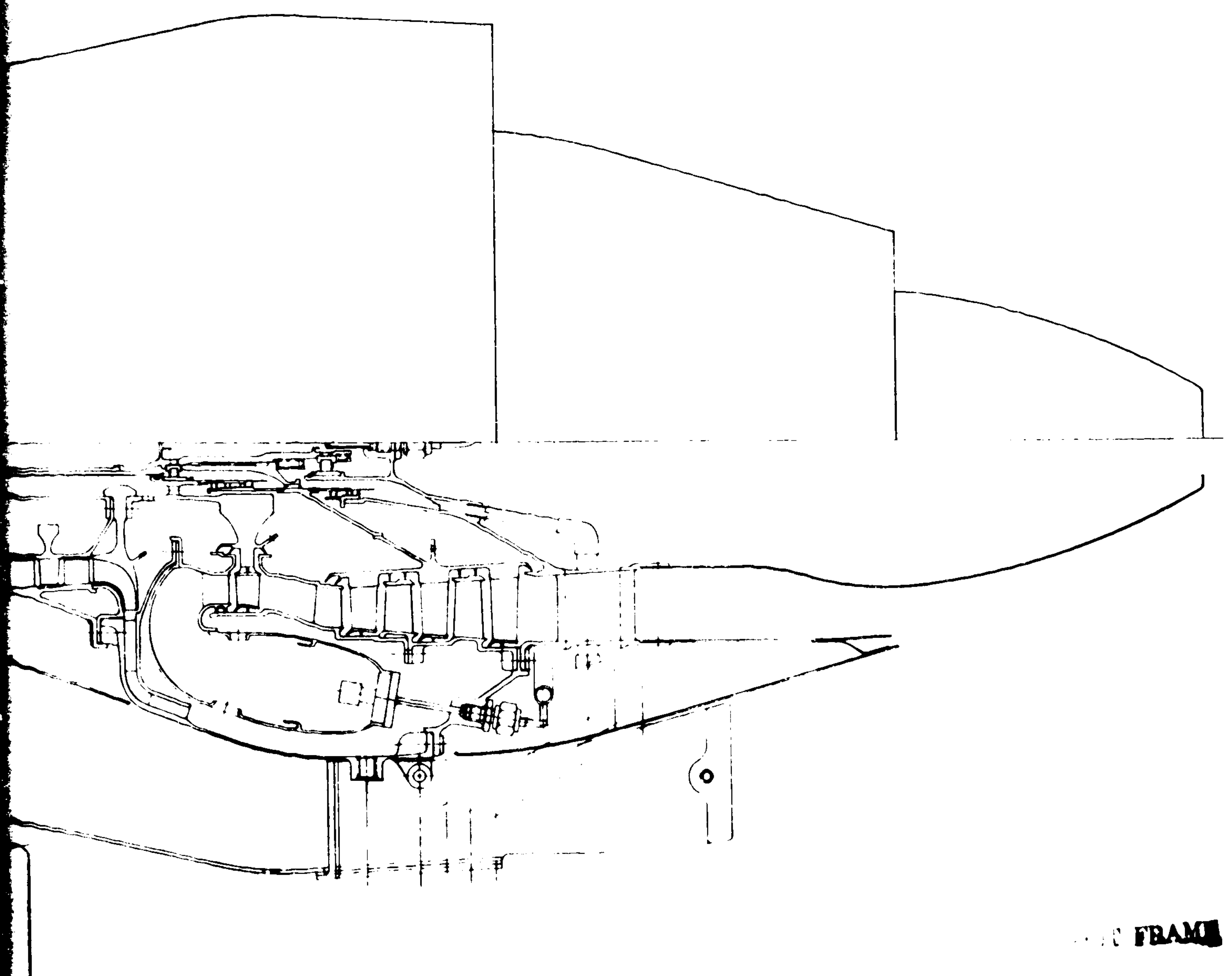
Figure 10. Initial Design Layout of the
Engine for Four-Seat Utility



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gine for Four-Seat Utility Aircraft.

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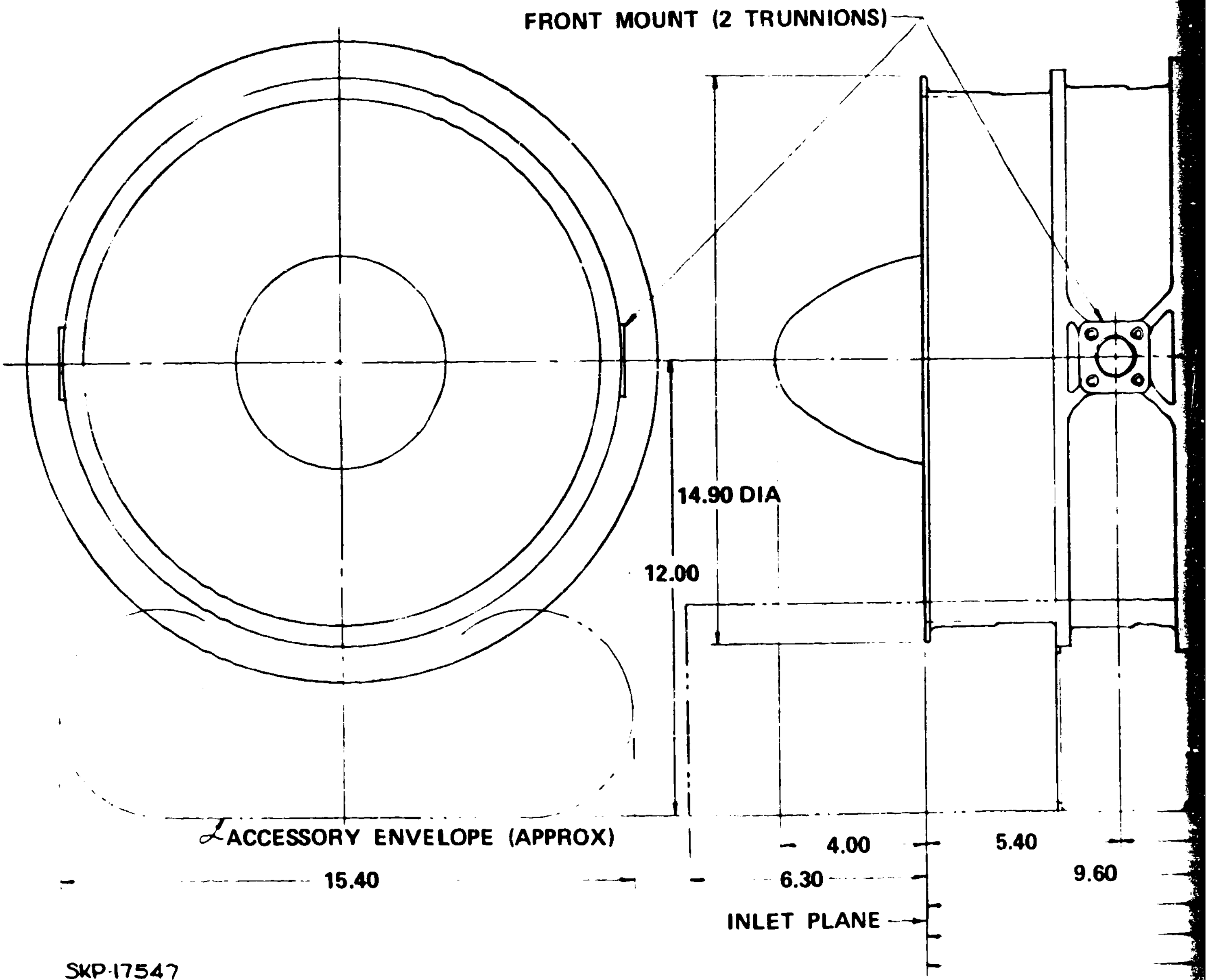

Figure 11. Engine Outline Drawi

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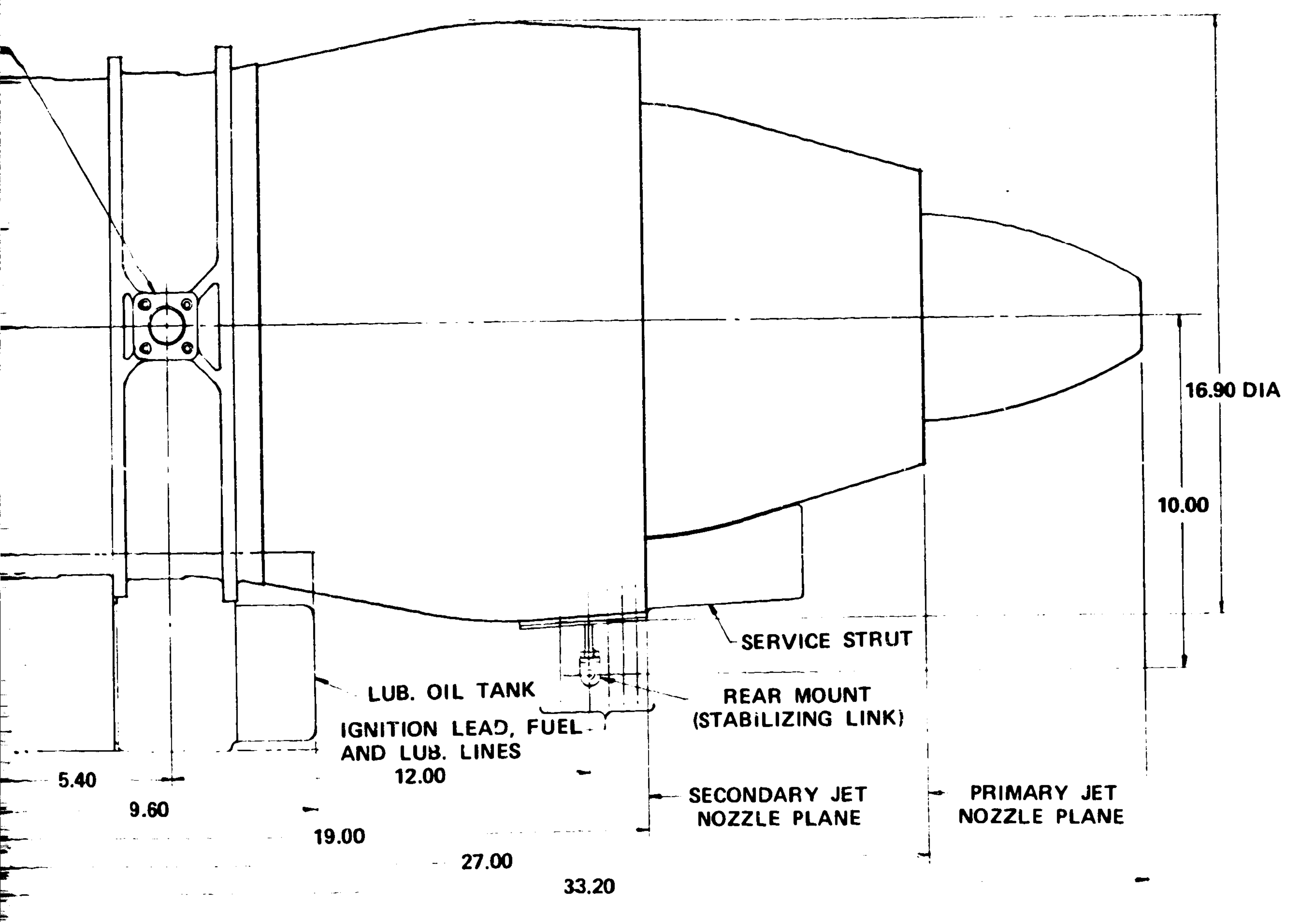


Engine Outline Drawing - Four-Seat Utility Aircraft.

Baseline Four-Seat, High-Performance Airplane

The "four-seat high-performance" classification is applicable to three specific categories of airplanes currently produced. First, there are those derived by modifying a utility airplane. With a moderate power increase and retractable landing gear, a significant performance increase is achieved. The second category provides substantially more power, but retains fixed landing gear. This formula results in a modest performance increase, but provides a large improvement in useful load. With little additional modification, six-seat variations are produced. The third category stresses both performance and useful load, having both large engines and retractable gear. There are few distinguishing performance characteristics between the four- and six-seat variations in this category. Currently, the combined sales of all three categories approaches the number of four-seat utility airplanes sold. These airplanes provide fast, economical transportation for both personal and business travel to a large segment of the general aviation market.

In the three airplane categories described here, the engines range from 200 to 300 horsepower, and cruise speeds vary from 214 km/h (133 mph) to 354 km/h (220 mph). With maximum fuel load at maximum cruise, ranges vary from 1139 km (708 sm) to 1889 km (1174 sm). Other performance figures show similar improvements over four-seat utility airplanes. A few models are available with turbocharged engines that provide 6096 m (20,000 ft) cruise altitude capability. In addition to the normal equipment and avionics complement in the utility class, airplanes in these categories are often equipped with autopilots, distance measuring equipment (DME), and a glide-slope receiver for instrument approaches. Turbocharged airplanes are normally equipped with oxygen systems. At present, no airplanes in these categories are pressurized.

The turbofan-powered baseline airplane selected for this study was derived from the four-seat utility airplane by adding an up-rated engine and retractable landing gear. An allowance was made for additional fuel to provide comparable cruise endurance at the higher cruise speed. Although this airplane was initially defined for the high-performance class, it was later determined that in a future market it would be more appropriately placed in an intermediate-performance class. In the engine commonality and family concept studies described later in this report, the high-performance designation is assigned to a refinement of this airplane, having cabin pressurization and a higher cruise speed. In the context of the present market, the performance of the airplane chosen for study is high. Therefore, this designation is retained for describing the study results.

Airplane configuration and synthesis modeling. - Initial analyses showed that the desired performance increase, engine up-rating, and retractable-gear were quantitatively compatible in the utility airplane. The airplane external geometry could be retained but a stronger, heavier structure would be required with a consequent increase in wing loading. It was determined that the weights and performance parameters (other than design cruise speed, altitude, and range) should be fallout values to be determined by GASP analyses. In this manner, it could be shown that up-rating in the "family" context is viable for turbofans. This economical method of expanding product lines is used universally by the manufacturers of propeller-driven light airplanes.

In normal use, GASP synthesizes a solution airplane from input data that includes a wing-loading parameter and a scaleable engine. For this case, fixed engine and wing sizes were required in order to provide an analogy to the procedure for up-rating an existing airplane. To do this, it is necessary to calculate a matrix of airplane solutions. Since the final gross weight is not known, wing loading must be an input variable. Similarly, engine sizing criteria (takeoff distance) must be variable. By plotting the appropriate quantities from the matrix solutions, the wing loading and takeoff distance that yields the desired engine and wing sizes may be interpolated. Then, a final synthesis run using these input parameters provides the complete definition of the solution airplane. Comparison of this solution with solutions in the original matrix will show the effects of not optimizing the up-rated airplane.

Baseline engine definition and performance analysis. - There are numerous ways to up-rate a turbofan engine. The usual procedure is to investigate the alternatives that ensure maximum commonality in both aerodynamic and mechanical design between the original and the up-rated engine. Modest power increases can be achieved by increasing turbine inlet temperature and rotor speeds as long as the original design constraints are not exceeded. Increases in allowable stresses can often be accommodated by material substitutions, which negates the need for design modifications. However, large power increases often require substantial changes to the aerodynamic flow path and the thermodynamic cycle. Such changes are made to increase the core airflow approximately in proportion to the desired power increase. The increased core power may then be used to increase core nozzle thrust. A portion of it may be supplied to the fan to increase flow and/or pressure ratio, and thereby, the fan nozzle thrust.

A principle goal in the design of the two- and four-seat utility turbofan airplanes was to achieve adequate performance specifics with conservative cycles and mechanical designs that could be substantially up-rated. The up-rating technique selected was to provide for: the addition of stages to the front of the core compressor, large turbine inlet temperature increases while avoiding the need for costly turbine blade air cooling, and fan flow and pressure ratio increases while retaining constant flow-path annulus areas. Properly executed, this technique permits commonality in most major structural components such as frames, casings and shaft systems. It was estimated that the core power level of the four-seat utility engine could be increased by a factor of two using this up-rating technique.

A preliminary evaluation of the thrust required for the four-seat, high-performance airplane indicated a need for 25- to 30-percent core power and a higher fan pressure ratio for best net propulsive efficiency at high cruise speeds. Th utility engine was consequently modified in the following manner. The fan pressure ratio was increased from 1.15 to 1.20. This required increased rotor speed and recambered stator vanes. The core pressure ratio and airflow were increased by the addition of a 1.3 pressure ratio "zero" stage to the compressor with a small accompanying speed increase. The core turbine was found to be adequate if the inlet nozzle area was opened about 5 percent. Evaluation of the fan turbine indicated that annulus areas were adequate, but all new blading would be required for optimum performance. Both fan and core jet nozzle area changes were also required. Cycle matching studies were carried out and resulted in a decision to retain the 954.3°C (1750°F) turbine inlet temperature of the utility engine and to accept the attendant decrease in bypass ratio.

