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FEASIBILITY OF V/STOL CONCEPTS FOR SHORT-HAUL TRANSPORT AIRCRAFT

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FEASIBILITY OF V/STOL CONCEPTS

FOR SHORT HAUL TRANSPORT AIRCRAFT

By Bernard L. Fry
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SUMMARY

Many concepts of V/STOL aircraft have been investigated during the last decade. This work has resulted in flying prototypes, ranging from somewhat primitive research aircraft to more sophisticated second-generation models suitable for operational evaluation. Several concepts have emerged as practical configurations. More recently, concepts of the helicopter type which can be converted in flight to a conventional aircraft configuration have evolved. The state of the art in V/STOL technology has now reached the point where the application of these V/STOL aircraft to civil transportation can be evaluated with a reasonable degree of confidence.

This report presents the results obtained in a study of VTOL and STOL short-haul transports conducted by The Boeing Company for NASA's Ames Research Center. The study is one of three concurrently sponsored by NASA. Five VTOL and two STOL aircraft have been analyzed in order to determine those most suitable for commercial short-haul operation and the research required to bring them to full operational status. The VTOL concepts studied were the tilt wing, jet lift, stowed-rotor helicopter, and tip-turbine lift fan aircraft. The STOL types were the fan-in-wing and the high-lift turbofan.

The study covered airplane design, operational techniques, noise and public acceptance, acquisition cost, direct operating cost, technical risk, and research requirements. In order to incorporate the operator's point of view, New York Airways and Trans World Airlines were consulted in the areas of operational analysis and airplane design. The General Electric Company were consultants on propulsion technology and costing.

The results of the study show that the turbofan STOL, tilt-wing VTOL, lift-fan VTOL, and jet-lift VTOL are the most

promising concepts. Furthermore, if solutions can be found to the noise-suppression problem for the jet-propulsion types, they can all be brought to operational status in the 1970-75 time period with research which is an extension of current technology.

The direct operating costs of V/STOL aircraft are potentially no higher than those of conventional short haul jet aircraft over 500 mile stage lengths, and will be lower than the operating costs of present turbine helicopters for very short trips down to 25 miles.

NOMENCLATURE

T/W or FV/W	Vertical Force to Weight Ratio
IFR	Instrument Flight Regulations
$C_{L_{max}}$	Maximum Lift Coefficient
$\ddot{\phi}$	Initial Angular Acceleration in Roll
$\ddot{\theta}$	Initial Angular Acceleration in Pitch
$\ddot{\psi}$	Initial Angular Acceleration in Yaw
V_{MO}	Maximum Operating Equivalent Airspeed
M_{MO}	Maximum Operating Mach Number
C_T	Thrust Coefficient = $\frac{\text{Propeller Thrust}}{\text{Air Density x Disc Area x Tip Speed}^2}$
σ	Propeller or Rotor Solidity = $\frac{\text{\# Blades x Blade Chord}}{\pi \text{ x Radius}}$
V_D	Design Dive Speed
N_{LIMIT}	Limit Load Factor g's
T_4	Turbine Inlet Temperature
C_L	Lift Coefficient

GW	Gross Weight
VOR	Very High Frequency Omnidirectional Range
CEP	Circular Error Probability
DME	Distance Measuring Equipment
PDVOR	Precision Doppler VOR
RVR	Runway Visual Range
KHZ	Kilohertz (1000 Cycles per Second)
VFR	Visual Flight Regulations
OWE	Operating Weight Empty
T_O	Static Thrust
A	Propeller Disc Area

GROUND RULES

This section outlines the study's major ground rules. It amalgamates those originally specified by NASA and additional rules and constraints applied with the agency's approval.

Design Flight Plan for Aircraft Sizing

The aircraft shall be sized to carry enough fuel for 500-statute miles nonstop, plus the reserve fuel specified herein. The 500-mile range requirement shall be met at maximum continuous cruise velocity. It is assumed that the operating conditions for maximum continuous cruise velocity will correspond to those for minimum block time and therefore to minimum, or near-minimum, direct operating cost. If this assumption is found to be invalid for a particular configuration, the configuration shall be resized to meet the range requirement at minimum direct operating cost. The 500-statute-mile range criterion shall be based on zero headwind. For purposes of sizing the aircraft, optimum cruise altitude will be used, up to a maximum of 30 000 feet. Standard day conditions will be assumed for fuel requirement and economic calculations, but the design take off and landing condition to which the propulsion system will be sized is sea level 86°F. The cruise rating of the engines shall not exceed 85 percent normal rated thrust or 83 percent normal rated power. Fuel requirements are detailed below and summarized in Figure 1.

1. Assume 500-statute-mile range at minimum direct operating cost.

2. Assume 2-minute at idle power for all engines for taxi at origin.

3. Assume 1-minute at takeoff power (T/W = 1 for VTOL aircraft) with no range or altitude credit for take-off segment.

4. Compute climb segment with range credit. The cabin angle shall not exceed 12 degrees during the climb.

5. Compute cruise segment at altitude required to minimize direct operating cost. Cruise may be made with an engine or engines shut down, providing that in the event of engine failure, FAA rules are met. Minimum direct operating cost shall be interpreted as maximum speed attainable without large increases in weight, power, size, or complexity. Designing for minimum direct operating cost at 500-miles stage length shall not unduly compromise either the direct operating cost at low stage lengths or gust sensitivity.

6. Compute descent segment with range credit. Descent segment ends at 1000-foot altitude required for entry to approach pattern. The cabin angle shall not exceed 6 degrees nose-down on the descent.

7. Add reserve fuel for holding 30-minutes at 5000 feet at or near airspeed for maximum endurance.

8. Complete IFR approach pattern from points A to E shown in Figure 1.

9. Initiate go-around at point E and fly for 1 minute at takeoff power to return to point A.

10. Complete IFR approach pattern from points A to E.

11. Assume 1 minute at landing power for landing segment from point E to point F.

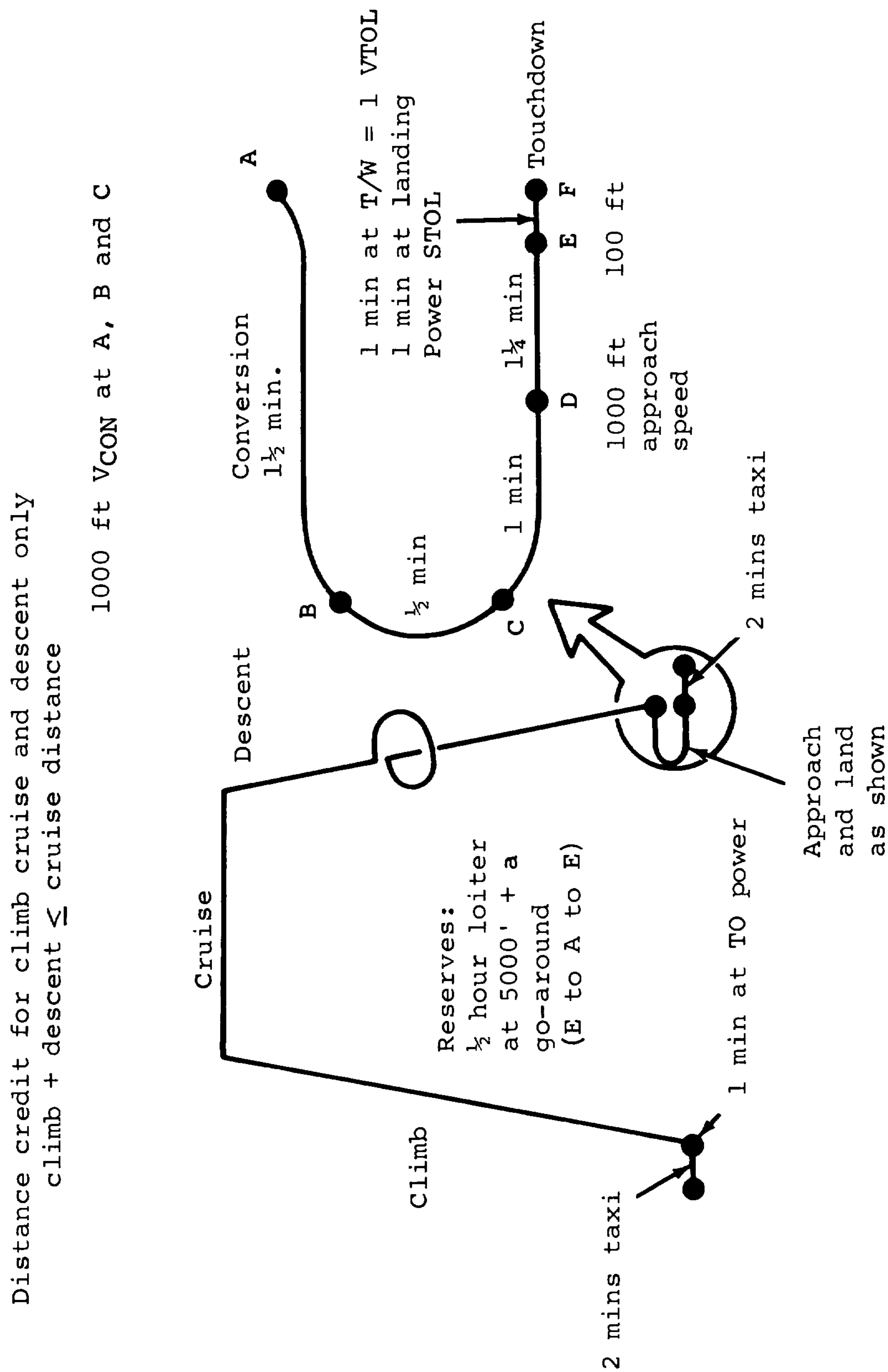


Figure 1. Mission Profile and Approach Pattern

12. Taxi at destination for 2-minutes at idle power (cruise engines only).

Fuselage and Cabin Layout

The cabin furnishings will be similar to those of current passenger transport aircraft, but lightweight seats will be used. Passenger accommodation will be for 60 or 120 passengers at 5 or 6 abreast. The seat pitch will be 32 inches, each seat will be 20 inches wide, and the aisle will be 20 inches wide. Two main entrances will be provided. They will have built-in airstairs. The following cabin furnishings will be provided:

1. Two washrooms, 35 by 38 inches

2. Galley for light refreshments

3. Carry-on baggage and coat racks at 2 cubic feet per passenger

5. Carpets, soundproofing and lights

Space for revenue cargo and stowed baggage will be provided under the cabin floor. Assume 3 pounds per cubic foot. If provision of this volume unduly compromises fuselage design, assume 5 pounds per cubic foot. Pressurization will be provided in the cockpit, passenger cabin, and all baggage locations at a differential determined by avoidance of climb and descent rate limitations by a cabin altitude lapse rate of 300 feet per minute. Emergency exits specified in FAR 25 will be provided as a minimum. One cabin window will be provided on each side for each row of seats, i.e., at 32-inch pitch. The windows shall be 12 inches wide and 18 inches high.

The flight deck shall be designed for a crew of two. The equipment necessary for operation under zero-zero landing conditions shall be provided.

Landing and Takeoff Performance

The landing and takeoff performance for the VTOL and STOL aircraft shall be based on operating from a dry concrete field at sea level on an 86°F day. A rolling coefficient of .02 shall be used. The performance shall be consistent with commercial operation and shall comply with Civil Air Regulations and with the VTOL flight requirements proposed in Reference 1. The performance values shall be based on calculations with the most critical engine failed. Performance with transmission and interconnect systems failed shall not be considered; these systems shall be designed to the same integrity as the basic airframe. When a landing ground roll is required, the total distance from 50 feet shall be multiplied by 1.67 to establish the landing field length. To avoid confusion, corresponding curves or values must be clearly marked; e.g., 1.67 times the calculated landing distance over 50 feet, or takeoff distance to 35 feet with an engine failed. The performance with all engines operating shall be computed for the purpose of assessing the penalty associated with an engine failure, and also to analyze the noise. Under no conditions shall the deceleration exceed .5g. The average braking coefficient shall be assumed to be .4, and reverse thrust can be used provided no uncontrollable asymmetrical forces occur.

The approach speed of VTOL and STOL aircraft must include sufficient margins so that, with the most critical engine failed, the aircraft can encounter a 10-knot sharp-edged vertical gust (at constant speed) or a 10-knot horizontal speed change (without a gust) without excessive buffeting or loss of control and without a power change. With the most critical engine failed, it must be possible to change the normal load factor $\pm$ .1 by changing angle of attack or power at constant speed without excessive buffet. With the most critical engine failed, it must be possible to attain a level flight path in the final landing configuration without a speed change. With all engines operative, it must be possible to increase the normal load factor by .3 by changing the angle of attack or power at constant airspeed.

For evaluation of wind tunnel polars in terms of buffet limits when no other evidence of separation or asymmetric moments exists, assume limit to be $C_{L_{max}}$ for non-immersed wings. For fully-immersed wings, assume angle of attack limit has been reached when a 5-percent loss of lift has occurred, at a constant thrust coefficient or tip speed ratio.

Takeoff and landing calculations should be made by a 2-degree of freedom numerical integration (unless it can be shown that simplifications do not result in differences over 5-percent).

VTOL Aircraft.- Contingency ratings for prime and auxiliary engines may be used for engine failure compliance. This rating shall be assumed to be equivalent to an extra 10-percent equivalent gas horsepower above the normal takeoff rating. Transition path shall be computed with allowance for stall margins (as for STOL aircraft) with and without an engine failure. Control and thrust margins are detailed under Flying Qualities.

STOL Aircraft. - The takeoff performance over a 35-foot obstacle shall be computed with and without the most critical engine failed. The operating performance shall be based on a balanced field length of 2000 feet. It is not intended that the turbofan STOL require a VTOL type lifting system and therefore, this aircraft may exceed this distance if it is found to be unattainable without such a system. The takeoff speed shall be at least 1.15 times the power on stall speed with the critical engine failed, provided that the speed margin is not less than 12-knots. The rate of descent shall not exceed 800 feet per minute at a height of less than 50 feet. The resulting force felt by the passenger is to be no greater than that during the majority of landings in current commercial transports. Limit for vertical velocity at contact shall be 300 feet per minute and for peak incremental acceleration is .3g. The structural design of the gear shall satisfy FAR 25.473 and 25.723 (maximum vertical velocity of 12 fps).

Flying Qualities

Aerodynamic Stabilizing and Control Surfaces. - Sufficient analysis of the sizes of these surfaces shall be made to ensure compliance with the static stability and the control requirements of FAR 25.161 through 25.181 (Civil Airworthiness Regulations, Transport Category). These requirements shall be met in all flight regimes for the STOL aircraft and in the conventional flight regime for all other types.

VTOL Control and Thrust Margins. - All of the following criteria shall be met:

1. Controls must be able to produce initial accelerations (Radians/sec^2) of:

	60 Passengers		120 Passengers	
	Required	Desired	Required	Desired
$\ddot{\phi}$	.6	1.2	.48	.96
$\ddot{\theta}$	.3	.6	.24	.48
$\ddot{\psi}$	.25	.5	.20	.40

The required values shall be used whenever the desired values give significant penalties in weight or installed power.

2. With all engines operating:

   a. With aircraft trimmed, but no other control input, total vertical force-to-weight (FV/W) must be at least 1.15.

   b. After aircraft is trimmed, FV/W must not be less than 1.05 when 50-percent lateral, 20-percent longitudinal, and 20-percent directional control is applied simultaneously.

   c. After aircraft is trimmed, FV/W must not be less than 1.05 when 100-percent control about any single axis is applied.

   d. Control system must be able to produce 100-percent about primary axis (lateral) and 50-percent on other axis. No FV/W specified.

3. With most critical engine inoperative:

   a. With aircraft trimmed, but no control input, FV/W must be at least 1.05.

b. After aircraft is trimmed, FV/W must not be less than 1.0 when 50-percent lateral, 20-percent longitudinal and 20-percent directional control is applied simultaneously.

STOL Control Requirements. - The following control initial angular acceleration criteria shall be met in the approach and initial climb flight modes:

	60 Passengers		120 Passengers	
	Required	Desired	Required	Desired
$\ddot{\phi}$	.22	.45	.10	.20
$\ddot{\theta}$	.20	.40	.09	.18
$\ddot{\psi}$	.18	.36	.08	.16

Weight and Center of Gravity

Useful Load. - Weights of the crew, passengers, luggage and cargo shall be as follows for the 60-passenger aircraft.

Pilot	(1)	190	
Copilot	(1)	190	Includes allowance
Stewardess	(1)	140	for luggage
Passengers	(Ea)	200	

Cargo - 10-percent of the passenger payload

For the purposes of sizing the checked baggage volume, the passenger weight shall be taken as 170 pounds for the passenger and 30 pounds for baggage. Trapped liquids and engine oil weight will be determined by engine size. Fuel weight will be based on mission fuel.

Landing Weight. - Design landing weight shall be equal to design gross weight to permit routine operation over very short stage lengths.

Load Factors and Design Speeds. - Design structural load factors shall be consistent with present day requirements for commercial aircraft. Limit flight load factors shall comply with FAR Part 25, paragraphs 25.337 and 25.341 (50 fps gust at Vc, design cruise airspeed, below 20 000 feet altitude, with a minimum load factor of 2.5g). In order to avoid excessive airframe weight, the design dive speed and V_{MO} shall be chosen such that cruise speeds may not exceed 400-knots EAS. M_{MO} shall not restrict cruise speed at minimum cruise weight.

Center of Gravity. - The center-of-gravity range of all aircraft shall be such that indiscriminate passenger loading may be accommodated. However, if this criteria severely penalizes the design of a particular V/STOL concept, a less severe cg requirement may be proposed to NASA for consideration. As a minimum requirement, assigned seating of the first 1/2 load factor will be required with indiscriminate seating of the second 1/2 load factor. These criteria shall apply in addition to any cg movement due to fuel usage.

CONFIGURATION DESIGN ANALYSIS

This section of the report describes the design philosophy and tradeoffs used in designing the 60-passenger versions of the seven different types of aircraft studied in the initial phase of the contract.

The aircraft have been designed to promote the best features inherent in each type. Examples of this philosophy are the choice of a low tip speed for the tilt-wing aircraft, in order to obtain low noise levels, and the use of thrust modulation or deflection for control of the jet-lift aircraft, in order to avoid more complex components in the hovering control system. Formal tradeoff studies have been made where clearly needed, but many parameters affect a large number of design areas and no meaningful tradeoffs have been possible in these instances. The choice of bypass ratio for the lift engines of the jet-lift aircraft is an example of such a complex parameter. The bypass ratio affects the weight, size, and specific fuel consumption of the engine, which, in turn, affects the size and drag of the lift engine pods, the wing structural weight, and the overall fuel weight. Noise is also an important consideration in the choice of bypass ratio of the lift engines. It is evident that, for a thorough analysis, the tradeoff studies to establish the optimum bypass ratio would consume a large amount of time. In cases of this kind, therefore, an engineering judgment has been made which takes into consideration the various factors involved. While further refinements would be possible if these designs were taken beyond the project design stage, it is not felt that any radical changes in aircraft configuration or size would result, and the basic conclusions of this study would therefore be unchanged.

The drag of the aircraft was calculated by standard Boeing methods modified as necessary to account for the unorthodox features of some of the aircraft. The equivalent flat plate drag and induced drag factors of the aircraft are compared in the Appendix and the aerodynamic cleanness of the various configurations are also shown in relation to existing aircraft.

A complete stability analysis, involving evaluation of all the relevant stability derivatives and analysis of the dynamic stability of the aircraft, was not possible within the scope of this study. The important consideration was to size the vertical and horizontal tail surfaces in a consistent manner in order to predict surface weights.

The horizontal tails were designed to give a five percent static margin with an aft center of gravity position. The only exception to this rule was the tilt wing aircraft which was given a tail volume coefficient consistent with transition stability and control requirements.

The vertical tails of the VTOL aircraft were sized to give good directional stability in conventional cruise flight. The STOL aircraft vertical tails were sized to give a minimum control speed consistent with takeoff and approach speeds.

The sizing of tail surfaces of the STOL aircraft included consideration of the engine failure case in the approach and takeoff conditions.

An assessment of the need for stability augmentation in the various aircraft concepts is given in the Appendix.

Weights

A combination of analytical, statistical and catalog sources were used to derive the weight data presented in this report.

The wing, tail, fuselage, rotors, propellers and drive system weights were computed from trend curves developed at The Boeing Company. Landing gear weights were based on statistically derived percentages of the respective gross weights. Flight control weights were determined from the number and complexity of the control functions for the individual configuration. Engine and fan weights were developed from engine manufacturer specifications. Nacelle and fan ducting weights were based on trend curves modified by experience gained in previous studies.

Fixed equipment weights (Auxiliary power unit, instruments, electronics, furnishings, etc.) were established using existing commercial aircraft weights adjusted to meet the study requirements.

The individual weight statements of the aircraft are contained in the following aircraft descriptions and a breakdown of the fuel weights is given in the Appendix.

Tilt Wing VTOL

The 60-passenger tilt wing aircraft, shown in Figure 2 has four propellers and four turboshaft engines which are coupled by interconnecting shafting. Pitch control in hover is provided by monocyclic (single-axis-cyclic) control propellers, yaw control by a spoiler-deflector system, and roll control by differential collective propeller blade angle. This means that the complete vertical takeoff system is contained within the wing; there is no tail rotor, no tail shafting, and no aft gearbox.

The 60-passenger tilt-wing aircraft chosen on the basis of the studies has a design gross weight of 71 704 pounds and an operating weight empty of 51 704 pounds. It cruises at 30 000 feet at a speed of 380 knots for the 500-statute-mile mission. For shorter stage lengths, the cruise altitude is generally reduced and the cruise speed may be slightly increased. Table 1 summarizes the group weights and general characteristics of the configuration.

Propulsion and control systems. - Four propellers were chosen since a two propeller configuration would not give adequate ground clearance with the wing down. The wing is completely immersed in the propeller slipstream (with the exception of the center section) for transition aerodynamic purposes. The propeller size chosen for this aircraft results from the upper and lower limits of propeller diameter being close together. The lower limit of 21 feet is given by a combination of the low tip speed (850 feet per second) desired from the noise standpoint, the maximum blade lift coefficient required

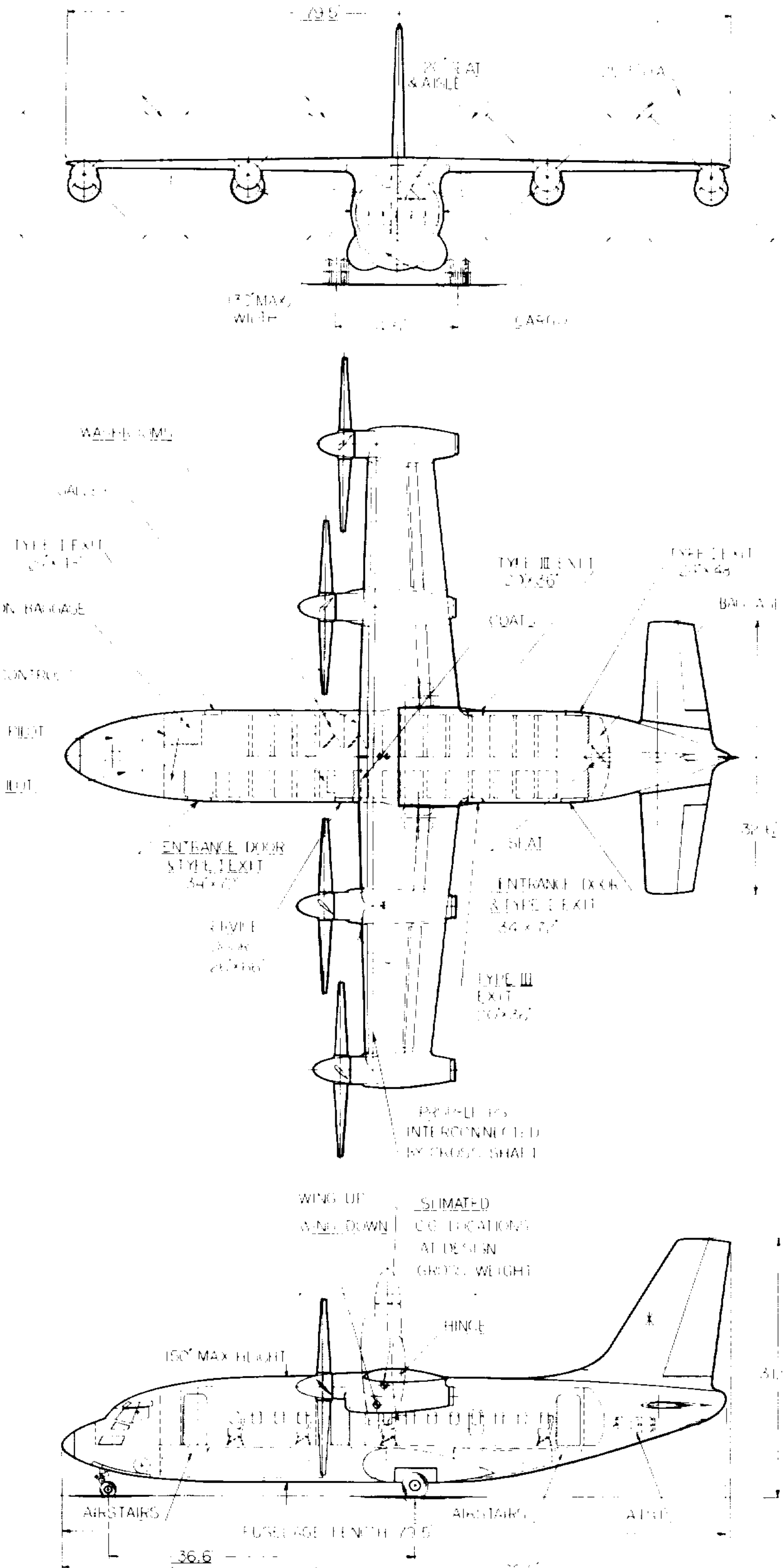


Figure 2. Tilt Wing VTOL General Arrangement

for adequate monocyclic control margins (C_t/σ = .125), and the blade solidity desired for propeller efficiency in hover and reasonable monocyclic control load (σ = .25). The 21-foot diameter is close to the upper limit for which propeller clearance can be provided in a wing-down emergency landing, without compromising landing gear. Provision of such clearance is obviously desirable, though by no means mandatory. For one thing, it simplifies ground handling during maintenance and overhaul. Even more important, the high wing loading which stems from the use of minimum-diameter propellers minimizes gust sensitivity and gives good cruise performance.

The propellers selected for this aircraft are of a design evolved by Boeing for other Vertol tilt-wing aircraft of similar performance. They are designed for high figure of merit in hover rather than high efficiency during cruise. The weight penalty resulting from the increased hover power and fuel required with propellers designed for cruise is considerably greater than the increased cruise fuel due to the bias of propeller design towards hover efficiency. Propellers on each side rotate down inboard, since it has been shown from Vertol Division wind tunnel tests that this retards stall at the wing root. Because of the placement of the engines on the wing, this rotation of the propeller will not aggravate tip stall.

The inconsistent requirements imposed by hover and cruise on the propeller performance were examined to determine the best rpm for the engine during cruise.

The shafting which interconnects the engines ordinarily operates in an unloaded condition. However, in the event of engine failure it transmits the remaining power equally to the four propellers. The dead engine is automatically decoupled from the load-carrying shaft by means of an overrunning clutch.

The turboshaft engines considered representative of 1970 technology have a pressure ratio of 14 and a maximum turbine inlet temperature of 2600°R.

Pitch control in hover is provided by monocyclic (single-axis-cyclic) control propellers. The monocyclic control, applied to the rigid propeller blades, produced an offset of the thrust from the axis of rotation. Vertol hover tests of monocyclic control have shown that thrust offsets of the order of 27 percent of the blade radius are readily obtainable at the propeller design lift coefficient.

TABLE 1
60 PASSENGER TILT WING VTOL
WEIGHT AND GENERAL CHARACTERISTICS SUMMARY

Weights

Wing	5 250
Tail	1 937
Body	9 620
Alighting Gear	2 775
Flight Controls	4 172
Reaction Controls	-
Powerplant Installation	(15 605)
Engine Section - Cruise / - Lift	1 250
Engine Installation - Cruise / - Lift	3 820
Lift Gas Generators	-
Drive System	5 310
Fuel System	350
Engine Controls	100
Starting System	170
Propeller Installation	4 605
Auxiliary Power Unit	530
Instruments and Navigation	675
Hydraulics	450
Electrical	2 000
Electronics	750
Furnishings and Equipment	(5 120)
Flight Provisions	515
Passenger Accommodations	3 838
Cargo Handling	473
Emergency Equipment	294
Air Conditioning and Anti-icing	1 370
Weight Empty	50 254
Crew and Crew Luggage	520
Unusable Fuel and Oil	175
Engine Oil	100
Passenger Service Items	655
Operating Weight Empty	51 704
Passengers and Luggage	12 000
Revenue Cargo	1 200
Fuel	6 800
Takeoff Gross Weight	71 704

TABLE 1. - Concluded
60 PASSENGER TILT WING VTOL
WEIGHT AND GENERAL CHARACTERISTICS SUMMARY

Physical Data	
Wing	
Area (sq ft)	787
Span (ft)	79.5
Aspect Ratio	8.03
Sweep at ¼ Chord (degrees)	0
(t/c) Root ℄ Fuselage	.18
(t/c) Tip	.09
Horizontal Tail Area (sq ft)	238
Vertical Tail Area (sq ft)	178
Fuselage Length (ft)	79.5
Design Cruise Conditions	
Cruise Speed (kt TAS)	380
Cruise Altitude (ft)	30 000
Structural Limits	
V_{MO} (kts EAS)	390
M_{MO}	.72
V_D (kts EAS)	425
N_{LIMIT} (Gust Critical)	3.09
Rotors or Propellers	
Diameter (ft)	21.05
Number of Blades	4
Solidity	.25
Maximum Tip Speed (fps)	850
Cruise Powerplants	
Number	4
Maximum Thrust (lbs)	-
Maximum Power (HP)	6740
Bypass Ratio	-
Pressure Ratio	14
T_4	2600°R
Inertias	
Roll	797,518
Pitch	494,035
Yaw	1,112,995

Monocyclic control alone is capable of providing 88 percent of the moment required for trim and control under the most severe aircraft center-of-gravity condition. Additional longitudinal control capability can be obtained, as well as longitudinal acceleration, by linking wing tilt and flap deflection to the stick. This capability is obtained at little or no additional cost, since the high wing rates are readily obtained from the moments generated by monocyclic control and flap deflections. Figure 3 illustrates the control capability of monocyclic alone and monocyclic coupled with wing tilt. As little as ± 5 degrees of wing tilt is capable of satisfying the combined trim and initial pitch acceleration requirements. The desired value of control power cannot be provided by this system and therefore the required value has been used. Yaw control in hover is provided by a spoiler-deflector control system. As shown by Boeing Company model tests, the major advantages of this type of control over a differential flap system are that there is little or no depreciation of control power in proximity to the ground and, since no upward flap movement is required, the flap can be optimized for transition performance.

Differential collective pitch, which is used for roll control in hover, can provide roll control up to 2 radians per second^2 with only minor loss in lifting force. Since ample yaw and roll control power can be provided by these systems without a weight penalty, the desired control powers have been used. A combination of 50 percent control about the roll axis and 20 percent about the other two axes causes a thrust loss of only 3.4 percent. The most severe hover requirement is therefore that which requires a thrust-weight ratio of 1.05 with one engine out on an 86°F day. The engines have been sized for this latter condition. An emergency power rating 10 percent above takeoff rating was assumed.

The horizontal tail is an all-movable control surface which is programmed to wing tilt during transition. The flaps are also programmed to wing tilt during transition.

<u>Wing design</u>. - The wing is sized to provide the same relationship between propeller disc and wing areas found necessary for good transition aerodynamic characteristics in Boeing Company's wind tunnel tests of other tilt wing configurations. This relationship, which is based on area with flaps extended, results in a wing-area-to-propeller-disc-area ratio of 0.63. The required wing area has been provided in chord,

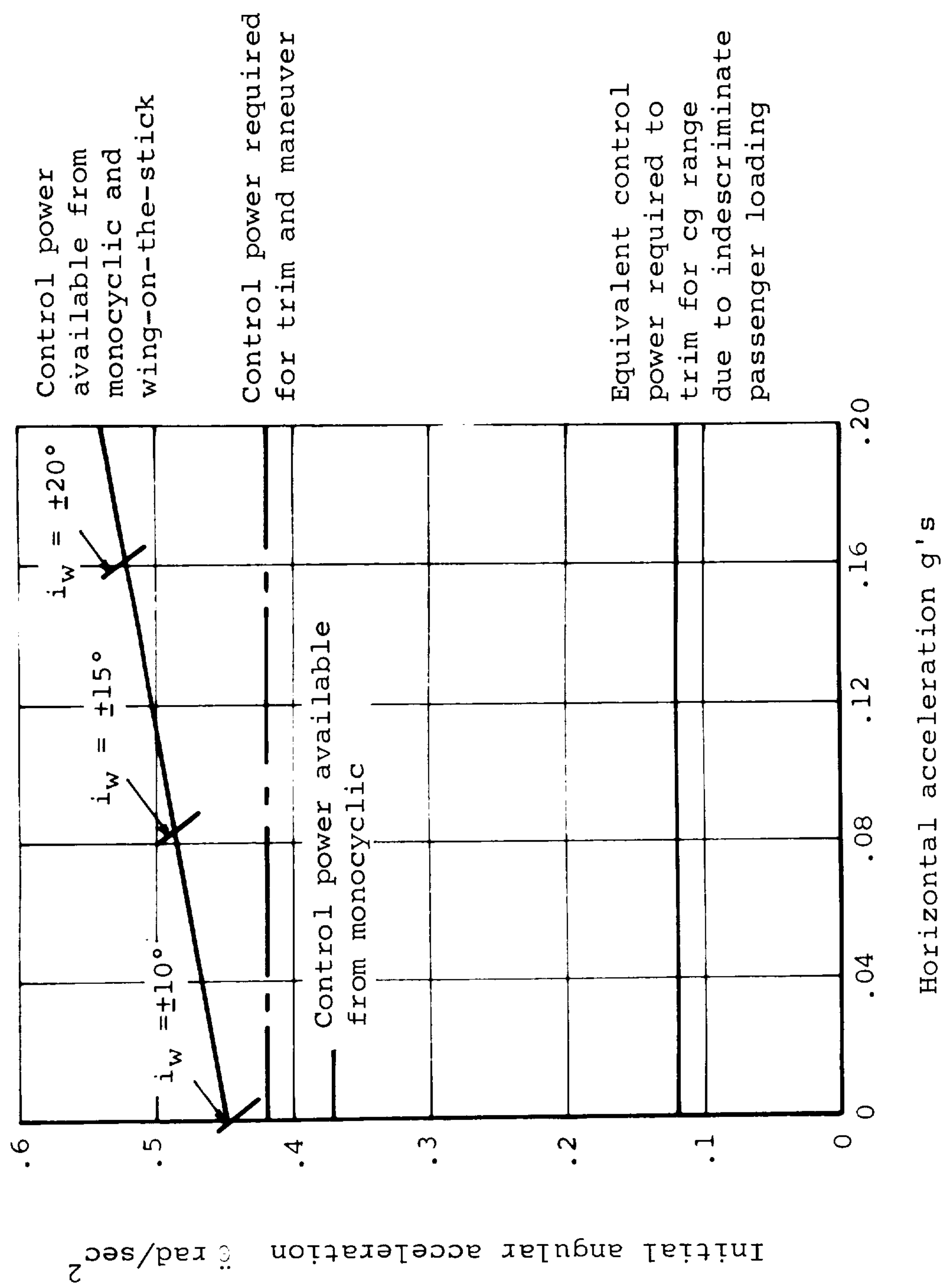


Figure 3. Longitudinal Hover Control Summary: 60-Passenger Tilt Wing VTOL

rather than span, and the wing does not extend beyond the outboard nacelle. This was done to increase span loading and thus improve the aircraft's gust sensitivity. Gust sensitivity is important for short stage lengths, in which the aircraft will cruise at low altitude and high equivalent airspeed. The wing has full-span leading-edge slats and full-span Fowler-action double-slotted flaps. Although not shown in Figure 2, it may be necessary to add fences to the wing to retard spreading of prematurely separated regions.

Performance. - Having selected wing loading and disc loading from the considerations described above, design cruise speed and altitude studies were conducted; the results are shown in Figures 4 and 5. High cruise speed generally produces the lowest direct operating cost because of reduced block time. However, the fuel, and therefore the required gross weight, increases with increasing cruise speed, so that above 380 knots further increase in cruise speed produced essentially no further reduction in cost. Designing for the small possible increase in speed, would result in worse direct operating costs at low stage lengths, where airplane size and cost have more impact on economics than at long stage lengths. The decision was therefore made to select, as a final choice for the 60-passenger tilt-wing, an airplane which would cruise at 380 knots for the 500-mile-stage-length mission. For shorter stage lengths, the airplane is capable of higher cruise speeds, since the reduced block time compensates for the increasing fuel consumption.

There is a similar tradeoff with respect to cruise altitude. Low cruise altitudes give low block times because they reduce climb and descent time, but they increase fuel requirements and, therefore, the size and cost of the aircraft. The combination of these conflicting influences results, as shown in Figure 5, in the reduction of direct operating cost with increasing altitude when the stage length is 500 statute miles. The maximum design cruise altitude was arbitrarily set at 30 000 feet since it is believed that this represents a typical cruise altitude for a 500 mile trip. The cruise altitude for minimum direct operating cost is a function of stage length; the optimum altitude decreasing as stage length decreases.