The design point pressure ratios, efficiencies, and losses assumed for the baseline four-seat high-performance engine are listed in Table 8. Off-design performance calculations resulted in the representative values of thrust, specific fuel consumption, and airflow given in Table 9. These values are based on up-rating the 1797 N (404 lb) thrust utility engine with no scale change. Synthesis analysis of the four-seat, high-performance airplane was done to hold the engine size constant.

The required modifications to the utility engine resulted in an estimated 9.98 kg (22 lb) weight increase to 62.6 kg (138 lb). The only engine envelope change was a 3.05 cm (1.2 in) increase in length to accommodate the added compressor stage.

TABLE 8. DESIGN POINT PRESSURE RATIOS, EFFICIENCIES AND LOSSES ASSUMED FOR THE FOUR-SEAT HIGH-PERFORMANCE TURBOFAN CYCLE

Inlet pressure recovery	0.995
Fan pressure ratio	1.200
Fan efficiency	0.890
Core compressor pressure ratio	5.200
Core compressor efficiency	0.780
Combustor pressure loss	0.040
Combustor efficiency	0.990
Core turbine efficiency	0.865
Core spool mechanical efficiency	0.980
Inter-turbine duct pressure loss	0.005
Fan turbine efficiency	0.875
Fan spool mechanical efficiency	1.000
Core exhaust pressure loss	0.000
Core jet nozzle velocity coefficient	0.958
Fan exhaust duct pressure loss	0.005
Fan jet nozzle velocity coefficient	0.978
Accessory power	746 w (1.0 hp)
Net thrust production margin	0.060

TABLE 9. REPRESENTATIVE PERFORMANCE VALUES FOR FOUR-SEAT HIGH-PERFORMANCE TURBOFAN

SLS thrust (1)	N (lb)	2086 (469)
SLS TSFC (1)	kg/N-h (lb/h/lb)	0.0425 (0.417)
SLS airflow (1)	kg/s (lb/s)	12.3 (27.1)
Design point thrust (1, 2)	N (lb)	1036 (233)
Design point TSFC (1, 2)	kg/N-h (lb/h/lb)	0.054 (0.530)
Design point airflow (1, 2)	kg/s (lb/s)	9.2 (20.3)
Design point bypass ratio (1, 2)		8.0

(1) Standard atmosphere

(2) Design point conditions: 201 km/h, 2286 m (125 mph, 7500 ft)

Parametric Synthesis Sensitivity Analyses

The sensitivity of the solution baseline airplane characteristics to wing loading, wing aspect ratio, takeoff distance and rate of climb were examined by GASP analyses. In the 2-seat trainer investigation, the wing loading and takeoff distance parameters were examined first, using a constant aspect ratio of ten. For each parameter variation, the solution airplane obtained met the design speed, altitude, range and payload stipulations.

In Figure 12, the sensitivity of gross and empty weights to wing loading and takeoff distance over a 15 m (50 ft) obstacle is shown. At all points on these curves the engine was sized by the takeoff distance requirements. Relative required-takeoff thrusts (sea level static) are given in Figure 13 for the same wing loading and takeoff distance parameter variations. Similarly, relative fuel flow at the start of cruise for the various solution airplanes is given in Figure 14. Relative values for best rate of climb at the cruise altitude are given in Figure 15.

At the values of wing loading and takeoff distance yielding lowest cruise fuel flow and gross weight, the sensitivities to aspect ratio were examined. At a constant wing loading of 97.6 kg/m^2 (20 lbm/ft^2) and takeoff distance of 610 m (2000 ft), airplane solutions were obtained for aspect ratios varying from 6 to 14. The relative gross and empty weight variations are shown in Figure 16. Across this range of aspect ratio, the variation in empty weight is insignificant. However, the wing and engine components of the empty weight vary by large percentages, and were found to be offsetting. A large portion of the gross weight variation is a function of the varying mission fuel requirements. The relative required takeoff thrusts plotted in Figure 17 shows minimum engine size occuring at an aspect ratio of 13. In Figure 18, the relative fuel flow at the start of cruise is shown to decrease continuously with increasing aspect ratio. Extrapolation of this curve indicates that an airplane optimized for minimum fuel consumption alone would have an aspect ratio in the range of 18 to 20. The highest value of best rate-of-climb was the solution airplane having the highest aspect ratio, as shown in Figure 19.

The sensitivity analyses performed on the two-seat trainer design were repeated for the baseline four-seat utility airplane, with similar findings. The major difference was the higher wing loading. The four-seat high performance airplane was not subjected to sensitivity analysis. The decision to have this design a close derivative of the utility version made it desirable to retain the same wing, and accept a fallout value of higher wing loading attendant to the expected gross weight increase. With its substantially higher cruise speed, the higher wing loading was expected to result in an airplane size having wing loading and resultant fuel consumption values near optimum.

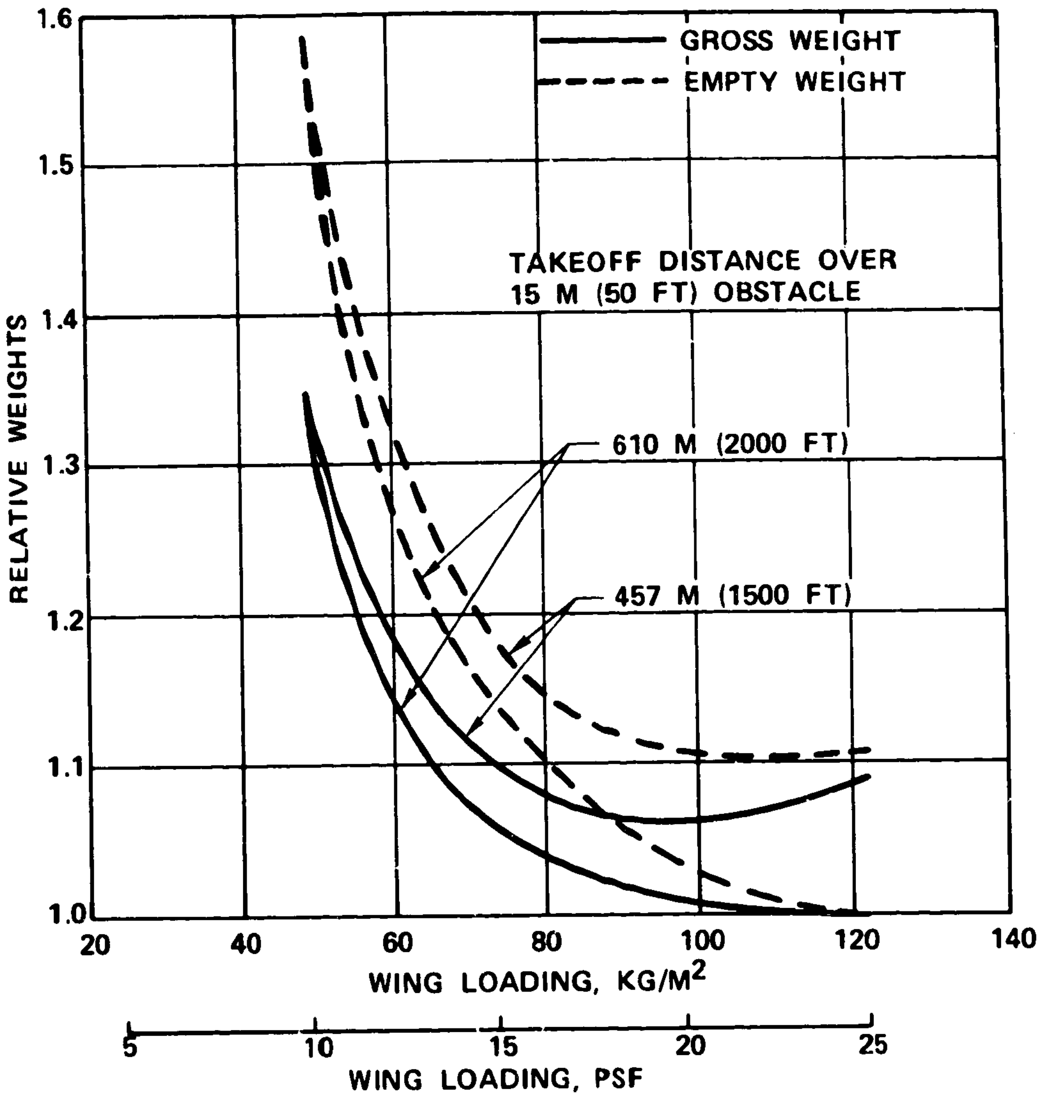


Figure 12. - Relative gross and empty weights versus wing loading and takeoff distance.

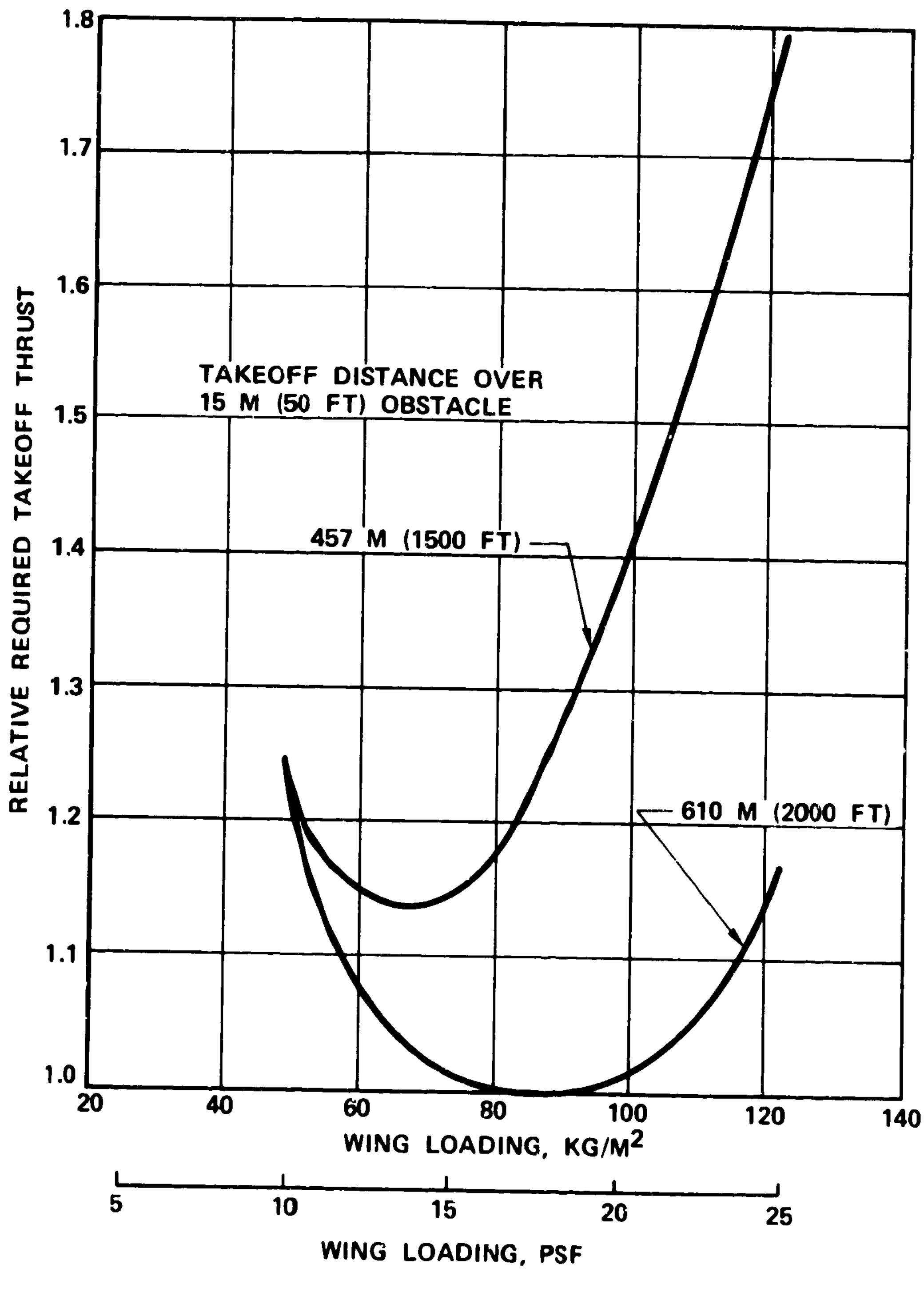


Figure 13. - Relative required takeoff thrust versus wing loading and takeoff distance.

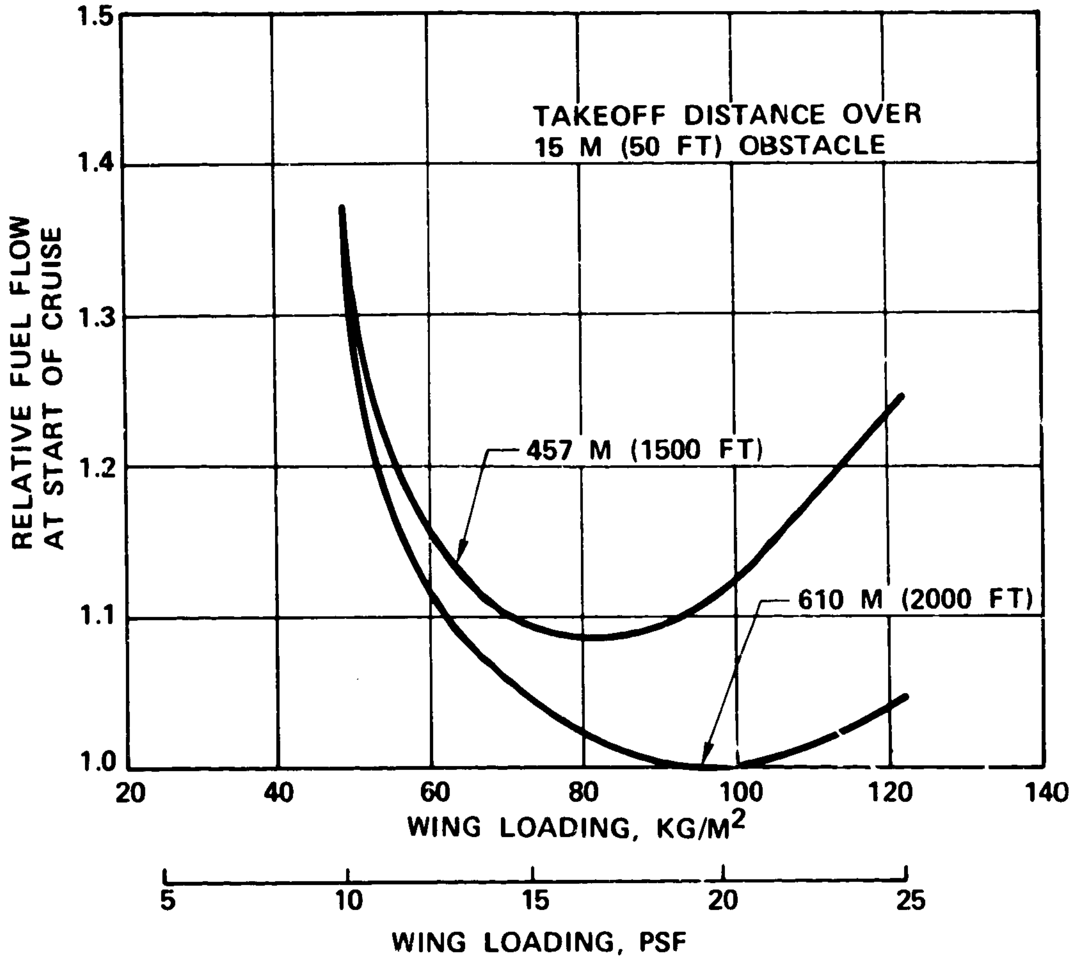


Figure 14. - Relative fuel flow at start of cruise versus wing loading and takeoff distance.