For the tilt-wing aircraft, the climb is restricted by cabin angle for all conditions except high altitudes (above 22 000 feet for design gross weight and above 29 000 feet for operating weight empty). Above these altitudes the airplane is not restricted by attitude angle and climbs at the airspeed for maximum rate of climb.

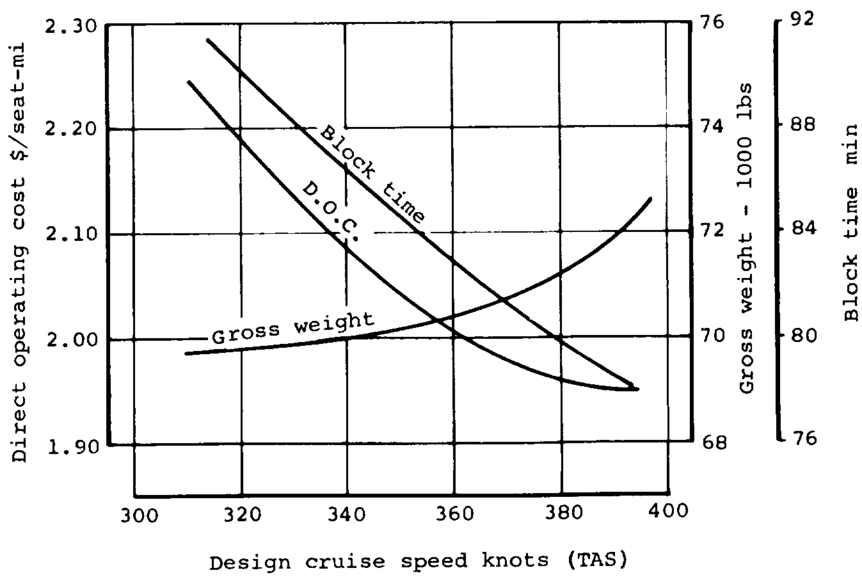


Figure 4. Typical DOC-Cruise Speed Tradeoff: 60-Passenger Tilt Wing VTOL

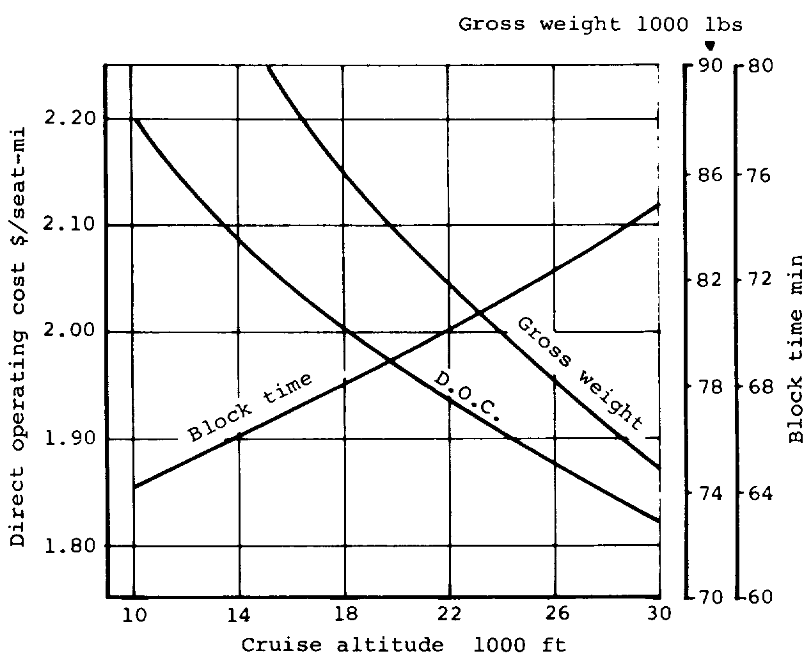


Figure 5. Typical DOC-Cruise Altitude Tradeoff: 60-Passenger Tilt Wing VTOL

Specific range during cruise is illustrated in Figure 6 as a function of airplane gross weight, cruise altitude, and true airspeed. Aircraft operation is limited at high speeds by maximum operating speed (V_{mo} = 390 knots EAS) and by maximum cruise power rating. A practical operating limit is imposed, however, by available fuel when the mission stage length is 500 statute miles. In that case, as shown in Figure 6, the aircraft is limited to 380 knots TAS when operating at an altitude of 30 000 feet and near to design gross weight.

In descent the tilt-wing airplane is limited by cabin attitude angle except for very high altitude in the case of the heavier airplanes.

Weights. - A group weight summary of the 60-passenger tilt-wing is shown in Table 1. Use of fiberglass propellers and the application of titanium to propeller and drive system installations aid in reducing weight. The weight of the flight controls system is high compared to the other configurations studied because of the additional complexity involved in the phasing and mixing of propeller and surface control systems. The flight control system weight is further compromised by the high control loads required to move flaps, spoilers, and propeller controls, in comparison with engine fuel controls and variable nozzles.

Fuselage and cabin layout. - Five abreast seating in a three-and-two arrangement is provided for the sixty passengers. The galley, washrooms, and coat rack were placed in the center of the cabin to avoid putting passengers in the plane of the propellers. Space for revenue cargo and stowed baggage is provided under the cabin floor. Front and rear entrance doors have carry-on baggage racks adjacent to them and are equipped with built-in airstairs.

Tilt Wing V/STOL

Ground rules. - Although a propeller-type STOL aircraft was not originally included in the study requirements, it was considered that such an aircraft should be designed for direct

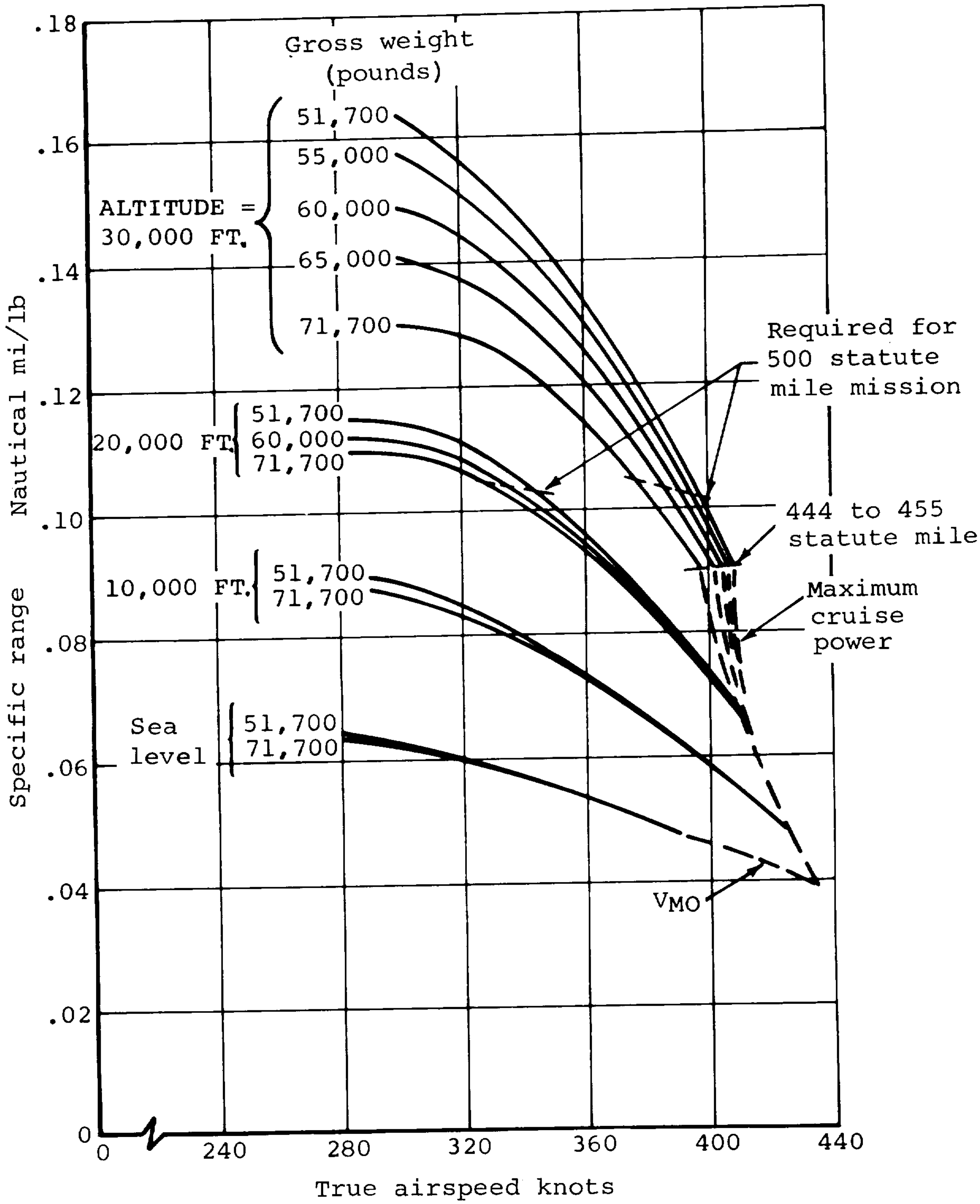


Figure 6. Specific Range and Cruise Speed: 60-Passenger Tilt Wing VTOL

comparison with the other types. Since the tilt wing type has excellent STOL capability the aircraft presented here was designed for a 1000-foot balanced field length.

Using the same basic configuration as the 60-passenger VTOL tilt-wing, a study was made to determine the size and weight of a 60-passenger STOL tilt wing. The ground rules employed were that, with 3 engines operating on a sea level 86°F day, the aircraft shall:

1. Take off over a 35-foot obstacle in 1000 feet.

2. Land over a 50-foot obstacle in a balanced field length of 1000 feet.

3. Perform a 500 statute-mile design stage length with the same NASA fuel requirements imposed on the other VTOL and STOL aircraft.

Since there was no test data for this configuration, an analytical approach was used to calculate the aerodynamic characteristics in transition.

The wing loading, the disc loading, and the power loading were determined from a nondimensional takeoff performance parametric study. Two parameters were held constant during the evaluation: the ratio of propeller disk to wing area, and double-slotted flap deflection, $\delta_F = 20°/20°$. The variables were: static thrust-to-weight ratio, static disc loading, and thrust-line angle of attack. Takeoff distances were obtained by a 2 degree-of-freedom step-by-step integration procedure. The disc loading to wing loading ratio of 0.56 (based on experience) was established as that which gives acceptable deceleration and descent characteristics during a landing approach. A lower disc loading limit of 43 pounds per square foot was used in order that the resulting wing loading would give satisfactory gust and cruise characteristics. Higher disc loading and corresponding higher wing loadings gave unacceptable ground runs.

The conclusions reached were that an aircraft having a thrust to weight ratio of .8, disc loading of 43 pounds per square foot, and wing loading of 78 pounds per square foot would give a 1000-foot takeoff without unduly compromising other considerations. Wing angle for takeoff at maximum gross weight is 20 degrees, and lift-off occurs at 66 knots. The takeoff performance at weights below design gross is shown in Figure 7. An analysis of the landing performance showed that the balanced field length of 1000 feet and the other NASA requirements could be met by the selected aircraft. This gave an approach speed of 38 knots and a thrust-line angle of attack of 37.7 degrees.

Fuel requirements. - Before proceeding with the aircraft fuel requirements it was necessary to determine a propeller efficiency. The propeller was selected for good cruise performance, since static efficiency was not so important here as it was for the VTOL. Based on a study by Vertol Division, a propeller was chosen that would have good cruise efficiency and had a static figure of merit FM = .75 for an activity factor of 120, integrated design lift coefficient C_{L_i} = .25, and tip speed = 850 fps. This information was based on Reference 5. From References 5 and 6, it was determined that efficiency at cruise speed was .865 at 80-percent rpm and .745 at 100-percent rpm.

The fuel required was obtained from an analysis of the 500 statute-mile range and resulted in a design gross weight of 64 000 pounds. Since the propeller diameter of 21.6 feet is very close to that of the tilt wing VTOL, the appearance of the V/STOL aircraft is similar to the general arrangement drawing of Figure 2. Summaries of the weights and general characteristics are given in Tables 2 and 3, and compared with the 60-passenger tilt wing VTOL.

VTOL performance. - A study was made to determine what the VTOL performance of this aircraft would be under standard day conditions with 3 engines operative. The results shown in Figure 8 indicate that payload must be off-loaded before a stage-length can be flown. These characteristics were determined under sea level standard day conditions with 3 engines operating at emergency power.

Since the tilt wing aircraft designed for vertical takeoff and landings has excellent short takeoff characteristics, it follows that a tilt wing designed for short takeoff and landings will have somewhat limited vertical takoff capability. It can be seen from Figure 8 that, if the takeoff is vertical, the passenger load factor ranges from 73 percent at 50 miles to 49 percent at 500 statute-miles range. Although the aircraft does not meet the suggested criteria in the original request for proposal, which stated that the 1000 foot STOL

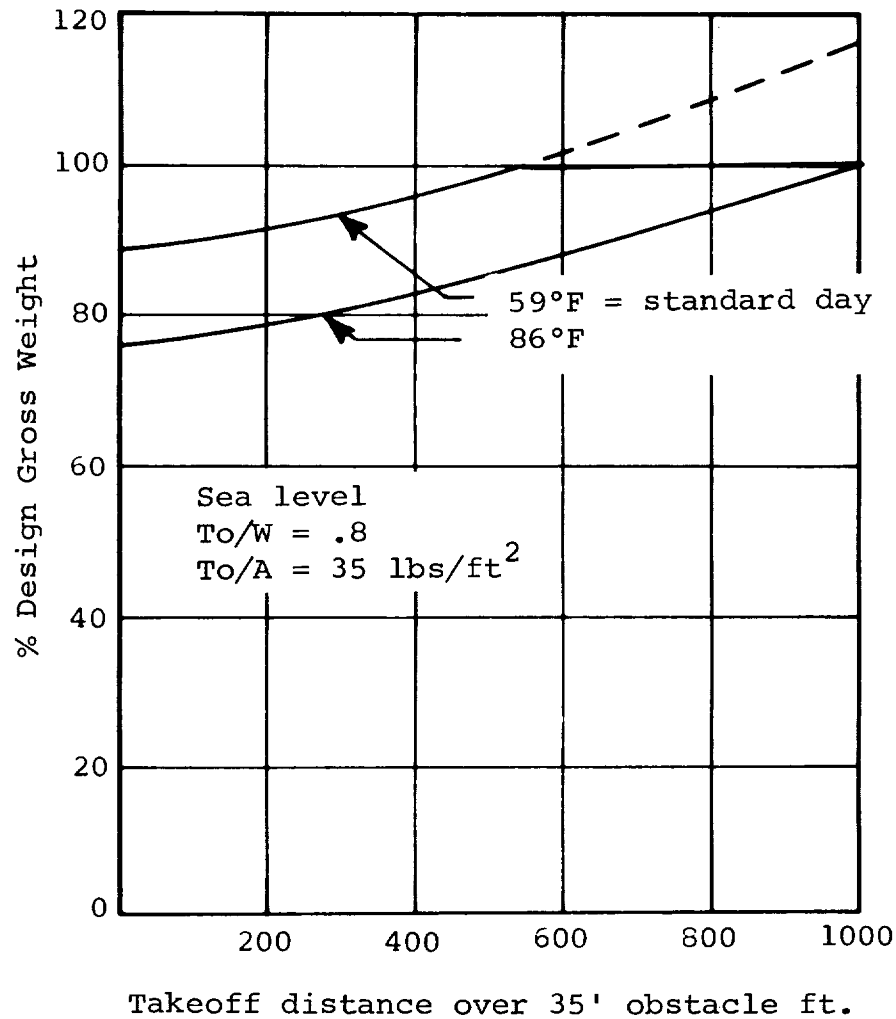


Figure 7. Takeoff Performance: Tilt Wing V/STOL

TABLE 2

60 PASSENGER TILT WING
COMPARISON OF VTOL AND V/STOL GROUP WEIGHTS

	VTOL	V/STOL
Weights		
Rotors	-	-
Wing	5 250	5 350
Tail	1 937	1 750
Body	9 620	9 200
Alighting Gear	2 775	2 460
Flight Controls	4 172	3 800
Reaction Controls	-	-
Powerplant Installation	(15 605)	(10 945)
Engine Section - Cruise / - Lift	1 250	950
Engine Installation - Cruise / - Lift	3 820	2 325
Lift Gas Generators	-	-
Drive System	5 310	3 580
Fuel System	350	350
Engine Controls	100	100
Starting System	170	170
Propeller Installation	4 605	3 470
Auxiliary Power Unit	530	530
Instruments and Navigation	675	675
Hydraulics / Electrical	2 450	2 450
Electronics	750	750
Furnishings and Equipment	(5 120)	(5 120)
Flight Provisions	515	515
Passenger Accommodations	3 838	3 838
Cargo Handling	473	473
Emergency Equipment	294	294
Air Conditioning and Anti-icing	1 370	1 395
Weight Empty	50 254	44 325
Crew and Crew Luggage	520	520
Unusable Fuel and Oil	175	175
Engine Oil	100	100
Passenger Service Items	655	655
Operating Weight Empty	51 704	45 775
Passengers and Luggage	12 000	12 000
Revenue Cargo	1 200	1 200
Fuel	6 800	5 025
Takeoff Gross Weight	71 704	64 000

TABLE 3

60 PASSENGER TILT WING

COMPARISON OF VTOL AND V/STOL GENERAL CHARACTERISTICS

	TILT WING VTOL	TILT WING V/STOL
Physical Data		
Wing		
Area (sq ft)	787	818
Span (ft)	79.5	80
Aspect Ratio	8.03	7.82
Sweep at ¼ Chord (degrees)	0	0
(t/c) Root ℄ Fuselage	.18	.18
(t/c) Tip	.09	.09
Horizontal Tail Area (sq ft)	238	247
Vertical Tail Area (sq ft)	178	178
Fuselage Length (ft)	79.5	79.5
Design Cruise Conditions		
Cruise Speed (kt TAS)	380	395
Cruise Altitude (ft)	30 000	30 000
Structural Limits		
V_{MO} (kts EAS)	390	390
M_{MO}	.72	.72
V_D (kts EAS)	425	425
N_{LIMIT}	2.5	2.5
Rotors or Propellers		
Diameter (ft)	21.05	21.6
Number of Blades	4	4
Solidity	.25	.196
Maximum Tip Speed (fps)	850	850
Cruise Powerplants		
Number	4	4
Maximum Power/Engine (ESHP)	6740	4000
Bypass Ratio	-	-
Pressure Ratio	14	14
T_4	2600°R	2600°R

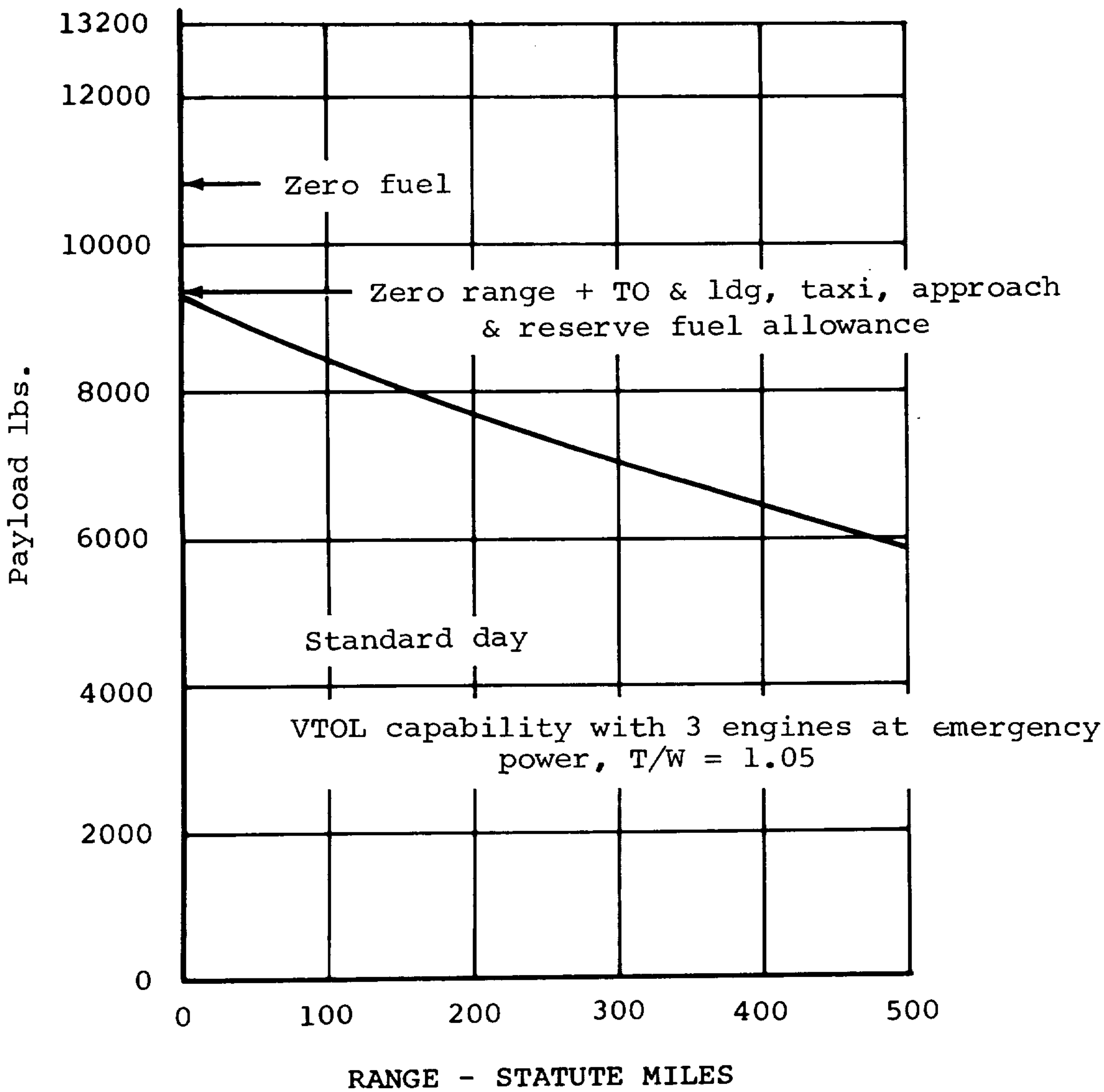


Figure 8. Payload-Range Capability with Vertical Takeoff: Tilt Wing V/STOL

aircraft should be able to carry their full payload over a 50 statute-mile stage length, the tilt wing V/STOL aircraft has a reasonable balance between vertical takeoff and short takeoff capability, so it has not been resized to meet this criteria. Because of the modest climb, cruise, and descent fuels for a tilt wing aircraft, the design gross weight of a tilt wing V/STOL aircraft designed to a 50 statute-mile range would be midway between the weight of the STOL aircraft designed here and the weight of the 60-passenger tilt wing VTOL.

Jet Lift VTOL

This type of aircraft requires a large number of engines, by contemporary standards, in order to ensure the safety of the airplane in the event of an engine failure. In addition, it is desirable to utilize the cruise propulsion system to provide lift in the hover mode of flight, so that a minimum of additional lift is needed in this flight mode. The large number of engines makes it very desirable to provide hover control without the additional complexity of bleed systems, separate control engines, or other such devices. The addition of a separate control system may reduce lift engine size, but will have an adverse effect on maintenance and acquisition costs.

The jet-lift design presented in this report is specifically designed to obviate the need for control devices in addition to the lift engines, and to permit the use of the cruise propulsion system for lift in hover.

A three-view drawing of the final 60-passenger jet lift configuration is shown in Figure 9. Five lift turbofan engines are installed in each of the pods mounted at the tips of the swept forward wing. The center of lift of these engines is forward of the center of gravity; this arrangement permits the thrust of four cruise engines mounted on the rear fuselage to be deflected for lift in hover. Roll control is attained by differential thrust of the two sets of lift engines, pitch control by differential thrust of the forward eight lift engines and the four cruise engines, and yaw control by differential fore and aft tilting of swivelling nozzles on the lift engines.

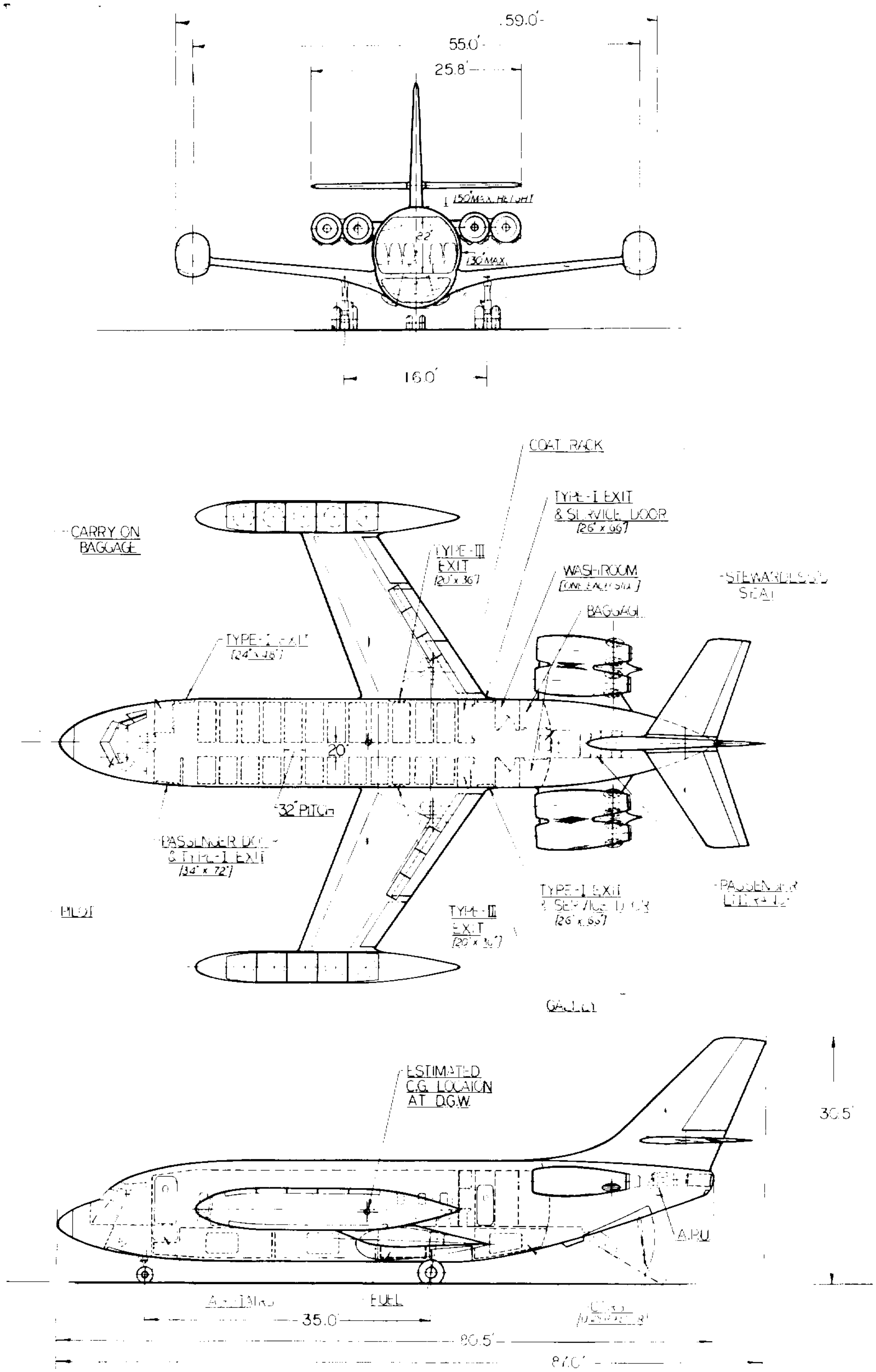


Figure 9. 60-Passenger Jet Lift VTOL General Arrangement

For comparative purposes a jet-lift aircraft with lift engines mounted in the fuselage was designed. It has the advantages, as compared to the tip pod layout, of minimum wing weight, low roll inertia, minimum roll response to lift engine failure, and the ability to have a wing optimized for cruise. However, it suffers from high fuselage weight, awkwark cockpit-to-cabin access, a possibility of high cabin noise and vibration levels, and a problem of the jet efflux near the wheels and fuselage. Although the weight of this configuration was not substantially different from the tip pod configuration, the disadvantages enumerated above were considered to be severe enough to warrant discontinuation of the fuselage-mounted engine study. Reference 2 indicates that fuselage-mounted engines may cause interactions which would result in lift losses, both in ground effect and in transition, and in possible handling problems. The weights and general characteristics of the chosen configuration are summarized in Table 4.

Propulsion and control systems. - The tip position for the lift engine pods was chosen in preference to a more inboard location for several reasons. The tip position gives minimum lift engine size, since the increased control arm gives smaller control thrust requirements, in spite of the increase in required control power caused by the increased roll inertia. An inboard location would increase interference drag and not give the favorable endplate effect of the tip pod. The inboard location would also require the pod to be beneath the wing and, since it would also lose some of the favorable effect of wing dihedral on jet efflux ground clearance, a high wing would be required to make this clearance adequate. The tip location gives good clearance on a low-wing aircraft. The low-wing is also preferred for ditching and for maintenance accessibility. Reference 2 indicates that the tip location also avoids unfavorable interactions of the propulsion and airframe aerodynamics. The pod is located on the wing tip such that the torsional axis of the wing passes through the center of the five lift engines. This avoids high torsional wing loads on all but the root of the wing in the hover mode.

The cruise engines were sized to match the desired cruise speed and altitude. A bypass ratio of three for the cruise engines was chosen in order to provide good climb performance and give a sizeable contribution to the hover lift. It was felt that larger bypass ratios than this might compromise

TABLE 4

60 PASSENGER JET LIFT VTOL

WEIGHT AND GENERAL CHARACTERISTICS SUMMARY

Weights		
Rotors		-
Wing		7 000
Tail		2 023
Body		10 450
Alighting Gear		3 230
Flight Controls		1 849
Reaction Controls		-
Powerplant Installation		(18 321)
Engine Section	- Cruise	1 435
	- Lift	3 979
Engine Installation	- Cruise	4 897
	- Lift	6 790
Lift Gas Generators		-
Fan and Ducting Installation		-
Fuel System		520
Engine Controls		380
Starting System		320
Propeller Installation		-
Auxiliary Power Unit		530
Instruments and Navigation		770
Hydraulics		500
Electrical		2 005
Electronics		750
Furnishings and Equipment		(5 220)
Flight Provisions		515
Passenger Accommodations		3 838
Cargo Handling		473
Emergency Equipment		394
Air Conditioning and Anti-icing		1 450
Weight Empty		54 098
Crew and Crew Luggage		520
Unusable Fuel and Oil		175
Engine Oil		120
Passenger Service Items		655
Operating Weight Empty		55 568
Passengers and Luggage		12 000
Revenue Cargo		1 200
Fuel		11 990
Takeoff Gross Weight		80 758

TABLE 4. - Concluded
60 PASSENGER JET LIFT VTOL
WEIGHT AND GENERAL CHARACTERISTICS SUMMARY

Physical Data	
Wing	
Area (sq ft)	712
Span (ft)	55
Aspect Ratio	4.25
Sweep at ¼ Chord (degrees)	-25
(t/c) Root ℄ Fuselage	.17
(t/c) Tip and at .3 Semispan	.11
Horizontal Tail Area (sq ft)	186
Vertical Tail Area (sq ft)	177
Fuselage Length (ft)	80.5
Design Cruise Conditions	
Cruise Speed (kt TAS)	466
Cruise Altitude (ft)	30 000
Structural Limits	
V_{MO} (kts EAS)	400
M_{MO}	.83
V_D (kts EAS)	450
N_{LIMIT}	2.5
Cruise Powerplants	
Number	4
Maximum Thrust (lbs)	6950
Maximum Power (HP)	-
Bypass Ratio	3
Pressure Ratio	16
T_4	2600°R
Lift Powerplants	
Number	10
Maximum Thrust (lbs)	9970
Bypass Ratio	2.5
Pressure Ratio	7
T_4	2360°R
Inertias (slugs ft^2)	
Roll	425,328
Pitch	831,092
Yaw	1,251,289

the design of the deflector nozzles. The cruise engines have an overall pressure ratio of 16 and a maximum turbine inlet temperature of 2600°F. The longitudinal position of the cruise engines on the rear fuselage was chosen in order to utilize fully the thrust of these engines for trim, control, and hover lift. It is recognized that further work would be required to ensure satisfactory stall characteristics with this arrangement.

A study was made of the effect of the hover lift and control criteria, given in the design ground rules, on lift engine size. The results of these studies are summarized in Table 5. It can be seen that the requirement to hover with one engine failed, with a thrust-to-weight ratio of 1.0 and control amounts of 50, 20, and 20 percent in roll, pitch and yaw, respectively, was the most critical.

Control powers are appropriate to the required, rather than the desired, values of control. Designing for the desired values of control power results in a considerable penalty in design gross weight, as is shown in the technical and economic tradeoff section of this report.

The choice of number of lift engines is somewhat subjective. While a large number of engines minimizes engine size, and the effect of an engine-out, fewer engines are obviously desirable for reduced maintenance costs. Eight engines, ten engines and twelve engines give total lift-engine thrust-to-gross-weight ratios of 1.24, 1.19 and 1.17, respectively. A ten-engine configuration was chosen as a compromise between these factors. While eight does not increase installed thrust to a prohibitive degree, it does result in a very large high-drag pod design. A high bypass ratio is desirable for the lift engines from the viewpoint of noise propagation. However, increase in bypass ratio leads to increasing engine size and weight which, in turn, affect lift engine pod size and drag, and engine installation and wing weight penalties. The lift engine bypass ratio of 2.5 was chosen as a compromise between noise propagation and engine size and weight. The considerable lift engine running time dictated by the taxi, takeoff, approach, and landing ground rules favored turbofan engines for low specific fuel consumption. The lift engines have an overall pressure ratio of eight and a maximum turbine inlet temperature of 2360°R.

TABLE 5

60 PASSENGER JET LIFT VTOL CONTROL SUMMARY

CASE	THRUST WEIGHT	CONTROL % ROLL	CONTROL % PITCH	CONTROL % YAW	ENGINE FAILED	REQUIRED THRUST LIFT	REQUIRED THRUST CRUISE
(1)	1.15	0	0	0	None	8 460	5 760
(2)	1.05	50	20	20	None	8 379	5 604
(3)	1.05	100	0	0	None	8 729	5 258
(4)	1.05	0	100	0	None	8 522	6 950*
(5)	1.05	0	0	0	Lift	9 150	4 530
(6)	1.05	0	0	0	Cruise	7 330	6 380
(7)	1.0	50	20	20	Lift	9 970*	4 060
(8)	1.0	50	20	20	Cruise	6 400	6 640

*Critical cases

Note: Engine out cases assume emergency thrust increase of 7 percent. Thrusts quoted are sea level standard takeoff ratings.

One of the disadvantages of the tip-mounted lift engines is that the aircraft has some response in roll to a lift-engine failure. Figure 10 shows this response, assuming no artificial damping and a lag in pilot response of one second. The full roll control power is applied at this point. The bank angle does not exceed 17.2 degrees, and it is evident that no power management system is required to automatically shut down an engine on the opposite side, or to apply differential thrust independent of the control system.

Wing design. - The wing design is a compromise between many factors. The forward sweep of 25 degrees and the mean wing thickness of 11.25 percent were chosen to obtain a critical Mach number of .8 at 30 000 feet at the mean cruise weight. Although the aspect ratio of 4.25 could have been lower without increasing required lift engine size there would have been insufficient span to install high-lift flaps and conventional roll control devices. In addition, the low lift-curve slope associated with a low-aspect-ratio wing would have resulted in large angles of attack being required in transition, and would have compromised the fuel consumption in loiter. The chosen aspect ratio was considered to be the minimum consistent with these considerations. A wing loading of 115 psf was chosen for this aircraft. This loading gives near-minimum cruise drag and low gust sensitivity. At the same time, it is not too high to allow conventional landing in an emergency and, in combination with double-slotted flaps, gives good transition performance.

Performance. - The jet-lift VTOL is designed to cruise at 30 000 feet for the 500-statute-mile stage lengths. While a higher cruise altitude would have resulted in slightly lower fuel requirements and design gross weight, it was felt that this altitude was realistic from an operational standpoint. The cruise Mach number of .8 is comparable to that of contemporary short-range jet transports. Higher cruise speeds would demand more highly swept or thinner wings and tail surfaces, with attendant weight penalties. Higher speeds might still improve direct operating costs slightly at the longer stage lengths, but they would be detrimental to operating costs at the short stage lengths, where the cruise speed would be restricted by the maximum equivalent airspeed given below.