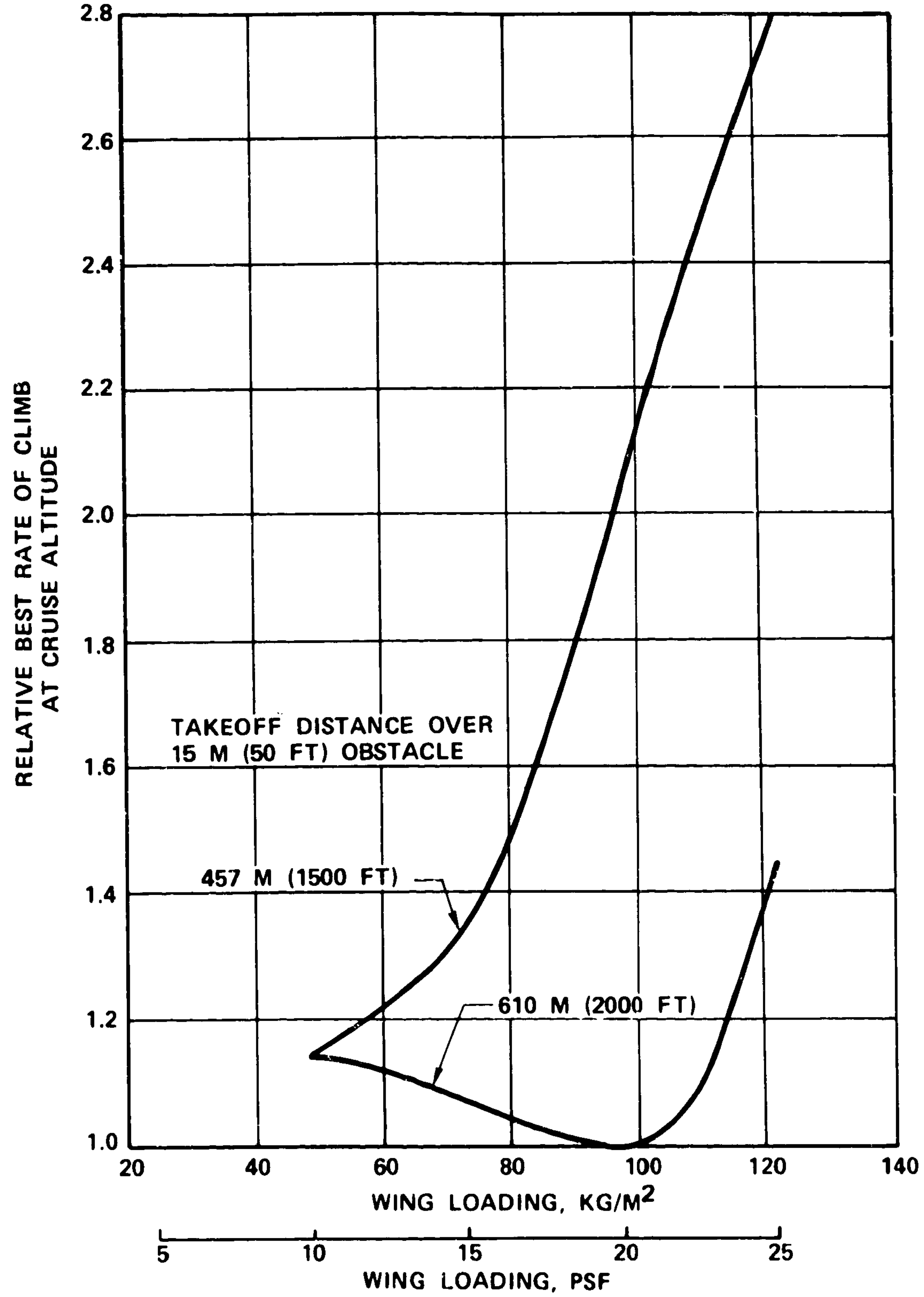


Figure 15. - Relative best rate of climb at cruise altitude versus wing loading and takeoff distance.

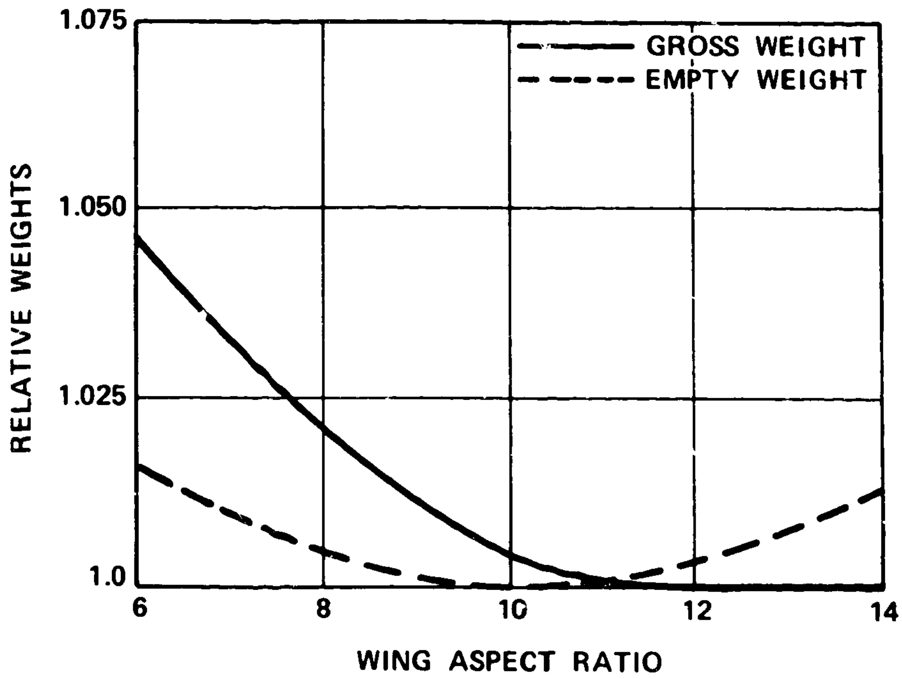


Figure 16. - Relative gross and empty weights versus wing aspect ratio.

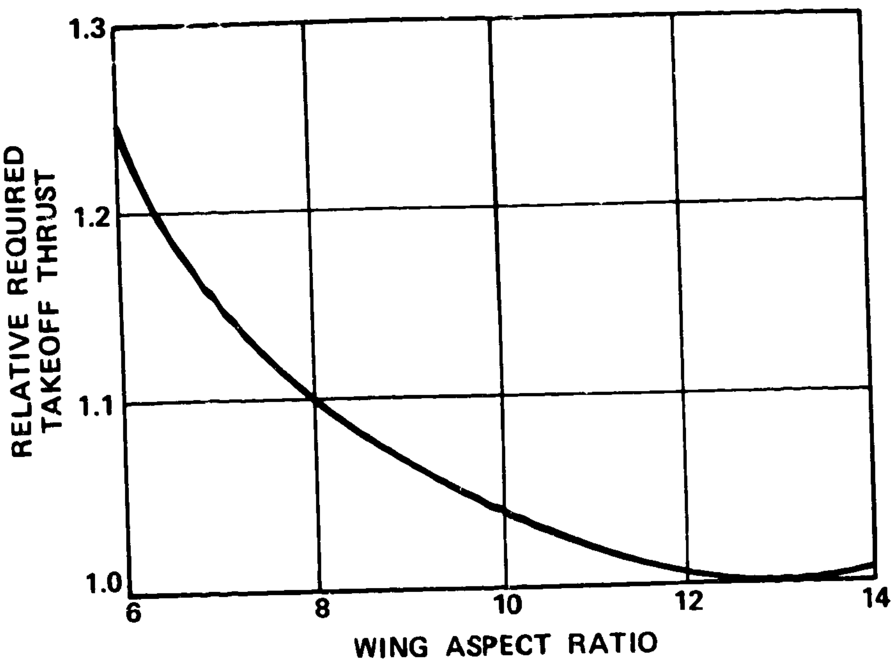


Figure 17. - Relative required takeoff thrust versus wing aspect ratio.

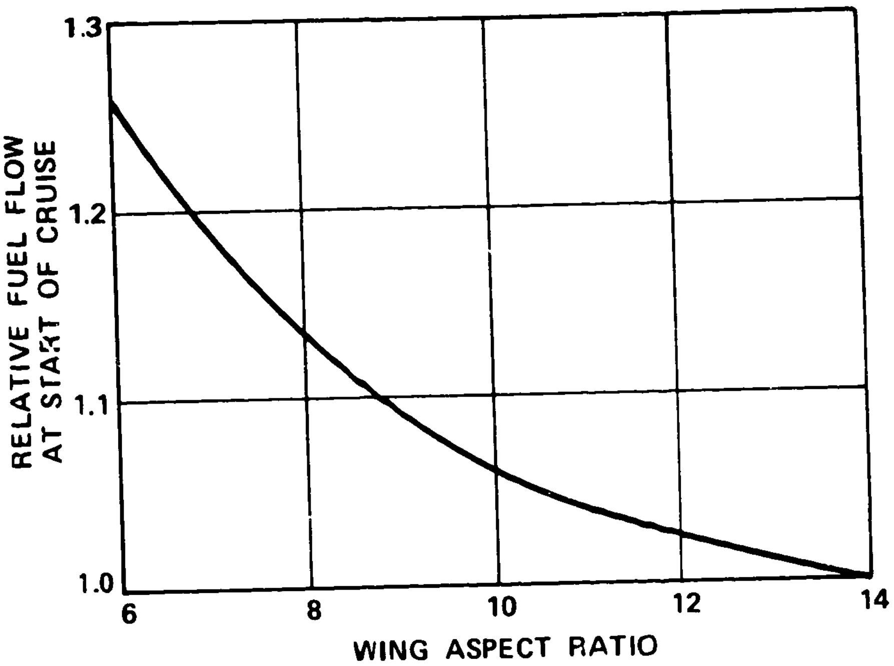


Figure 18. - Relative fuel flow at start of cruise versus wing aspect ratio.

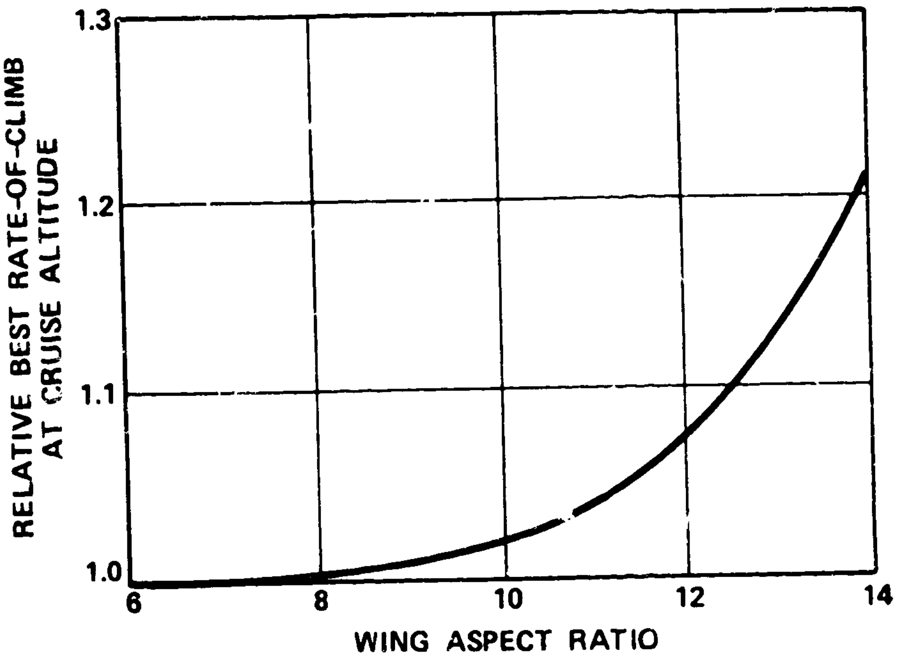


Figure 19. - Relative best rate-of-climb at cruise altitude versus wing aspect ratio.

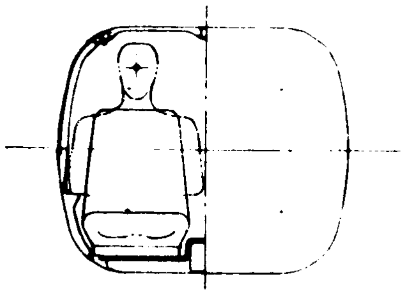
The most important result of the parametric synthesis sensitivity analyses was the significant impact of the wing loading and aspect ratio parameters on airplane size and fuel consumption. The effect of these parameters on drag, and consequently on the power required, is notable. The wing profile drag is nearly a direct function of wing area and induced drag is inversely proportional to the square of the wing span. Reference 10 discusses the drag reduction benefits of reduced wing chords, higher aspect ratio and greater wing loading on general aviation light airplanes. While an aspect ratio of 12 was eventually selected for the "best solution" airplanes, it was recognized that if appropriately-designed airfoil sections were available, still higher aspect ratios would have provided more fuel-efficient airplanes. The GA(W)-1 airfoil section used in these studies has a thickness/chord ratio of only 17 percent. Using this section resulted in a rapid wing weight increase at aspect ratios higher than 12. The greater spar depth afforded by a 21 percent section would have an offsetting effect on wing weight. The short chords of the study-airplane wings result in low Reynolds number, which further inhibits selection of higher aspect ratio. An airfoil section designed to have desirable characteristics in the 0.5 to 3.0 million Reynolds number range would have important advantages in stall behavior and low-speed performance of the turbofan-powered light airplanes.

"Best-solution" Airplane Design Results

The determination of "best-solution" conceptual designs for each of the three light-single airplanes was based on the results of sensitivity analyses and additional design iterations using GASP. In these analyses, the results were judged by several criteria. With design cruise speed, altitude, range and payload fixed, the major solution airplane variables were airplane weights, wing geometry and engine thrust levels. Performance parameters such as rate-of-climb, stall speed, landing and takeoff distance, and fuel consumption also varied between solutions. The most important goal of the study was to achieve predicted fuel consumption rates equal to or less than current propeller-driven airplanes in each category, while meeting contemporary standards for all other parameters. Thus, the principal criterion for selecting the "best solutions" from the sensitivity study matrices was minimum fuel consumption. Final iterations were performed to obtain satisfactory values for airplane weights, geometry and performance characteristics of secondary importance.

The "best solution" two-seat trainer design is depicted in the three-view drawing, Figure 20. There is total consistency between this drawing, the GASP analysis results and the original baseline design stipulations. The four-seat utility three-view drawing shown in Figure 21 illustrates the simple derivation of this configuration from the trainer design. A 1.0 m (3.3 ft) fuselage "stretch" was provided, and the scaled-up wing was relocated to a conventional unswept, high-wing configuration. The four-seat high-performance derivative shown in Figure 22 is identical to the utility airplane configuration except for the retractable landing gear feature. The higher thrust engine is accomodated within the same nacelle dimensions. As with the engines, the three airplanes were configured in a manner that would ensure a high degree of design and parts commonality.

GASP-computed performance and aerodynamic data for each "best-solution" airplane are given in Table 10. The weight breakdown for each of the three airplanes is listed in Table 11, and dimensions and areas describing the respective geometries are listed in Table 12.