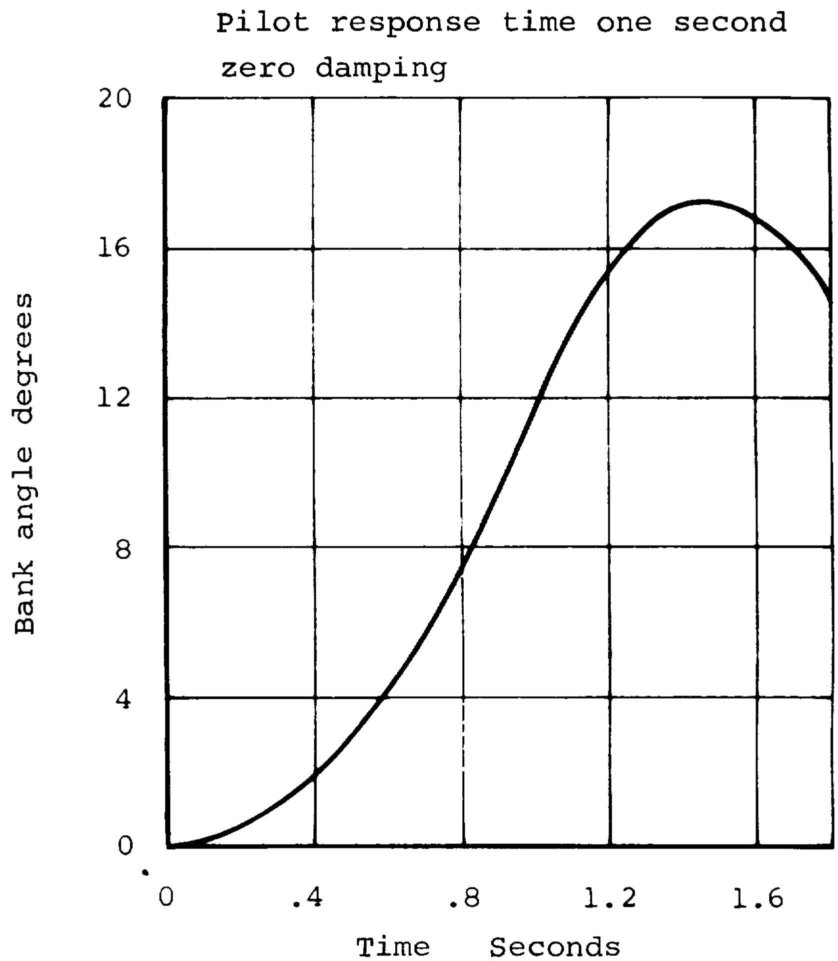


Figure 10. Roll Response with One Engine Out: Jet Lift VTOL

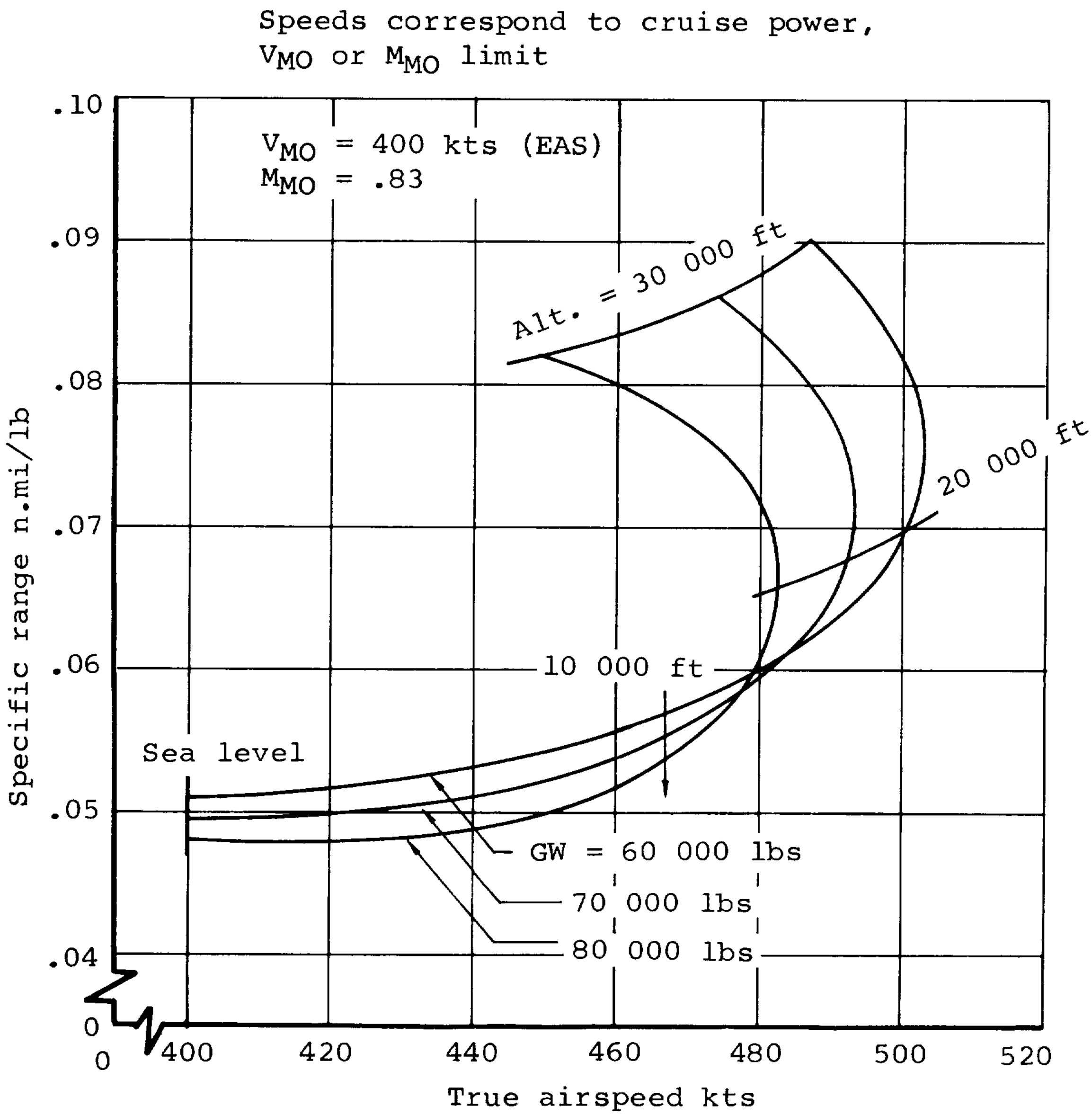


Figure 11. Cruise Speed and Specific Range: 60-Passenger Jet Lift VTOL

A maximum operating Mach number of .83 was selected to permit use of the full cruise speed capability at lighter weights, and high descent speeds from the higher altitudes. Since short-haul aircraft would be operated at low altitude for short stage lengths, a maximum equivalent airspeed limitation of 400 knots was stipulated. This limit is somewhat higher than that set for contemporary jet transports, but does permit rapid descents from the lower altitude.

The aircraft climbs at maximum rate of climb and is not limited by the attitude angle restriction that influenced the tilt-wing aircraft.

Figure 11shows the cruise speed and specific range of the aircraft as a function of gross weight and altitude. For the long-range missions for which cruise altitude is 30 000 feet, the cruise speed ranges from 450 knots to 466 knots.

The descent performance was calculated at idle thrust, since the total fuel consumed for this type of descent was significantly less than for a maximum-rate-of-sink descent. The descent is restricted in speed by cabin attitude angle limits.

Weights. - A weight summary for the 60-passenger jet-lift configuration is presented in Table 4. The powerplant installation weight represents about 23 percent of the design gross weight of 80 758 pounds. Using the wing-tip-mounted lift pods for vertical takeoff and landing creates internal wing loads which are greater at $N = 1.5$, which is possible on a standard day with low control inputs, than the normal flight loads at $N = 2.5$ making the VTOL mode the design condition for this aircraft. The wing box weight associated with the tip-mounted pods is about 60 percent higher than that of a conventional wing of the same size. However, this weight penalty is more than offset by the absence of a separate hover control system, and gives a wing structure sufficiently stiff to obviate the classical divergence of swept forward wings.

Fuselage and cabin layout. - The 60 passengers are accommodated in five-abreast seating. Due to close proximity of the trailing edge of the wing root to the cruise engine nacelles, it is not possible to provide a side entrance door at the rear of the aircraft. Instead, a rear ventral entrance and stairway are provided. There is also an airstair at the forward passenger door. Carry-on baggage and coat racks are provided at the front and rear of the aircraft, and two washrooms are installed at the rear of the aircraft, where noise levels are likely to be highest due to the rear-mounted cruise engines. Holds for revenue cargo and baggage are provided beneath the cabin floor. The galley is located at the rear of the cabin.

Stowed-Rotor VTOL

Several concepts of stopped-or stowed-rotor aircraft were considered before selecting the tandem configuration shown in Figure 12. Weight and general data summaries for this configuration are given in Table 6. Configurations with a folded trailed single rotor, but no rotor fairing (i.e., not stowed) were not examined in detail because of the drag penalty of the exposed trailed rotor. The drag penalty is discussed in Reference 3 and illustrated in Figure 13, taken from the same reference. The trailed rotor concept may also have dynamics and handling problems associated with unsupported blades of relatively low stiffness.

Rotor folding. - Single-rotor configurations of both shaft-driven and warm-cycle gas-driven types were analyzed. It was found that the rotor stowage problem was more severe than that of the tandem configuration, since the rotor locations of the latter permitted stowage without retraction of the rotor hub or transmission. The central location of the single rotor indicates the use of hub retraction for stowage, if adequate airframe clearance is maintained when the rotor is deployed. The alternative is a large central hub body into which the blades retract. Both of these solutions impose severe penalties in weight and complexity on single-rotor configurations. The bulky, high-torque-loading transmission associated with a single large-diameter shaft-driven rotor also presents weight and installation problems which are compounded by hub retraction. In addition, a single-rotor aircraft (assuming the blades are rigid) may experience cyclic pitching and rolling moments as the rotor is stopped for conversion; this is not the case with the synchronized rotors of a tandem configuration.

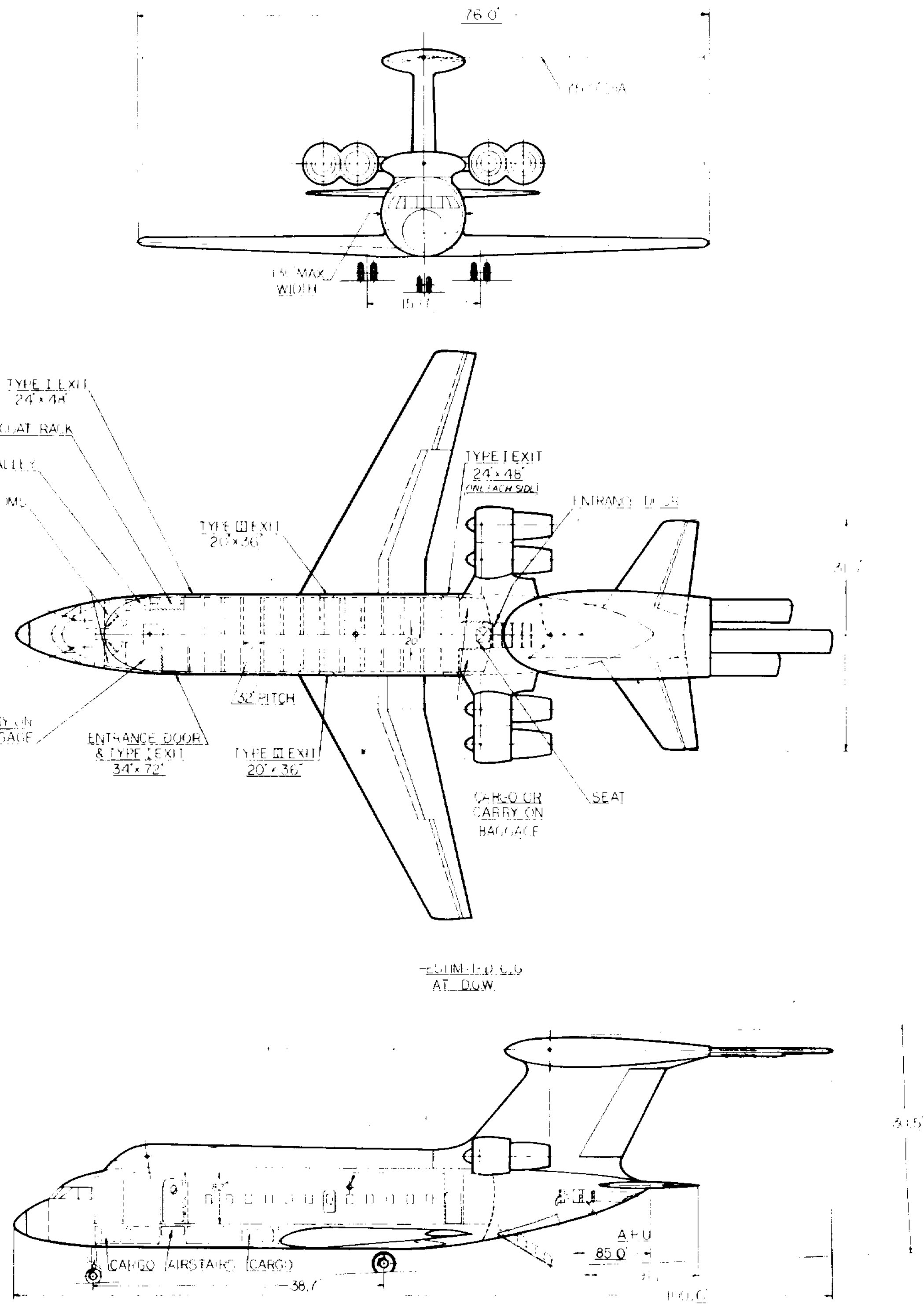


Figure 12. 60-Passenger Stowed Rotor VTOL General Arrangement

TABLE 6. - Concluded
60 PASSENGER STOWED ROTOR VTOL
WEIGHT AND GENERAL CHARACTERISTICS

Physical Data	
Wing	
Area (sq ft)	875
Span (ft)	76
Aspect Ratio	6.6
Sweep at ¼ Chord (degrees)	26
(t/c) Root ℄ Fuselage	.18
(t/c) Tip	.09
Horizontal Tail Area (sq ft)	275
Vertical Tail Area (sq ft)	268
Fuselage Length (ft)	84
Design Cruise Conditions	
Cruise Speed (kt TAS)	340
Cruise Altitude (ft)	25 000
Structural Limits	
V_{MO} (kts EAS)	350
M_{MO}	.65
V_D (kts EAS)	390
N_{LIMIT}	2.5
Rotors or Propellers	
Diameter (ft)	75
Number of Blades	3
Solidity	.07
Maximum Tip Speed (fps)	740
Cruise Powerplants	
Number	4
Maximum Thrust (lbs)	-
Maximum Power (HP)	7300
Bypass Ratio	6
Pressure Ratio	20
T_4	2600°R
Inertias	
Roll	282,540
Pitch	2,435,201
Yaw	2,712,741

TABLE 6

60 PASSENGER STOWED ROTOR VTOL

WEIGHT AND GENERAL CHARACTERISTICS

Weights	
Rotors	9 456
Wing	5 050
Tail	2 300
Body	13 002
Alighting Gear	3 715
Flight Controls	3 375
Reaction Controls	-
Powerplant Installation	(19 104)
Engine Section - Cruise / - Lift	2 244
Engine Installation - Cruise / - Lift	6 950
Lift Gas Generators	-
Drive System	9 100
Fuel System	550
Engine Controls	100
Starting System	160
Propeller Installation	-
Auxiliary Power Unit	530
Instruments and Navigation	675
Hydraulics	450
Electrical	2 000
Electronics	750
Furnishings and Equipment	(5 120)
Flight Provisions	515
Passenger Accommodations	3 838
Cargo Handling	473
Emergency Equipment	294
Air Conditioning and Anti-icing	1 470
Weight Empty	66 997
Crew and Crew Luggage	520
Unusable Fuel and Oil	175
Engine Oil	100
Passenger Service Items	655
Operating Weight Empty	68 447
Passengers and Luggage	12 000
Revenue Cargo	1 200
Fuel	12 808
Takeoff Gross Weight	94 455

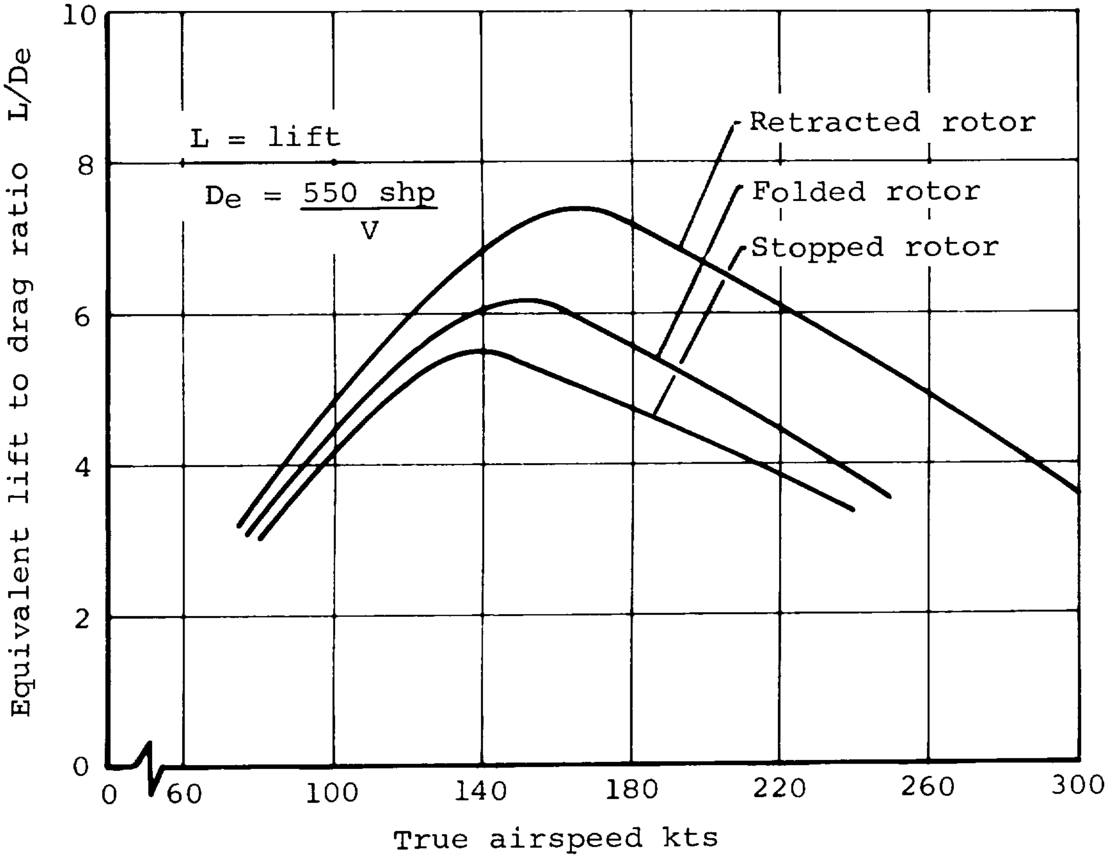


Figure 13. Stowed Rotor VTOL Drag Comparison of Convertible Helicopters

A shaft-driven single-stowed-rotor aircraft was evaluated in the initial phase of the study. Two methods of lowering the rotor hub for rotor stowing were considered. These were a retractable transmission and a sliding shaft arrangement. While the latter scheme requires the transmission and shaft to occupy the central portion of the cabin, this was considered to be more acceptable than the extreme complexity of retractable transmissions. The configuration was evaluated at a gross weight of 95 000 pounds and found to be deficient in fuel weight by 4 000 pounds.

A warm cycle gas-driven rotor was also investigated. This aircraft has four lightweight turbofan (bypass ratio 1.6) engines which supply air for driving the rotor and for yaw control. Warm cycle was investigated in preference to hot cycle because of the reduced noise level with the lower tip jet velocities of the former system. It was found that a blade thickness/chord ratio of .21 would be required to obtain sufficient duct cross section area and this, together with the high hub to rotor diameter ratio, would give a low hover figure of merit of the order .5. The high blade thickness would also necessitate a low transition speed and therefore compromise wing design. These factors together with the complexity of folding blade hinges incorporating gas ducts and the drag penalty of the large hub required for rotor stowage led to a decision to discontinue study of this configuration.

Propulsion. - The tandem configuration presented in Figure 12 is powered by four convertible turbofan engines. The thrust of the fans can be modulated at constant power-turbine speed by variable inlet vanes while shaft power is also provided to drive the rotors. During hover and low-speed flight, the fans are decoupled. For transition, the fans are engaged to provide propulsive thrust and at the same time shaft power is provided for rotor lift. The natural fuselage length for a 60-passenger cabin with five-abreast seating, and the maximum blade overlap of 33 percent radius dictated by physical blade interference, gave a rotor diameter of 75 feet. This corresponds to a disc loading of 11 pounds per square foot and the corresponding hover power gave a matched cruise speed of 330 knots at 25 000 feet. Higher disc loadings would increase rotor solidity and make blade stowing very difficult. To obtain lower loadings the center-to-center distance of the rotors would have to be increased, necessitating a longer and therefore heavier fuselage. The required hover power would decrease and the net effect would be a heavier, slower aircraft. The natural fuselage size and maximum overlap were therefore allowed to dictate the rotor size.

Conversion. - Conversion to the cruise configuration is accomplished by unloading, decoupling, braking, and stopping the rotors, which are then folded in the trailing position and enclosed by retraction of the doors and fairings on the fuselage and aft pylon. When the fairings are open, they are positioned to provide rotor clearance for hover and transition. The droop stops of the rotor blades are centrifugally operated to lock out the flapping hinges when the rotor is stopped for conversion.

Control. - Hover and transition: Control in this mode is obtained in the same manner as for a conventional tandem rotor helicopter. That is, differential collective pitch for longitudinal control, lateral cyclic for roll control, and differential lateral cyclic for yaw control. The power requirements for these controls are small and therefore the desired values of control power have been provided. The hover power is dictated by the requirement to hover with one engine failed at a thrust-to-weight ratio of 1.05. Conventional flight: In this mode longitudinal, lateral and directional control are obtained with elevator, ailerons and spoilers, and rudder, respectively.

Wing design. - The wing and its high-lift devices have been designed to permit conversion at 130 knots equivalent airspeed using a 1.2 stall speed criteria. This results in a wing loading of 108 pounds per square foot and the choice of 35-percent-chord Fowler flaps covering 70 percent of the span. These flaps, together with full-span leading edge slats, give the aircraft a trimmed maximum lift coefficient of 2.75. The wing is swept in order to improve ride qualities, reduce fatigue loads, and attain correct center-of-gravity location. The full-span slats prevent wing stall during high-angle descents.

Performance. - Matching the installed thrust to the power required for hover gives a cruise speed of 330 knots at an optimum altitude, from a DOC standpoint, of 25 000 feet. Higher cruise speeds could obviously be attained by increasing the installed thrust, but this would have increased the size and weight of an already large aircraft.

The aircraft climbs at maximum rate of climb since the climb is not attitude angle restricted. The true airspeed and specific range during cruise are shown in Figure 14 as a function of gross weight and altitude. The airplane cruises at 320 knots to 330 knots true airspeed during cruise at 25,000 feet altitude on the 500-statute mile mission. The descent performance was calculated at idle thrust. The descent is limited by cabin attitude angle restrictions and the true airspeed on descent is less than that for maximum rate of descent.

Weights. - A weight summary of the stowed rotor configuration is presented in Table 7. Large weight penalties in the rotors, body and associated groups resulting from the complexities resulting from blade folding make this the heaviest of the VTOL concepts. The design includes fiberglass rotor blades with a titanium hub. The weight of the flight controls includes rotor as well as surface controls.

Fuselage and cabin layout. - The 60 passengers are accommodated in 5-abreast seating. Due to close proximity of the trailing edge of the wing root to the engine nacelles, it was not possible to provide a side entrance door at the rear of the aircraft. Therefore, a rear ventral entrance and stairway was provided. There is also an airstair at the forward passenger door . Carry-on baggage and coat racks are provided at the front and rear of the aircraft, and the two washrooms are also installed at the front of the cabin. Holds for revenue cargo and baggage are provided beneath the cabin floor and on the left side of the rear entrance. The galley is located at the rear of the cabin.

Lift Fan VTOL

The CX-6 study investigated several configurations of lift fan concepts for both VTOL and STOL aircraft. The most promising VTOL lift fan concept resulting from that study employed four independent tip-turbine fan gas generator combinations to provide powered lift. The fans were mounted in the wing root fore and aft of a curved torque box. They were independent in that there was no cross-ducting. Each fan received its air supply from its own gas generator which was mounted on top of the fuselage. One of the advantages of this type of configuration is the possibility of designing to survive a lift fan failure.

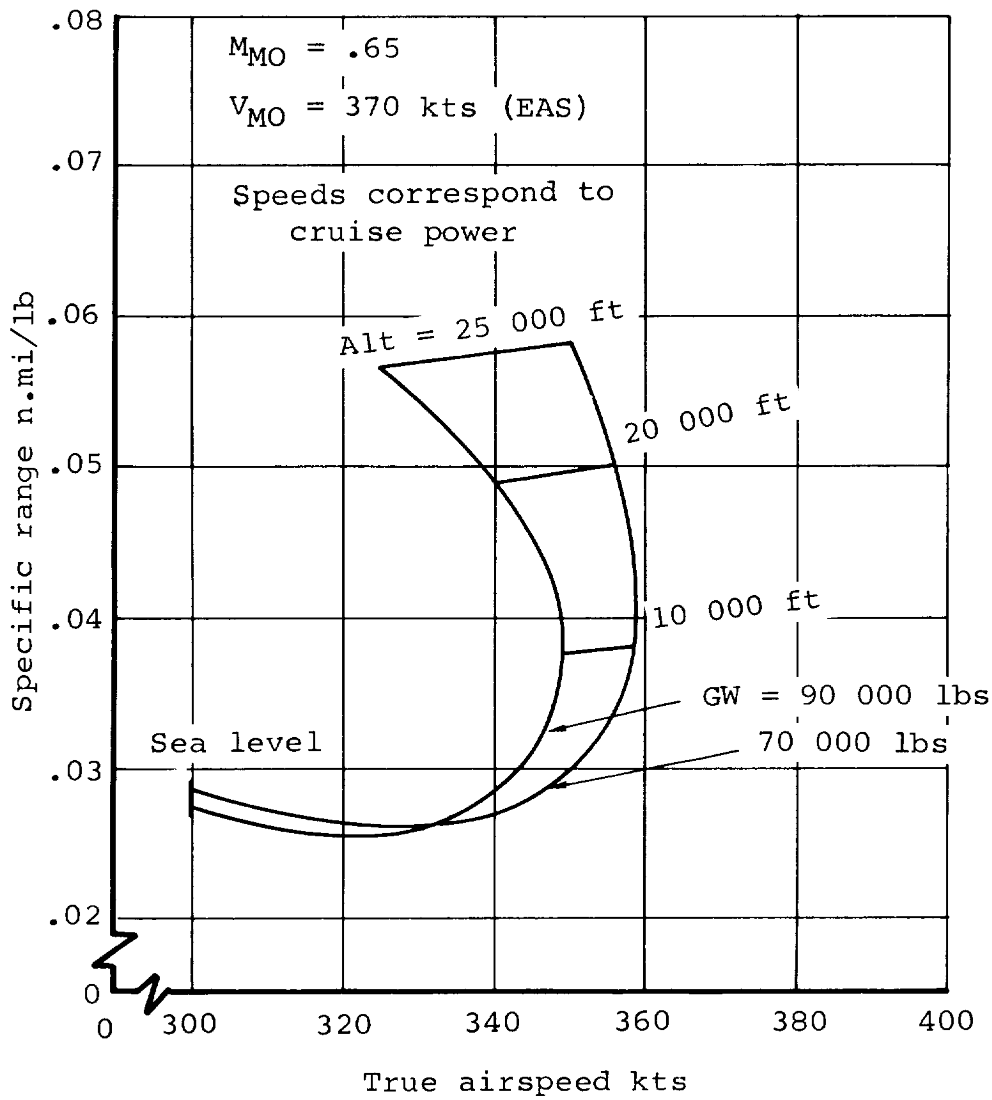


Figure 14. Cruise Speed and Specific Range: 60-Passenger Stowed Rotor VTOL

The hover control system consisted of bleed-burn reaction nozzles at the airplane extremeties. Air was supplied to the nozzles by turbocompressors which were driven by bleed air from the gas generator exhaust. These studies were used as a basis in deriving the civil transports for the NASA.

NASA directed that the base airplanes be sized to accomplish the 500 statute-mile-range mission with a 60-passenger payload. At the midpoint of the study, it was directed that the effect of increasing the payload to 120 passengers be examined for the most promising configurations.

The first VTOL configuration developed for the NASA study was a lift fan arrangement quite similar to the preferred CX-6 concept. However, the nozzle burning feature was eliminated from the hover control system on the somewhat arbitrary assumption that the complexity and resulting environment would not be tolerated for commercial operation.

When this lift fan concept was resized for the 120-passenger payload in the second phase of the study, it was found that a reasonable configuration was impossible unless burning was used at the reaction nozzles to decrease the airflow required, or the lift fans were cross-ducted to eliminate the asymmetrical roll moment induced by a gas generator failure, or both. In order to obtain a more valid assessment of the effect of payload on the configuration, the 60-passenger airplane was reworked to incorporate nozzle burning and cross-ducting.

The final aircraft, incorporating cross-ducting in the roll sense and nozzle burning, is illustrated in Figure 15. The weights of the aircraft with and without nozzle burning are compared in Table 8 and the general characteristics of the final configuration are summarized in Table 8.

Propulsion. - Cruise power slightly greater than for conventional transports was found desirable. For designs using lift fans, it reduces the thrust required from the fans, thereby causing less compromise to the wing planform. At the same time, better climb and transition capability can be expected. Therefore, the cruise engines were sized to a T/W = .35 based on takeoff gross weight for the basic mission and sea level static thrust at 59°F. The cruise turbofan engines have a bypass ratio of 3, a pressure ratio of 20, and a maximum turbine inlet temperature of 2600°R.

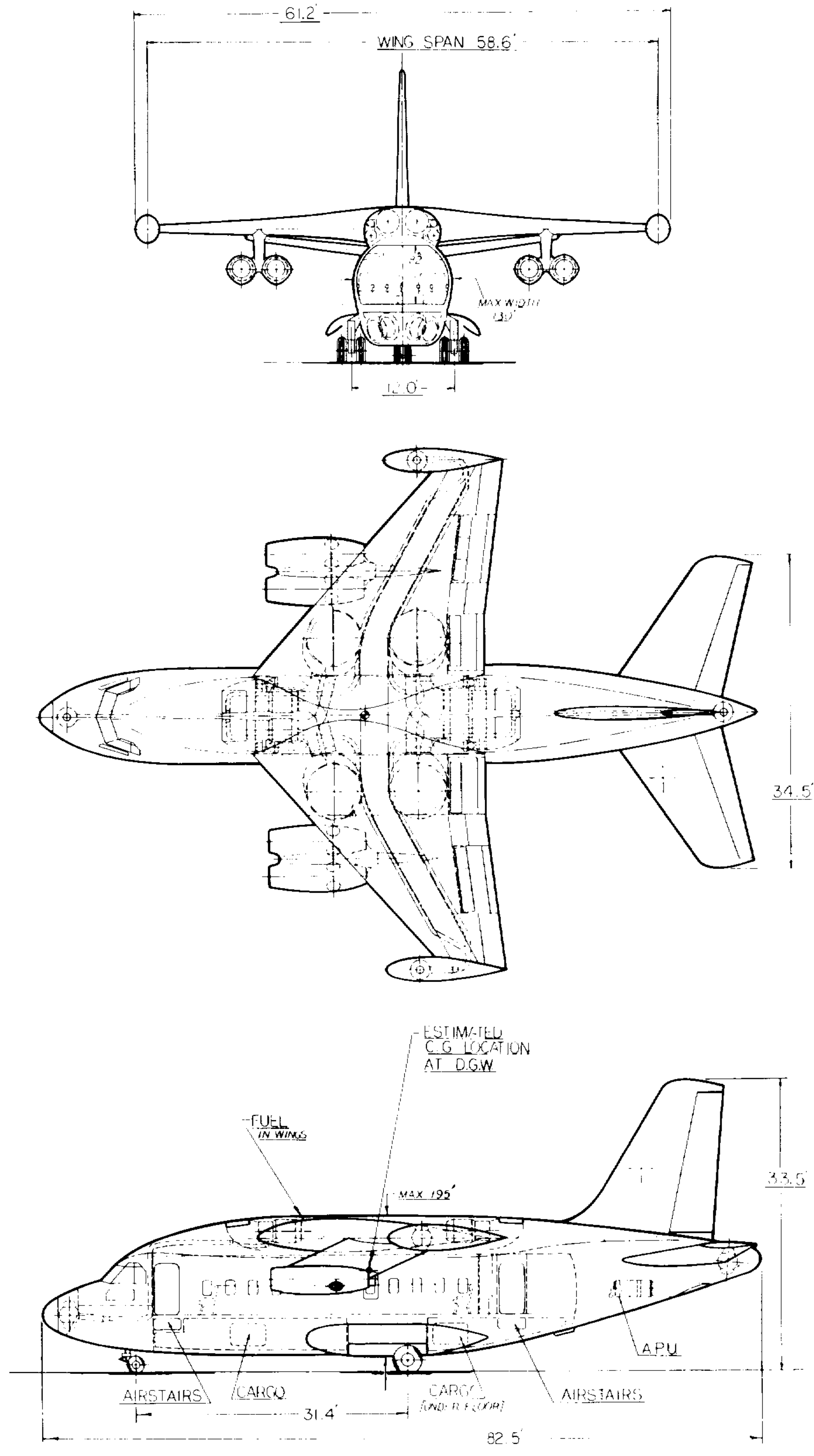


Figure 15. 60-Passenger Lift Fan VTOL General Arrangement

TABLE 7

60 PASSENGER LIFT FAN VTOL

VARIATION OF WEIGHTS DUE TO TYPE OF REACTION CONTROL

Weights		NOZZLE BURNING	NON-BURNING NOZZLE
Rotors		-	-
Wing		5 774	6 350
Tail		2 557	3 420
Body		11 890	12 210
Alighting Gear		3 155	3 420
Flight Controls		2 000	2 000
Reaction Controls		2 030	3 280
Powerplant Installation		(15 411)	(17 574)
Engine Section	- Cruise	1 344	1 344
	- Lift	-	-
Engine Installation	- Cruise	5 000	5 250
	- Lift	-	-
Lift Gas Generators		2 660	3 680
Fan and Ducting Installation		5 452	6 320
Fuel System		475	500
Engine Controls		300	300
Starting System		180	180
Propeller Installation		-	-
Auxiliary Power Unit		530	530
Instruments and Navigation		700	700
Hydraulics		450	450
Electrical		2 000	2 000
Electronics		750	750
Furnishings and Equipment		(5 182)	(5 182)
Flight Provisions		515	515
Passenger Accommodations		3 838	3 838
Cargo Handling		473	473
Emergency Equipment		356	356
Air Conditioning and Anti-icing		1 430	1 430
Weight Empty		53 859	59 296
Crew and Crew Luggage		520	520
Unusable Fuel and Oil		175	175
Engine Oil		100	100
Passenger Service Items		655	655
Operating Weight Empty		55 309	60 746
Passengers and Luggage		12 000	12 000
Revenue Cargo		1 200	1 200
Fuel		10 720	11 600
Takeoff Gross Weight		79 229	85 546

TABLE 8

60 PASSENGER LIFT FAN VTOL

WEIGHT AND GENERAL CHARACTERISTICS SUMMARY

Physical Data	
Wing	
Area (sq ft)	1055
Span (ft)	58.6
Aspect Ratio	3.2
Sweep at ¼ Chord (degrees)	35
(t/c) Root ℄ Fuselage	.145
(t/c) Tip	.100
Horizontal Tail Area (sq ft)	360
Vertical Tail Area (sq ft)	188
Fuselage Length (ft)	82.5
Design Cruise Conditions	
Cruise Speed (kt TAS)	466
Cruise Altitude (ft)	30 000
Structural Limits	
V_{MO} (kts EAS)	400
M_{MO}	.83
V_D (kts EAS)	450
N_{LIMIT}	2.5
Cruise Powerplants	
Number	4
Maximum Thrust (lbs)	6960
Maximum Power (HP)	-
Bypass Ratio	3
Pressure Ratio	20
T_4	2600°R
Lift Powerplants	
Number	4 Gas Gen., 4 Lift Fans
Maximum Thrust (lbs) per fan	17 600
Bypass Ratio	8 (Fans)
Pressure Ratio	12 (Gen.)
T_4	2600°R
Fan Diameter (ft)	6.45
Fan Pressure Ratio	1.3
Effective Thrust Augmentation Ratio	2.5

The thermodynamic cycle of the lift fans was selected to minimize the fan diameter thereby causing minimum compromise to the wing planform. This required the use of the maximum fan pressure ratio (R_{fan}) which (according to General Electric Company) was 1.3 for a single stage tip-turbine fan. The gas generator turbine inlet temperature of 2600°R was selected to be consistent with the cruise engine philosophy. The corresponding bypass ratio is 8.0. A partial-admission (163°) entry scroll was used to facilitate the fan installation. (the small performance improvements effected by use of full-admission fans is more than offset by wing planforms compromise.)

The lift fans are sized to provide a T/W = 1.05 based on takeoff gross weight and fan thrust at sea level for a temperature of 86°F. The remaining T/W = .10 required by the ground rules is available from the control nozzles.

Hover control. - Four bi-directional reaction control burn nozzles located at the airplane extremeties also have vectoring capability to provide yaw control. Air is supplied to the nozzles from a manifold of four pressure ratio 8 turbocompressors which are driven by exhaust air bled from the lift fan gas generator. It is anticipated that a "segmented" burner would be utilized with only one "pilot ring" normally burning. As the control demand increases, additional burning segments are added to increase the nozzle exhaust temperature to a maximum of 3000°R. Such a system is unquestionably more complex and costly, but the environment in regards to temperature, noise, erosion, etc., may be very little worse than the non-burning arrangement. This is because approximately 60 percent of the maximum control demand is available without employing the burning feature. It is felt that demand in excess of this amount will seldom occur.

The high specific thrust (and low airflow requirement) of the burning system effects a reduction in duct sizes over the system without burning. Consequently, the system was optimized by reduction of the turbocompressor pressure ratio from 12 to 8. Thus, the airflow required from the gas generator to drive the turbocompressor is reduced approximately 30 percent with negligible change in duct size.

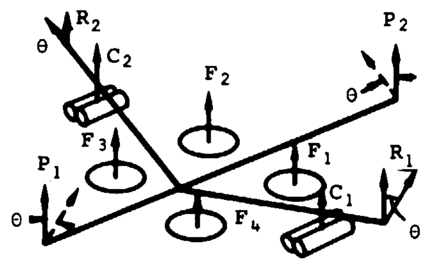
The critical hover control condition for sizing the pitch nozzles is 100 percent pitch control plus trim at T/W = 1.05. For sizing the roll nozzles and the turbocompressors it is 20 percent pitch, 50 percent roll, 20 percent yaw control plus trim at T/W = 1.0 with an outboard cruise engine out. A summary of control forces is given in Figure 16.

It should be noted that it was necessary to install four cruise engines in order to realize a significant reduction in asymmetrical roll moment with an engine out. Also, the loss of a lift fan gas generator in this configuration is not the same as a fan failure because half of the exhaust gas from each generator is ducted to a fan on one side of the fuselage and half to the fan on the opposite side. Therefore, the control system as designed is not capable of sustaining a non-catastrophic fan failure, but for a 4000 lb weight penalty can be designed to allow for such a failure so that the aircraft may sink but not upset. The aircraft was not so designed since the ability to withstand a fan failure was not called for in the ground rules. A more direct arrangement in which the turbocompressors are eliminated and the bleed air is ducted to the nozzles is usually the first to be considered for this type system. However, previous studies have shown that for this system the gas generator mass flow to the control system would have to be 75% of that to the lift fans, necessitating such large gas generators that a prohibitive weight penalty results. Another alternate arrangement which used self-contained jet engines in place of the turbocompressors was investigated in previous studies. This installation was slightly lighter but necessitated separate fuel, starting and control systems as well as qualification of another engine. The associated cost would undoubtedly be higher than the turbocompressor arrangement.

Wing design. - Selection of the wing planform on the basis of cruise efficiency would result in choosing a wing loading of 100-120 pounds per square foot and an aspect ratio of 6 to 7. The combined effects of weight and geometry on performance necessitate compromises that result in lower values. Although time did not permit extensive parametric investigation of wing planform for this study, sufficient data was generated during and prior to the CX-6 study to permit quite valid selection of the wing parameters. Further optimization would result in minor variations, but would have negligible effect on either specific configurations or comparative analysis between them.

The geometry associated with housing the lift fans in the wings limits the wing loading to about 75 pounds per square foot for the VTOL lift fan arrangement. Selection of

AXIS	RADIUS OF GYRATION FT.	INITIAL ACCEL. RAD/SEC^2	MAXIMUM MOMENT FT-LBS	MOMENT ARM - FT	100% CONTROL FORCE - LB
Pitch	16.3	.3	196 600	74	2 660
Roll	9.2	.6	125 000	58.6	2 140
Yaw	17.1	.25	180 200	58.6 & 74	-
Trim	-	-	39 700	74	530



θ ∘ is nozzle angles for yaw

Takeoff gross weight 79 400 pounds

Pitch trim allowance assumed = ±6" travel of cg at takeoff gross weight

**Critical case for this item

*F_T = Total control force
F_c = Control force per compressor

CASE	F_T* / F_c LB	F_1 / F_3	F_2 / F_4 LB	C_1 / C_2 LB	P_1 / P_2 LB	R_1 / R_2 LB	θ ∘
100% yaw + trim at T/W = 1.05	8 920 2 230	15 060 15 060	15 060 15 060	11 600 11 600	2 830 1 770	±1 080 ±1 080	37.4**
Lift fan gas generator inoperative trim at T/W = 1.05 +6.5% emergency thrust	6 700 2 230*	9 940 16 020	9 940 16 020	12 360 12 360	2 400 3 190	555 555	-
Cruise engine inoperative trim at T/W = 1.0 +20% pitch 50% roll and 20% yaw +2.3% emergency thrust	7 580 1 895	15 400 15 400	15 400 15 400	5 940 11 880	810 810	2 980** 2 980**	8.85
100% pitch + trim at T/W = 1.05	6 380 1 595	15 050 15 050	15 050 15 050	11 600 11 600	3 190** -3 190**	- -	- -

Figure 16. Final Configuration Control Summary: 60-Passenger Lift Fan VTOL

a low aspect ratio was made because the maximum takeoff gross weight is more sensitive to weight variations than to changes in drag. This is due in part to the short range involved and in part to the pyramiding effect of weight growth caused by changing lift thrust to keep pace with empty weight.

From the maintenance standpoint and for safety during emergency ditching procedures, a low wing configuration would be desirable. This arrangement did not appear feasible for lift fan concepts for the following reasons:

1. Severe reingestion would most likely occur for all propulsion units.

2. An unconventional landing gear, e.g., the B-52 bicycle arrangement, would be required since the fans and gas generators would occupy the space normally reserved for the main landing gear.

3. Adverse ground effects (suckdown) and ground erosion would be more severe.

All configurations which utilize lift fans have relatively simple wing flap systems similar to the C-135 and 707-120 consisting of double-slotted mechanical flaps at the trailing edge and full-span Krueger flaps simply hinged at the leading edge. Unless transition problems are encountered in future investigations, or emphasis is placed on STOL operation without the auxiliary lift system operating, it does not appear logical to use more powerful wing flaps. In a sense, this would be a duplication of lift systems.

Performance. - This aircraft was designed to cruise at 30 000 feet at a Mach number of .8. The same remarks on the choice of these parameters given in the jet lift VTOL performance section apply to this aircraft. The cruise performance of this aircraft is summarized in Figure 17.

Weights. - The weight of the 60-passenger lift fan appears in Table 7. The minimum weight airplane was achieved by concentrating the lift system as near as possible to the center of gravity and locating the hover controls units at the extremeties such that the total thrust may be directed up or down. Weight penalties in the wing are minimized by locating the fans so they do not interrupt the wing torque box. The gas generators and associated ducting for the fans located on top of the fuselage add additional weight to the fuselage.

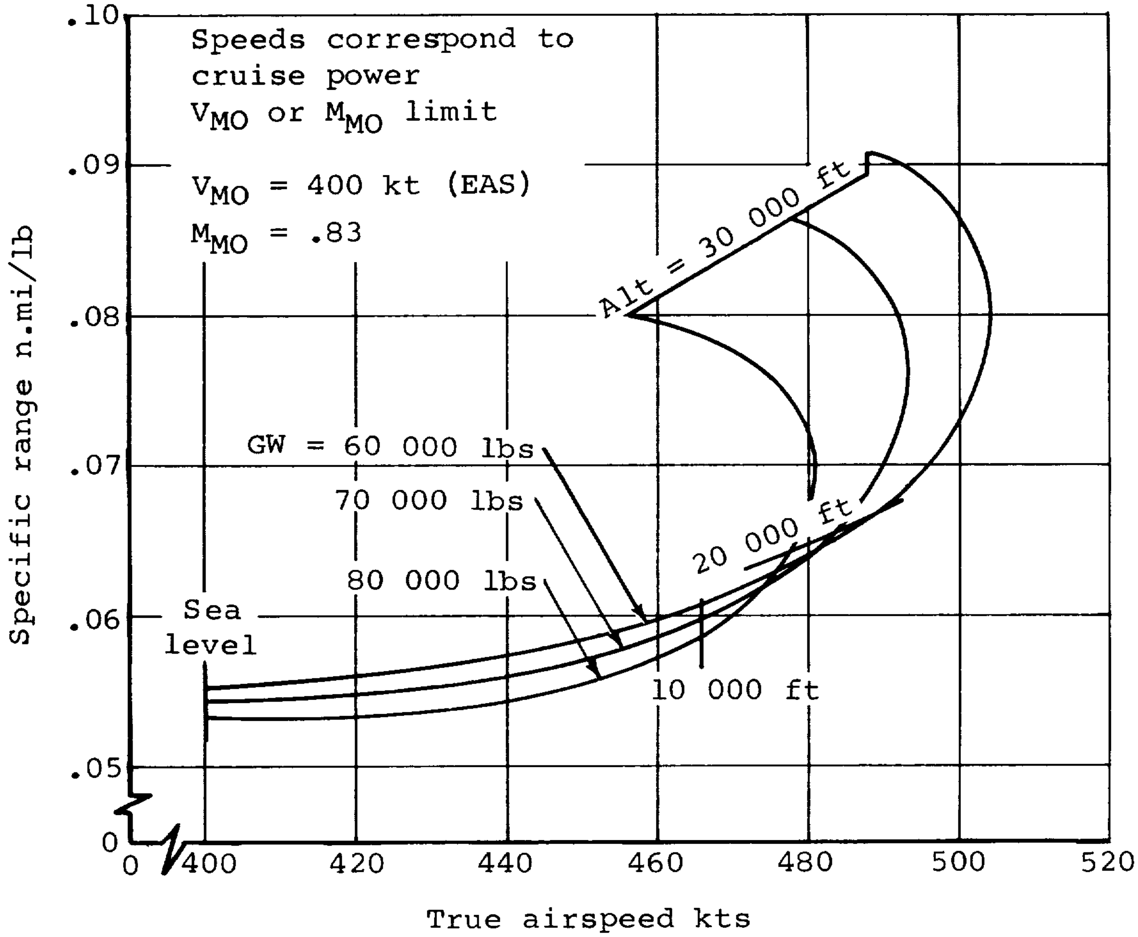


Figure 17. Cruise Speed and Specific Range: 60-Passenger Lift Fan VTOL

Fuselage and cabin layout. - The passengers are accommodated in five abreast seating. Interior furnishings include two washrooms located at the back of the cabin, a galley for light refreshments, and carry-on baggage and coat racks. Passenger doors are located at fore and aft ends of the fuselage on the left hand side. Front and rear entrance doors are equipped with built-in airstairs. Revenue cargo and stowed baggage space is provided under the cabin floor.

Fan-In-Wing VTOL

Initially the term "fan-in-wing" was interpreted to mean that the lift fans were located along a spanwise line in the wing rather than chordwise as used for the lift fan concept. But, after studying arrangements of this nature with two fans in each wing -- either within the torque box or ahead of a narrow torque box -- it was found to be more desirable to use one large fan in each wing and locate it within the torque box although there is a significant weight penalty associated with such a wing design; the takeoff gross weight was nearly the same as the Lift Fan VTOL because the geometry permitted an increase in wing loading with a decrease in wing area. Design of a 2-fan aircraft such that it will sink, but not upset in the event of a non-catastrophic fan failure, gives a weight penalty of 5000 lbs. on gross weight. This penalty is due to the increased gas generator and control system size required to provide trim moments, to offset the loss of lift of the failed fan, with only two gas generators providing control air to the turbocompressors. Due to this penalty, the aircraft has not been designed to allow fan failure, but the resulting level of safety is no different than that of a tilt-wing or other rotorcraft. Perhaps a more significant disadvantage of this concept is that it has limited growth potential because the fan size becomes physically unwieldy at higher gross weights and may become impractical to build. Future advances in material and fabrication technology may alleviate this difficulty.

The weight summary and the general characteristics of this aircraft are presented in Table 9 and a general arrangement drawing is given in Figure 18.

Propulsion. - The general comments made under this heading for the lift-fan VTOL apply equally to this aircraft.

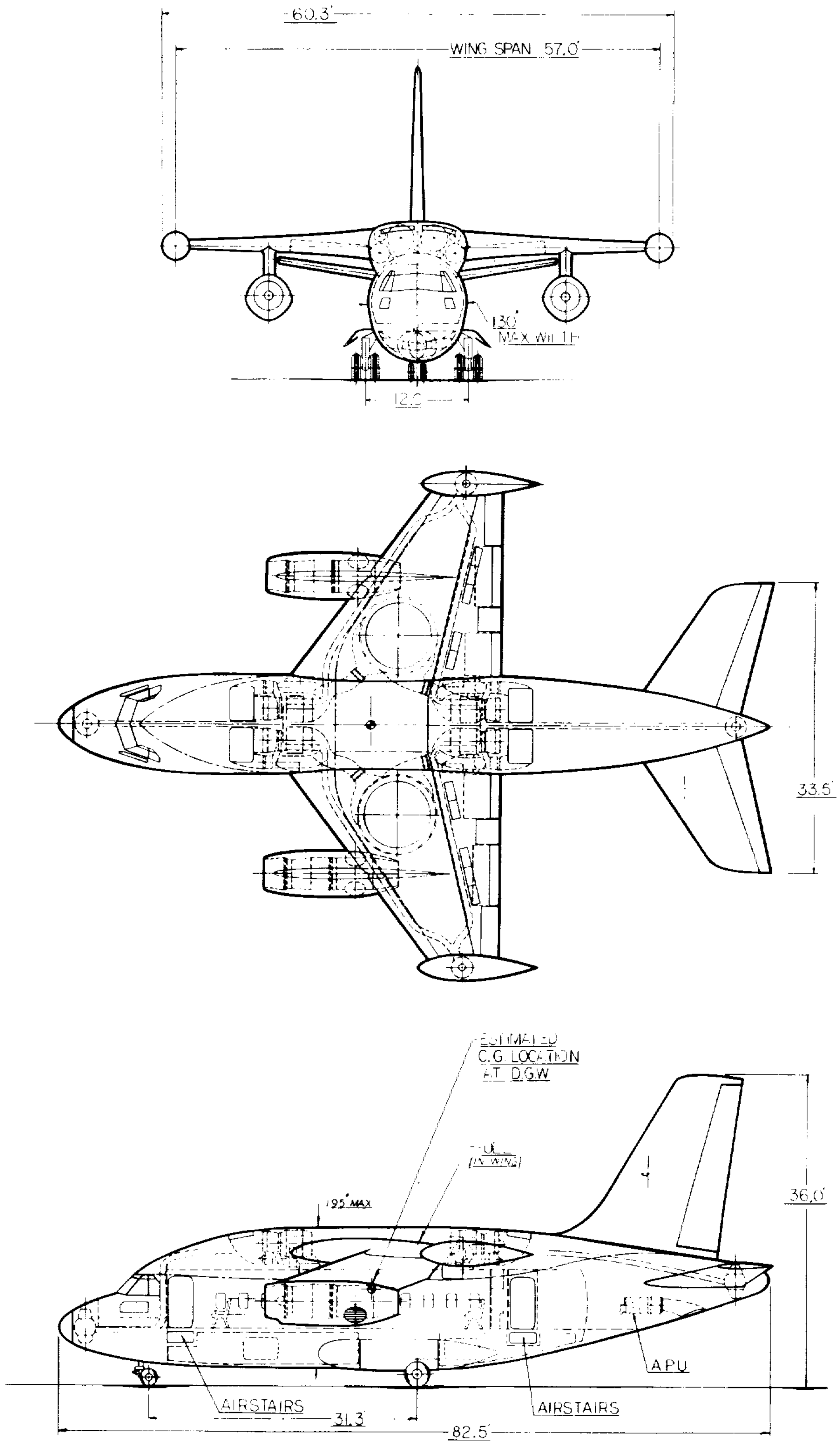


Figure 18. 60-Passenger Fan-in-Wing VTOL General Arrangement

TABLE 9

60 PASSENGER FAN-IN-WING VTOL

WEIGHT AND GENERAL CHARACTERISTICS SUMMARY

Weights	
Rotors	-
Wing	6 560
Tail	3 220
Body	12 100
Alighting Gear	3 465
Flight Controls	2 000
Reaction Controls	3 180
Powerplant Installation	(18 235)
Engine Section - Cruise	1 350
- Lift	-
Engine Installation - Cruise	5 186
- Lift	-
Lift Gas Generators	3 620
Fan and Ducting Installation	7 134
Fuel System	505
Engine Controls	300
Starting System	140
Propeller Installation	-
Auxiliary Power Unit	530
Instruments and Navigation	680
Hydraulics	450
Electrical	2 000
Electronics	750
Furnishings and Equipment	(5 140)
Flight Provisions	515
Passenger Accommodations	3 838
Cargo Handling	473
Emergency Equipment	314
Air Conditioning and Anti-icing	1 410
Weight Empty	59 720
Crew and Crew Luggage	520
Unusable Fuel and Oil	175
Engine Oil	100
Passenger Service Items	655
Operating Weight Empty	61 170
Passengers and Luggage	12 000
Revenue Cargo	1 200
Fuel	11 602
Takeoff Gross Weight	85 972

TABLE 9. - Concluded
60 PASSENGER FAN-IN-WING VTOL
WEIGHT AND GENERAL CHARACTERISTICS SUMMARY

Physical Data	
Wing	
Area (sq ft)	1025
Span (ft)	57
Aspect Ratio	3.16
Sweep at ¼ Chord (degrees)	30
(t/c) Root ℄ Fuselage	.135
(t/c) Tip	.100
Horizontal Tail Area (sq ft)	335
Vertical Tail Area (sq ft)	253
Fuselage Length (ft)	82.5
Design Cruise Conditions	
Cruise Speed (kt TAS)	466
Cruise Altitude (ft)	30 000
Structural Limits	
V_{MO} (kts EAS)	400
M_{MO}	.83
V_D (kts EAS)	450
N_{LIMIT}	2.5
Cruise Powerplants	
Number	2
Maximum Thrust (lbs)	14 900
Maximum Power (HP)	-
Bypass Ratio	3
Pressure Ratio	20
T_4	2600°R
Lift Powerplants	
Number	4 Gas Gen., 2 Fans
Maximum Thrust (lbs) per fan	38 200
Bypass Ratio	8 (Fans)
Pressure Ratio	12 (Gen.)
T_4	2600°R
Fan Diameter (ft)	9.6
Fan Pressure Ratio	1.3
Effective Thrust Augmentation Ratio	2.5

Control. - This aircraft was studied up to the stage of the study where the selection of the most promising concept was made. At this point it was dropped in favor of the lift fan VTOL aircraft. As is explained in the lift fan VTOL section this aircraft was changed to incorporate burning at the control nozzles at a later stage of the study. The fan-in-wing VTOL therefore, does not have nozzle burning. If such a control system were incorporated a similar weight saving to that achieved on the lift fan VTOL would be made.

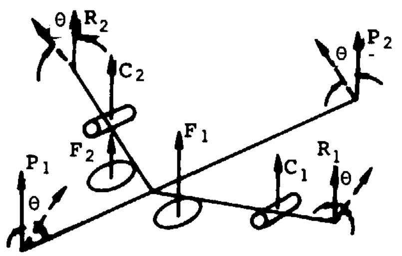
The critical hover control condition for sizing the roll nozzles and the turbocompressors is 20 percent pitch, 50 percent roll, 20 percent yaw plus trim control at T/W = 1.0 with one cruise engine failed. For sizing the pitch nozzles, it is trim control only at T/W = 1.05 with one cruise engine failed. A summary of the control forces is given in Figure 19.

Wing Design. - Aside from the changes associated with relocating the lift fans, the philosophy of this concept is the same as the lift fan and is directly comparable with it.

The location of the lift fans was chosen after consideration of the three arrangements shown in Figure 20. The arrangement A of Figure 20 in which all the lift thrust is located ahead of a narrow torque box was discarded as a very poor, if not impossible , structural design. For the arrangement B in Figure 20, employment of both cross-ducted and non-cross-ducted systems was considered. If no cross-ducting is used, the installation is simplified and capability to sustain a non-catastrophic fan failure is inherent. Larger control ducts and turbocompressors are required, however, than for the cross-ducted concept. On the other hand, the duct installation for the cross-ducted arrangement is difficult because of the number of ducts involved and the mechanics of threading them to the appropriate sources. In both cases, an undesirable fuel system results from having to provide fuel volume elsewhere than in the wing.

The arrangement C of Figure 20 was selected as the most desirable and is the one adopted for this aircraft. From a structural point of view this is somewhat better than two-fan arrangement in that only one cutout is necessary, and it does not extend so far spanwise. Two gas generators are used to drive each fan. Consequently, the loss of a gas generator does not introduce asymmetrical moments as severe as those of the non-cross-ducted arrangement A of Figure 20. This arrangement

AXIS	RADIUS OF GYRATION FT.	INITIAL ACCEL. RAD/SEC^2	MAXIMUM MOMENT FT-LBS	MOMENT ARM - FT	100% CONTROL FORCE LB
Pitch	15.8	.3	198 000	74	2 680
Roll	10.0	.6	158 500	56.4	2 810
Yaw	17.0	.25	191 000	56.4 & 74	-
Trim	-	-	42 500	-	575



θ° is nozzle angles for yaw

Takeoff gross weight 85 000 pounds

Pitch trim allowance assumed = ± 6" travel of cg at takeoff gross weight

**Critical case for this item

*F_T = Total control force
F_C = Control force per compressor

CASE	F_T * LB / F_C LB	F_1 LB	F_2 LB	C_1 LB / C_2 LB	P_1 LB / P_2 LB	R_1 LB / R_2 LB	θ°
100% yaw + trim at T/W = 1.05	14 480	32 200	32 200	12 400	2 050	-	24.6**
	3 620			12 400	-2 050	-	
Cruise engine inoperative Trim at T/W = 1.05 +6.5% emergency thrust	12 700	34 300	34 300	-	-1 110	5 400	-
	3 175			13 200	3 550**	-2 660	
Cruise engine inoperative Trim at T/W = 1.00 +50% roll 20% pitch 20% yaw +6.5% emergency thrust	14 490	34 300	34 300	-	3 380	±5 470	
	3 620**			13 200	- 170	±5 470	5

Figure 19. Control Summary: 60-Passenger Fan-in-Wing VTOL

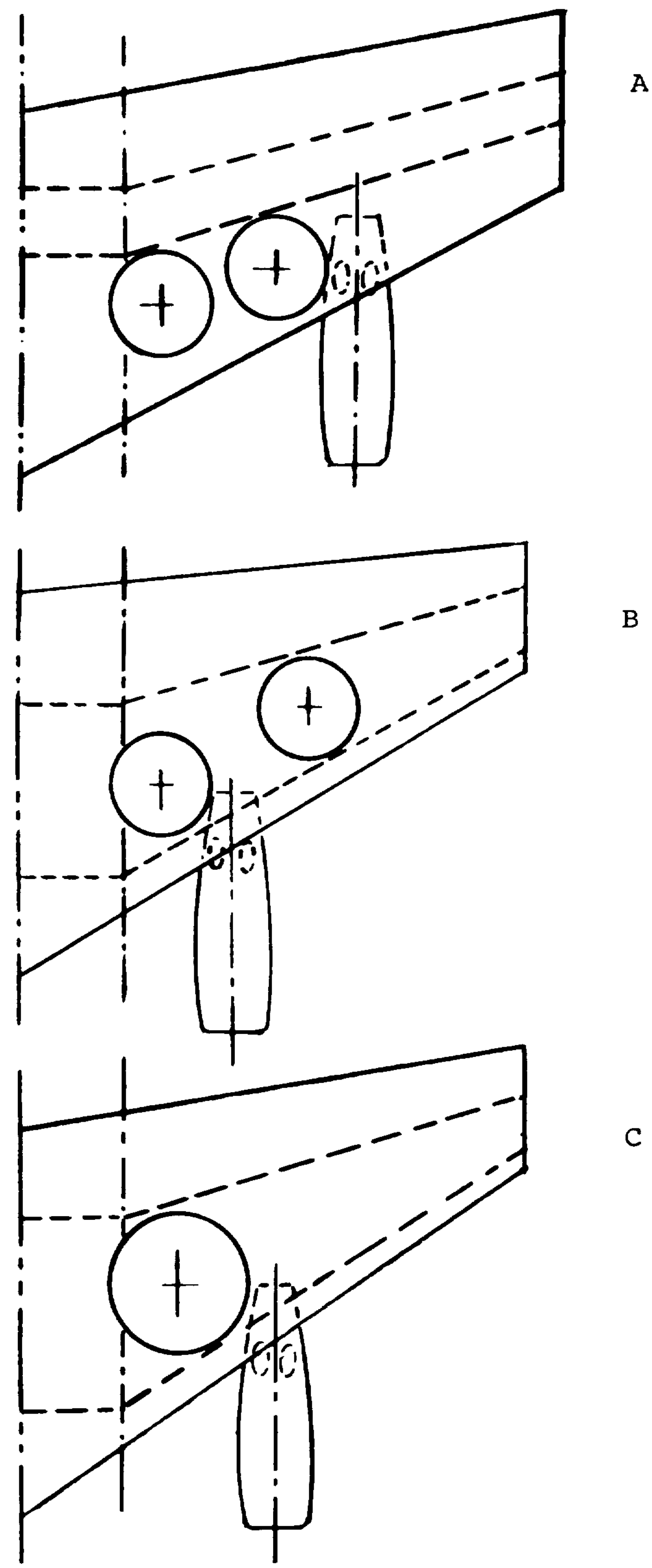


Figure 20. Fan Configurations Considered: Fan-in-Wing VTOL

requires the lowest amount of total control thrust of the three arrangements considered, but does not have capability to withstand a fan failure.

The general comments on wing loading, aspect ratio and location in the lift fan VTOL description apply to this aircraft.

Performance. - Like the other turbofan powered aircraft in this study, this aircraft was designed to cruise at 30 000 feet at .8 Mach number. The general philosophy outlined in the jet lift VTOL description applies here. The cruise performance is summarized in Figure 21.

Weights. - A weight summary of the 60-passenger fan-in-wing VTOL appears in Table 9.. The design philosophy of this concept is similar to the lift fan VTOL. This configuration is substantially heavier than the lift fan however, since it incorporates a bleed air, non-cross-ducted control system in lieu of the much lighter nozzle-burning cross-ducted arrangement employed in the lift fan VTOL. The fan-in-wing was not reconfigured incorporating the nozzle burning system because it was not among the concepts selected for further study. It is believed that if the fan-in-wing had the nozzle burning system its weight would be similar to the lift fan VTOL.

Fuselage and cabin layout. - This is generally similar to that of the lift-fan VTOL.

STOL Aircraft Considerations

As a part of the study the design of 60-passenger airplanes for operation from a 2000 foot field was investigated. The landing field length is defined as the landing distance from 50 feet without a flare and without any delay in application of brakes or reverse thrust, multiplied by 1.67; the takeoff field length is the takeoff distance over 35 feet with one engine out. The landing performance was found to be the more severe and became the design condition.

Figure 22 puts the 2000 foot field length in perspective. This figure shows the combination of aerodynamic and propulsive forces which are required as a function of field length. At very short field lengths there is a negligible aerodynamic contribution and the propulsion system is dominant. This is

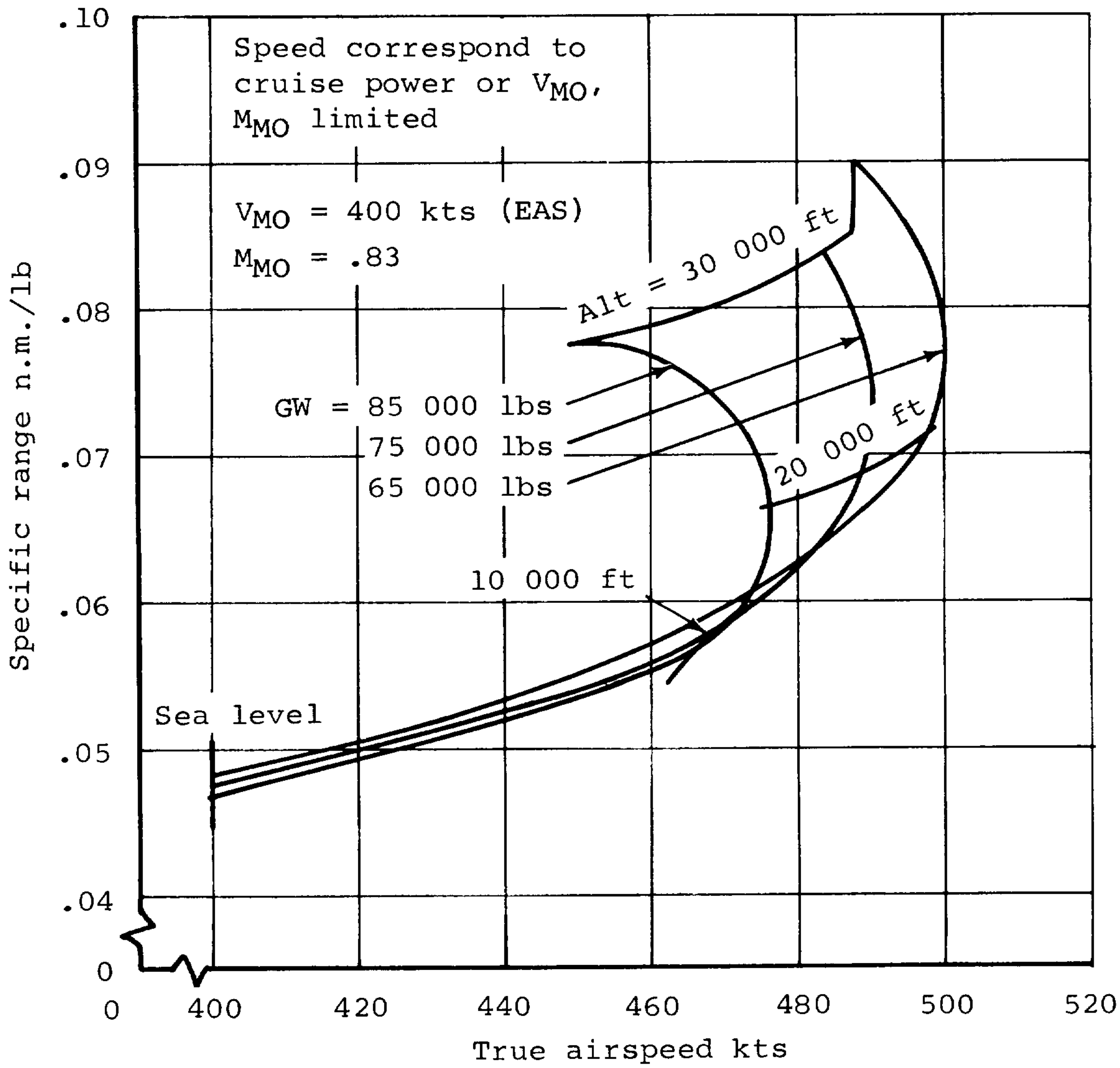


Figure 21. Cruise Speed and Specific Range: 60-Passenger Fan-in-Wing VTOL

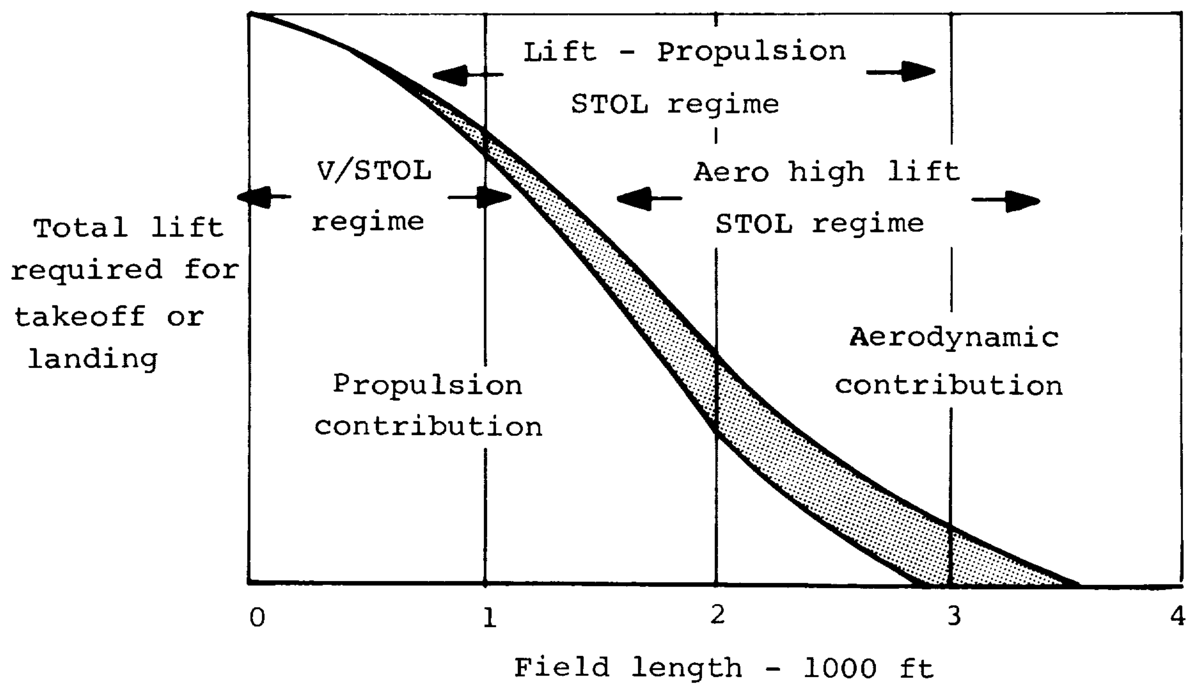


Figure 22. V/STOL Basic Concept Field Length Regimes

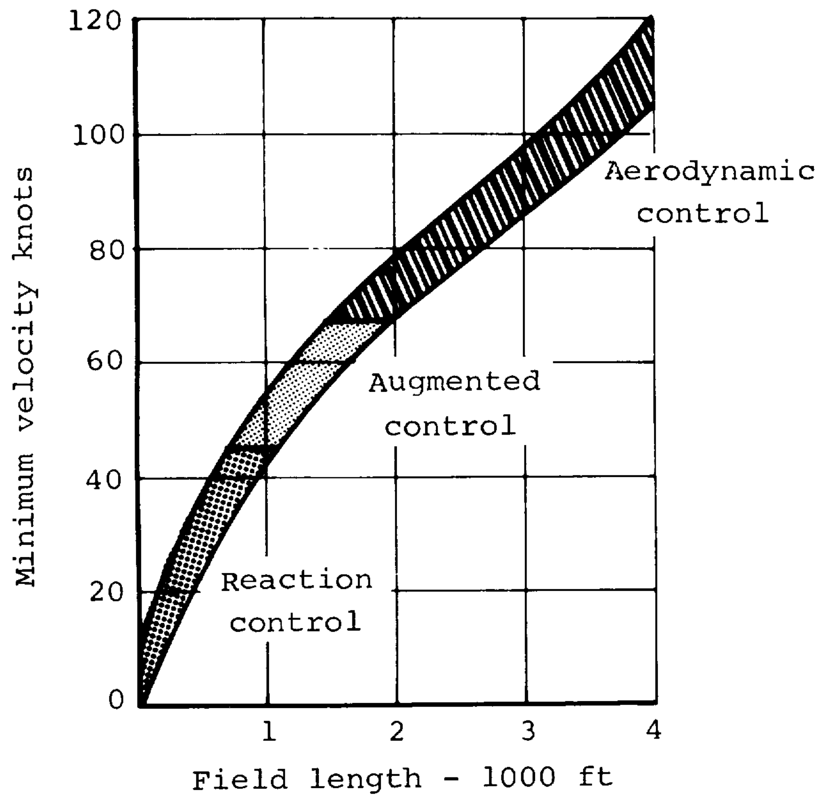


Figure 23. Effect of Field Length on Required Type of Control System

the region of the V/STOL airplanes. The companion picture for control system requirements is shown in Figure 23.

As field length increases, the line on Figure 22 separating the aerodynamic and propulsion contribution becomes a widening band. This indicates the variation in the aerodynamic portion of the lift that is possible at any given distance, through changes in wing loading, aspect ratio, flap complexity, and various forms of high lift.

The 2000 foot field length falls within the region where either high lift, or lift propulsion, STOL airplanes are feasible. It is between these types that a choice is to be made. For this study the lift propulsion type was specified as lift fan-in-wing, and the high lift type selected was an externally blown flap boundary layer control system.

Figure 23 is a curve of minimum flying speed associated with various field lengths. Superimposed on this curve are areas showing the type of control to meet the specified required values for various speed ranges, and, therefore for the different field lengths. For a 2000-foot field length, aerodynamic control is just adequate, while lesser distances require control augmentation using boundary layer control on the control surfaces.

Fan-In-Wing STOL

The general arrangement drawing for this 60-passenger STOL fan-in-wing configuration is shown in Figure 24. It is an STOL configuration in which wing lift is supplemented by fans located in the wing and by deflection of cruise engine thrust.