CABIN SECTION

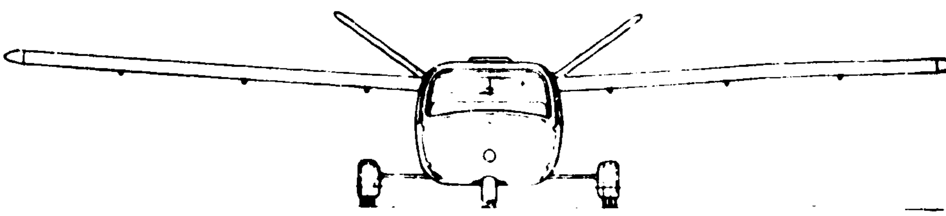


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Figure 20. "Best-Solution" Two

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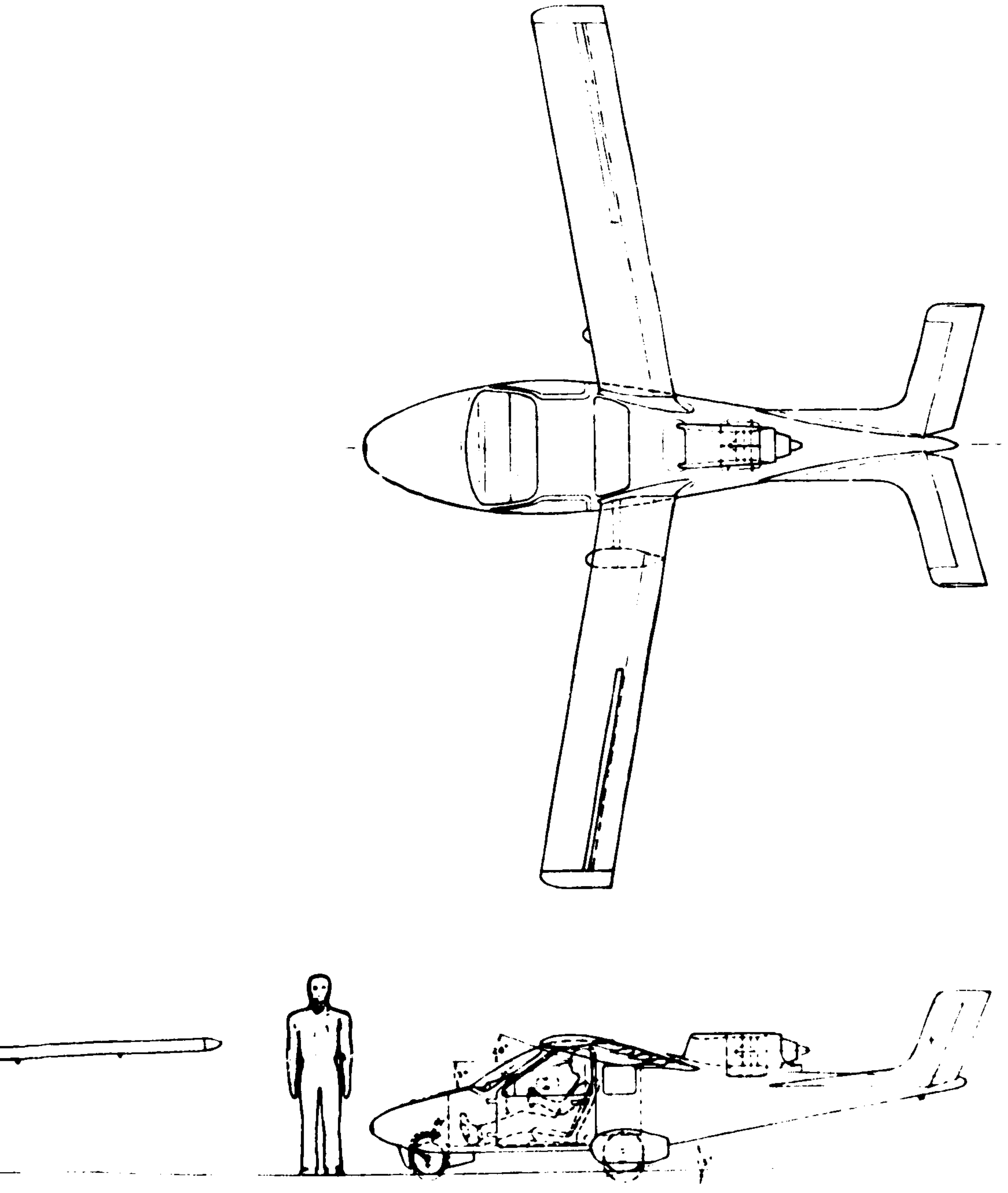
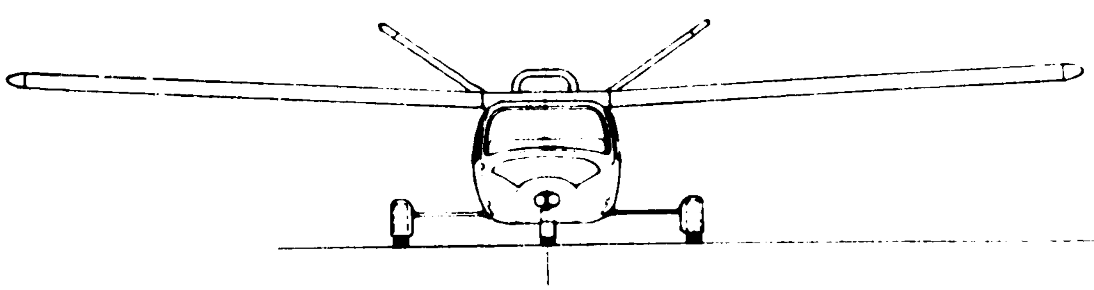
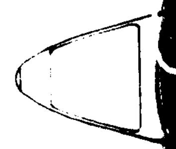


est-Solution" Two-Seat Trainer Design.





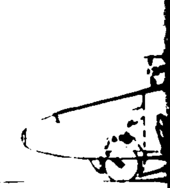


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Figure 21. Four-Seat Utility Airplane [illegible]
from Two-Seat "Best-Soluti[illegible]

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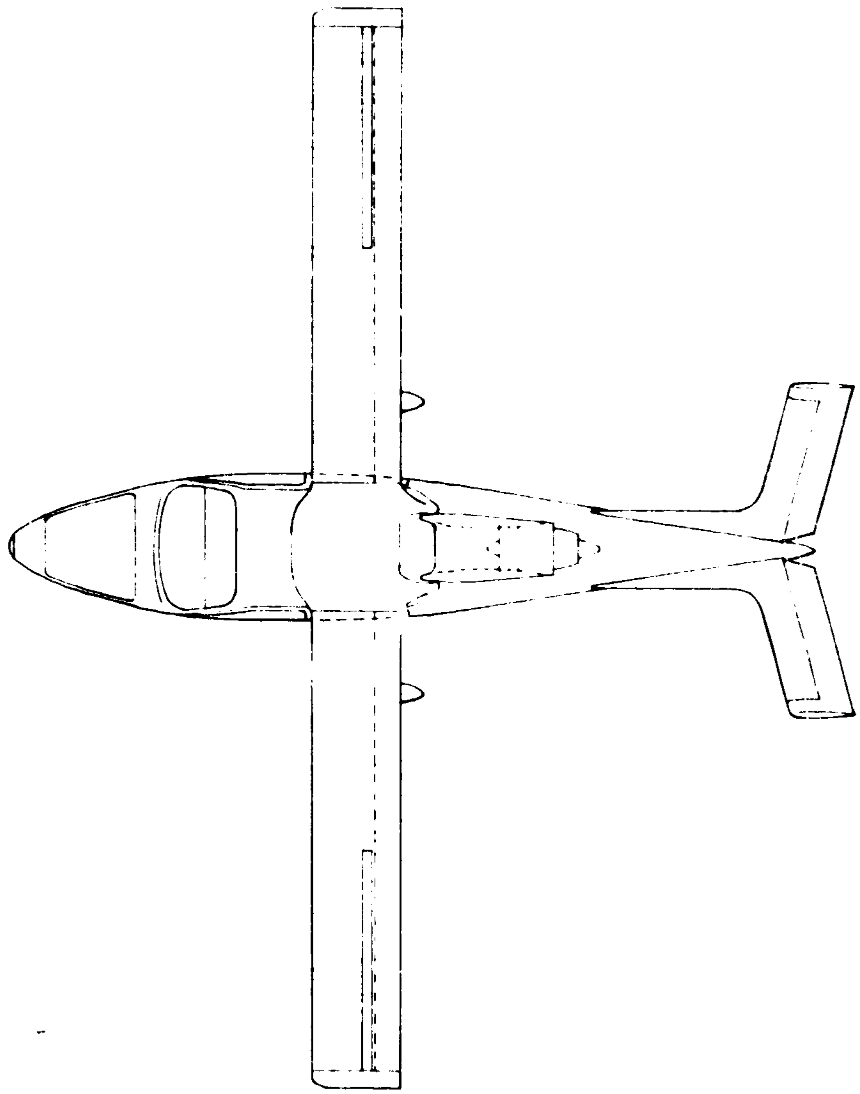

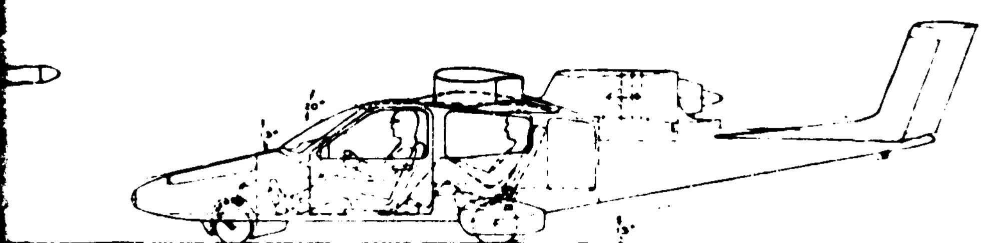

ɑt Utility Airplane Design Derived
wo-Seat "Best-Solution" Design.

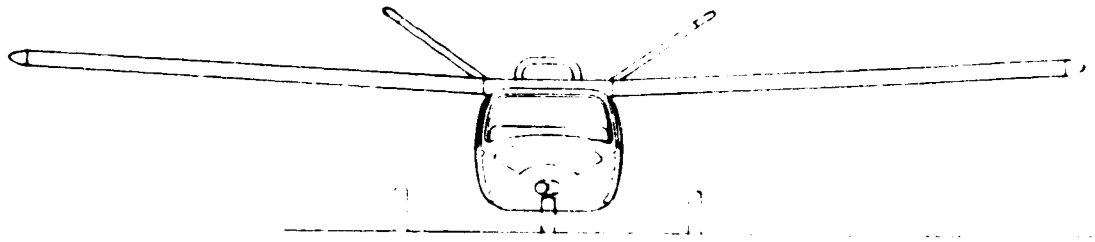

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Figure 22. Four-Seat High-Perform
of Two-Seat "Best-Solu

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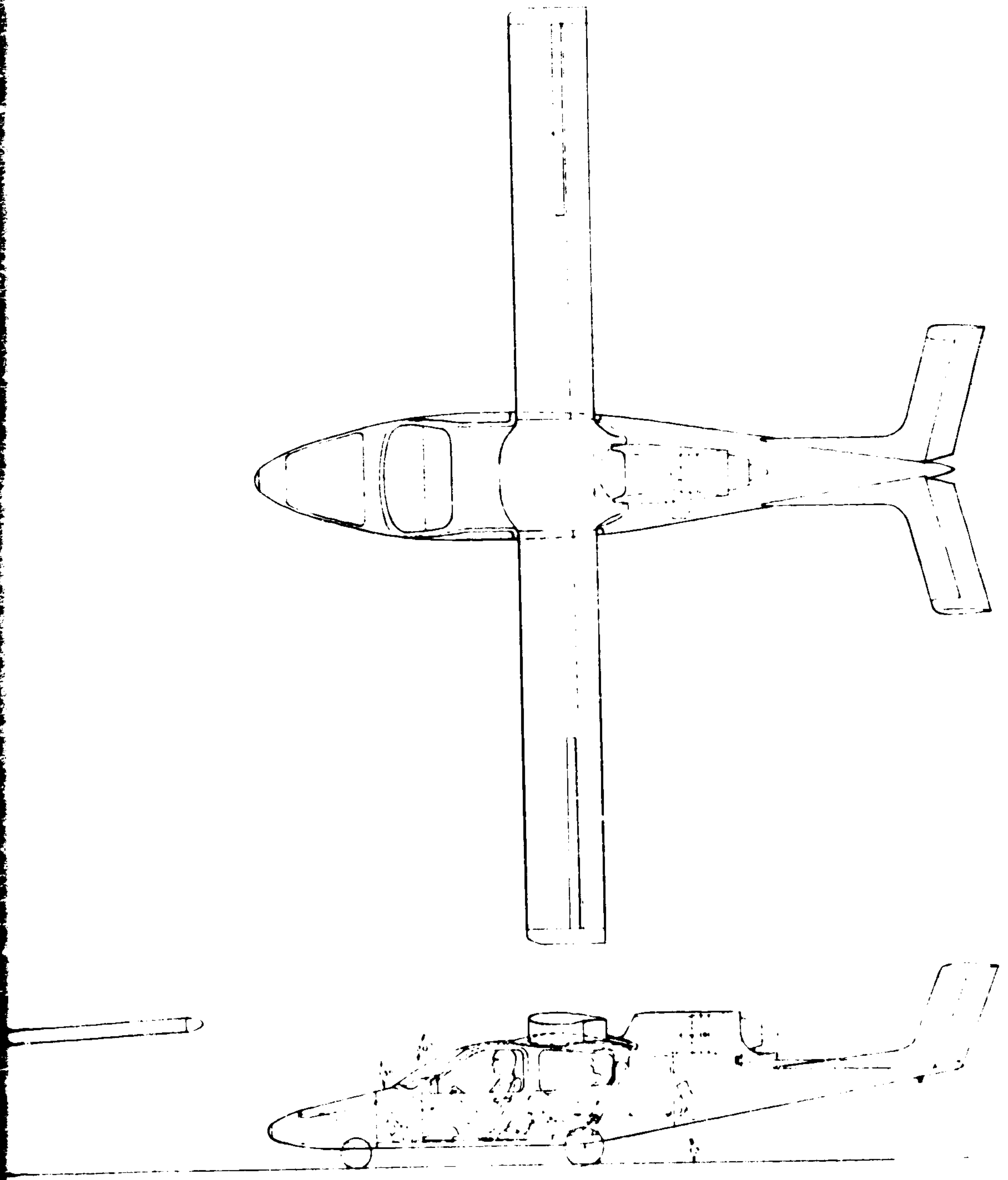

ır-Seat High-Performance Airplane Derivative
Two-Seat "Best-Solution" Design.

FOLDOUT FRAME 2

TABLE 10. GASP-COMPUTED PERFORMANCE AND AERODYNAMIC DATA ON TURBOFAN-POWERED LIGHT SINGLES

Items	Units	Two-seat Trainer	Four-seat Utility	Four-seat Hi-Perf.
Performance Data				
Specified cruise speed	km/h (mph)	201 (125)	241 (150)	322 (200)
Specified cruise altitude	m (ft)	2285 (7500)	3048 (10,000)	3048 (10,000)
Range with design payload	km (sm)	644 (400)	1287 (800)	1609 (1000)
Takeoff distance over 15 m (50 ft) obstacle	m (ft)	580 (1902)	620 (2035)	616 (2022)
Landing distance over 15 m (50 ft) obstacle	m (ft)	344 (1127)	363 (1191)	377 (1237)
Stall speed with full flaps	km/h (mph)	12.5 (45)	85 (53)	88.5 (55)
Max rate of climb at sea level	m/min (fpm)	207 (679)	384 (1260)	428 (1405)
Avg. cruise fuel consumption	l/hr (gph)	28.4 (7.5)	37.3 (9.85)	51.9 (13.7)
Fuel mileage	km/l (mpg)	7.1 (16.7)	6.46 (15.2)	6.21 (14.6)
Aerodynamic Data				
Wing loading	kg/m^2 ($lb\ ft^2$)	97.65 (20)	122 (25)	133 (27.2)
Wetted area	m^2 (ft^2)	31.5 (339)	38.9 (417)	38.8 (417)
Cruise Reynolds No./foot	million	0.974	1.094	1.458
Mean skin friction coefficient	o	0.00488	0.00445	0.00376
Effective flat plate area	m^2 (ft^2)	0.154 (1.653)	0.172 (1.855)	0.146 (1.571)
Cruise C_{DO}	o	0.0285	0.0252	0.0213
Cruise C_{Di}	o	$0.0351\ C_L^2$	$0.0351\ C_L^2$	$0.0351\ C_L^2$
$C_{L\ Max}$ with full flaps	o	3.92	3.47	3.47
Horizontal tail volume coefficient	o	1.12	1.12	1.12
Vertical tail volume coefficient	o	0.066	0.066	0.066

TABLE 11. GASP-COMPUTED WEIGHT BREAKDOWNS ON TURBOFAN-POWERED LIGHT SINGLES

Items	Units	Two-seat Trainer	Four-seat Utility	Four-seat Hi-Perf.
Propulsion group (installed)	kg (lb)	27.7 (61)	52.6 (116)	62.6 (138)
Structures group (total)	kg (lb)	157.9 (348)	235.4 (519)	249 (549)
Wing	kg (lb)	61.2 (135)	94.8 (209)	98.9 (218)
Tail	kg (lb)	12.2 (27)	19.5 (43)	20.9 (46)
Fuselage	kg (lb)	58.1 (128)	76.2 (168)	77.1 (170)
Landing gear	kg (lb)	22.7 (50)	36.3 (80)	43.5 (96)
Nacelle	kg (lb)	3.2 (7)	8.6 (19)	8.6 (19)
Flight controls group (total)	kg (lb)	10.0 (22)	15.9 (35)	16.8 (37)
Cockpit controls	kg (lb)	5.44 (12)	6.4 (14)	6.8 (15)
Fixed wing controls	kg (lb)	5.0 (11)	9.5 (21)	10.0 (22)
Fixed equipment	kg (lb)	59.9 (132)	77.1 (170)	77.1 (170)
Empty weight	kg (lb)	255.8 (564)	381 (840)	406 (895)
Design payload	kg (lb)	181.4 (400)	272.2 (600)	272.2 (600)
Maximum payload	kg (lb)	181.4 (400)	362.9 (800)	362.9 (800)
Maximum fuel	kg (lb)	88.9 (196)	181 (399)	230 (507)
Gross weight	kg (lb)	526.2 (1160)	834.2 (1839)	908.1 (2002)

TABLE 12. GASP-COMPUTER DIMENSIONS AND AREAS
ON TURBOFAN-POWERED LIGHT SINGLES

Items	Units	Two-seat Trainer	Four-seat Utility	Four-seat Hi-Perf.
Fuselage:				
Length	m (ft)	5.49 (18)	6.49 (21.3)	6.49 (21.3)
Width	m (ft)	1.22 (4)	1.22 (4)	1.22 (4)
Wetted area	m^2 (ft^2)	16.07 (173)	18.58 (200)	18.58 (200)
Wing:				
Aspect ratio	o	12	12	12
Area	m^2 (ft^2)	5.[illegible] (58)	6.84 (73.6)	6.84 (73.6)
Span	m (ft)	8.05 (26.4)	9.05 (29.7)	9.05 (29.7)
Geometric mean chord	m (ft)	0.67 (2.20)	0.76 (2.48)	0.76 (2.48)
Quarter chord sweep	rad (deg)	-0.1745 -(10)	0 (0)	0 (0)
Taper ratio	o	1.0	1.0	1.0
Thickness chord ratio	o	0.17	0.17	0.17
Horizontal tail, V-configuration:				
Area (Projected)	m^2 (ft^2)	1.29 (13.9)	1.68 (18.1)	1.68 (18.1)
Span (Projected)	m (ft)	2.58 (8.45)	2.97 (9.76)	2.97 (9.76)
Mean chord	m (ft)	0.50 (1.64)	0.57 (1.86)	0.57 (1.86)
Thickness chord ratio	o	0.010	0.010	0.010
Moment arm	m (ft)	3.14 (10.3)	3.41 (11.2)	3.41 (11.2)
Vertical tail, V-configuration:				
Aspect ratio (Projected)	o	1.71	1.75	1.75
Area (Projected)	m^2 (ft^2)	0.98 (10.6)	1.20 (12.9)	1.20 (12.9)
Span (Projected)	m (ft)	1.30 (4.26)	1.44 (4.74)	1.44 (4.74)
Moment arm	m (ft)	3.14 (10.3)	3.41 (11.2)	3.41 (11.2)
Nacelle:				
Length	m (ft)	0.98 (3.2)	1.22 (4.0)	1.22 (4.0)
Wetted area	m (ft)	3.06 (10.05)	5.33 (17.5)	5.33 (17.5)

Comparisons were made of the data in these tables with data on several currently-produced airplanes of similar performance and utility categories. Each of the turbofan-powered designs exhibited much lower weights than the current airplanes. Gross weights ranged from 24 to 41 percent lower, reflecting 44 to 58 percent lower empty weights with comparable useful loads. Lower propulsion system weights, from approximately 40 to 75 percent, accounted for a large portion of the empty weight differences. However, the greatest differences occurred in the airframe weights, the turbofan-powered airframes being 38 to 50 percent lighter than the current piston-engined airframes. The airframe weight differences can be attributed to the synergistic or compounding effects of the much lighter turbofan propulsion systems, and dramatically smaller wings of the turbofan-powered designs. Although the aspect ratio is typically 60 percent greater, the wing spans were found to be lower by a ratio approximately equal to the ratio of gross weights, thus reducing wing root bending moments. The area differences resulting from both smaller spans and shorter chords, together with lower gross weights, were shown by several preliminary wing-weight estimating formulas to account for the lighter wings. Lighter landing gears, of course, resulted from the lower gross weights, and also from having GASP calibrated with a lightweight, tubular steel gear from an airplane currently in production.

Comparisons of cruise fuel consumption and fuel mileage showed the two-seat trainer to be about 30 percent worse than a current popular piston-engined trainer having similar performance. Late in the study, further analysis indicated that with minor changes in the turbofan cycle characteristics, equal fuel mileage could be achieved. The four-seat utility airplane was found to have equal fuel consumption, and the four-seat high-performance design to have 10 to 20 percent lower fuel consumption than current piston-engined airplanes in their respective performance classes. Published surveys indicate that jet fuel prices currently average 15 percent less than aviation gasoline prices. Together with fuel mileage improvements, the study airplanes were shown to have potential for reducing seat-mile fuel costs up to 35 percent.

It was not possible to carry out in-depth cost analyses in this conceptual design study. However, a cursory examination of cost-related factors was made to ascertain the potential for economic viability of future light-airplane turbofans. As stated previously, it is expected that the major technical challenge will be the achievement of acceptable engine costs. The results of this airplane design investigation have shown that the inherent qualities of turbofans can contribute to this achievement by reducing other elements of airplane cost.

The lower airframe structural weights and smaller airframe component dimensions exhibited by the study airplanes could result in substantial airframe material and labor cost savings versus equivalent piston-powered types. These savings could be used to offset higher engine costs or to reduce the price of the airplanes if engine cost parity were achieved. The GASP cost analysis techniques, based on cost/weight correlations, were used to estimate the engine costs that would result in airplane price parity for each type. An engine costing about $5000 was found to yield a trainer airplane price equal to that of a popular piston-powered trainer. Similarly, a $6000 engine for a four-seat utility airplane and a $12,000 engine for the high performance airpland would result in price parity with comparable airplanes. These figures, of course, are higher than the current prices paid for piston engines for equivalent airplanes, but are substantially lower than for the smallest turbofan yet produced.

In addition to fuel cost savings, other potential operating cost advantages were identified for the study airplanes. For example, the overhaul period (TBO) of mature, light airplane turbofans can be expected to greatly exceed those of piston engines. Selection of modest cycles and conservative designs for future turbofans could ensure that advantage. In addition, the elimination of propeller maintenance and overhaul is a significant cost reduction, particularly on higher-performance airplanes using variable-pitch, constant-speed propellers. A further example relating to maintenance cost is the gradual deterioration of airplane secondary structure that results from engine vibration. The high-amplitude vibratory characteristics of the piston engine/propeller system produces large resonances in the lightweight structures typical of light aircraft. This eventually results in deterioration and increased maintenance burdens. The very low vibration level of turbofans is clearly advantageous, and could contribute to longer airframe life as well as lower maintenance costs.

The main purpose of the study of light singles was to define the engine and airplane design characteristics that would together provide low fuel consumption at the low end of the general aviation performance spectrum. The conceptual design results shows that low fuel consumption is possible with modest engine cycle quality and a high-quality wing design. It may become desirable to adopt turbofan propulsion for widespread use in general aviation to meet environmental regulations, to improve performance, or simply as a product enhancement measure. The study series results show that it can be done across the performance spectrum without sacrificing the high efficiency in fuel usage exhibited by today's light aircraft.

PHASE II - DETAILED EVALUATION OF ENGINE DESIGN

The sensitivity of airplane ownership cost to engine performance quality is an important consideration in high-performance airplanes having high utilization rates. The definition of an engine that is optimum with respect to ownership cost requires that the engine and airplane size, performance and cost interrelationships be determined through sensitivity analyses. Variations in engine parameters such as fan and core pressure ratios and turbine inlet temperature affect engine specific fuel consumption, specific weight and installed drag. In turn, the variations have important impact on airplane size, first cost and direct operating cost. Tradeoff analyses are required between the offsetting effects of fuel efficiency, weight, drag and engine cost. The determination of parameters that minimize airplane fuel consumption is of paramount importance in defining engines for high-performance business airplanes. At a utilization rate of 1000 hours per year, the cost of the fuel an engine consumes in one year approaches the original cost of the engine. Thus, a modest improvement in fuel consumption accompanied by a substantial engine cost increase can be a cost-effective tradeoff, yielding significantly lower overall ownership cost.

In contrast, the ownership cost of lower performance airplanes such as the light singles classes considered in this study is much less sensitive to the rate of fuel consumption. At the lower utilization rates typical of light airplane operation it could require five to ten years worth of fuel bills to equal the original engine cost. The original engine cost, as reflected in the price of the airplane therefore has much greater impact on ownership cost.

The optimization methods used in the definition of the turbofans for this study are considered to have provided adequate fuel efficiency predictions for the study airplanes. Having achieved fuel consumption rates equal to, or better than, current piston-engine powered light singles, it was decided to forego detailed synthesis sensitivity and tradeoff analyses on the effects of turbofan engine cycle parameter changes. It was determined that with the exception of a brief review of turbofan environmental and safety characteristics, a better course was to concentrate the remaining study effort on the turbofan engine commonality and family concept investigation. This course provided a unique opportunity to investigate the potential for significant engine cost reduction.

Chemical Emissions And Noise Analyses

The development of modern, high-bypass-ratio turbofans has been marked by the attention paid to the attainment of environmental compatibility. The achievements to date have been facilitated by the inherent qualities of the gas turbine generally and the turbofan specifically. By operating well below stoichiometric fuel-air ratios, the emissions of unburned hydrocarbons (UHC) and carbon monoxide (CO) can be held to low levels compared with emissions from contemporary piston engines. Being an internal-momentum-change engine, the turbofan lends itself to design manipulation of noise-generating sources and to inlet and exhaust duct treatments that can yield very low noise levels.

In order to classify aircraft gas turbine engines with regard to emissions, the Environmental Protection Agency (EPA) has defined "Class P2" as all aircraft turboprop engines. This class includes a broad range of engine sizes, cycle parameters, and engine and combustor configurations. All of these factors influence emissions. Combustion system modifications which bring one engine model into compliance with the EPA standards may not be satisfactory for other engines in the Class P2.

Oxide of nitrogen (NO_x) emissions from the AiResearch TPE331 Turboprop Engine family are within the 1979 EPA standards. Although unburned hydrocarbon (HC) and carbon monoxide (CO) emissions do not currently meet the standard, the results of a broad-based AiResearch development program have shown that compliance can be achieved. By operating on the primary fuel atomizers alone during taxi-idle conditions, the emission level of this group of engines is within the EPA limits. It is interesting to note that, because combustion efficiency is improved by this operating technique, the engine fuel consumption during the EPA "landing-takeoff" cycle is reduced five percent.

Under a contract with NASA Lewis Research Center, AiResearch is examining three approaches for emissions reduction for the EPA "Class T1" engines using the TFE731-2 Turbofan Engine as the test vehicle. This class includes all turbojet and turbofan engines (except those designed to operate at supersonic speeds) of rated power less than 35.6 kN (8000 lb) thrust. The three concepts addressed in this research program are:

(a) Minor modification of the existing combustion system (including production fuel nozzles with external air assist, pre-combustor bleed, water-methanol injection, radially-inserted airblast nozzles, circumferentially-staged combustion, etc.).

(b) Incorporation of combustor-dome-mounted airblast fuel nozzles requiring significant combustor redesign.

(c) Incorporation of a premix/prevaporized fuel system requiring radical combustor redesign.

Approximately 30 percent of the test program has been completed to date. Based on available test data and rig-to-engine data correlations, it appears that the minor modifications concept will require water-methanol injection to meet the HC, CO and NO_x standards. However, the ability to meet the visible smoke limit with this method is marginal. In addition, the installation and logistics problems associated with this method are undesirable.

The second concept will meet the HC emissions requirement, while the smoke number is very low. However, CO emissions are marginal and the required NO_x reduction has not been demonstrated. At the time of this writing, tests have not been carried out on the third concept. However, it is expected that the planned tests will demonstrate promising results with the premix/prevaporized fuel system.

It was previously pointed out that the small size and low cycle pressure ratios of the study engines were detrimental factors. Thus, considerable development effort might be required to achieve emissions levels below the EPA 1979 T1 standard. The absolute emissions levels allowed by the standard were calculated for the 961 N (216 lb_f) two-seat trainer engine. For comparison purposes, the levels applicable to a 100 hp piston engine that powers a current trainer of similar performance were also calculated. The interesting result was that, when both engines meet the applicable EPA limits, the turbofan would have from 2 to 22 times lower emissions. Table 13 lists the values that were calculated by the procedures specified in the EPA standard (Ref. 11). Both the requirements of the standard, and the calculated values reflect the inherently different emission qualities of the two engine types.

The noise characteristics of the study engines were evaluated and were found to be well within the limits of requirements applicable to future light aircraft. The four-seat utility turbofan noise signature was calcula[illegible] to be below the Federal Aviation Regulation (FAR) Part 36, Appendix [illegible] limit for propeller-driven light aircraft. Without acoustic attenuating treatment, the noise level was predicted to be 2.3 dB(A) below the limit at the applicable airplane gross weight, and approximately 6 dB(A) below the limit applicable to a heavier, equivalent-performance, propeller-driven airplane. These points and the Appendix F limits are plotted in Figure 23. Based on this analysis, both the two-seat trainer engine and the four-seat high-performance engine are projected to have noise signatures lower than the applicable requirements. Further reductions in noise signatures would be possible

TABLE 13. QUANTITATIVE COMPARISON OF CHEMICAL EMISSION LIMITS APPLICABLE TO PISTON AND TURBOFAN TWO-SEAT TRAINER ENGINES.

	74.6 kW (100 hp) Piston Engine	961 N (216-pound thrust) Turbofan Engine
Allowable HC, kg/cycle (lb/cycle)*	0.086 (0.19)	0.0145 (0.032)
Allowable CO, kg/cycle (lb/cycle)*	1.90 (4.20)	0.0852 (0.188)
Allowable NOX, kg/cycle (lb/cycle)*	0.068 (0.15)	0.0336 (0.074)

*Landing-takeoff cycle defined by CPA standard (Reference 11).

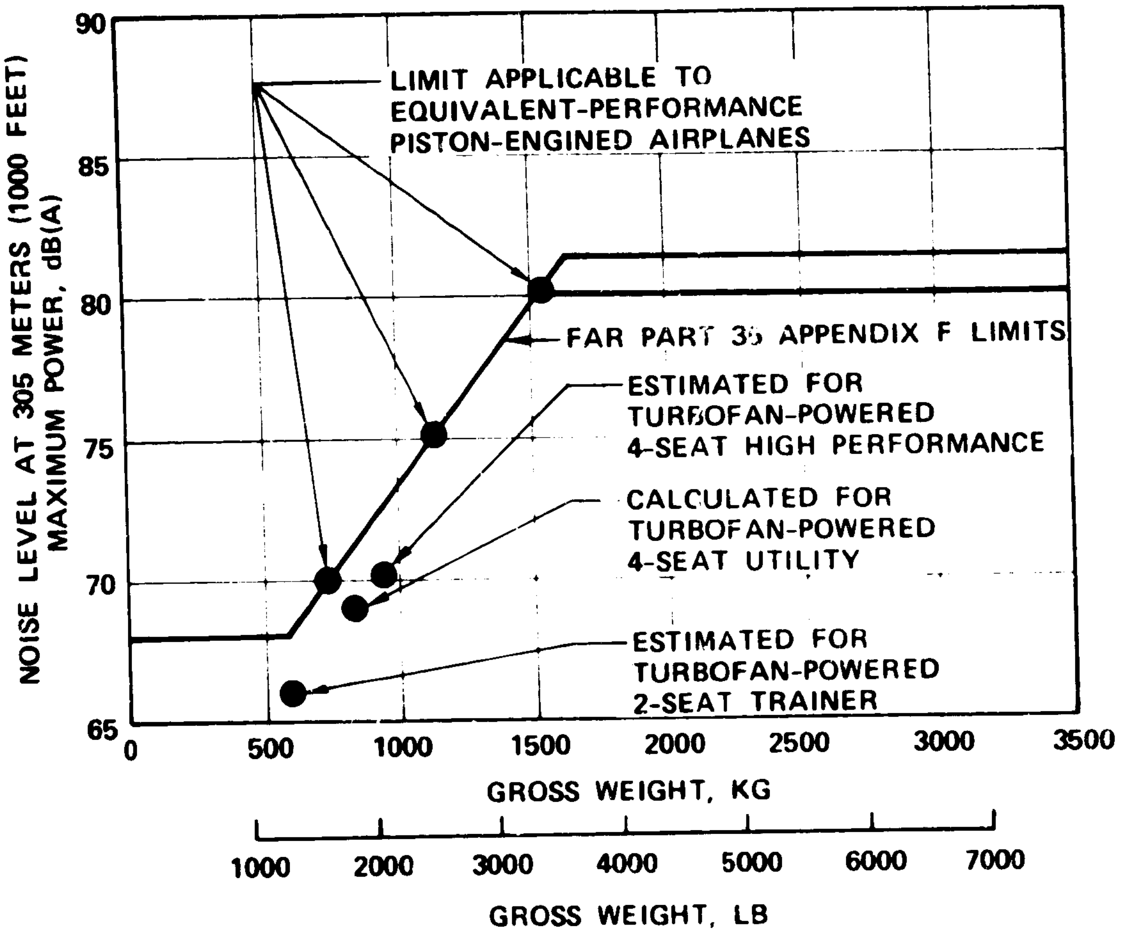

Figure 23. - Calculated noise level of turbofan-powered 4-seat utility airplane and FAR Part 36 Appendix F limits.

by employing attenuating treatment in the nacelles. It is concluded that, with additional acoustic research and development effort, the potential exists for reducing turbofan powered light airplane noise signatures to values significantly below the current and proposed FAR Part 36 requirements, for both propeller-driven and jet aircraft.