When the development of an STOL configuration employing lift fans is dictated, the location of the fans and the selection of a fan-in-wing concept follow quite obviously. In order for this concept to be at all competitive with the turbofan blown flap concept, it must be free of any reaction control system to keep the weight low. Since the failure of any engine must not introduce forces exceeding the capability of the aerodynamic control surfaces, the fans must be as close to the cg as possible and the use of two gas generators per fan is desirable. This resulted in a configuration very similar to the fan-in-wing VTOL but with smaller fans and without the hover control system. A total lift thrust/gross

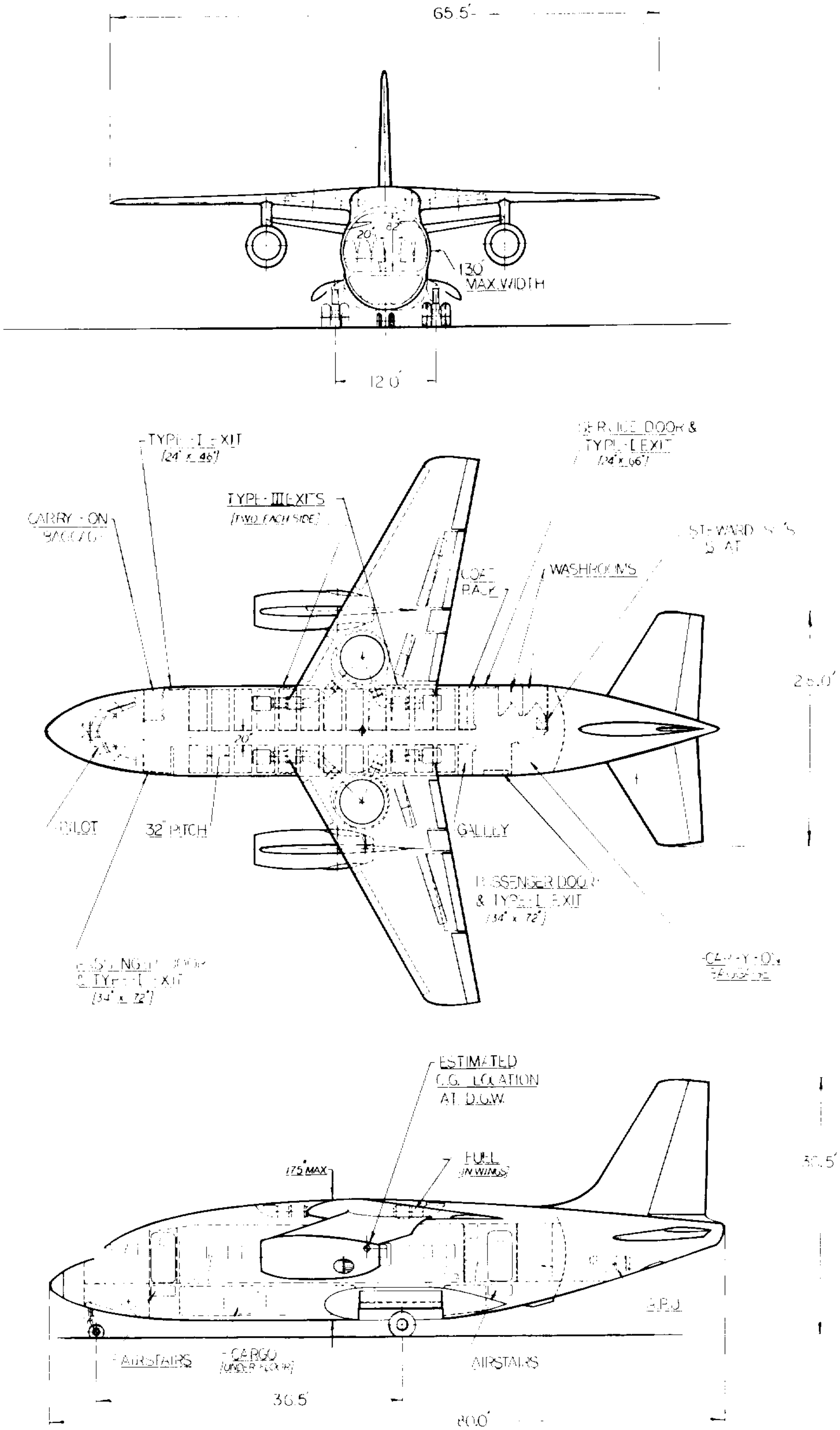


Figure 24. 60-Passenger Fan-in-Wing STOL General Arrangement

weight ratio of .70 was required to meet the field length requirement. The associated fan size permitted reasonable wing load and aspect ratio. The gross weight of this configuration is somewhat greater than that of the turbofan STOL and is more complex because of the lifting system.

Lift fan gas generators are much smaller than for comparable VTOL configurations, where they also powered the reaction control system. This reduction in size and the absence of the control system turbocompressors allow a much smaller engine compartment above the body. No increase in frontal area is necessary to house the gas generators.

A typical variation of gross weight with field length is shown in Figure 25. The change in slope for the design point airplanes as the lift propulsion requirement decreases is due to the installation weight not reducing significantly as the lift propulsion system decreased in size. A knee to the curve occurs in the region of 2000 feet indicating that the design point is still in a good region for this concept.

The off load performance is limited by the minimum control speed. As the airplane weight is reduced the change in approach speed and therefore field length is small.

The weight summary and the general aircraft characteristics are given in Table 10.

Propulsion and control systems. - To determine the thrust to weight ratio needed to meet takeoff and landing requirements, CX 6, STOL data was utilized. CX-6 experience showed that a combined T/W from both cruise and lift systems of .70 was necessary to meet the requirements specified in the "Design Ground Rules". The cruise engine size was selected by the same method as used on the VTOL airplanes -- T/W = .35 on a sea level standard day. This provides good climb performance as well as the required cruise thrust. A lift fan T/W of .41 supplies the remaining lift necessary to meet the required total T/W.

Subsequent to the sizing of this aircraft, NASA data became available which showed that a thirty percent lift augmentation could be expected for this wing-fan combination in the takeoff and landing mode. This would allow a 33 percent reduction in fan thrust and give a 3000 lb. reduction in gross weight to meet the design ground rules.

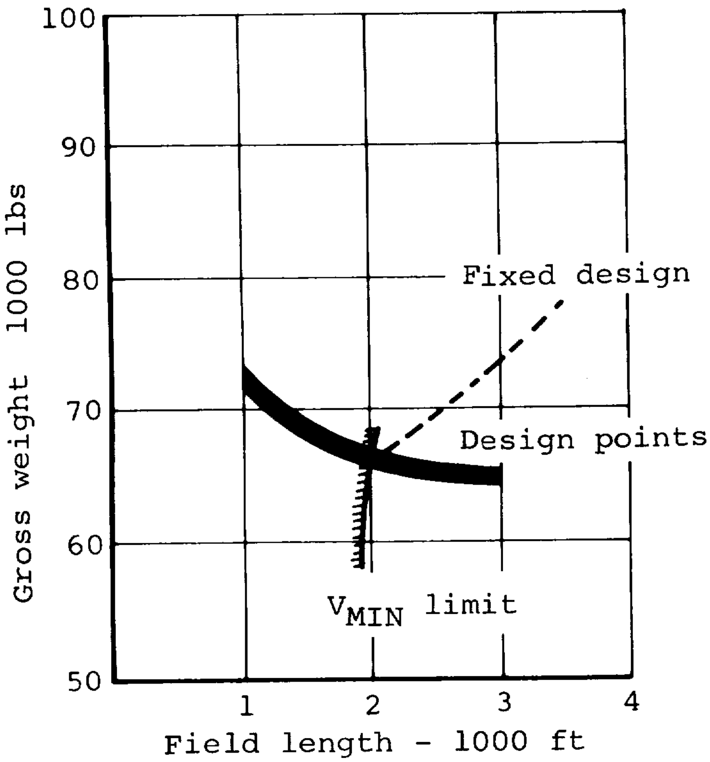


Figure 25. Typical Effect of Field Length on Gross Weight: 60- Passenger Fan-in-Wing STOL

TABLE 10

60 PASSENGER FAN-IN-WING STOL

WEIGHT AND GENERAL CHARACTERISTICS SUMMARY

Weights	
Rotors	-
Wing	5 830
Tail	2 120
Body	10 510
Alighting Gear	2 680
Flight Controls	2 000
Reaction Controls	-
Powerplant Installation	(8 860)
Engine Section - Cruise	1 250
- Lift	-
Engine Installation - Cruise	3 980
- Lift	-
Lift Gas Generators	660
Fan and Ducting Installation	2 280
Fuel System	380
Engine Controls	170
Starting System	140
Propeller Installation	-
Auxiliary Power Unit	530
Instruments and Navigation	680
Hydraulics	450
Electrical	2 000
Electronics	750
Furnishings and Equipment	(5 140)
Flight Provisions	515
Passenger Accommodations	3 838
Cargo Handling	473
Emergency Equipment	314
Air Conditioning and Anti-icing	1 410
Weight Empty	42 960
Crew and Crew Luggage	520
Unusable Fuel and Oil	175
Engine Oil	100
Passenger Service Items	655
Operating Weight Empty	44 410
Passengers and Luggage	12 000
Revenue Cargo	1 200
Fuel	7 721
Takeoff Gross Weight	65 331

TABLE 10.- Concluded
60 PASSENGER FAN IN WING STOL
WEIGHT AND GENERAL CHARACTERISTICS SUMMARY

Physical Data	
Wing	
Area (sq ft)	823
Span (ft)	65.5
Aspect Ratio	5.2
Sweep at ¼ Chord (degrees)	25
(t/c) Root ℄ Fuselage	.136
(t/c) Tip	.082
Horizontal Tail Area (sq ft)	261
Vertical Tail Area (sq ft)	169
Fuselage Length (ft)	80
Design Cruise Conditions	
Cruise Speed (kt TAS)	472
Cruise Altitude (ft)	30 000
Structural Limits	
V_{MO} (kts EAS)	400
M_{MO}	.83
V_D (kts EAS)	450
N_{LIMIT} (Gust Critical)	2.8
Inertias (slugs ft^2)	
Roll	196 220
Pitch	292 435
Yaw	519 885
Cruise Powerplants	
Number	2
Maximum Thrust (lbs)	11 500
Bypass Ratio	3
Pressure Ratio	20
T_4	2600°R
Lift Powerplants	
Number	4 Gas Gen., 2 Fans
Maximum Thrust (lbs) per fan	15 800
Fan Bypass Ratio/Pressure Ratio	8/1.3
Pressure Ratio	12 (Gen.)
T_4	2600°R
Fan Diameter (ft)	6.17
Augmentation Ratio	2.5

A feature of the lift propulsion STOL design is the ability to always match the cruise propulsion to the conventional flight requirements. For this reason the airplane always operates economically in cruise.

The variation of thrust required with field length is shown on Figure 26. This figure shows the available thrust on an 86°F day at sea level. As the field length increases the lift propulsion required decreases, but the ratio of weight of lift propulsion, to lift thrust, increases because the installation weight of the fans does not decrease as fast as the thrust.

Wing design. - The aircraft wing was sized for a wing loading of 80 pounds per square foot. A high wing was chosen to minimuze the possibility of adverse ground effect.

The wing design incorporates double-slotted flaps at the trailing edge and Krueger flaps and slots at the leading edge.

The choice of flap design for the fan-in-wing STOL stems from two requirements. At the flying speed associated with a particular field length, the obvious use of a flap is to increase C_L and thereby reduce the size of the lift propulsion system. This is worthwhile only if the weight of the flap necessary to produce the lift increment is less than the weight of propulsion system it replaces. At the low speeds associated with short field lengths it is lighter to use thrust and ignore lift. As the design field length and flying speed increase, the increment in lift for a given weight of flap increases with the square of the velocity. For that reason the flap system associated with these airplanes becomes more complex, leading to higher usable lift coefficients, as the field length increases. At the 2000-foot design point a double-slotted flap with a maximum C_L of about 2.5 was used.

The second requirement is best illustrated at a short field design point where thrust can be obtained at less weight than lift. In this case a flap would be used to reduce the speed at which the airplane can operate with the lift propulsion shut off. This speed is directly related to the traffic speed and to the structural design speed of such things as wheels and lift fan doors, which are only used during takeoff and landing, but must be extended into the airstream before the low speed associated with the short field length can be achieved.

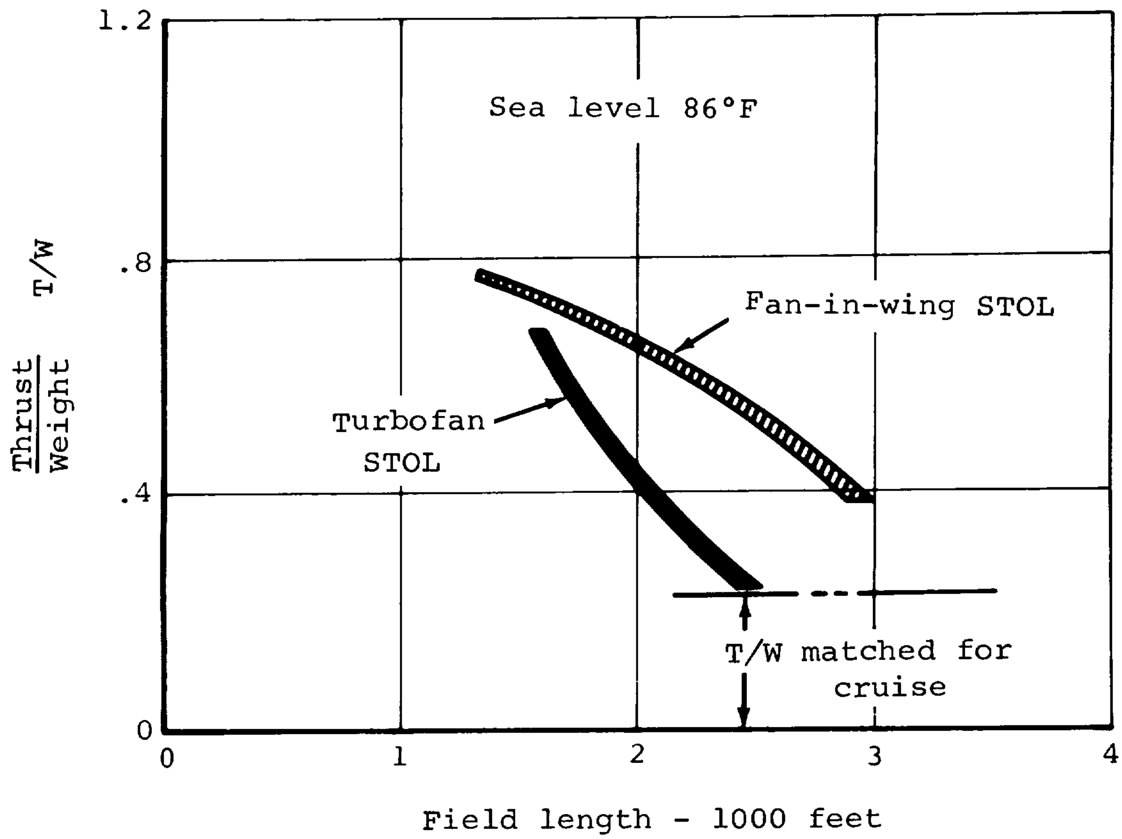


Figure 26. Variation of Thrust Required with Field Length: 60-Passenger STOL Aircraft

The weight savings that can be realized in this way will far exceed the weight of the appropriate flap.

Performance. - The aircraft was designed to cruise at 30 000 feet and a Mach number .8. The cruise performance is summarized in Figure 27. The takeoff and landing performance is shown in Figure 28 for the design case, and with all engines operating, sea level standard day, for comparison.

Weights. - A summary of the weights for the 60-passenger fan-in-wing STOL is presented in Table 10. The design gross weight of this configuration is 65 331 pounds. It is similar in weight to the 60-passenger turbofan STOL except for the addition of, and associated weight penalties realized in incorporating, two lift fans, four gas generators and required ducting. The fuselage weight is slightly higher because of the gas generator installation.

Fuselage and cabin layout. - This is generally similar to the lift fan VTOL.

Turbofan STOL

This concept represents a pure STOL configuration which obtains its short field capability by use of a powerful high-lift wing flap system rather than by the installation of an extra powerplant to provide vertical lift. Exhaust gas from the cruise engines is directed over the double-slotted trailing edge flaps to provide boundary layer control and thrust redirection. The engine exhaust spreads under the wing, passes through the slots and energizes the boundary layer. A variable trailing edge flap segment is used for flight path control. Moving this drag flap effectively rotates the force vector.

The 2000-foot STOL airplane, using the externally blown flap, is shown in Figure 29 and the weights and general characteristics are summarized in Table 11. The airplane is very conventional in appearance. Four cruise engines are used to give good spanwise flap coverage.

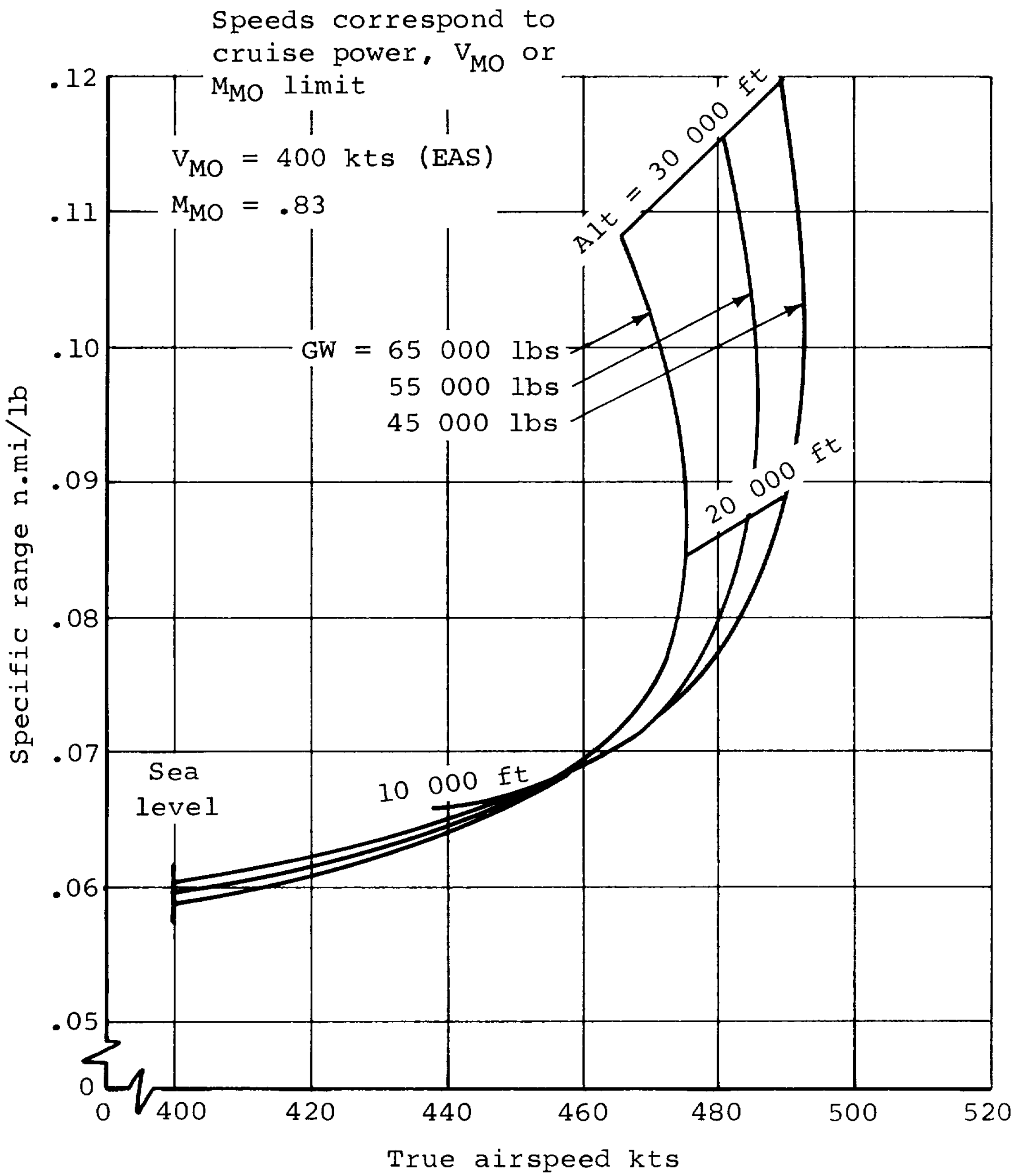


Figure 27. Cruise Speed and Specific Range: 60-Passenger Fan-in-Wing STOL

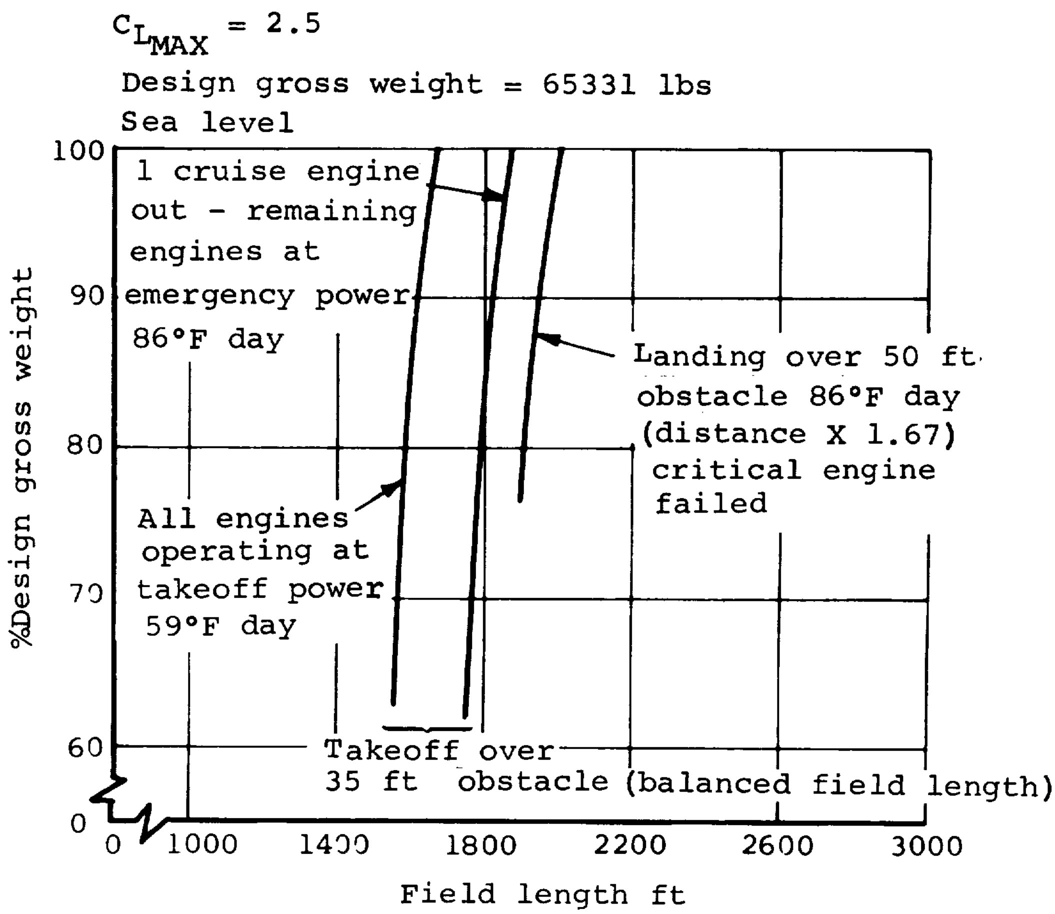


Figure 28. Takeoff and Landing Performance: 60-Passenger Fan-in-Wing STOL

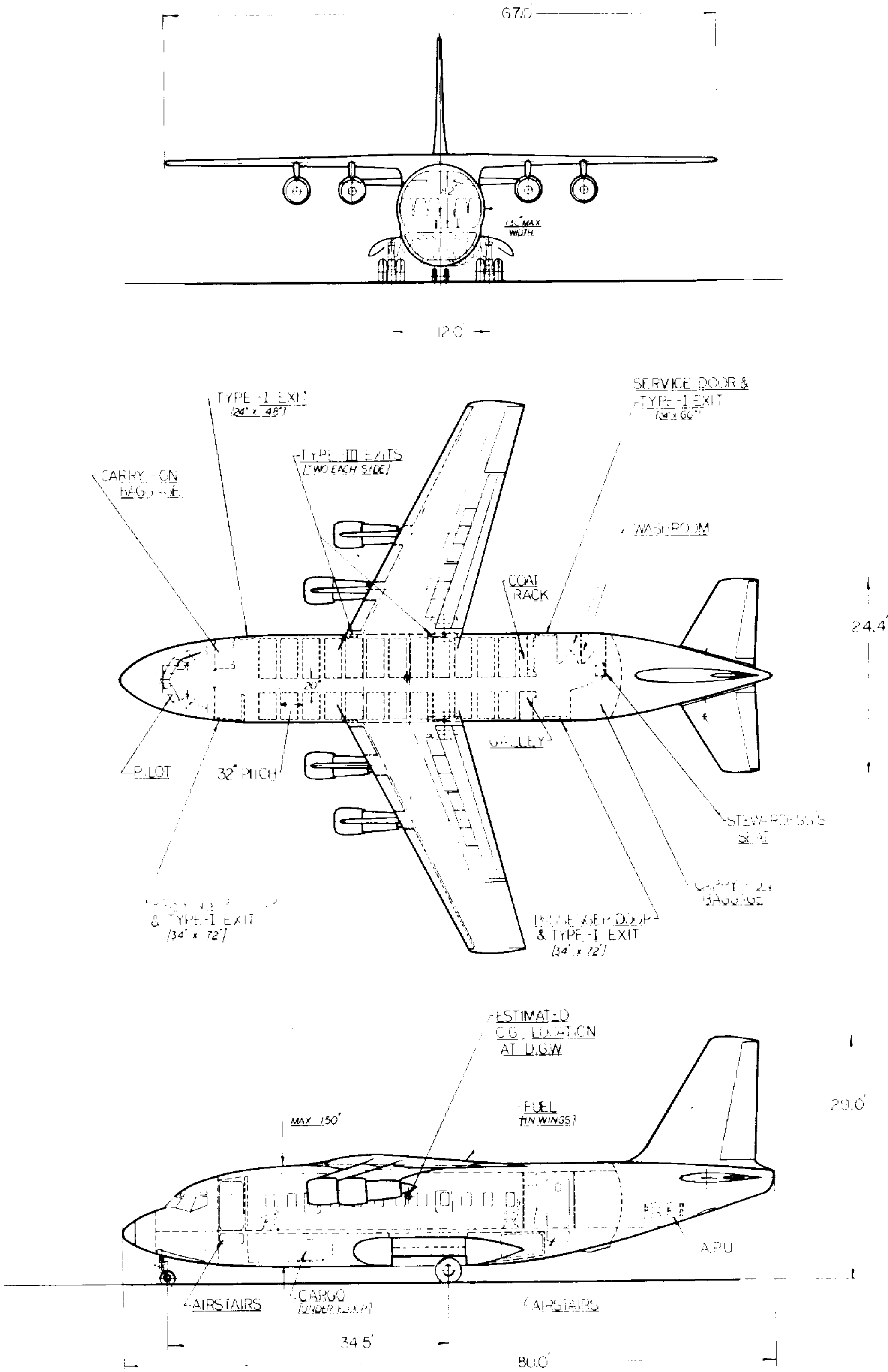


Figure 29. 60-Passenger Turbofan STOL General Arrangement

TABLE 11

60 PASSENGER TURBOFAN STOL

WEIGHT AND GENERAL CHARACTERISTICS SUMMARY

<u>Weights</u>	
Rotors	-
Wing	5 895
Tail	1 765
Body	9 990
Alighting Gear	2 591
Flight Controls	2 150
Reaction Controls	-
Powerplant Installation	(7 638)
Engine Section - Cruise	1 483
- Lift	-
Engine Installation - Cruise	5 500
- Lift	-
Lift Gas Generators	-
Fan and Ducting Installation	-
Fuel System	365
Engine Controls	120
Starting System	170
Propeller Installation	-
Auxiliary Power Unit	530
Instruments and Navigation	675
Hydraulics	450
Electrical	2 000
Electronics	750
Furnishings and Equipment	(5 120)
Flight Provisions	515
Passenger Accommodations	3 838
Cargo Handling	473
Emergency Equipment	294
Air Conditioning and Anti-icing	1 370
Weight Empty	40 924
Crew and Crew Luggage	520
Unusable Fuel and Oil	175
Engine Oil	100
Passenger Service Items	655
Operating Weight Empty	42 374
Passengers and Luggage	12 000
Revenue Cargo	1 200
Fuel	7 250
Takeoff Gross Weight	62 824

TABLE 11. - Concluded
60 PASSENGER TURBOFAN STOL
WEIGHT AND GENERAL CHARACTERISTICS SUMMARY

Physical Data	
Wing	
Area (sq ft)	749
Span (ft)	67
Aspect Ratio	6.0
Sweep at ¼ Chord (degrees)	25
(t/c) Root ℄ Fuselage	.136
(t/c) Tip	.082
Horizontal Tail Area (sq ft)	180
Vertical Tail Area (sq ft)	146
Fuselage Length (ft)	80
Design Cruise Conditions	
Cruise Speed (kt TAS)	472
Cruise Altitude (ft)	30 000
Structural Limits	
V_{MO} (kts EAS)	400
M_{MO}	.83
V_D (kts EAS)	400
N_{LIMIT} (Gust Critical)	2.8
Rotors or Propellers	
Diameter (ft)	-
Number of Blades	-
Solidity	-
Maximum Tip Speed (fps)	-
Cruise Powerplants	
Number	4
Maximum Thrust (lbs)	7500
Maximum Power (HP)	-
Bypass Ratio	3
Pressure Ratio	20
T_4	2600 °R
Inertias (slugs ft^2)	
Roll	197 240
Pitch	281 220
Yaw	511 660

This configuration appears to be the most desirable STOL concept so long as more stringent field length requirements are not specified. At shorter field lengths lift propulsion concepts are more desirable; as the design field length reduces, a vertical capability is developed by these lift propulsion machines. The turbofan STOL configuration does not have this versatility.

Propulsion and control systems. - Some oversizing of the cruise engines is required to obtain the lift coefficients required to meet the 2000-foot field length. When thrust in excess of that required for cruise is needed for STOL performance, it is provided by increasing the size of the cruise engines. Small amounts of extra thrust are relatively cheap, since a new installation is not required and the installation weight to thrust ratio will remain fairly constant. Putting extra thrust into the cruise system to provide the takeoff and landing performance results in a mismatch for level flight which grows increasingly severe as the field length decreases. This mismatch is minimized by the choice of bypass ratio. The characteristic variation of thrust with speed and bypass ratio allows a good cruise match to be maintained by increasing the bypass ratio as the thrust required increases.

The thrust required for this STOL is shown on Figure 26 in relation to the fan-in-wing STOL and V/STOL requirements. For the high lift system the cruise thrust needs to be augmented by about 50 percent for the 2000-foot field length. The total thrust to weight ratio approaches one at a field length of about 1200 feet. The effect of this thrust requirement on the gross weight of this aircraft as they vary with field length is shown on Figure 30. A knee in the high-lift line occurs at about 2000 feet with the weight increasing rapidly at lower field lengths. This change in slope is the effect of the extra thrust which is being put into the cruise system to provide the high lift. In addition, an increasingly poor cruise match with attendant fuel penalties results.

Four powerplants were used to cover a large percentage of the flap span with exhaust air and to reduce the yawing moment due to engine failure. The short duct fan engine installation incorporates thrust reversers for both the primary and secondary air. Both deflectors are of the same basic design which incorporates a translating sleeve with integral blocker doors which direct the flow forward through concentric rings of turning vanes. The effective thrust to weight ratio

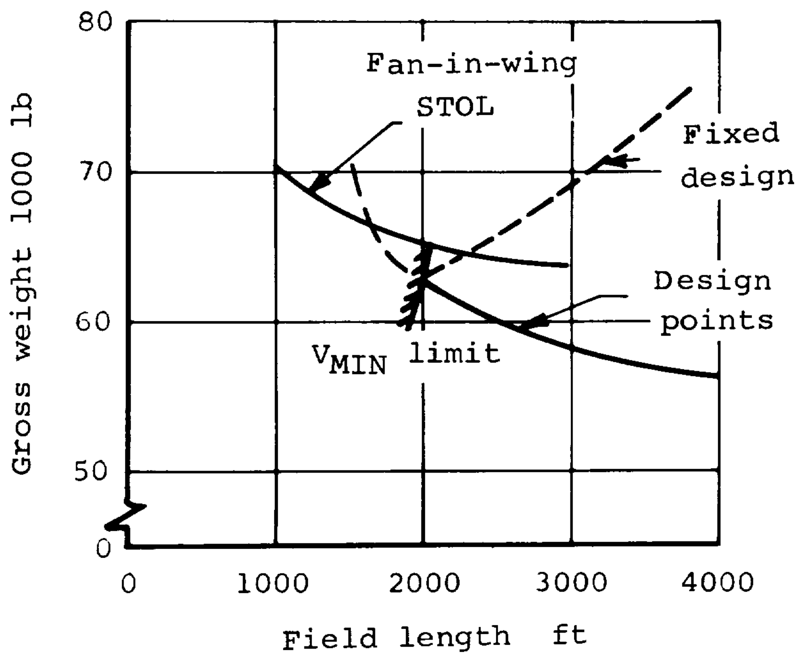


Figure 30. Effect of Field Length on Gross Weight:
60-Passenger Turbofan STOL

of the turbofans on a 86°F day at sea level was limited to .41 since it is believed that a higher ratio would result in undesirable pitching moments caused by the flap. The net T/W of .41 on a 86°F day corresponds to a gross value at sea level standard temperature of .47. The centerline of thrust is at a small angle with the wing chord. The angle is chosen to give optimum flow conditions over the flap. C-5A experience showed that an angle of 4½ degrees was optimum for both low speed and high speed flight.

An earlier study on a similar aircraft in the CX-6 program did not indicate that blowing of the elevator and ailerons would be necessary, but marginal conditions existed for the rudder.

It is apparent from the V/STOL cutoff that the 2000-foot field length airplane will not have any vertical capability, and therefore the control system will be designed for the 2000-foot case. Figure 23 is a curve of minimum flying speed associated with various field lengths. These are minimum control speeds which result in approach speeds for the indicated distances. Superimposed on this curve are areas showing the type of control required for various speed ranges and consequently for the different field lengths. For the design distance of 2000 feet a conventional aerodynamic control system will be adequate. In parametrically examining STOL airplanes at other distances the aerodynamic control was used. For this reason, the designs for distances less than 2000 feet will be somewhat optimistic.

Wing design. - The aircraft wing was sized for a wing loading of 85 pounds per square foot at initial takeoff. Wing sweep was limited to 25 degrees to increase the lift at low speeds. A high wing was selected since close proximity of the ground would adversely affect the flap performance.

The flap system on this aircraft is similar to that of the Boeing proposal for the C-5A Heavy Logistic Transport. At the leading edge, a simple Krueger flap is located inboard of the inboard engine. Outboard of the inboard engine to the wing tip, a flexible (drooping) leading edge is employed combined with hinged slats which form part of the lower leading edge surface in the stowed position. The trailing edge flap system consists of two double-segmented and double-slotted flaps per wing. The aft segment of each flap is movable relative to the main segment. A linkage system regulates motion of the aft segment as a function of the main flap travel and also allows a limited independent aft segment travel. The independent aft segment travel is used to control the glide slope during landing. At the approach C_L the horizontal forces can vary from thrust which is sufficient for go around, to drag for deceleration and approach, all at constant power setting. The aft segment of the outboard flap also functions as a flaperon to provide supplemental lateral control and trim. Spoilers are located in the upper surface of the wing aft of the rear spar to augment lateral control and provide aerodynamic braking for both flight and ground operation.

Performance. - This aircraft was designed to cruise at 30 000 feet altitude at a Mach number of .8. The cruise performance of this aircraft is summarized in Figure 31. The off-load performance, as was the case with the fan-in-wing STOL, is limited by the minimum control speed. This is illustrated in Figure 32 which shows the takeoff and landing performance as a function of percent design gross weight.

Weights. - The weights for the 60-passenger turbofan STOL are presented in Table 11. This configuration is the lightest of the concepts studied. Externally blown flaps, drooped leading edge, and leading edge slats result in high wing and surface control weights. Oversized cruise engines, required to obtain lift coefficients to meet the 2000-foot field length specification, add to the powerplant weight.

Fuselage and cabin layout. - This is similar to the lift fan VTOL.

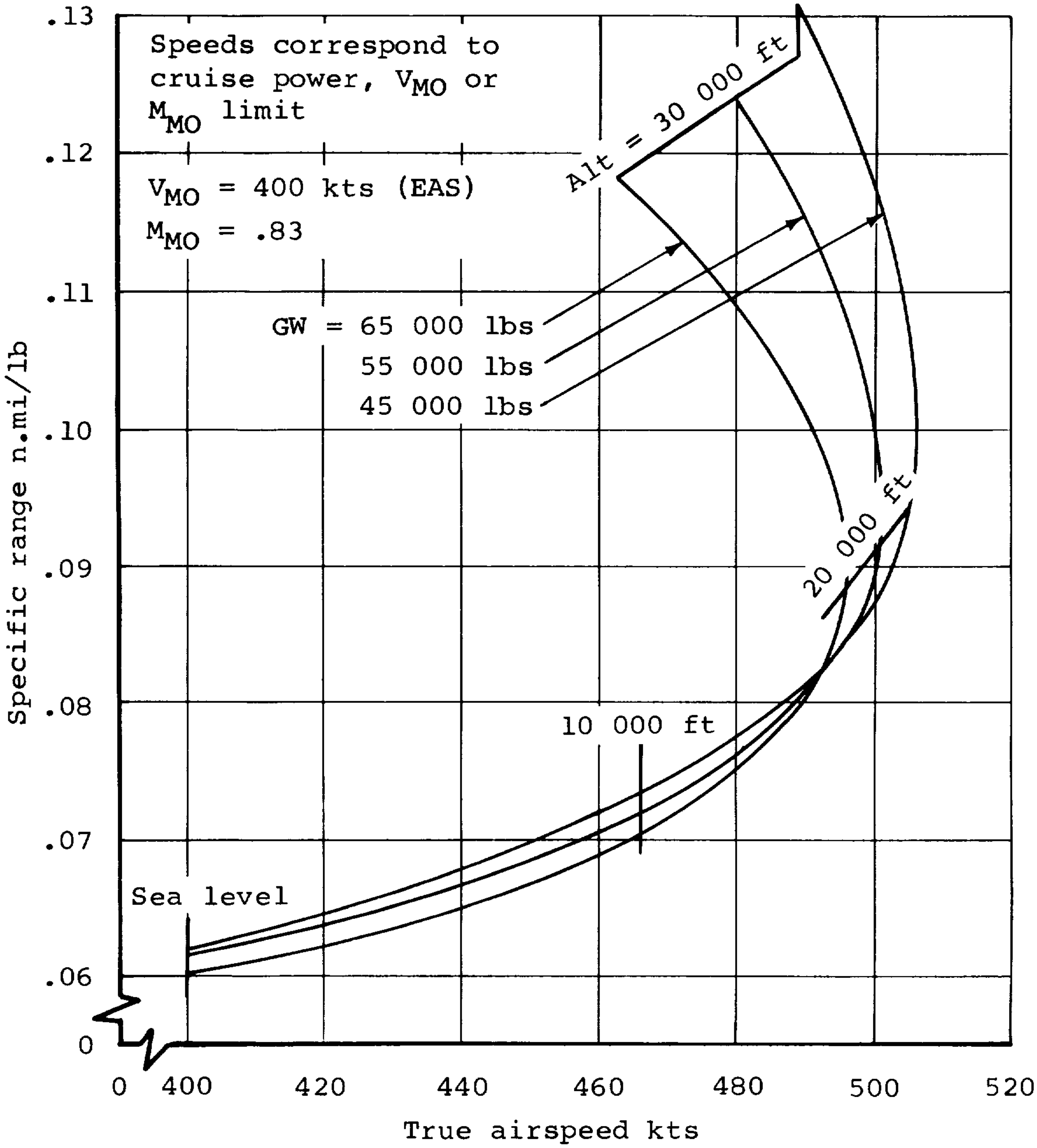


Figure 31. Cruise Speed and Specific Range: 60-Passenger Turbofan STOL

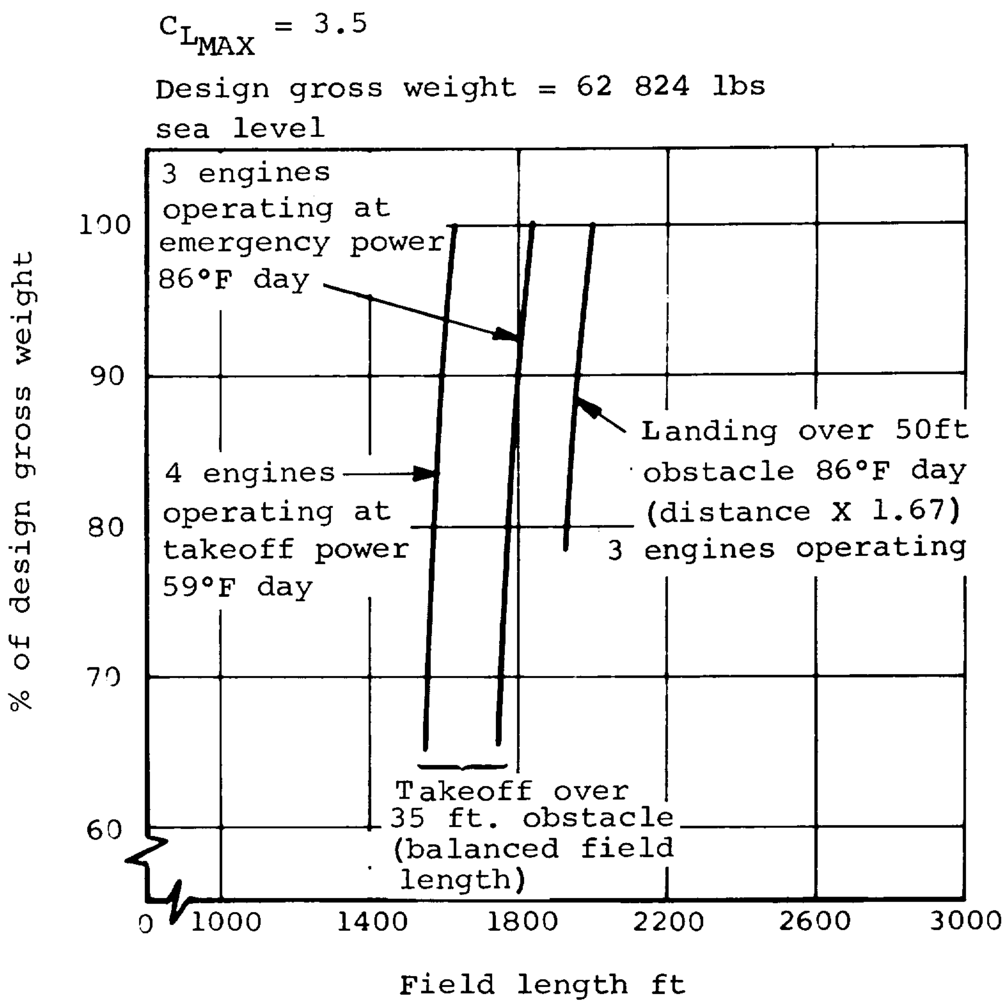


Figure 32. Takeoff and Landing Performance: 60-Passenger Turbofan STOL

Approach Techniques, Air Maneuvers, and Ground Time

For the direct operating cost evaluation over a hypothetical route structure, rather than the NASA specified approach patterns, optimum approach, landing and takeoff aerial maneuvers were used. These patterns are subdivided under four main headings.

1. VTOL takeoff

2. VTOL approach and landing

3. STOL takeoff

4. STOL approach and landing

Charts of these four representative flight patterns are shown in Figures 33 through 37. The assumptions used in deriving these patterns are discussed in the paragraphs which follow.

All the VTOL aircraft considered may be certificated for one-engine-out hover operation and vertical flight paths.

All VTOL aircraft operate from a pad which is directly adjacent to the terminal building.

All STOL aircraft are capable of takeoff over a 35-foot obstacle and can land over a 50-foot obstacle within a 2000-foot field length.

The VTOL aircraft will take enroute distance credit to a point much closer to the terminal than the STOL aircraft. As shown in Figure 33 and 34, distance credit for VTOL's begins about one mile out on takeoff and continues to about 2.5 miles from destination. These values are averages of conditions at both an uncongested suburban area terminal site and a center-city terminal site where avoidance maneuvers will be necessary. As shown in Figures 36 and 37, distance credits for STOL's must begin and end at a greater distance from the terminal due to the runway/wind alignment problem.

Conversions of VTOL aircraft will take place during the climb patterns or descent portions of the enroute segment of the flight.

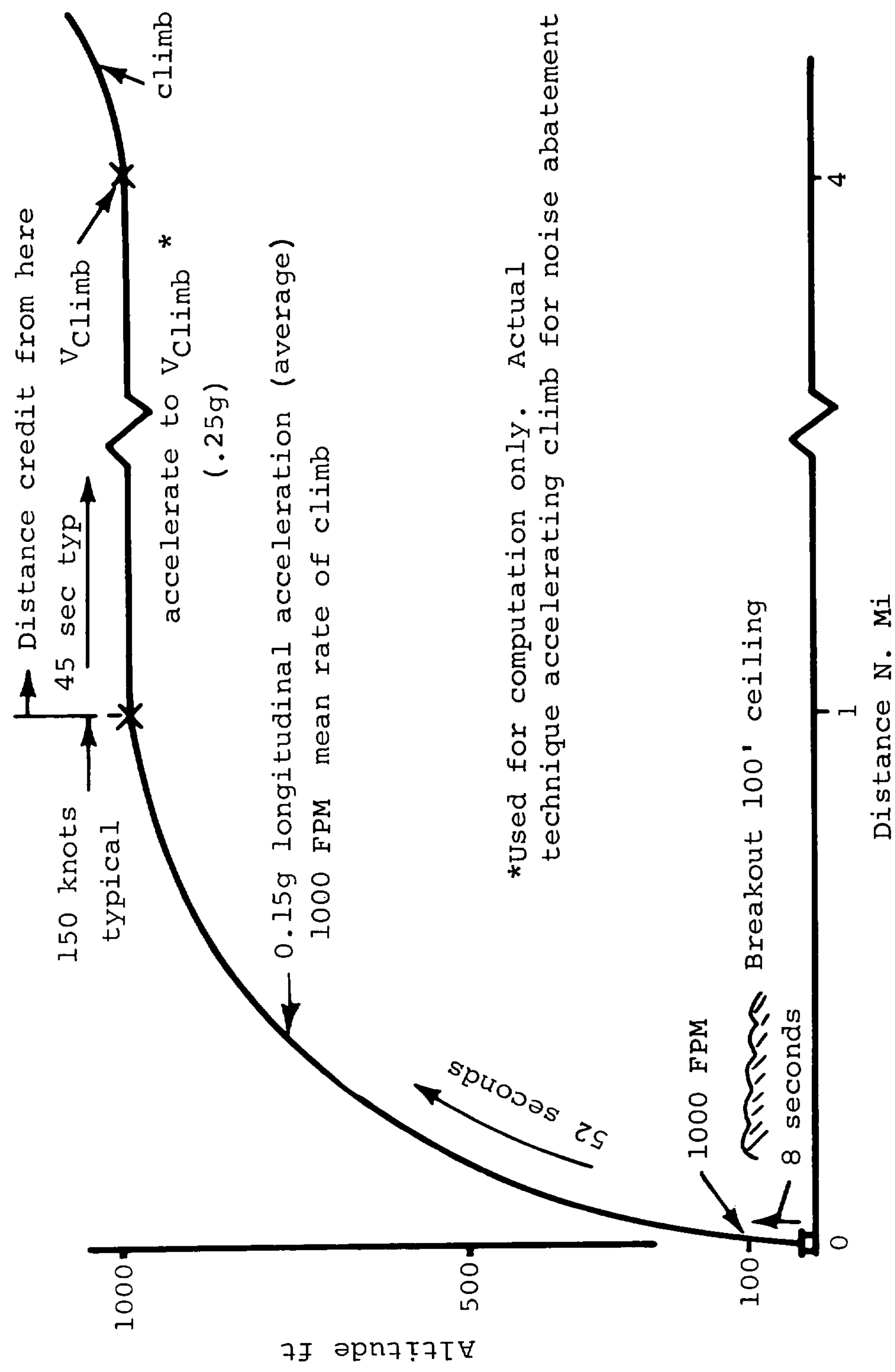


Figure 33. VTOL Takeoff Pattern, VFR and IFR

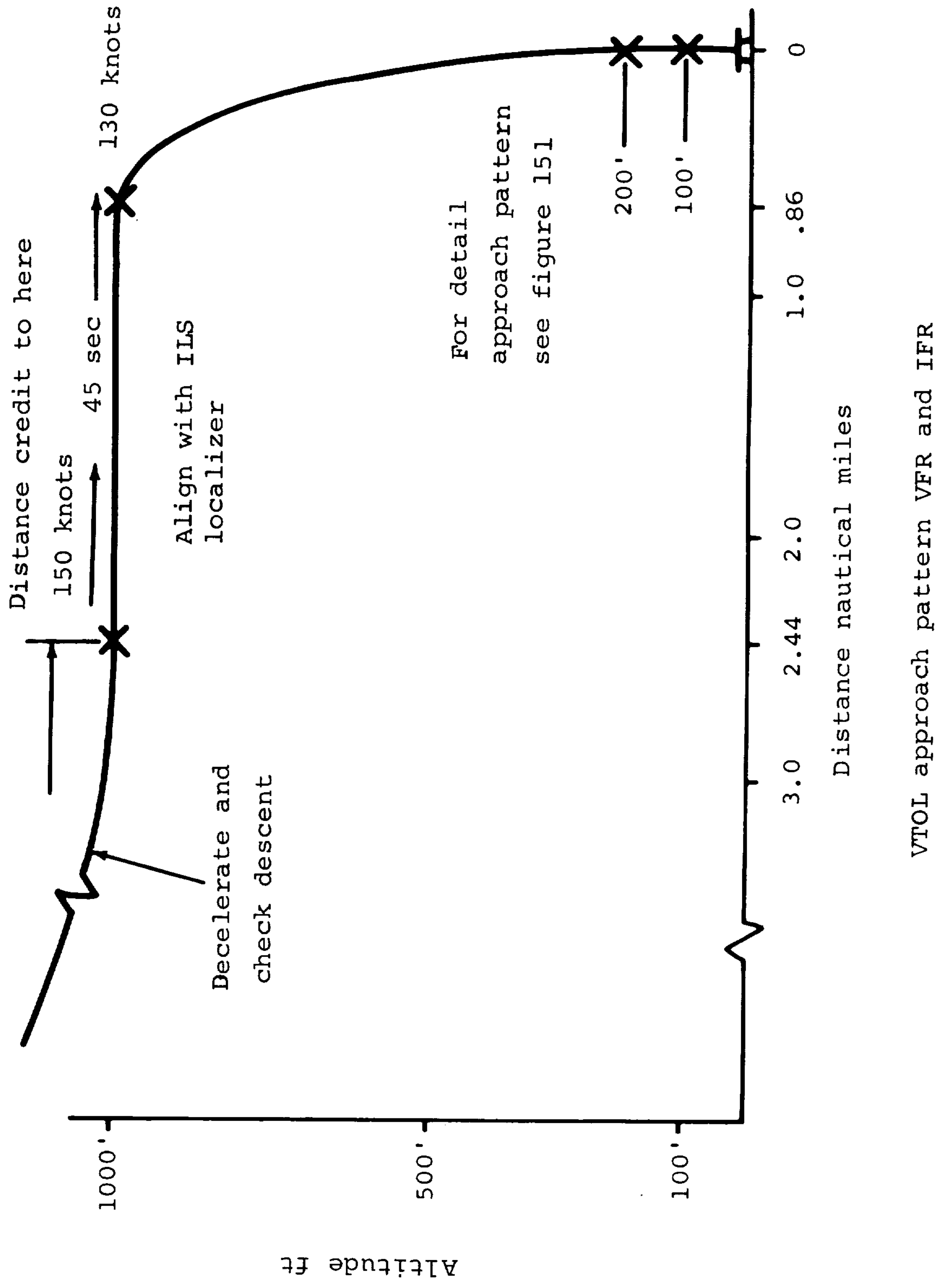


Figure 34. VTOL Approach Pattern, VFR and IFR

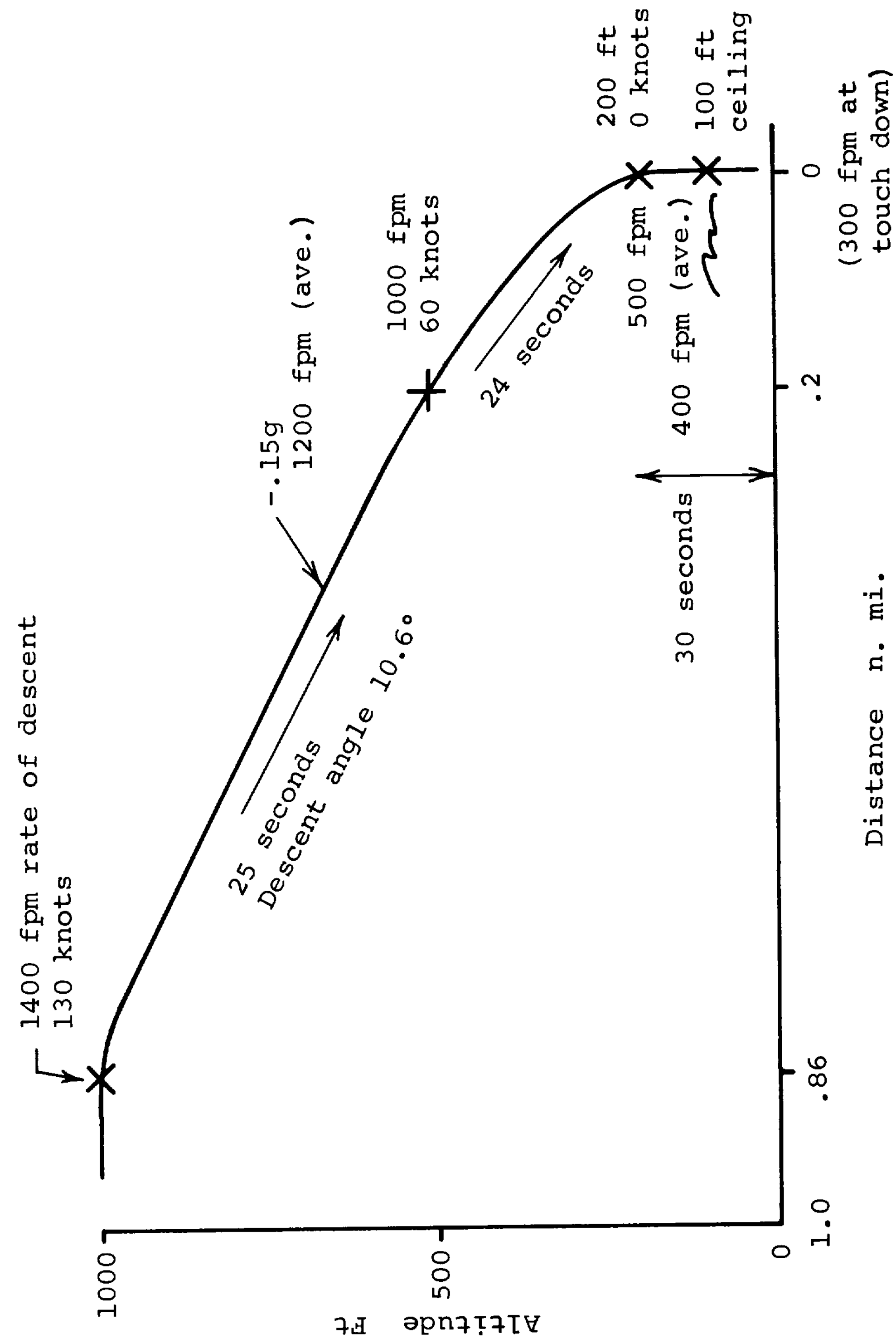


Figure 35. VTOL Final Approach and Landing VFR and IFR.

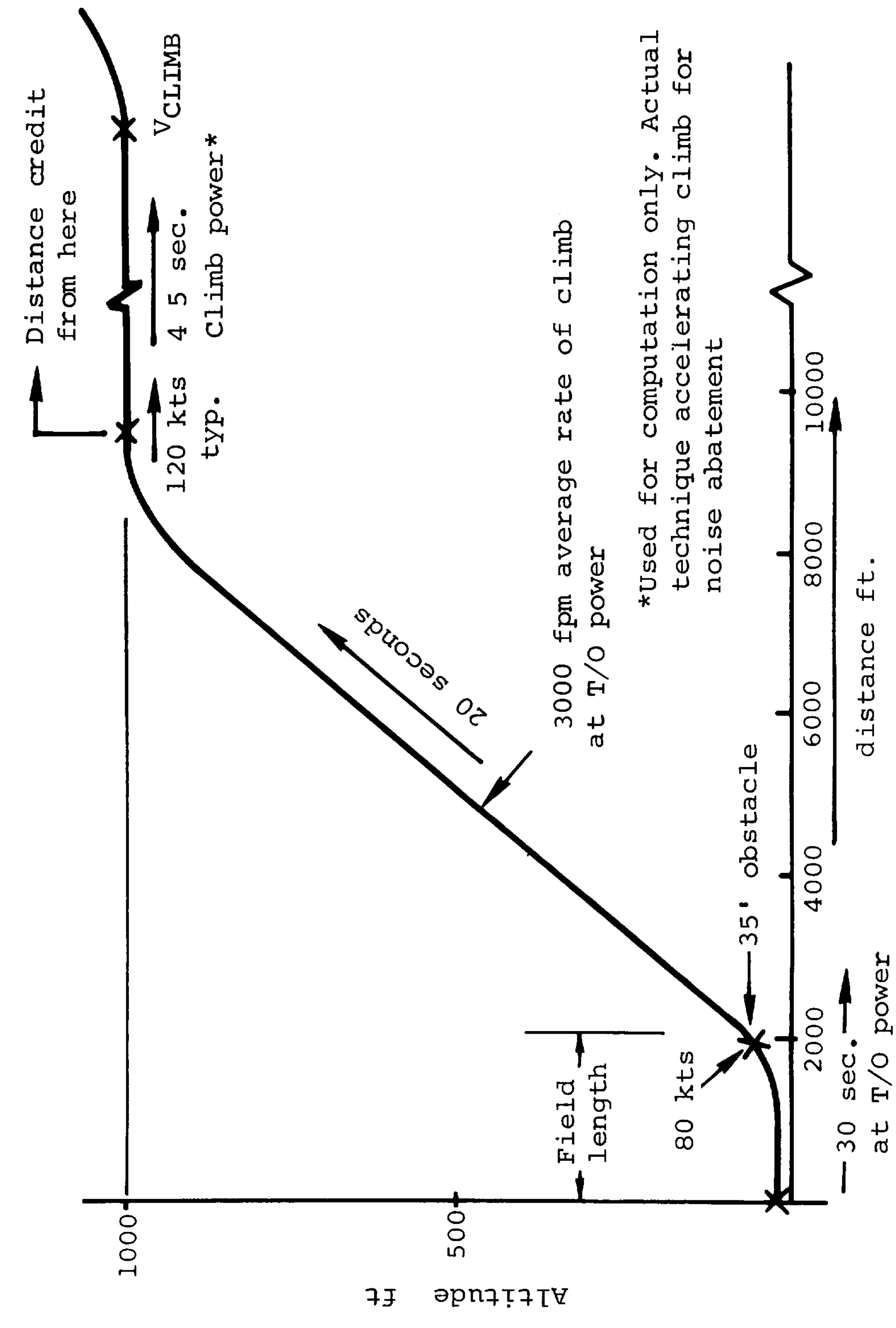


Figure 36. STOL Takeoff Pattern, VFR and IFR

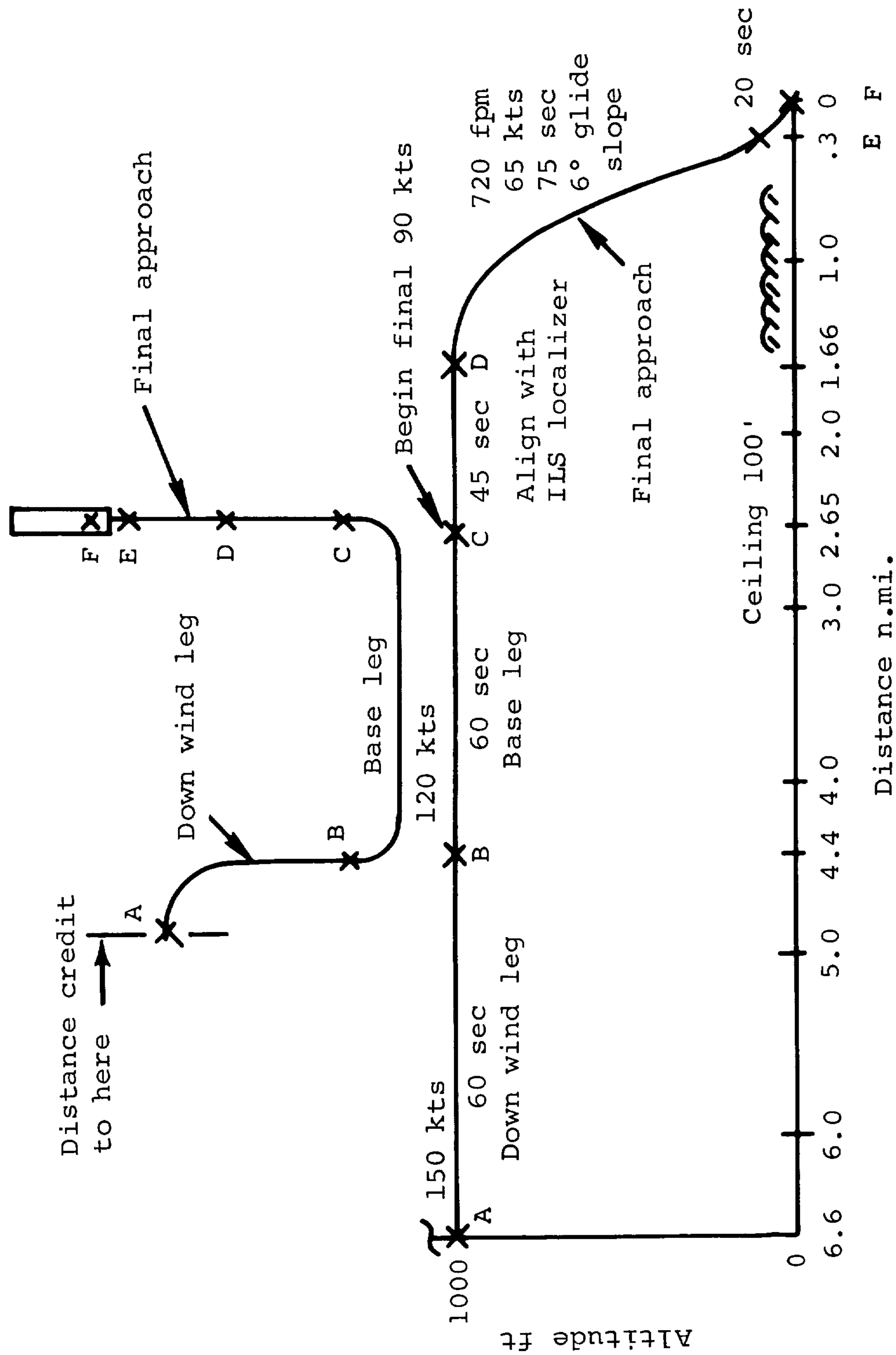


Figure 37. STOL Approach and Landing Pattern, VFR and IFR

The existence of navigation and landing aids, discussed in subsequent sections, indicates that the flight patterns are possible and practical.

No performance beyond the capabilities of the aircraft is required to execute these maneuvers.

Air Navigation Systems

For a short-haul transport aircraft to function properly, it must be able to navigate safely along existing airways, in and around conventional takeoff and landing (CTOL) airports and in and out of central city vertical takeoff and landing (VTOL) terminals. Central city terminal operation demands that the accurate location of the aircraft be known at all times. Human factors related to an optimum navigation/display system are of utmost importance.

The following discussion will describe and indicate the relative advantages and disadvantages of several generic types of navigation systems.

Dead reckoning. - Dead-reckoning navigation involves estimating the change in position from the time of a position fix using the best available knowledge of the aircraft's velocity and heading. Simple dead reckoning has an accuracy typically ±5 percent of the distance traveled.

Inertial. - Inertial navigation systems sense instantaneous accelerations and angular changes of the aircraft exclusively by self-contained means, and process these data in the associated navigation computer to generate the positional and velocity information.

Present day systems have accuracies in the order of one nautical mile per flight hour, with the promise of accuracies in the order of .5 nautical mile per flight hour or better in the future.

Doppler radar. - Doppler radar navigation systems provide velocity information by measuring the doppler shift of a transmitted radar beam. The aircraft's heading reference senses angular movements of the aircraft. The resultant signals are then processed by the associated navigational computer to generate positional data. Historically the accuracy for a doppler system is in the order of .5 percent of the distance traveled.

Rho-Theta. - Rho-Theta navigation systems are ground-based radio systems which provide bearing and distance information.

In normal use, aircraft are piloted along the radials which emanate from the ground stations forming the national airway system. VOR system accuracy is typically ± 2.5 degrees of the indicated bearing; DHE accuracy is ± 600 feet + .2 percent of the indicated distance. Future improvements are estimated to have a bearing accuracy around ± .3 degrees.

Hyperbolic. - Hyperbolic navigation systems require ground stations of a known location. Measurement of the difference in time of arrival of electromagnetic energy from the several transmitters yield intersecting families of hyperbolic lines of position. The present position is related to geography by use of a map of the area having the hyperbolic grid overprinted (see Figure 38).

DECCA is a continuous wave (CW) hyperbolic system which relates phase measurement to transmission time by having an accurate knowledge of the transmitted frequency. As a result of multipath contamination, DECCA's accuracy is typically ±100 feet during the day, and ±1.0 nautical mile at night.

LORAN systems are pulse type systems. Accordingly, multipath contamination is minimized. LORAN A measures the time delays between reception of synchronized pulse transmissions from the several ground stations. LORAN C and D compare phases, in addition to time delays, to achieve typically ±100 feet, day and night.

OMEGA is a hyperbolic navigation system with world-wide coverage. The positional accuracy estimated for OMEGA is 1 nautical mile.

Augmented systems. - Augmented navigation systems make use of the advantages of one navigation system to overcome the deficiencies of another system. For example, the acceleration and orientation information of an inertial system can be used with the velocity data of a doppler radar system. The accuracy of such a doppler-inertial system is typically ±.5 nautical miles per flight hour.

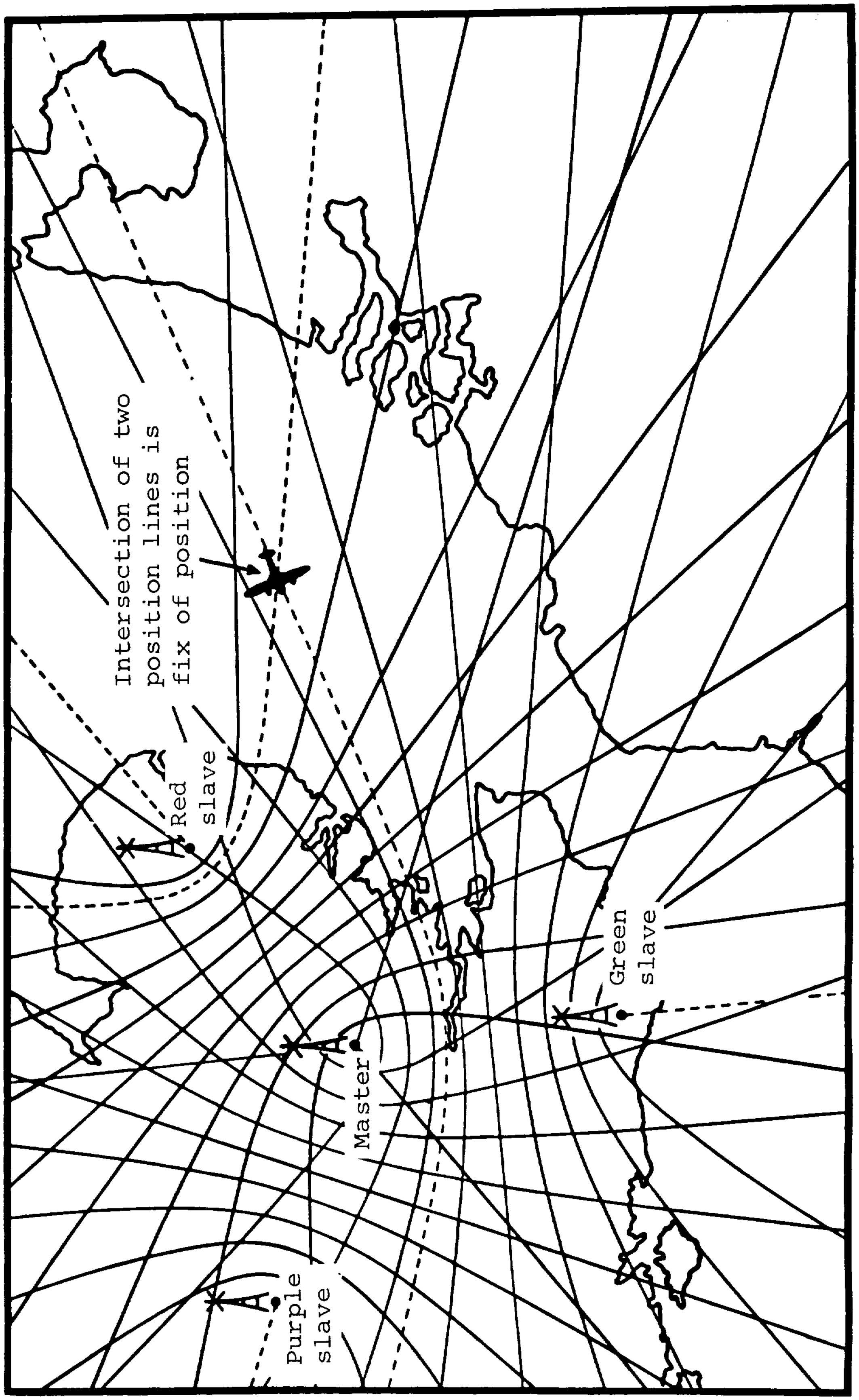


Figure 38. Position Fixing with Hyperbolic Navigation Systems

Radio-inertial systems similarly use the accurate position fixing capability of radio navigation systems to periodically update an inertial system. Accuracies of such systems are typically ±.5 nautical miles.

Heading references. - Dead reckoning navigation systems require heading references to maintain orientation with respect to the earth. Magnetic heading references have a limited accuracy as a result of local anamalies and changes in magnetic variations. It is not at all uncommon for magnetic heading references to be in error as much as 5 degrees.

Gyroscopic heading references sense the angular velocity of the earth about its axis. The orientation of a gyro-compass is always with reference to true (geographic) north. Gyroscopic heading references can be aligned to within .1 degree of true north and have typical drift rates of .15 degrees per hour.

Computers. - Navigation computers operate on the output data from navigation system sensors to perform any required calculations, integrations, or coordinate conversions. Both analog and digital computers can be used to provide these functions. The advent and implementation of microcircuits has given the edge to digital computers over analog computers due to their accuracy and reliability.

Displays. - Human factors must be considered to determine the optimum output display from a navigation system to best enable the pilot to complete the mission. An alpha-numeric readout can provide latitude-longitude data and distance to-go. A course indicator or horizontal situation indicator (HSI) can indicate distance to or from a DME beacon and bearing to a VOR station; or a pictorial display can be used to indicate the aircraft's position over a map of the region being overflown or show the aircraft's position in relation to a preplotted flight path.

Recommendations. - For comparative purposes, the accuracy for various navigation systems has been shown in Table 12. These figures are based upon a 300 nautical-mile stage length and 300 knots cruise velocity.

Table 13 is a trade-off chart comparing the various systems on a System Effectiveness basis. The factors considered for each classification are explained in Table 14.

TABLE 12
NAVIGATION SYSTEM ACCURACY

SYSTEM TYPE	300 N.Mi. @ 300 Knots ERROR (CEP)
Dead Reckoning	15 N.Mi.
Inertial	1.0 N.Mi.
Doppler Radar	1.5 N.Mi
Doppler-Inertial	1.0 N.Mi.
VOR/DME	14 N.Mi.
PDVOR/DME	1.87 N.Mi.
Radio-Inertial	1.0 N.Mi.
Radio-Doppler	1.0 N.Mi.
Hyperbolic	.02 N.Mi.

Dead reckoning is deemed inadequate because of poor performance. Inertial, doppler radar, doppler-inertial, and radio-inertial provide fair-to-good performance, but because of their high costs of acquisition and utilization, they are considered non-optimum systems for the short-haul transport aircraft mission.

The VOR/DME system appears quite attractive due to the prevalence of presently operating ground stations. But, the position fix accuracy attainable, and the restricted airspace available for maneuvering, indicate that simple VOR/DME will not be adequate. However, improved systems, in conjunction with a course line computer would probably be quite adequate. But such a system has not been flight tested sufficiently to prove the overall reliability and accuracy.

Hyperbolic systems, however, have been successfully flight tested and have shown that they can provide the necessary performance for the short haul transport mission.

Human factors considerations indicate that a pictorial display, providing a preplotted flight path, to be optimum for the mission. Such a display provides an accurate indication of the aircraft's position as well as heading commands to maintain the desired flight path. Therefore, a hyperbolic navigation system equipped with a coordinate converter driving a pictorial display is recommended for the short haul transport aircraft as the primary navigation system.

TABLE 13

NAVIGATION SYSTEM TRADE-OFF CHART

SYSTEM	PERFORMANCE	AVAILABILITY	UTILIZATION	COST OF ACQUISITION	COST OF UTILIZATION
Dead Reckoning	Poor	Very Good	Fair	Low	Very Low
Inertial	Fair	Fair	Fair to Good	High	High
Doppler Radar	Fair	Fair to Good	Fair to Good	Moderate to High	Moderate to High
Rho-Theta VOR/DME	Poor	Good	Fair	Moderate	Moderate
PDVOR/DME	Fair	Good	Fair	Moderate	Moderate
Hyperbolic	Very Good	Good	Good	Moderate	Moderate
Doppler-Inertial	Good	Fair	Fair to Good	Very High	Very High
Radio-Inertial and Radio-Doppler	Good	Fair	Good	High	High

TABLE 14

SYSTEM EFFECTIVENESS EVALUATION FACTORS

FACTORS		CONSIDERATIONS
Performance ("How well?")		Design adequacy Design simplicity Specifications Human factors Man-machine interface Compatibility
Availability ("How long?")		Equipment reliability Equipment maintainability Supportability Serviceability Reparability Training
Utilization ("How often?")		Mission length Mission reliability Deployment Environment
Cost of Acquisition	Development	Operational analysis System definition System design Hardware design Test and evaluation
	Production	Procurement Manufacture Installation Test Training
Cost of Utilization	Operations	Personnel Facilities Utilities Special inputs
	Maintenance	Personnel Facilities Spares Logistics Diagnostic aids
	External costs due to failures	

For increased reliability and as a back-up system, the aircraft should also be equipped with the latest VOR/DME equipment. Figure 39 is a simplified block diagram of the recommended navigation system for the short haul transport aircraft.