Turbofan Added-Safety Characteristics

In reviewing the conceptual design results of the light singles study, the potential of turbofans for added safety was examined. The fundamental design, operational and installation characteristics of the small turbofans would differ greatly from those of the current light-airplane propulsion systems. Several safety-oriented factors were identified that relate to these characteristics:

(1) The kerosene-based jet fuel used in gas turbine engines has lower volatility and lower flash point than aviation gasoline and thus reduces fire hazards.

(2) The efflux from a turbofan has negligible swirl compared with propeller efflux, thus reducing adverse torque effects that can contribute to aircraft control hazards.

(3) Because of its comparatively small size and light weight, the installation flexibility and low inertia of the turbofan can be used to effect more crashworthy airplane configuration alternatives.

(4) The lighter weight of both engine and airframe in the study airplane results indicates that greater use could be made of energy-absorbing material in cabin construction with smaller penalties in cost and performance.

(5) With turbofans, the ground-operations hazard of an exposed propeller is eliminated.

(6) Pilot work-load is reduced, with single-lever power management and automatic control of engine operating limits.

(7) The turbofan can contribute to reduced pilot fatigue with lower cabin noise and vibration levels.

Government regulations and certification requirements complemented by manufacturer's quality assurance standards, ensure that no significant differences may exist between engine types with respect to integrity and reliability. The safety advantages cited for turbofans result from inherent, fundamental differences. No attempt was made in this study to quantify these advantages. thus, it is not possible to predict their potential for net effects on general-aviation safety.

PHASE III - ENGINE COMMONALITY AND FAMILY CONCEPT STUDY

Basic Criteria

In the complete turbofan study series, which includes References 1 and 3 as well as this report, the engines cycles and configurations have been each defined to have best performance and maximum cost-effectiveness at each of the specified airplane performance levels. The cruise speed specified for the study airplanes ranged from 161 to 648 km/h (125 to 403 mph) at altitudes from 2286 to 7315 m (7500 to 24,000 ft). The conceptual designs were to carry from two to six people over ranges from 643 to 1851 km (400 to 1151 sm). The specified equipment ranged from a basic Instrument Flight Rule (IFR) package in the two-seat trainer to a full complement of "jet standard" avionics in the pressurized, high-performance twin. The study airplanes thus spanned the spectrum of performance capabilities exhibited by the currently-produced light airplanes.

Although the engine sizes, cycles and configurations derived in the studies varied, a review of the characteristics of each engine revealed that commonality potential exists. With a high degree of design and parts commonality there would be potential for substantial cost reduction if the engines were in concurrent production.

Such commonality is found to exist in the light airplane piston-engine families that have been produced in large quantities over the past 40-year period. These families span the broad range of power, performance and cost requirements that are characteristic of the light airplane propulsion market. An example of these diverse requirements is the use, by just one light-airplane manufacturer, of many engine models ranging from 100 shaft horsepower to approximately 2000 gas horsepower. It can be concluded that the large number of models produced and the commonality in design, parts and manufacture achieved in the piston-engine families are the factors largely responsible for their cost-effectiveness, and in turn, for the large market they enjoy.

It is reasonable to assume that turbofans must eventually exist in sizable engine families to be viable candidates for powering the full spectrum of future general-aviation, light airplanes. In the final study phase, emphasis was placed on examining an engine family concept based on the engine configuration selected in the light-singles study. The commonality potential between family members was readily identified. However, due to the limited scope of this conceptual study, the cost reduction benefits could not be quantified.

Candidate Turbofan Family

To derive a rational family of engines it was necessary to examine the size, performance, and cost requirements exemplified by the current light airplanes. It was also necessary to examine the characteristics of the several turbofans defined in the study series in order to identify those of fundamental importance in each class studied. The engines for the two- and four-seat singles, the military trainer engines in the 460 km/h (285 mph) class, and the 650 km/h (400 mph) high-performance, six-seat twin engine each provided a reference point in the matrix of engine requirements.

A generalized matrix of airplanes was first defined to be responsive in size and performance to the current market. The basic characteristics that set the airplanes apart are the number of seats, the number of engines, and the cruise speeds. The current market has obvious gaps with respect to these characteristics, some of which will be filled by future offerings. For the purpose of this study, liberty was taken in filling an occasional gap with an airplane addressed to a projection of future requirements. Two high-performance, pressurized, single-engine airplanes that were predicted are examples that could appear in the future as manufacturers product lines are filled out in response to market demands.

Seating capacity characterizes basic airframe size. With two-abreast seating, fuselage width varied from under 1.22 m (4 ft) to about 1.37 m (4.5 ft) depending on aisle width requirements. Fuselage height can vary from 1.07 m (3.5 ft) to as much as 1.5 m (5 ft), but is primarily a function of the height of a seated man. With about 0.9 m (3 ft) per seat row required, the number of seat rows is the principal variable that determines fuselage length. In this manner, the seating capacity substantially defines the fuselage, and in turn, is a large determinant of airplane weights, wing size and the consequent drag polar.

It was found from the study results that basic engine frame size could be correlated with the number of seats. For low-, intermediate-, and high-speed airplanes with the same seating capacity, it was found that the different thrust levels required could be generated within the same engine flow-path dimensional areas. With fan pressure ratio, core pressure ratio, and bypass ratio each varied as a function of design cruise speed, the corrected airflows through major engine components can be held to nearly the same values for each required thrust level. Thus, a first commonality feature was identified for the candidate engine family. That is, major engine components such as frames, ducts, casings, and the like, can be common to three engines having substantially different cruise thrust ratings.

Unlike the piston engine, the specific fuel consumption of a turbofan can be varied to suit the airplane performance envelope. Cycle quality can be a trade-off quantity versus engine weight, cost, and various installation-related parameters. The thermal efficiency of a turbofan is mainly a function of cycle pressure ratio. In a conventional front-fan arrangement, the cycle pressure ratio is the product of fan pressure ratio and the core pressure ratio. When fan pressure ratio is chosen to maximize propulsive efficiency for the desired cruise speed, the core pressure ratio can be varied in consideration of the thermal efficiency and the attendant trade-offs. The choice of core pressure ratio determines the amount of core-engine turbomachinery, and bears directly on the weight, complexity and cost.

The determination of a best core pressure ratio that maximizes the cost-effectiveness of the airplane involves evaluation of the interrelationships between engine and airplane size, performance, and cost factors. Throughout the general aviation turbofan studies, the determination of best core pressure ratio was a principal issue. This important parameter was evaluated by performing synthesis sensitivity and trade-off analyses with the use of GASP. The GASP analysis results show that best core pressure ratio is principally a function of airplane cruise speed. For example, at low cruise speed, airplane fuel consumption is naturally low, because the power required is low. Low-speed airplanes designed for utility functions are comparatively low in price. Furthermore, utilization rates are typically low in utility service. Therefore, a lower engine and airplane cost is a more important factor in ownership cost than is the rate of fuel consumption. In the study of light singles, it was shown that very modest cycles provided low fuel consumption, commensurate with or better than today's fuel-efficient light airplanes. At high cruise speed, high power is required and fuel consumption is consequently high. Fast, expensive airplanes are typically used at higher utilization rates. Thus, the cost of fuel becomes a more significant factor in total cost of ownership. Higher priced, more efficient engines become cost-effective, as was shown in the results of the 650 km/hr (400 mph) light-twin study.

In summary, a basic rationale was developed for a responsive candidate engine family:

(1) Basic engine frame size or through-flow capacity is a function of the number of seats or airplane cabin size.

(2) The engine performance quality (the fan pressure ratio for propulsive efficiency and core pressure ratio for thermal efficiency) is a function of airplane cruise speed.

To define the specific engine characteristics, it was first necessary to rationalize the light, propeller-driven airplanes into size and performance categories, with pertinent increments between categories. With respect to size, the current fleet consists of two-, four-, and six-seat singles. The twin-engine fleet consists of four-, six-, and eight- to ten-seat airplanes. The larger turboprop twins, with capacities up to 22 seats and gross weights in the 4080 to 5670 kg (9000 to 12,500 lb) category, were considered to be a unique market outside the scope of the study.

With respect to speed, there is a veritable spectrum of speeds represented in the current airplanes, from about 201 km/h (125 mph) to 560 km/h (350 mph). The scatter that results from varying attainments in individual designs can, however, be eliminated. The speeds can be rationalized into utility, intermediate, and high-performance categories, with differences between singles and twins resulting from necessary power-loading differences.

Table 14 provides a list of designations assigned to the engine/airplane size and performance categories identified. These designations are used throughout the following description of the engine family characteristics.

In Table 15 the applications, thrust level, and estimated 1990 market potential are given for a candidate 10-engine family. In the applications identified for each engine, the basic airplane characteristics are defined. Number of engines, number of seats, landing gear configuration, and cabin pressurization are considered the basic variations that determine airplane size and price class. The first three engines in the list are those defined in the light-singles study, and the remaining engines are derivatives from these.

The derivation formula is that defined in the light-singles study--that is, the variations in engine frame size are achieved by scaling the engine aerodynamics, with the basic engine cycles remaining constant. The variations of performance quality are achieved by adjusting fan pressure ratio according to flight speed and by "zero staging" the core compressor. In adding "zero" stages to the front of the core compressor, the pressure ratio, the airflow, and the power level are all increased as functions of the stage pressure ratio.

The thrust levels given beyond the three light-singles engines are approximate values that would result from the scaling and uprating increments chosen. They are, of course, values appropriate to the thrust requirements of the airplanes for which they are intended.

TABLE 14 - TURBOFAN ENGINE FAMILY DESIGNATIONS

Frame Size Designations:

I	For Two-Seat Airplanes
II	For Four-Seat Airplanes
III	For Six-Seat Airplanes
IV	For Eight + Seat Airplanes

Performance Quality Designations:

U	For Utility Class Airplanes
IP	For Intermediate-Performance
HP	For High-Performance

TABLE 15 - CANDIDATE 10-ENGINE FAMILY

Designation	Application (2)		Thrust (SLS)	1990 Market Potential
	Singles	Twins		
I (1)	2	-	960 N (216 lb)	5915
II-U (1)	4	4R	1797 N (404 lb)	8991
II-IP (1)	4R	4R	2082 N (468 lb)	5087
II-HP	4RP	4RP	2447 N (550 lb)	2027
III-U	6	6R	3062 N (675 lb)	2361
III-IP	6R	6R	3492 N (785 lb)	626
III-HP	6RP	6RP	4092 N (920 lb)	918
IV-U	-	8 + RP	4448 N (1000 lb)	1617
IV-IP		8 + RP	5160 N (1160 lb)	1217
IV-HP		8 + RP	6005 N (1350 lb)	1152

(1) Engines in this study.

(2) "2, 4, 6 and 8+" = No. of seats: "R" = Retract Gear; "P" = Pressurized

The projected 1990 market potential was derived by regrouping and projecting the figures in Table 16 for recent annual airplane deliveries. The quantity given for each engine class is an extrapolation at the overall general aviation unit production growth rate experienced over the past 20 years. Thus, the quantities do not reflect the growth-rate variations between classes that are likely to occur. However, the table is given to provide a perspective on the relative production quantities that could exist between the 10 engines. Together with the size and performance-quality variations between engines, the relative quantities would have significant effects on engine cost variations. These figures also highlight the significance of the small engines as a high-production base for the family.

Selected characteristics of a generalized, conceptual airplane family are presented in Figures 24 through 27. In each figure, the data has been plotted against airplane seating capacity and engine frame size. Although a degree of rationalization was used in establishing the bounding limits of the airplane performance values, effort was made to ensure the consistency and accuracy of the intermediate increments of all derived data. For example, performance and size differences between the singles and twins, using the same engines, reflect their installed power differences due to the single-engine climb requirements of twins.

The results of the light singles and high-performance light twin studies were used as baselines in the development of the engine and airplane families. Thus, the airplane aerodynamic qualities and engine cost-effectiveness characteristics established in those studies are inherent in the families. For example, all the airplanes were assumed to have wings sized for optimum wing loading, with 12 aspect ratio and full-span Fowler flaps.

An iterative procedure was used in developing the data on the engine/airplane family. First, engine scaling and uprating increments were selected, with cycle and performance quality varying as direct functions of the increments. Spot checks were then made on several airplanes in the desired family to ascertain the applicability of the appropriate engines. The preliminary design method developed in the light twin study (Ref. 1) was used to evaluate the airplane gross weights and thrust requirements for selected cruise speeds and ranges. Cruise speeds, gross weights, and engine sizes were then adjusted iteratively to achieve consistency in interrelated parameters such as fan pressure ratio and cruise speed, takeoff thrust and gross weight, engine cruise thrust and airplane drag at altitude for best lift/drag ratio. This ensured that each engine/airplane solution in the projected family was near optimum with respect to minimum size and fuel consumption--the factors having greatest impact on cost-effectiveness.

TABLE 16. AVERAGE ANNUAL DELIVERIES OF PROPELLER-DRIVEN AIRPLANES IN 1972-74 PERIOD BY U.S. MANUFACTURERS

Airplane Class (1)	Units	Price Range, $
Two-seat FG Singles: 74.5 - 112 kw (100-150 hp)	2,751	10,700 - 18,995
Four-seat FG Singles: 112 - 134 kw (150-180 hp)	2,896	16,055 - 26,535
Four-seat RG Singles: 134 - 149 kw (180-200 hp)	764	26,500 - 33,500
Four-Six-Seat FG Singles: 171 - 223.5 kw (230-400 hp)	1,809	25,700 - 42,725
Four-Six-Seat RG Singles: 212 - 223.5 kw (285-300 hp)	828	38,990 - 59,000
Four-Six-Seat Twins: 149 - 186 kw (200-250 hp)	643	63,300 - 88,200
Four-Six-Seat Twins: 194 - 216 kw (260-290 hp)	695	89,000 - 198,000
Six-Eleven-Seat Twins: 223.5 - 325 kw (300-435 hp)	678	138,000 - 241,000
Six-Twenty Two-Seat Twins: 410 - 633 kw (550-850 hp)	285	459,000 - 815,000
Total	11,349	

(1) FG = Fixed gear; RG = Retractable gear.

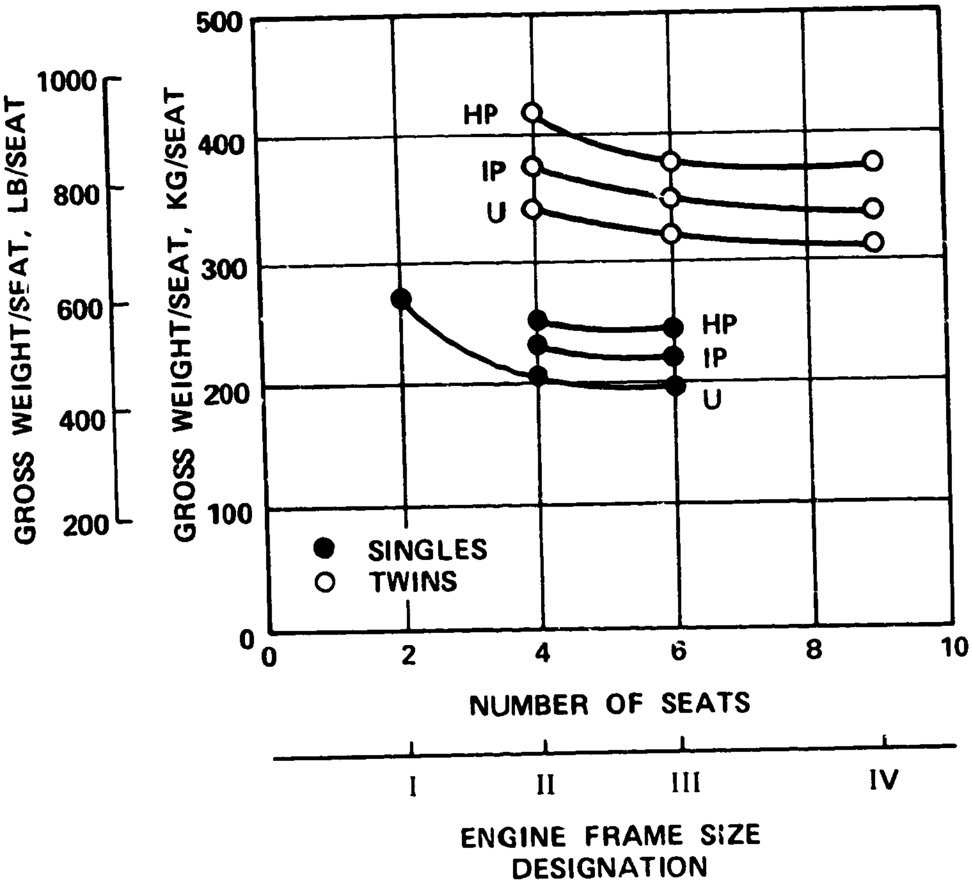

Figure 24. - Airplane gross weight per seat versus number of seats and engine frame size.