All-Weather Landing Systems

As weather conditions deteriorate, the problems of maintaining traffic flow in the terminal area multiply rapidly. The Federal Aviation Agency, in cooperation with International Civil Aviation Organization (ICAO), has established categories of weather minima for landing of various classes of aircraft at variously equipped airports. Table 15 summarizes the weather minima for landing in terms of runway visual range and cloud ceiling.

TABLE 15
WEATHER MINIMA FOR LANDING

OPERATION	PROPELLER RVR (ft)	PROPELLER CEILING (ft)	JET RVR (ft)	JET CEILING (ft)
Category I	2600	200	4000	300
Category II	1300	100	1200	100
Category IIIA	700	50	700	50
Category IIIB	150	0	150	0
Category IIIC	0	0	0	0

A recently introduced localizer antenna yields a more uniform and more accurate radiation pattern than those formerly possible. This new antenna will aid in certifying airports for Category IIIC operations.

The glide-slope radiation pattern must be linearized especially in the region where the pilot is approaching his decision altitude (minimum).

Transmissometer equipment for measuring runway visual range (RVR) must be installed parallel to the instrument runway near the approach end, with extreme standards of installation, calibration and test. An additional transmissometer installation further down the instrument runway is under consideration.

Similarly, the airborne equipment must meet increased accuracy standards prior to being relied on for guidance to the lower altitudes involved.

Although the aircraft of this study will be able to operate following the same flight path as their fixed-wing counterparts full utilization of their increased maneuverability and hover capability will require a new generation of ground-based equipment.

Several versions of these equipments are in various stages of development. A steep-descent angle system will have to be installed at all V/STOL ports to yield all-weather operation which at most locations will be the difference between a profit and loss situation. A ground station to provide continuous coverage of the V/STOL port site will add approximately $50 000 to $100 000 to the cost of the terminal. Antenna relocation and replacement, and installation of radio-frequency convertors are examples of alterations which might be required in the aircraft configuration. These may be reflected in increased avionics costs of $2000 to $3000, and a weight penalty of 3 to 5 pounds.

Displays are a very important aspect of all-weather land-problem and solution. As pointed out above, a coupled auto-pilot system will be necessary for the completely blind landing. However, the human pilot will demand the capability of overriding the automatic equipment at any time. The capability to override the automatics requires some form of visual guidance display to the pilot of many bits of information:

1. A failure-warning signal

2. Guidance information is necessary to command the pilot after he has assumed active control of aircraft maneuvering.

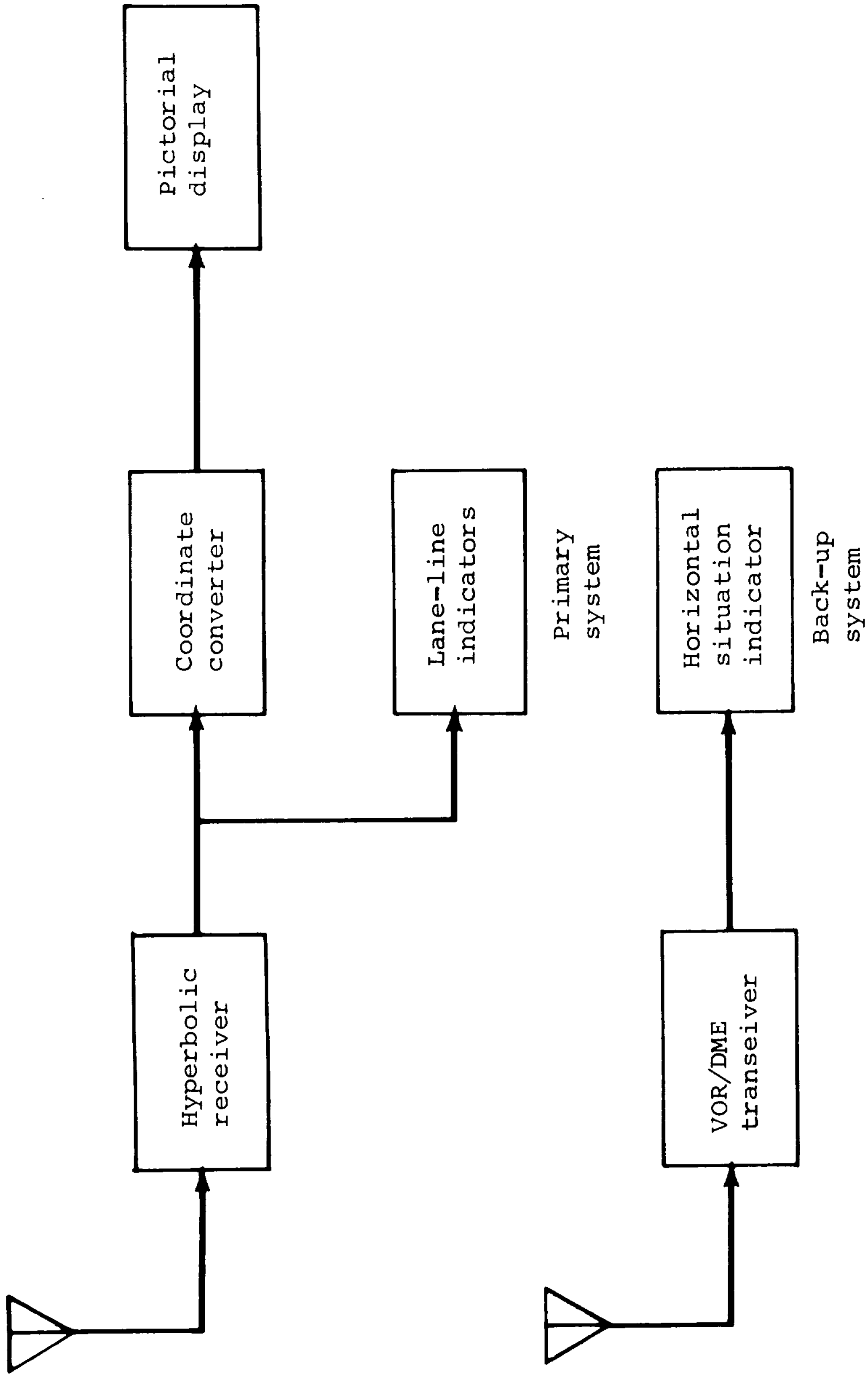


Figure 39. Navigation System Block Diagram

3. Positional information (attitude, altitude, velocity, etc.) must be given to the pilot to allow him to compare the guidance information with the "path made good".

The format of the information presented must yield accurate interpretation with no loss of time. Proper sensing will greatly improve response time and accuracy. The display must be as close as possible to the natural line of sight through the windscreen.

Several types of head-up displays have been demonstrated with favorable results. This capability can be added at a weight penalty of 30-40 pounds and a cost of approximately $20 000. A typical display presentation is shown in Figure 40.

Air Traffic Control

Air traffic control (ATC) is accomplished by a group of human controllers on the ground who have aircraft flight data and information on weather conditions, the existence and location of other aircraft in the airspace of interest, the traffic-handling capacity of the airways and airports, and the operational status of all navigational aids used by the aircraft.

The ATC system used now is divided into the enroute portions and the terminal areas.

Radar is used to search and track all air traffic in the radar range. This information is then displayed via a cathode-ray tube.

Discrimination between targets is accomplished manually by plastic markers and paper "flight strips". Identification of targets is verified by oral position reports from the aircraft crew. The problems involved currently include:

1. Cockpit communications workload

2. Controller communications workload

3. Crowding of the assigned airways

4. Coordination of traffic transfers between sectors

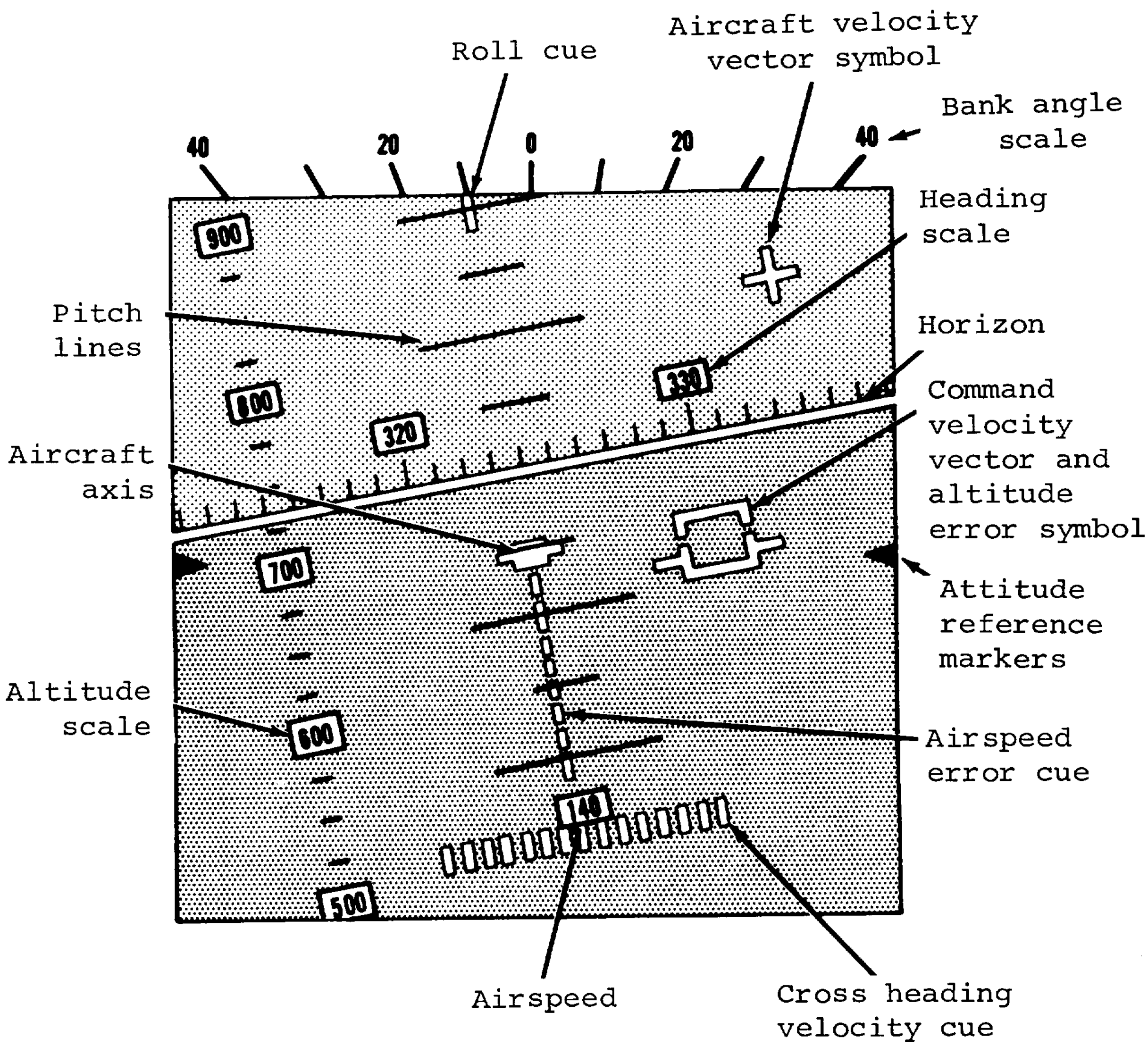


Figure 40. Vertical Display

5. Accuracy limitations of the radars and navigational aids due to difficulties associated with the geographical site.

The presently envisioned 50-Kilohertz (KHz) spacing on VHF communication channels will be adequate for the increased communications load.

The Federal Aviation Agency (FAA) is currently in the midst of a major program for updating the ground equipment of the ATC system. This program leads to a high degree of automation in the field of data collection, processing, and display. Functional block diagrams are shown in Figures 41 and 42. This procedure is intended to reverse the current trend of handling the continuously increasing amount of air traffic by holding constant the amount of traffic each controller is responsible for, but decreasing the geographical area he is cognizant of. Computerizing the system will relieve the human controller for more meaningful work and allow him to concentrate on moving the traffic.

In the terminal area, it is possible to supervise, from one location, traffic of more than one airport/heliport provided their geographic proximity makes it desirable.

The next generation equipment programmed for the enroute traffic environment will also be applicable to the terminal area. For example: flight plans can be entered into the computer memory on a published schedule basis and then withdrawn to aid in runway/landing pad utilization, since this factor is the most critical in determining traffic capacity of a terminal. Advance information concerning landing/takeoff space availability will allow adjustments of speed and/or flight path to optimize fuel consumption -- directly affecting Direct Operating Charges. Figure 43 shows diagramatically, the Terminal Area Operations. A similar type of chart can be shown for enroute operations. These vehicles will be capable of making use of currently unused airspace in the terminal area and enroute altitudes beneath present commercial air traffic.

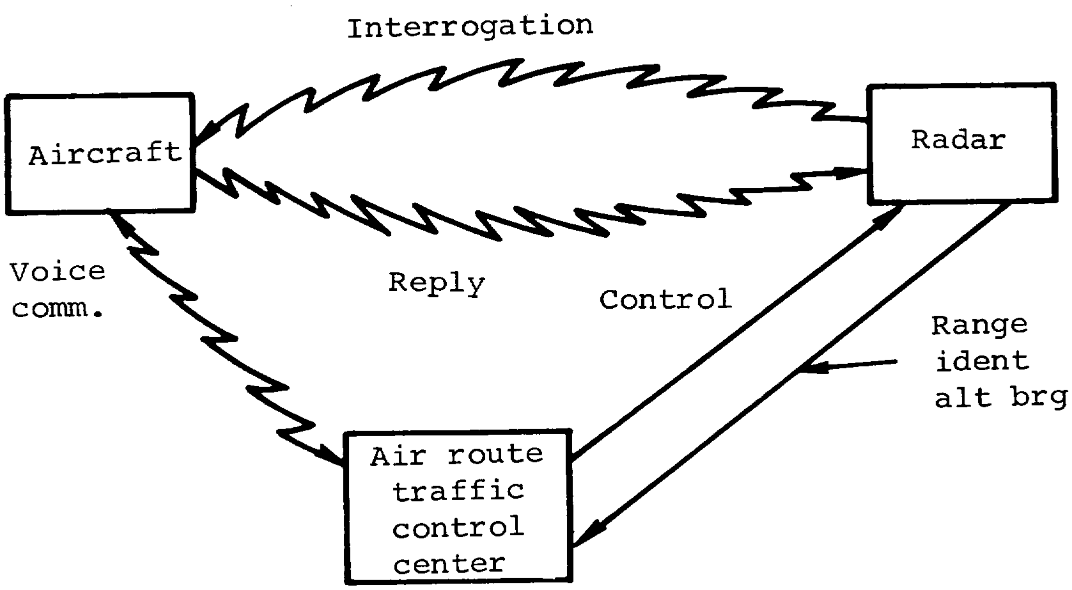


Figure 41. Air Traffic Control System Block Diagram

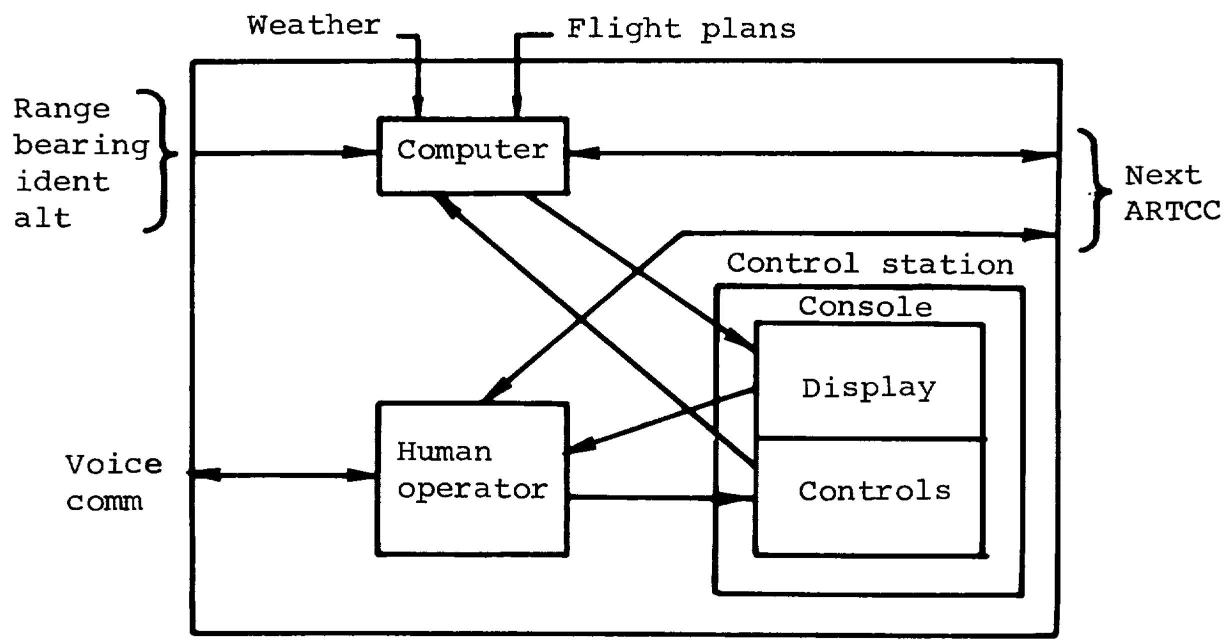


Figure 42. Air Route Traffic Control Center

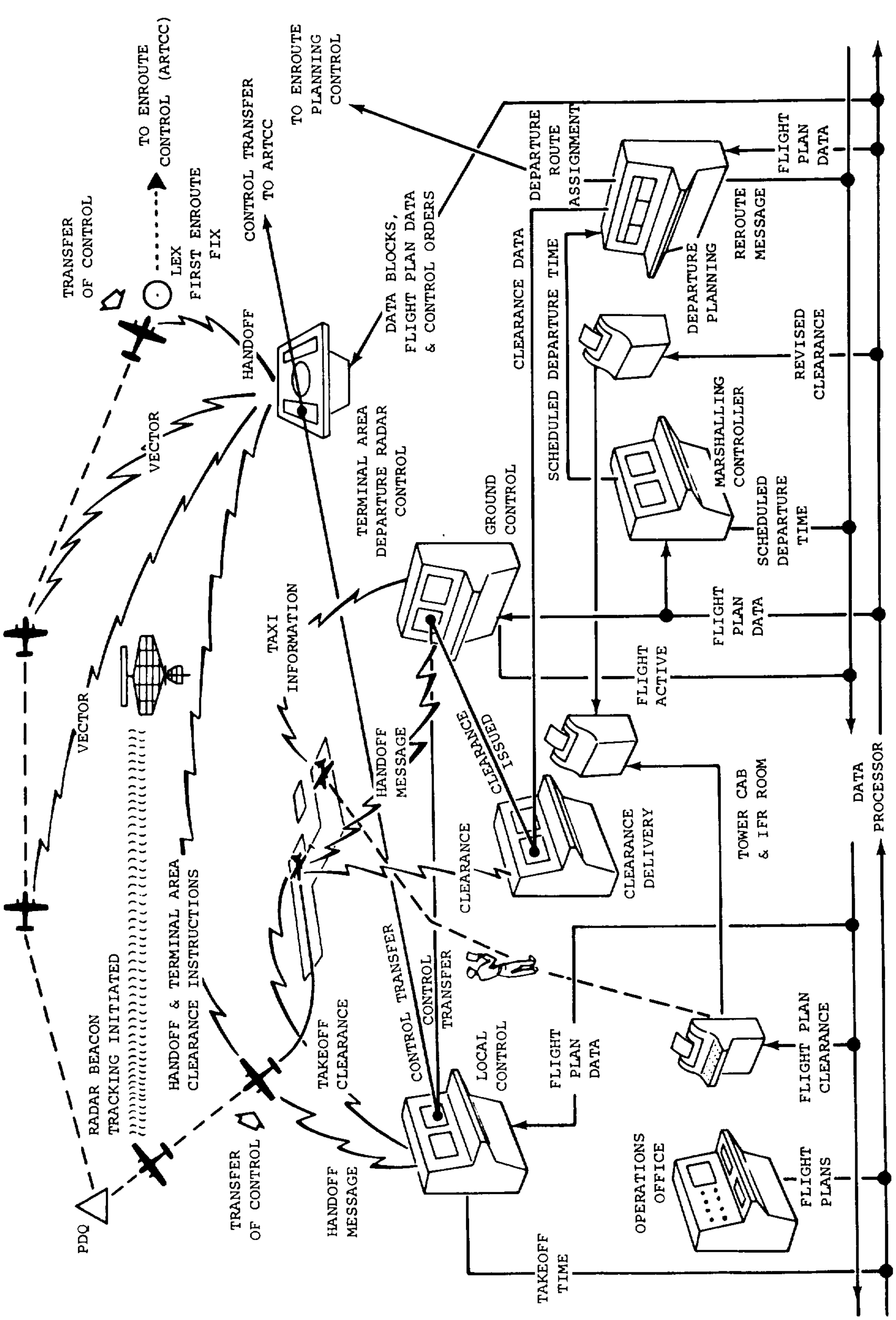


Figure 43. Departure Terminal Operation

Noise

An important design consideration in aircraft for public acceptance is acoustical noise. The importance of the problems introduced because of objectionable noises is underscored by concerted community action against any particular source of annoyance of sufficient magnitude. The aircraft designer, fortunately, has methods available to anticipate and partially control these noises and, where possible, enhance passenger and public appeal of future V/STOL aircraft.

Under present consideration is a family of short haul transport aircraft for use primarily in and between urban districts. Noise predictions based on related types of aircraft acoustical signatures and theoretically or empirically derived parametric relationships are used to estimate the desirability, or lack of such, of each type of noise signature.

Methods for predicting noise levels. - The methods for predicting noise levels are primarily of two types. One is based on the similarity of the proposed aircraft or powerplant to existing configurations. Fairly accurate predictions can be made by suitably modifying or interpolating physical measurements to include a wide variety of noise sources. Among this category fall the propeller, rotor, and jet propulsion families. The other method has as its justification a theoretically derived relationship between the various design parameters and the resulting acoustical power levels. Certain types of pure jet and fan noises fall into this category. However, the most common method of predicting the majority of aircraft noises consists of a combination of the above.

Noise level predictions. - Figures 44 and 45 compare overall sound pressure levels and perceived noise levels of the various configurations in takeoff and cruise, respectively. The PNdb concept is a recognized annoyance rating for jet noises. There is considerable disagreement in the two types of noise ratings in some cases and each should be interpreted carefully with regard to a particular aircraft. The pressure of two or more discrete frequency components in any one octave,

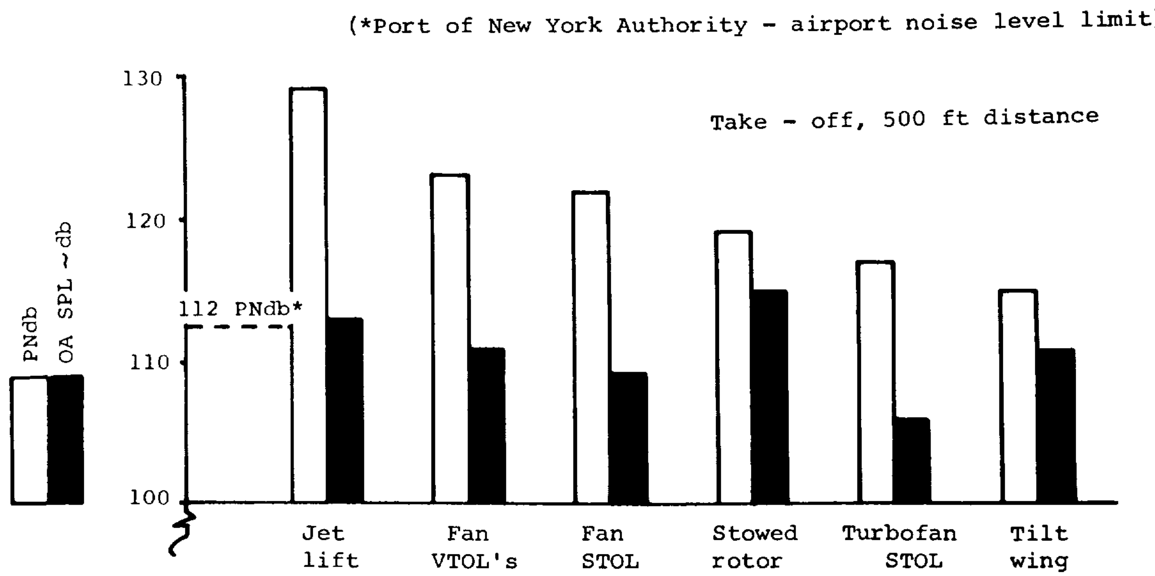


Figure 44. Overall Sound Pressure Levels and Perceived Noise Levels at Takeoff

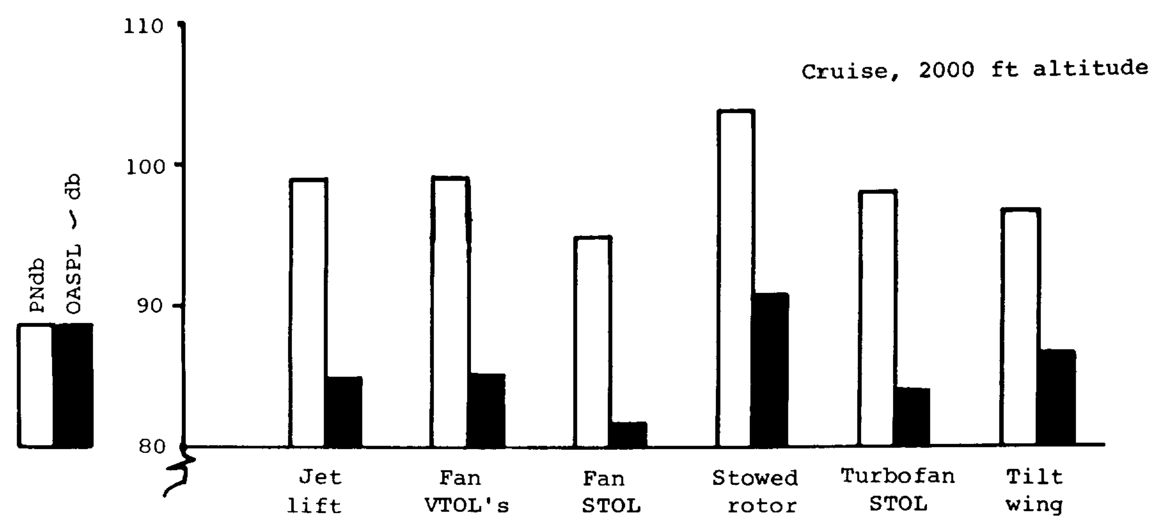


Figure 45. Overall Sound Pressure Levels and Perceived Noise Level in Cruise

the modulation of rotor noise at the rotor blade fundamental frequency, or the duration of the noise are not accounted for in these single-number rating schemes.

At takeoff the tiltwing and turbofan STOL would be rated as the least objectionable, although, at distances greater than the 500 feet for which noise values are given in Figure 44, the tilt wing noise would tend to attenuate less than the jet and fan types. On an annoyance basis, the jet lift is probably the worst offender in the takeoff configuration. A comparison of noise intensity heard on the ground from the aircraft cruising at 2000 ft is given in Figure 45. It can be seen that there is little to choose between the concepts with the exception of the comparatively heavy high drag stowed rotor. Again it could be expected that the tilt wing would be heard at a greater distance than the turbofan types. While this is important militarily from the detection standpoint it is unlikely to be a significant annoyance factor.

<u>Further work required</u>. - There are three primary areas of investigation which ought to be expanded. One of these is powerplant noise reduction and control. Perhaps the most difficult area of treatment is the powerplant intake duct noise due to the interaction of fan or compressor rotor and stator blades. Much work remains to be done to make these techniques practical to the aircraft designer. Some practical results have been achieved in the field of jet exhaust noise suppression. These results could perhaps be applied to some of the designs considered here. However, the extent to which noise suppression devices can be successfully combined with such hardware as swivelling turbofan nozzles is not yet finally established.

Another important area requiring further research is in the analysis and prediction of noise levels associated with certain types of powerplants, aircraft, and their operation. The majority of prediction methods used in this study are an extension of known trends in physical data applied to similar noise sources. This invariably leads to a certain error in accuracy of the predicted data. New types and applications of noise generating propulsion units need further testing to obtain noise data and verify prediction methods.

The third major area for improving acoustical engineering methods lies in the physiological and psychological effects of noise magnitude, frequency, phasing, modulation, duration, and mechanisms of auditory perception. Listener reactions have been studied for the presence of pure tones in random noise and for the signal-to-ambient noise ratio. A program is presently being planned at Boeing to determine the relative annoyance of the different noise characteristics encountered during this study. This and additional works need to be documented, verified, and disseminated for inclusion in a comprehensive noise evaluation of future aircraft.

Ride Qualities

Since these short haul transports will spend much of their flight time at low altitudes, gust sensitivity as it effects passenger comfort is of greater importance than with long range high-flying aircraft. Poor ride qualities could severely affect the economy of the aircraft by forcing flights in turbulent conditions to be made well below the normal cruise speed. Their gust sensitivity is compared in Figure 46 to the values for the Electra. The tilt wing, which has no higher gust sensitivity than the Electra, is the most sensitive. The jet lift, which has high wing loading and low aspect ratio, is at the opposite end of the scale. The analysis was made assuming rigid airframe and therefore the absolute values are conservative.

Passenger Appeal

What might be called general passenger appeal has played a part in the development of the commercial airline market. The introduction of jet aircraft met with general enthusiasm from the public, initially because of decreased journey time but, after experiencing jet travel, quietness and smoothness became additional factors in "jet appeal".

In the case of V/STOL aircraft, the convenience of city-center-to-city-center travel is the major time saving. The differences in block time between the aircraft over short stage lengths are minor. Therefore, passenger appeal will be a matter of comfort, dependent on noise, vibration, smoothness of transition, etc. This point is too subjective for meaningful comparison in this report.

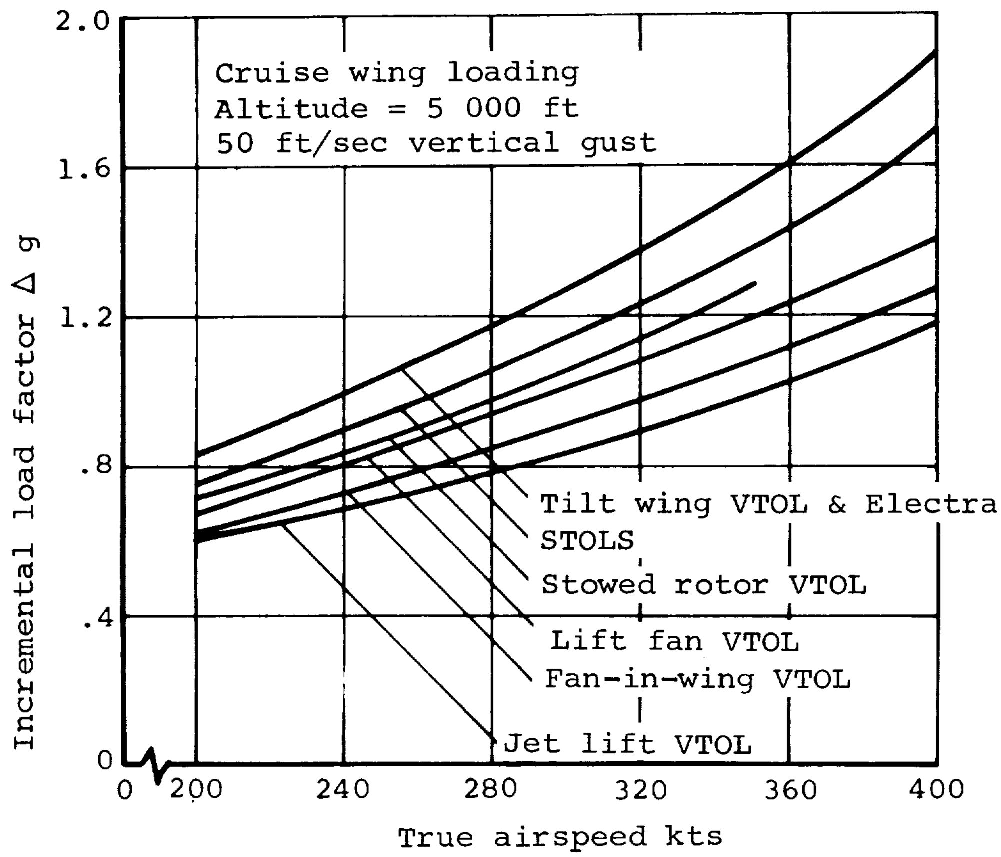


Figure 46. 60-Passenger Aircraft Comparison of Gust Sensitivity

ACQUISITION COSTS

The cost studies contained in this report rely on a technique of pricing developed by the Boeing Company which reduces design configurations into aircraft systems. The Boeing Company has achieved this standardization and commonality of cost packages by employing a system referred to as the Universal Aircraft Systems Breakdown, which provides the ability to evaluate the cost of flyaway aircraft systems by using characteristics such as weight and power data.

The breakdown consists of two major classifications, structural elements and nonstructural elements, and is further subdivided within these major headings by the applicable aircraft operating systems, based on the design configuration. To measure or evaluate these operating systems, cost regression curves for both program tasks and contract end items were developed from Boeing and industry data to reflect the system acquisition cost, resulting in total program system acquisition cost versus total program system cumulative weight/thrust.

The availability of this technique allows expedient evaluation for production quantities of any aircraft regardless of configuration. However, this basic tool was sensitive only to weight considerations, and required further refinement to allow for additional factors of complexity to be introduced, resulting in an effect on cost.

The effect of the complexity factors on the cost of the individual aircraft system for each program task is summarized as follows:

	300 Aircraft	600 Aircraft
1. Jet Lift VTOL	1.040	1.027
2. Tilt Wing VTOL	1.017	1.013
3. Stowed Rotor VTOL	1.021	1.014
4. Lift Fan VTOL	1.042	1.032
5. Fan-in-Wing VTOL	1.024	1.017
6. Fan-in-Wing STOL	1.014	1.009
7. Turbo-Fan STOL	1.001	1.001

NOTE: Base program (no complexity) - 1.000

Each model operating system (cost package) was evaluated individually to establish the complexities of design, tooling and manufacturing, relative to the basic regression cost curves developed, and adjusted by this evaluation to determine the relative magnitude of the task between similar packages contained in models selected for this study.

SCOPE

Costs including both the Nonrecurring and Recurring phases, were compared for the seven (7) basic 60 passenger aircraft and four (4) 120 passenger models, in quantities of 300 and 600 units. A tabulation of the Contract Items and Program Tasks, which were evaluated individually, included in these phases is as follows:

NONRECURRING

1. R D T & E

   a. Design - Total engineering and support effort to determine configuration that meets the specification.

   b. Test - Total engineering and support effort to complete component test, ground test, and flight test, which includes FAA certification.

   c. Tool (Soft) - Total tool cost to complete prototype aircraft.

   d. Prototype- Total cost of a flyaway vehicle used for testing and developing a satisfactory production model.

2. Support to Production

   a. Tool (hard) - Total tool cost required to produce 300 and 600 aircraft.

3. Support to Air Vehicle

   a. Publications-Total cost of publications, which includes:

(1) Pilot Handbook
(2) Operating Manual
(3) Illustrated Parts List
(4) Weight Book
(5) Maintenance Handbook

RECURRING

1. Aircraft - The total cost of a flyaway vehicle.

2. Spares - The total cost of spares required when the aircraft is delivered.

For the purpose of this study, a flyaway vehicle is a fully operational vehicle, excluding support items.

Cost elements considered within the foregoing tasks and contract items encompass both direct and indirect costs, including 10% profit.

RESULTS

The results of this study shown in Table 16 reflect current aircraft technology (to 1970). As might be expected, the turbo-fan STOL is the least expensive aircraft by virtue of its lack of propulsion system complexity, while the fan-in-wing STOL which has a lifting propulsion system but no VTOL controls, falls between the turbo-fan STOL and the least costly VTOL, the tilt wing. The latter aircraft's low cost relative to the other VTOL concepts is due not only to its lower gross weight, but also to the low cost per pound of transmissions and rotors compared with engine costs. The latter fact is also responsible for the stowed rotor cost not greatly exceeding the jet lift and lift fan concept costs despite its much higher weight. Although the jet lift propulsion system consists solely of engines, its propulsion cost does not greatly exceed that of the lift fan aircraft because it has only two basic propulsion VTOL control devices as against five for the lift fan types.