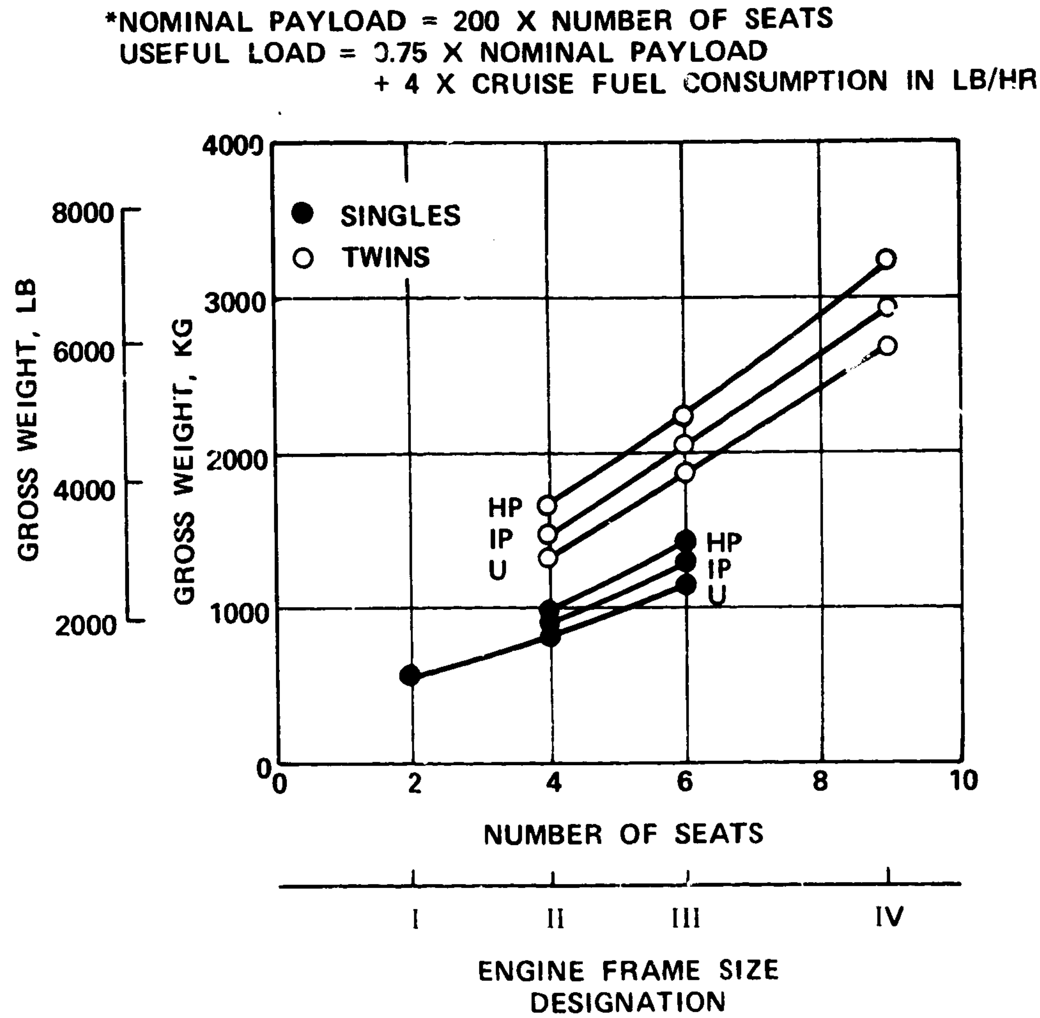

Figure 25. - Airplane gross weight versus number of seats and engine frame size.

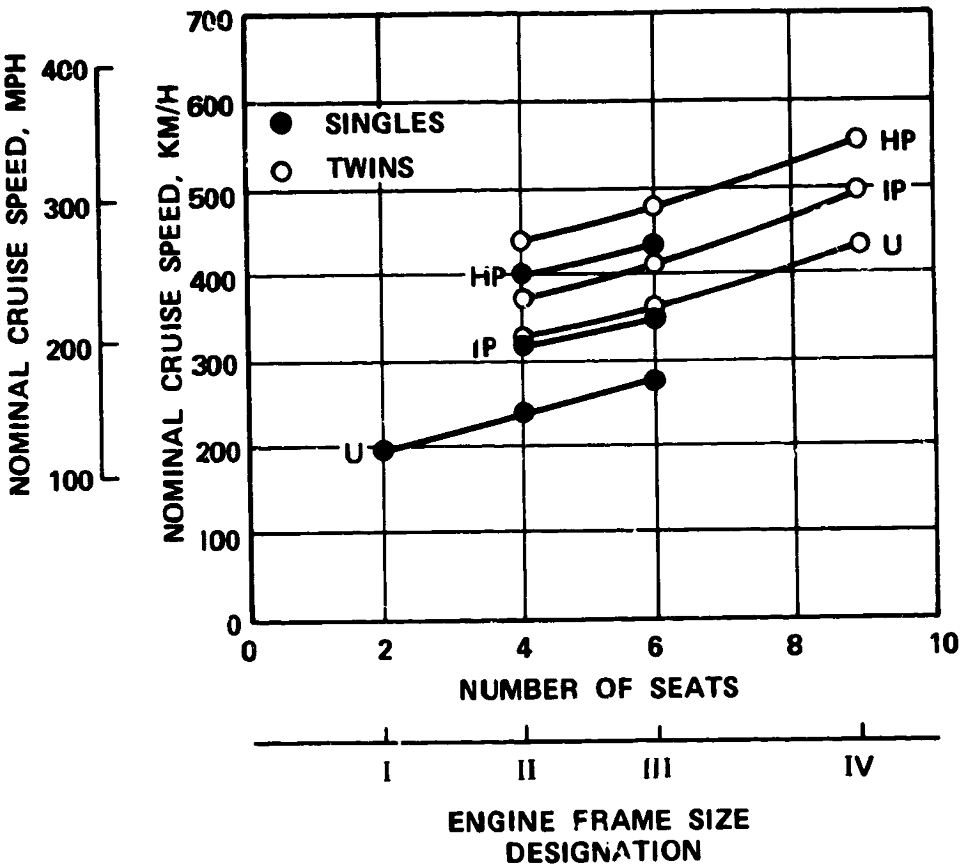

Figure 26. - Airplane cruise speed versus number of seats and engine frame size.

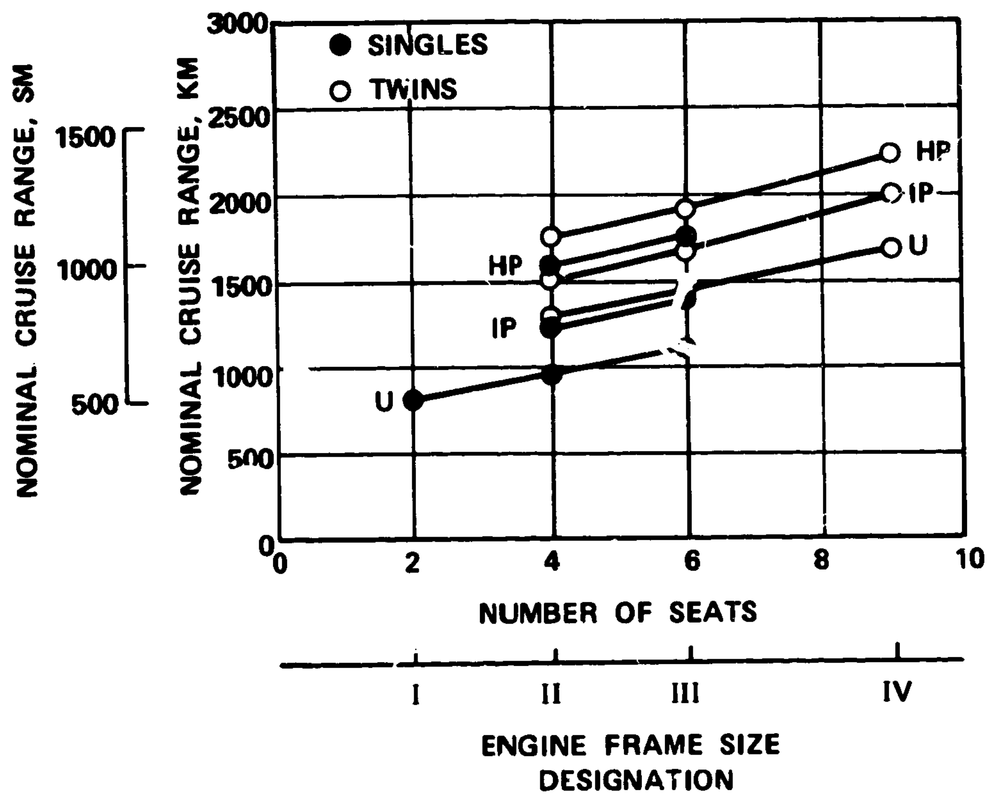

Figure 27. - Airplane cruise range versus number of seats and engine frame size.

Figures 28, 29 and 30 define the engine size characteristics and are self-explanatory. Figure 31 relates applicable cruise conditions to the three engine-performance-quality designations. Figures 32 and 33 give the cycle parameters chosen to be responsive to the requirements for cost-effectivenes in each performance class. Figure 34 shows the resultant engine cruise performance levels anticipated, in terms of specific fuel consumption and specific thrust.

The derivation of a candidate 10-engine family was intended to be an example of a comprehensive approach to the solution of the turbofan cost problem. It has illustrated that turbofan design elements can be manipulated in desirable increments to give a broadly applicable family having high commonality in design and parts. It cannot be claimed that the choice of aerodynamic componentry or that the scaling and "zero" staging methods employed in defining the family member relationships are ideal solutions. Other component configurations and family derivations that appear equally viable should be explored in depth in order to identify the most cost-effective alternative. This example clearly has shown, however, that derivation of a responsive turbofan family, completely analogous to existent piston-engine families, can be accomplished.

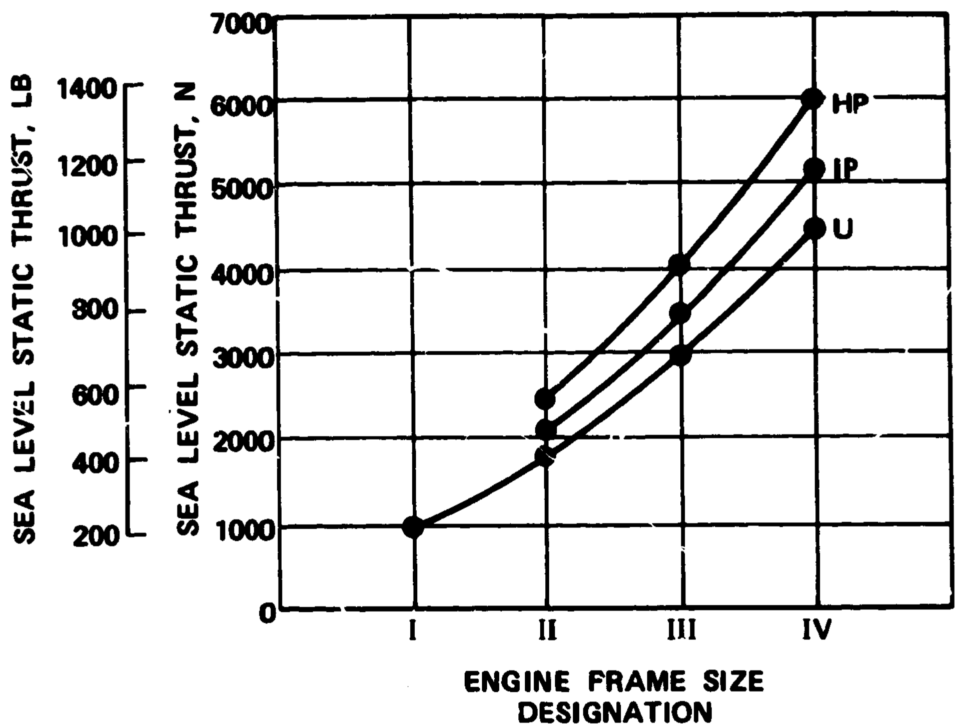

Figure 28. - Sea level static thrust versus engine frame size.

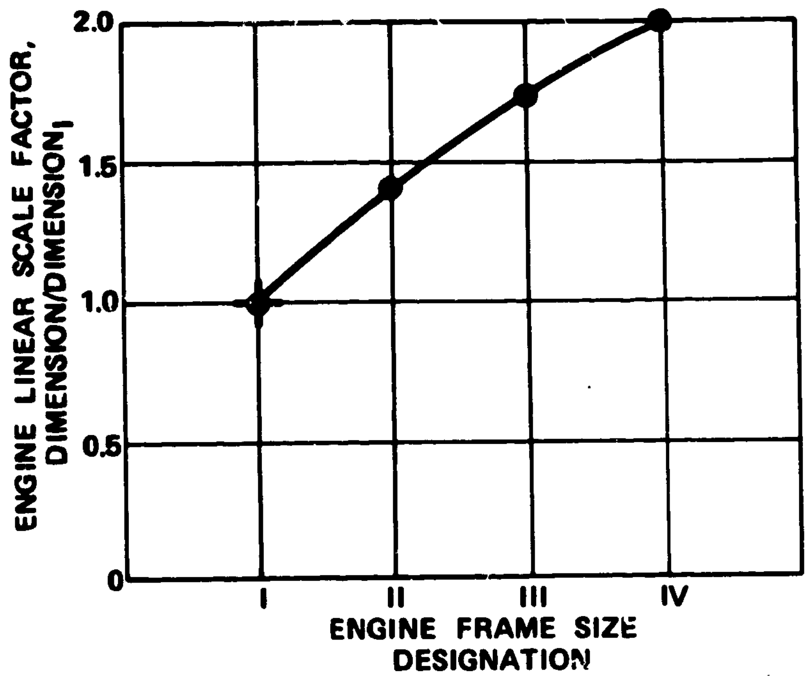

Figure 29. - Linear scale factor versus engine frame size.

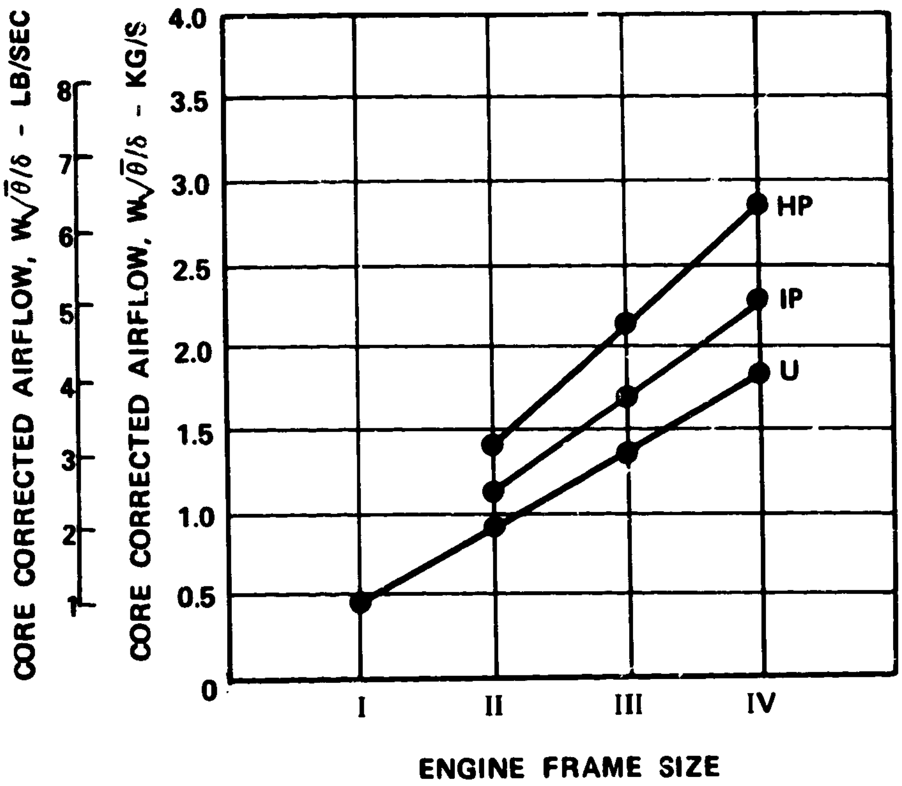

Figure 30. Core flow and performance quality versus engine frame size.

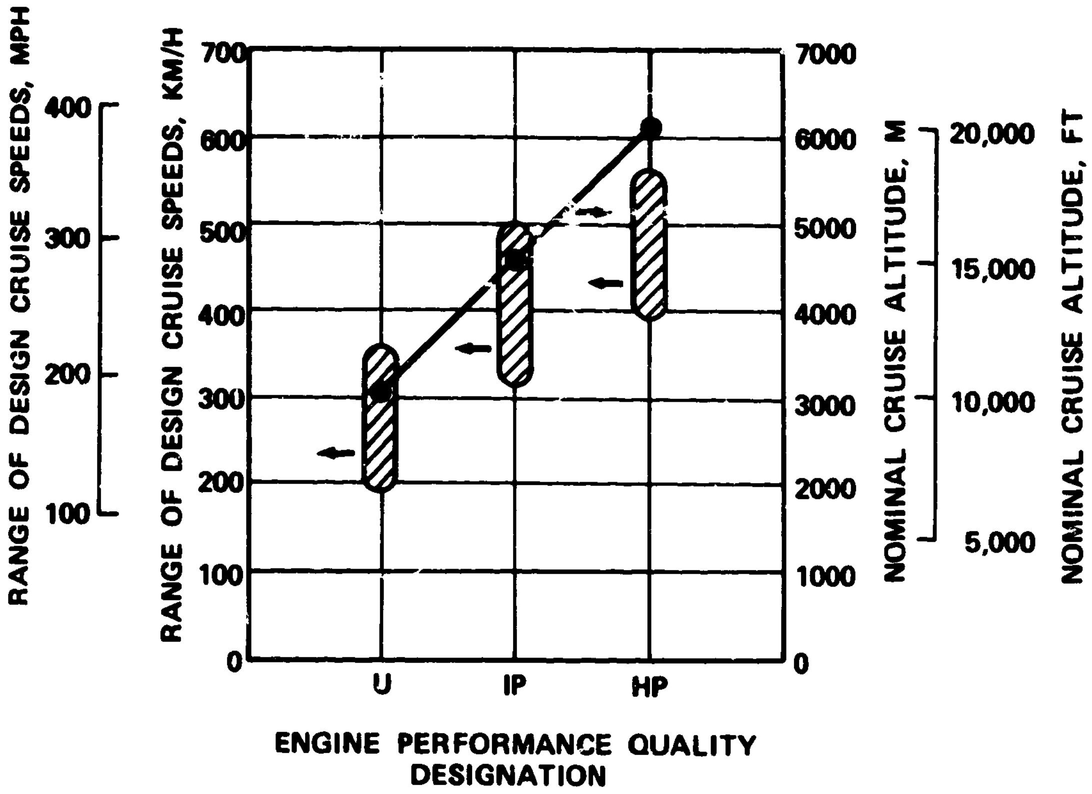

Figure 31. - Cruise speed and altitude versus engine performance quality.

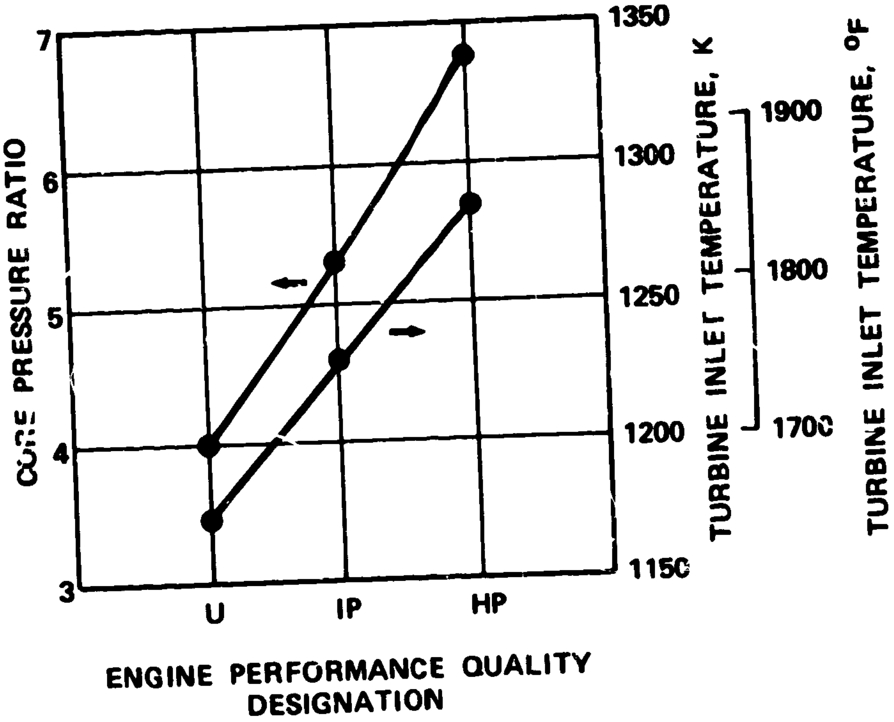

Figure 32. - Core pressure ratio and turbine inlet temperature versus engine performance quality.

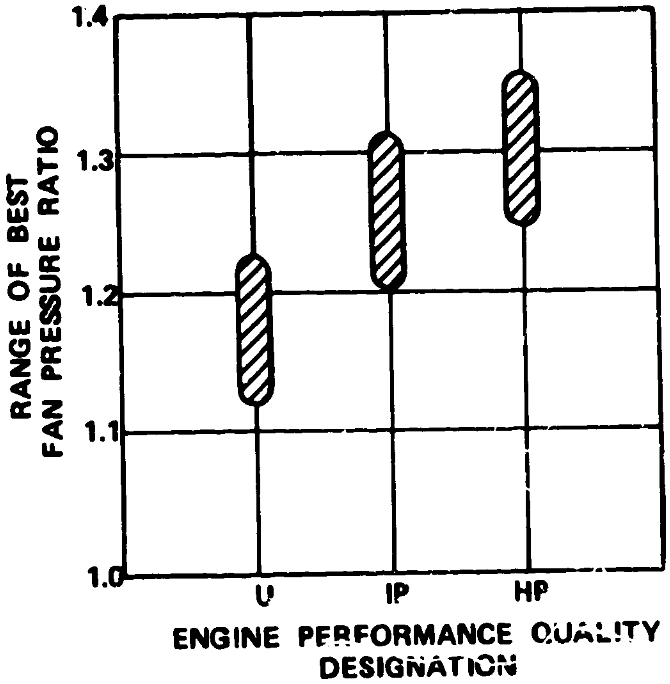

Figure 33. - Fan pressure ratio versus engine performance quality.

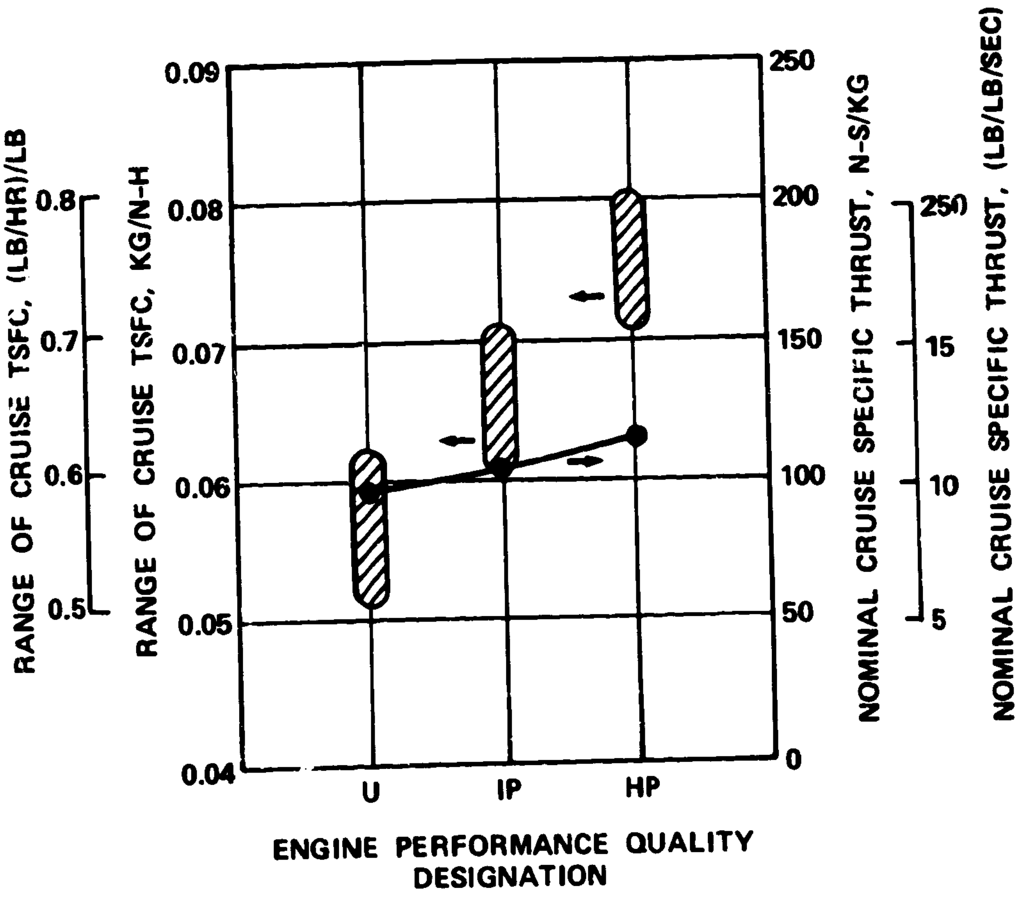

Figure 34. - TSFC and specific thrust versus engine performance quality.

DISCUSSION OF RESULTS

The results of this study have been compared with those of a recent NASA study (Reference 12) that examined the applicability of modern wing technology to both piston/propeller and turbofan-powered light airplanes. The comparison of results has revealed differences that are due to variations in approaches taken in the respective studies. Insight into these variations is presented in the following paragraphs.

This study has emphasized modern design aspects of the total aircraft made possible by a turbofan installation--not just the powerplant performance alone. Full advantage has been taken of the modern technology afforded by the GA(W)-1 wing technology and spoilers that allow full-span flaps. It is important to recognize that advanced technology, particularly that related to the advanced wing designs, can apply to propeller-driven aircraft as well (piston or turbine powerplants). Thus, the comparative results stating comparable or improved performance over current light aircraft must be evaluated in light of the older aeronautical technology in current two- and four-place aircraft.

The potential of modern wing design for small propeller-driven single-engine aircraft has been demonstrated in Reference 12, and the performance improvement potential presented is truly significant. The NASA authors of Reference 12 also co-monitored the contracted study reported herein, and having access to the turbofan engine weight and performance characteristics being developed, they chose to perform an independent airplane synthesis evaluation of the turbofan-powered, two-place aircraft using GASP. For the identical airplane mission specification, they ended with an airplane design gross weight 22 percent higher than that presented in this report (1414 lbs versus 1160 lbs). The NASA authors then proceeded to trace the differences in the design assumptions used in each case and their findings show that the design presented herein has reduced drag for the wing, fuselage, landing gear, and nacelle; and reduced weight in the fuselage, tail, and landing gear relative to their own study. The NASA authors were careful to point out that they used generalized, current aircraft trends in terms of their aerodynamic and weight estimating techniques. In contrast, the approach used in this study was to rigorously search for and apply to the study the weight and drag characteristics of the best examples of component design found in contemporary light airplanes.

Thus, it can be presumed that the results presented in this report represent an optimistic assessment of the potential for improvement in light-aircraft design from having incorporated a full complement of modern aeronautical technology. However, it is contended that a significant amount of this potential improvement stems directly from the use of the turbofan engine. The shorter landing gear with partially buried nose gear, and the reduced airfoil and fuselage drag from natural laminar flow are the primary examples. It is freely admitted that this study may represent an optimistic assessment from the "engine man's" point of view. A final chapter of this evaluation of turbofan-powered, single-engine light aircraft is now being conducted by two airframe manufacturers--Cessna Aircraft Company and Gates Learjet Corporation. Both are sponsored by NASA contracts. They have been encouraged to review the assumptions and results of this study very carefully.

Finally, it should be pointed out again that minimum weight and cost are not the only determinants of quality in modern light aircraft design. Environmental standards are yet to be finalized, but the potential for improvement in both noise and emissions levels with turbofan engines would be remarkable. Likewise it is contended that both improved safety (visibility, safer fuel, lack of propeller torque) and better crashworthiness (engine aft with energy-absorbant structure forward of the pilot) would result from the use of turbofans. These factors are more difficult to evaluate in a study of this nature, but it is hoped the airplane manufacturers will consider them in their own design studies.

CONCLUSIONS AND RECOMMENDATIONS

The general aviation turbofan study series constitutes an in-depth analysis of the applicability of modern turbofans to light aircraft. The comprehensive treatment of environmental and efficiency factors, and the concern with cost factors has provided a large amount of data to evaluate, and from which to draw conclusions. Because the modern synthesis analysis techniques that were used throughout the study were carefully cross-checked with conventional design methods and results, the data is considered valid.

The basic conclusion that has been drawn from the study results is that new designs incorporating turbofans provide an attractive alternative for future light-aircraft. As an alternative to the piston engine/propeller system, specific advantages can be cited:

(a) Comparable or improved fuel consumption, relative to current piston-powered light aircraft when engine/airframe efficiency is maximized.

(b) Optimized airplane designs have lower airframe structural weight and potentially lower airframe cost.

(c) Noise and emission characteristics superior to current piston engines can be realized without impairment to performance, operating cost, or safety.

(d) Potential for lower operating cost, with less maintenance, extended overhaul periods, and lower fuel cost.

(e) Improved aircraft safety, with safer fuel, no torque, lighter engine/airframe weight and no propeller.

(f) Product enhancement, with quiet, vibration-free cabin, easy starting, and single-lever power management.

If turbofans are to be viable in future light airplanes, they must be cost-effective. In effectiveness they rate high. Regarding cost, there are encouraging possibilities:

(a) A broad line of technically responsive engines would have a 1990 market potential of nearly 30,000 units per year and benefit from the economies of high production.

(b) A family of 10 engines, with 4 frame sizes and 3 cycle-quality levels, can adequately cover the light-airplane spectrum of requirements.

(c) By disciplined scaling rules and consistent uprate/down-rate methods, the 10-engine family can have a high degree of commonality.

(d) The combined research and development capabilities of NASA and the aircraft gas turbine industry can be an effective force in solving the potential problem of high engine cost.

The foregoing conclusions make it possible to recommend further development of the light-airplane turbofan concept. Further validation of the concept by means of studies conducted by general aviation airplane manufacturers is essential. The light-single categories investigated in this study are judged to be the greatest technical challenge. It is recommended, therefore, that airplanes in these categories be defined by conventional preliminary design methods and evaluated by syntheses analysis, using the NASA General Aviation Synthesis Program.

It is also recommended that an experimental engine program be undertaken, complemented by a continuing, advanced engine components research program. These programs are necessary to validate the technology requirements and exploit the turbofan's potential for environmental compatibility, low ownership cost, improved safety and high fuel efficiency.

REFERENCES

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

2. Galloway, T. L. and M. H. Waters: Computer Aided Parametric Analysis for General Aviation Aircraft: Society of Automotive Engineers Technical Paper 730332, April 1973.

3. Heldenbrand, R. W., G. L. Merrill, G. A. Burnett: Study of Small Civil Turbofan Engines Applicable to Military Primary Trainer Airplanes, Final Report. NASA CR 137575, April 1975.

4. Anon.: 1975 Aircraft Directory, Flying Annual and Pilots Buying Guide, 1975.

5. McGhee, R. J. and W. D. Beasley: Low-Speed Aerodynamic Characteristics of a 17-Percent-Thick Airfoil Section Designed for General Aviation Applications: NASA Technical Note, TN-D-7428, December 1973.

6. Wentz, W. H. Jr.: New Airfoil Sections for General Aviation Aircraft: Society of Automotive Engineers Technical Paper 730876, October 1973.

7. Cumberford, R.: Jiminy Cricri: Air Progress, August 1974.

8. Roux, R. J.: Good Grief It's A Cricket: Sport Aviation, May 1974.

9. Larrabee, E. E.: Propellers of Minimum Induced Loss and Water Tunnel Tests of Such a Propeller: Proceedings of the NASA-Industry-University General Aviation Drag Reduction Workshop, July 14-16, 1975.

10. Kohlman, D. L.: Drag Reduction Through Higher Wing Loading: Proceedings of the NASA-Industry-University General Aviation Drag Reduction Workshop, July 14-16, 1975.

11. Anon.: Control of Air Pollution from Aircraft and Aircraft Engines - Emission Standards and Test Procedures for Aircraft: Federal Register, Tuesday, July 17, 1973, Volume 38, No. 136, Part II Environmental Protection Agency.

12. Schairer, Edward T. and Thomas L. Galloway: Parametric Analysis of Advanced Technology Applied to a Single-Engine Trainer: Society of Automotive Engineers Technical Paper 760459, April 1976.