TABLE 16 COMPARISON OF ACQUISITION COSTS 60 PASSENGER SIZE

	Total	Nonrecurring	Recurring	Spares
	$	(300 A/C Program)		
VTOL				
Jet Lift	5.6	1.0	3.6	1.0
Tilt Wing	4.7	1.0	3.1	.6
Stowed Rotor	6.2	1.2	4.2	.8
Lift Fan	5.4	1.2	3.3	.9
Fan-In-Wing	5.8	1.2	3.6	1.0
STOL				
Fan-In-Wing	4.2	.9	2.6	.7
Turbofan	3.5	.7	2.2	.6

$ IN MILLIONS 1.0 0 1.0 2.0 3.0 4.0

	Total	Nonrecurring	Recurring	Spares
		(600 A/C Program)		
VTOL				
Jet Lift	4.2	.5	3.0	.7
Tilt Wing	3.6	.5	2.7	.4
Stowed Rotor	4.7	.6	3.6	.5
Lift Fan	4.0	.6	2.8	.6
Fan-In-Wing	4.3	.6	3.0	.7
STOL				
Fan-In-Wing	3.1	.5	2.2	.4
Turbofan	2.6	.3	1.9	.4

ASSUMPTIONS

To establish a consistent program costing base for all models or configurations, the following assumptions were applied throughout the evaluation:

1. All aircraft are produced to the same delivery schedule.
2. Basic design complies to specifications and is fixed throughout the manufacturing phase.
3. The degree of complexity assigned to each model, determines the amount of testing and hence, the number of prototype aircraft required for each model.

4. Engines are not available as off-the-shelf items and consequently the costs include a full developmental program.

5. All costs are expressed in terms of a 1965 dollar.

DIRECT OPERATING COSTS

Direct operating costs were calculated partly by the 1960 Air Transport Association (ATA) "Standard Method of Estimating Comparative Direct Operating Costs of Transport Airplanes" and partly by other methods. The ATA method provides reasonable direct operating costs for the aircraft configurations of this study in several areas. The ATA formula and constants were used for fuel and oil, insurance and liability, depreciation, and maintenance burden rates.

Flight crew costs are higher today than are calculated by the formula, so crew pay was increased 22 percent to put it in closer agreement with 1965 contracts.

Maintenance costs for the aircraft and engines were analyzed in greater detail than is permitted by the ATA method in order to make the study more sensitive to the substantial differences in the aircraft configurations and to assess the effects of frequent takeoffs and landings. Maintenance costs, including burden, represent more than one-quarter of the direct operating costs.

Assumptions and Ground Rules

Times between overhaul for dynamic systems were assumed as 1000 hours; for cruise engines, 5000 hours with two intermediate hot section inspections. Lift engine overhauls were assumed at every 5000 cycles (start, operate, shut down; two cycles per flight). Production rates were assumed at 6 per month for run of 300 civil aircraft, and at 12 per month for 600 (civil-plus-military) aircraft. Fuel cost was 11 cents per gallon, and labor was $3.00 per hour.

All airports of origin and destination were assumed to be at sea level. Standard atmospheric conditions and zero wind were used.

For all but the hypothetical route shown in figure 47 two flight patterns were used. In the short pattern a non-productive fixed time of 4 minutes was used and all flight distance was credited to block distance until reaching 1000 feet altitude on descent. The long pattern includes without distance credit, a 4 1/4 minute approach pattern from 1000-foot altitude and taxi; take-off and landing allowances for a total non-productive fixed time of 10 1/4 minutes.

On the hypothetical route structure the flight patterns discussed in the "OPERATIONS ANALYSIS" section were applied. These will be referred to as the optimum patterns.

Method of Approach

Calculations of DOC's for analysis of technical tradeoffs were by a simplified method giving satisfactory relative values for optimizing the designs, but not necessarily yielding absolute costs comparable to those of the final calculations. Final DOC's were determined by the ATA method with modified flight crew and maintenance costs. Crew costs calculated by the ATA formula were increased 22 percent for this study.

Airframe maintenance cost estimates were based on experience with existing aircraft and on recent detailed studies. Maintenance manhour estimates for systems and subsystems of each aircraft configuration were developed from reliability and maintainability analyses, including inspections, scheduled maintenance, ground support equipment and publications. Direct maintenance material costs per year were taken as a fixed perpentage of the acquisition cost of recurring spares. Flight-time-sensitive items such as flight controls and alternators, were grouped and reported as costs per hour. Cycle-sensitive items, like flaps, brakes and tires were reported as costs per trip. Total airframe maintenance cost per trip was the sum of the hourly costs multiplied by flight time of the trip, plus the cyclic costs. This method reflected the penalty on hourly maintenance costs of frequent short trips.

Engine overhaul and line maintenance costing was based directly on trunk airline experience. Overhaul costs recognized the effects of flight time, engine operating temperature on each part of the flight, rated specific power, cost, frequency of hot section inspections and time between overhauls. Line maintenance cost per engine flight hour was constant.

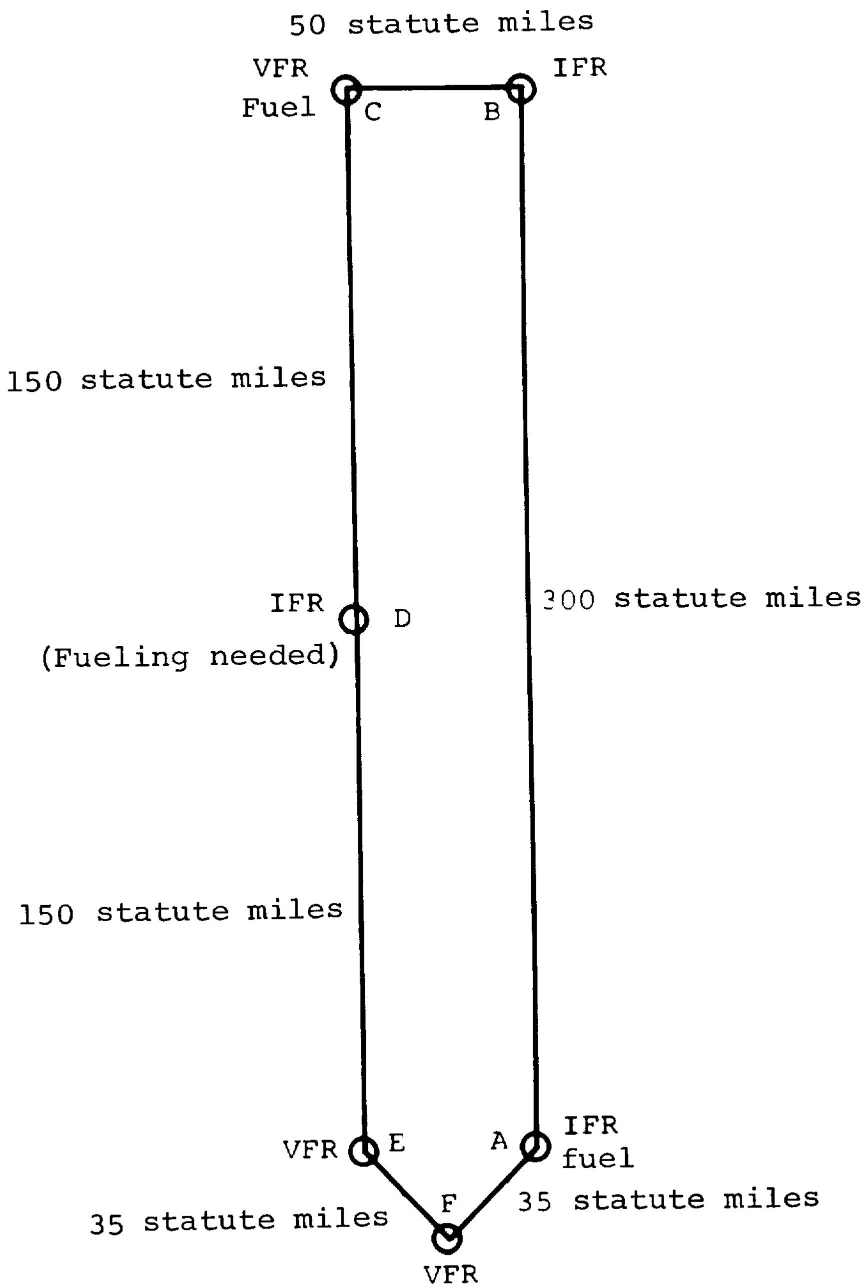


Figure 47. Hypothetical Short Haul Route

Direct operating costs of each finalized aircraft were found to assess the effects of stage length, non-productive time, inclusion of airplane development costs, production quantity, engine state of development (date of technology), design payload, annual utilization, and route structure.

RESULTS

Direct operating costs per aircraft-mile and per seat-mile are presented in Figure 48 for the seven original 60-passenger concepts operating on the long pattern. Breakdowns of these costs are also given in Table 17 for 25- and 500-mile block distances.

In selecting the final four aircraft, the DOC's were also plotted in Figure 49 with STOL's on the long pattern and VTOL's on the short pattern to reflect their respective flight capabilities. The turbofan is the least expensive STOL to operate and the tilt wing the least expensive VTOL. Since the tilt wing uses the same propulsion components for lift as for cruise, it shows the best ability to minimize the typical rise of costs on very short flights. However, the use of propellers in cruise, as opposed to fans in all the other aircraft, penalizes the tilt wing's cruise speed and hence DOC on longer blocks. The operating cost cross over for the tilt wing and turbofan STOL is at 100 miles.

The aircraft having engines to provide lift during takeoff and landing have high costs on the short block lengths.

DOC's for the four final 60-passenger configurations operated on the long pattern are shown in Figure 50, for reference in the subsequent sensitivity studies.

The effect on operating costs of the nonproductive block times associated with the short and long flight patterns is shown in Figure 51. All aircraft respond similarly to non-productive time changes.

Figure 52 demonstrates the effect of utilization on DOC for 100-mile stage lengths. In all other parts of the DOC analysis, utilization was held constant at 2000 block-hours per year. As a practical matter, the utilization will probably change with block distance and nonproductive time if the aircraft is to be operated profitably. All configurations show approximately 23-percent decrease in DOC when utilization is doubled

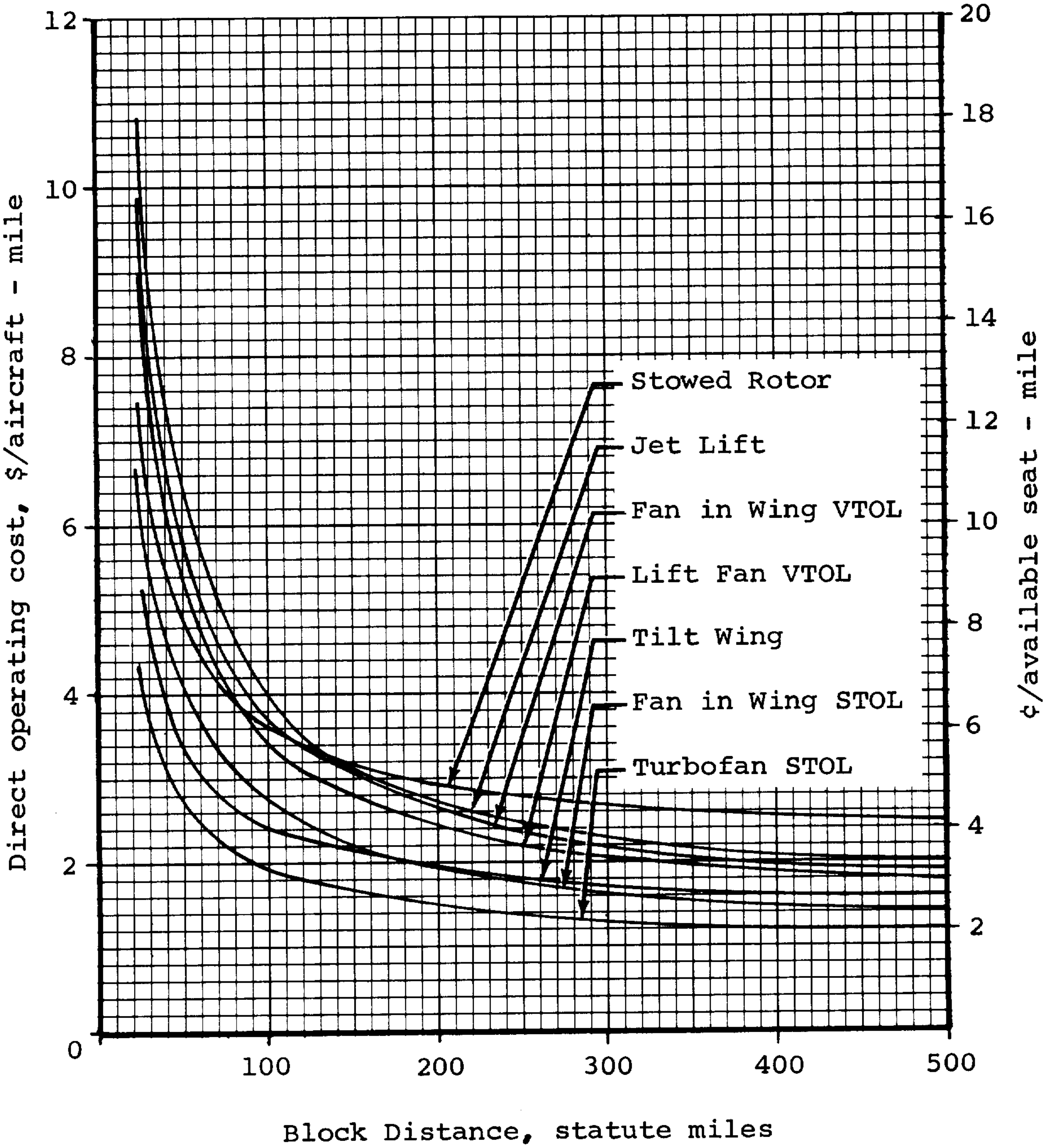


Figure 48. Comparison of Direct Operating Costs Over the Range of Block Distances, Long Pattern

TABLE 17
DIRECT OPERATING COST BREAKDOWN
60-PASSENGER AIRCRAFT*
$/Aircraft-Mile

Aircraft	Jet Lift	Tilt Wing	Stowed Rotor	Lift Fan VTOL	Fan/Wing VTOL	Fan/Wing STOL	Turbofan STOL
25 Statute Mile Stage Length							
Flying Operations	3.440	2.014	2.700	3.103	3.165	2.177	1.610
Maintenance (incl. burden)	4.408	1.191	1.956	3.305	3.863	2.420	1.154
Depreciation	2.970	2.204	2.834	2.578	2.797	2.110	1.582
Total	10.818	5.229	7.490	8.986	9.825	6.707	4.346
500 Mile Stage Length							
Flying Operations	.691	.585	.871	.653	.672	.522	.466
Maintenance (incl. burden)	.523	.362	.720	.499	.543	.387	.316
Depreciation	.807	.608	.912	.639	.712	.528	.396
Total	2.021	1.555	2.503	1.791	1.927	1.437	1.178

* 300 Aircraft, development costs included; 2000 hr/yr utilization; long pattern

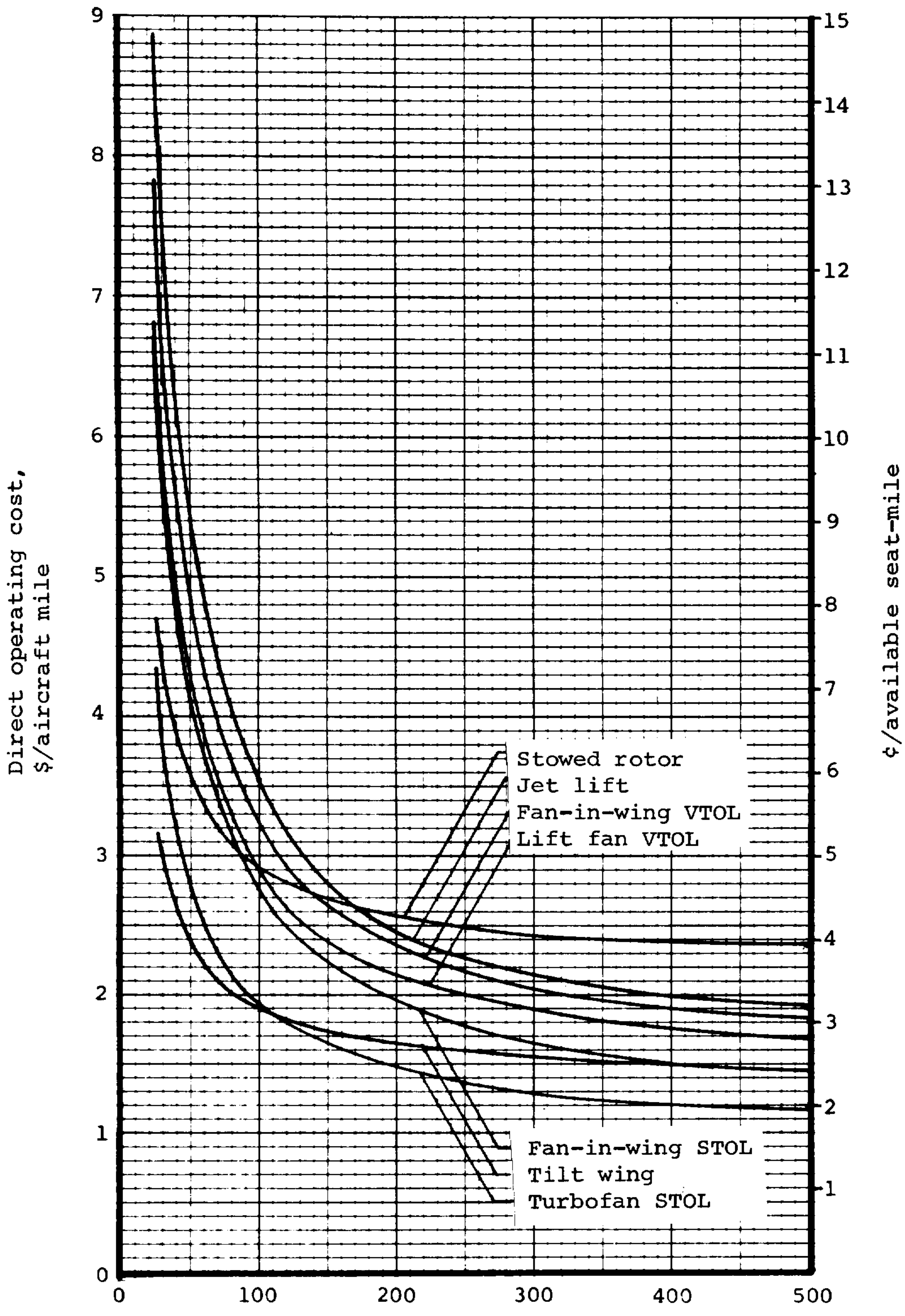


Figure 49. Comparison of Direct Operating Costs Over the Range of Block Distances, STOL Long Range Pattern, VTOL Short Pattern

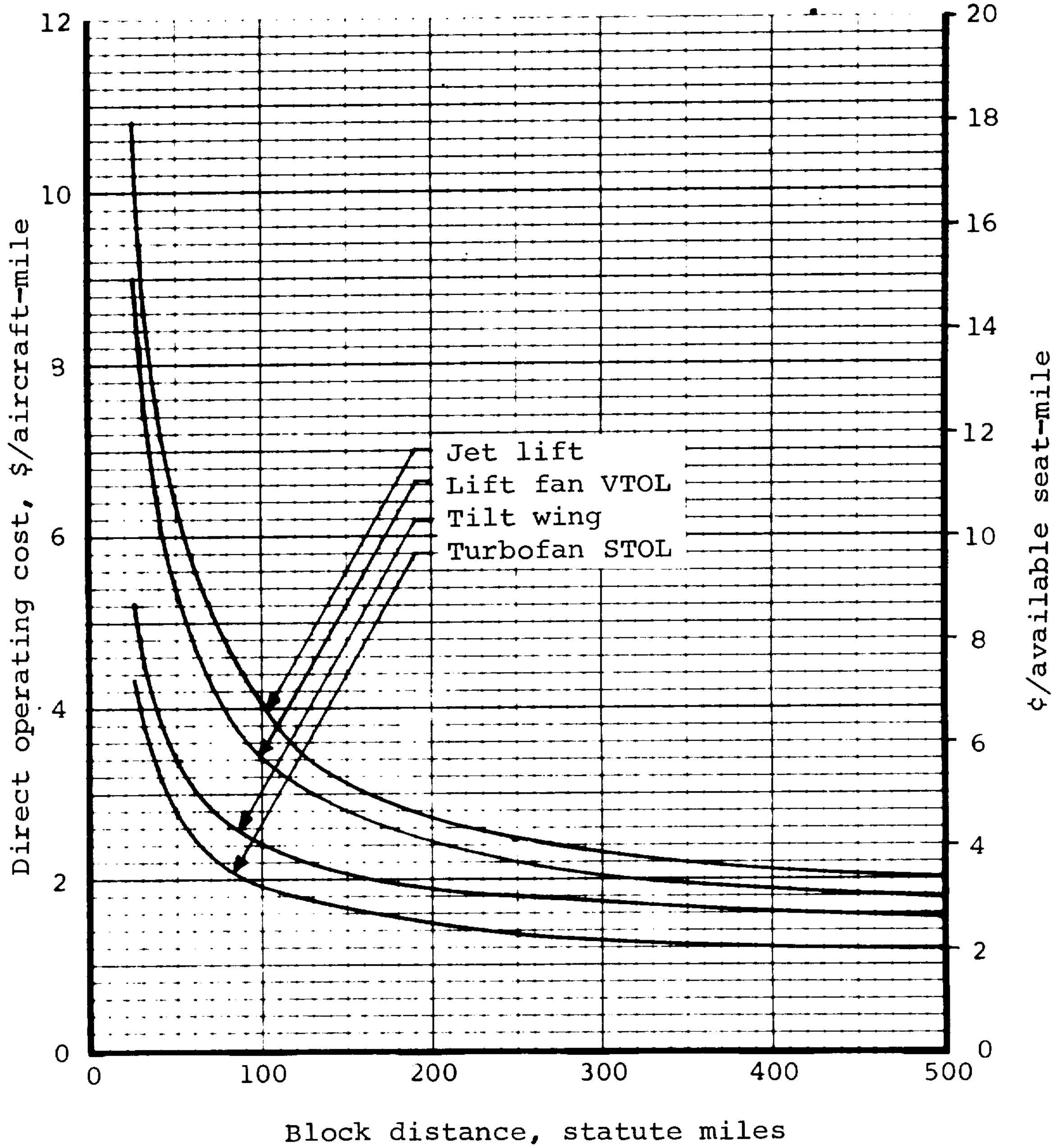


Figure 50. Comparison of Direct Operating Costs of Four Final Configurations Over a Range of Block Distances, Long Pattern

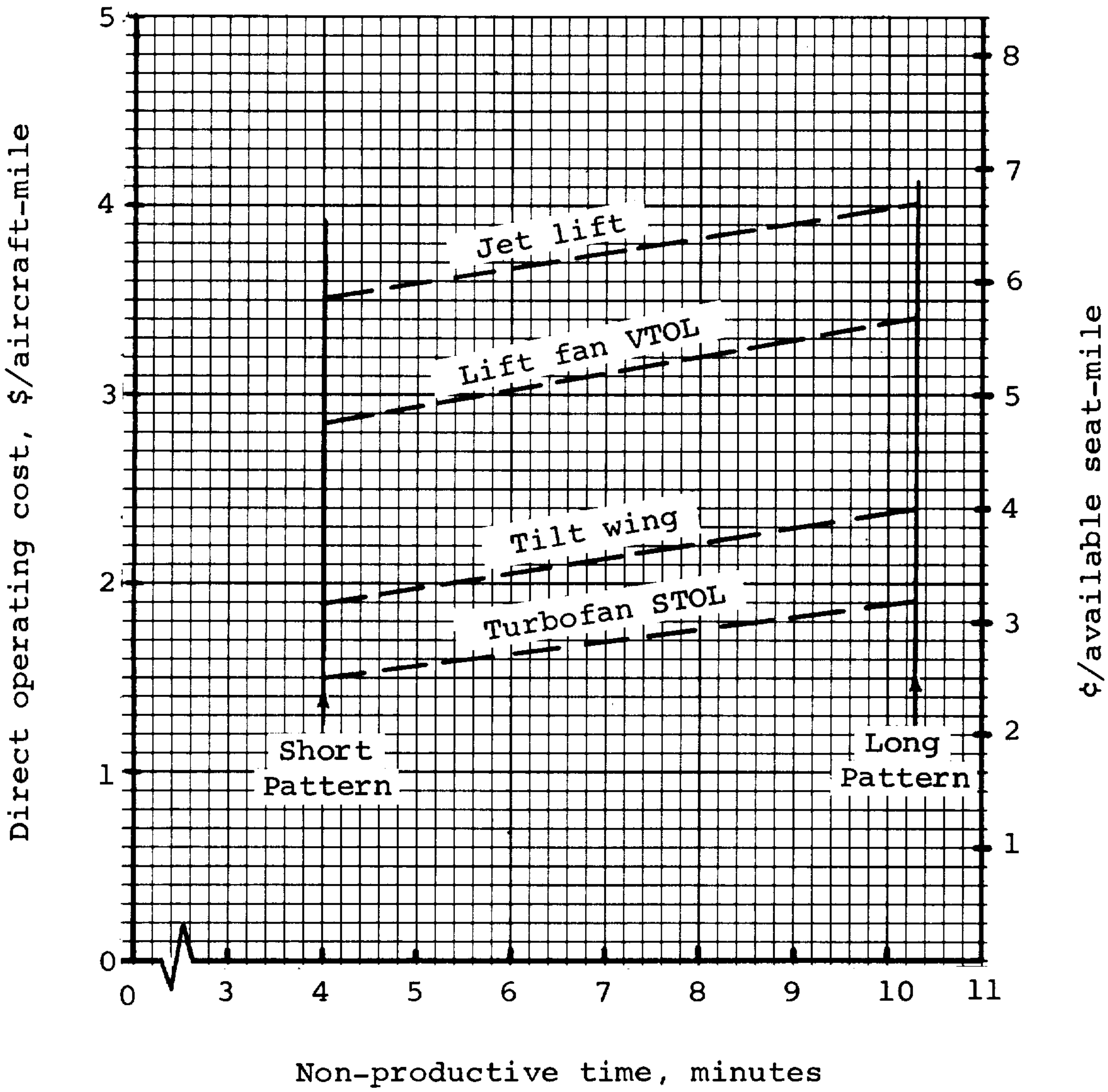


Figure 51. Sensitivity of Direct Operating Cost to Non-Productive Time for 100-Mile Block Distance

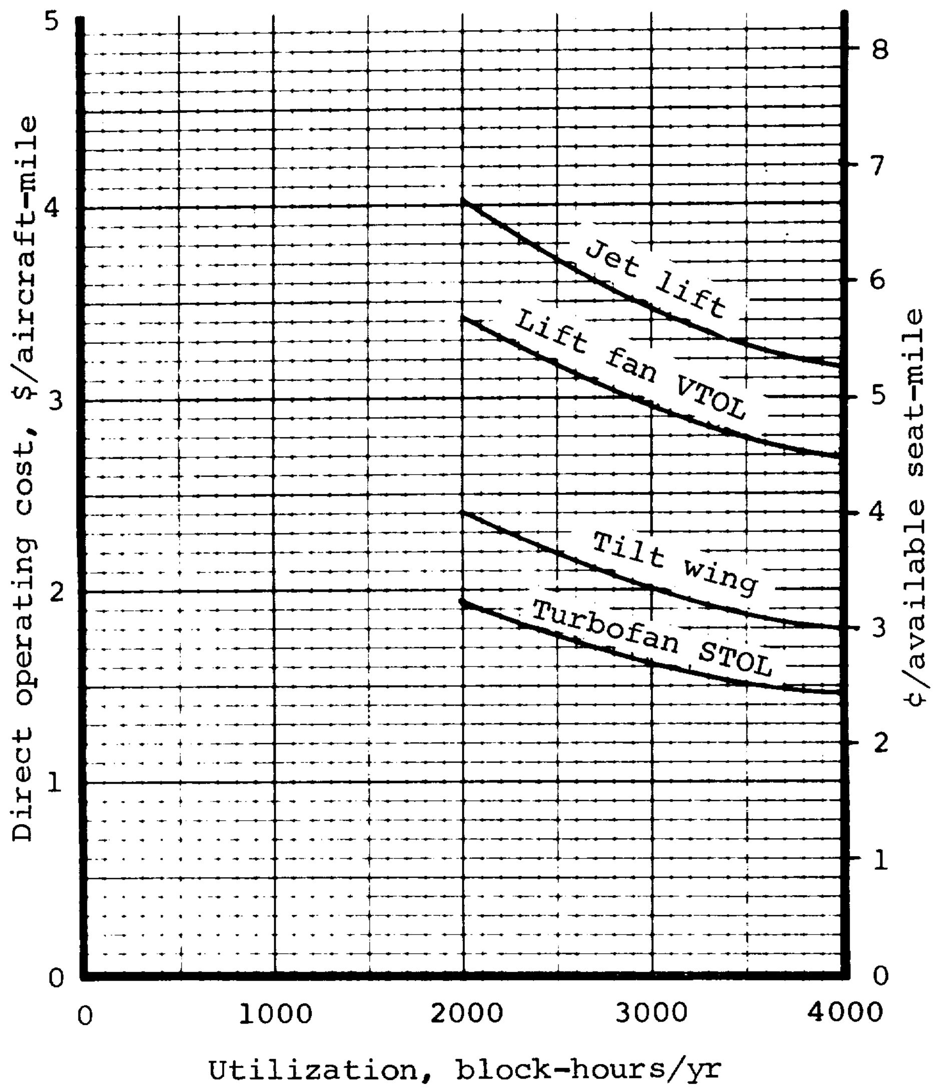


Figure 52. Sensitivity of Direct Operating Cost to Utilization for 100-Mile Block Distance

from 2000 to 4000 hours.

The reduction in direct operating costs resulting from changes in initial price are presented in Figures 53 through 56 for the four final aircraft. DOC's are shown for a production run of 300 aircraft with all development costs included, with engine development costs excluded, and for 600 aircraft with no development costs. It can be seen, especially for the lifting engine concepts, that reduction of engine costs is most important on the short stage lengths, where the lift-engine operating times are the highest percentages of the flight times.

The influence of design changes on DOC are given in the "Design Payload" and "1980 Propulsion Technology" subsections of the "TECHNICAL AND ECONOMIC TRADEOFFS" section, page 144.

HYPOTHETICAL ROUTE

Operation of the four final 60-passenger aircraft on a hypothetical short haul round trip route (Figure 47) is analyzed in Table 18 . The optimized IFR/VFR flight profiles discussed in the "OPERATIONS ANALYSIS" section are used in this operation. Segment and total round trip costs are shown for the 720-mile route.

DOC's for the VTOL's (short pattern) are very near those shown in Figure 49 at the average distance (120 mi.). For the turbofan STOL, the costs are slightly below those of Figure 49 because the optimized profiles reflect changes in non-productive time and point to start distance credit, compared to the basic flight profile. This indicates that for similar non-productive times the DOC over a mixed stage length route structure may be approximated to that on the average stage length. The overall ranking of the aircraft with increasing DOC does not change from that established by the aircraft stage length results.

Reference 7 indicates that direct operating costs of 4.4 cents per seat mile or below will give profitable V/STOL operation. On this basis, over the hypothetical route structure, the turbofan STOL, tilt wing VTOL and lift fan VTOL are economically acceptable and the jet lift VTOL is very nearly acceptable.

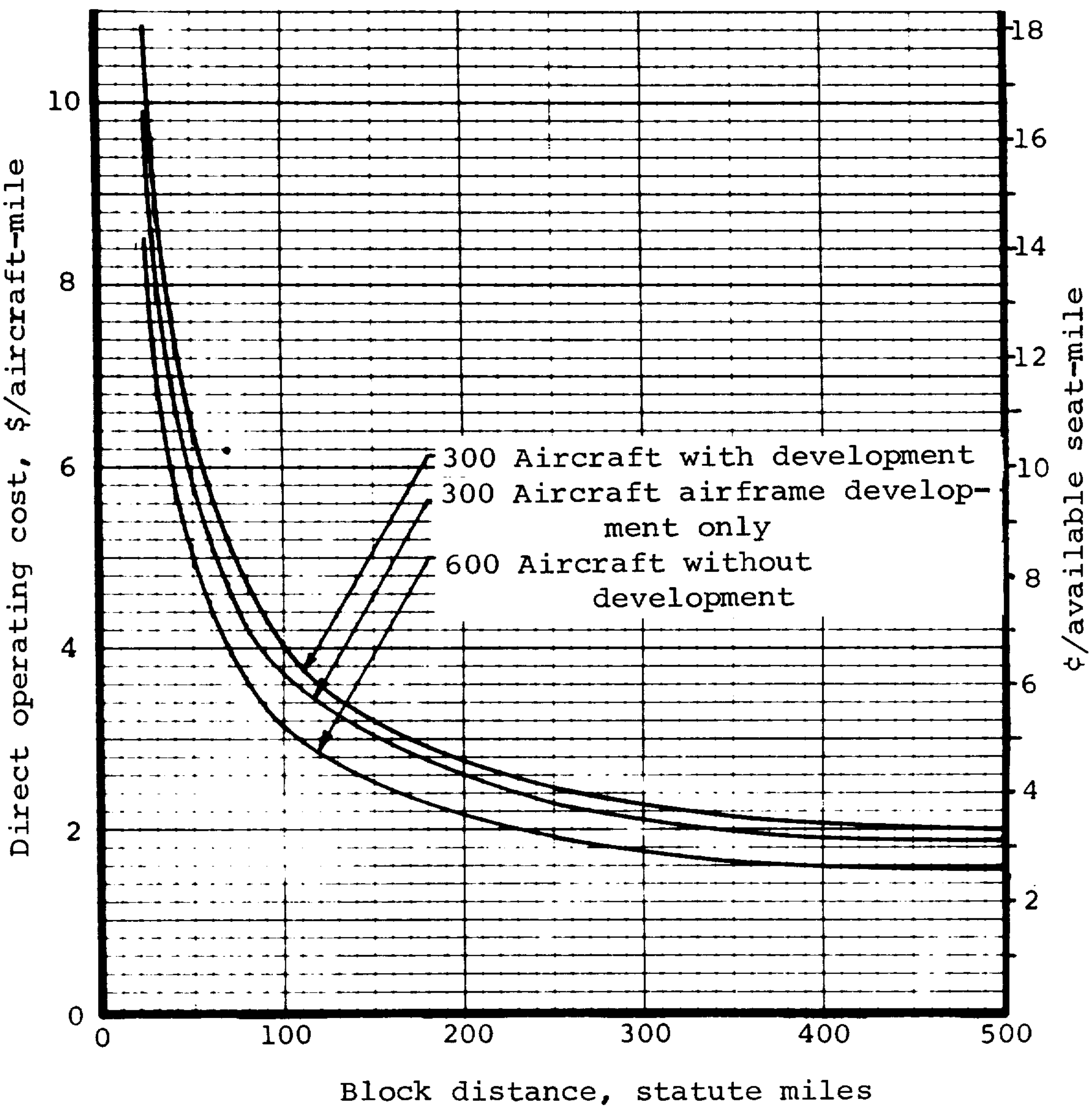


Figure 53. Sensitivity of Jet Lift Direct Operating Costs to Development Costs and Market Size

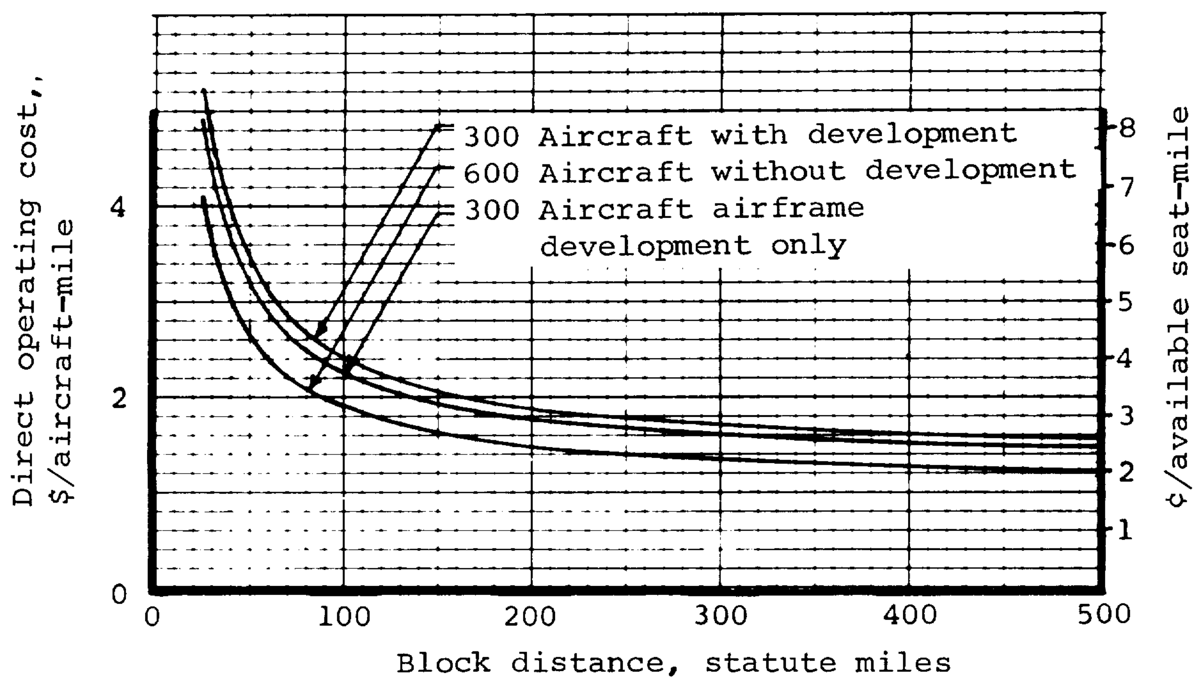


Figure 54. Sensitivity of Tilt Wing Direct Operating Costs to Development Costs and Market Size

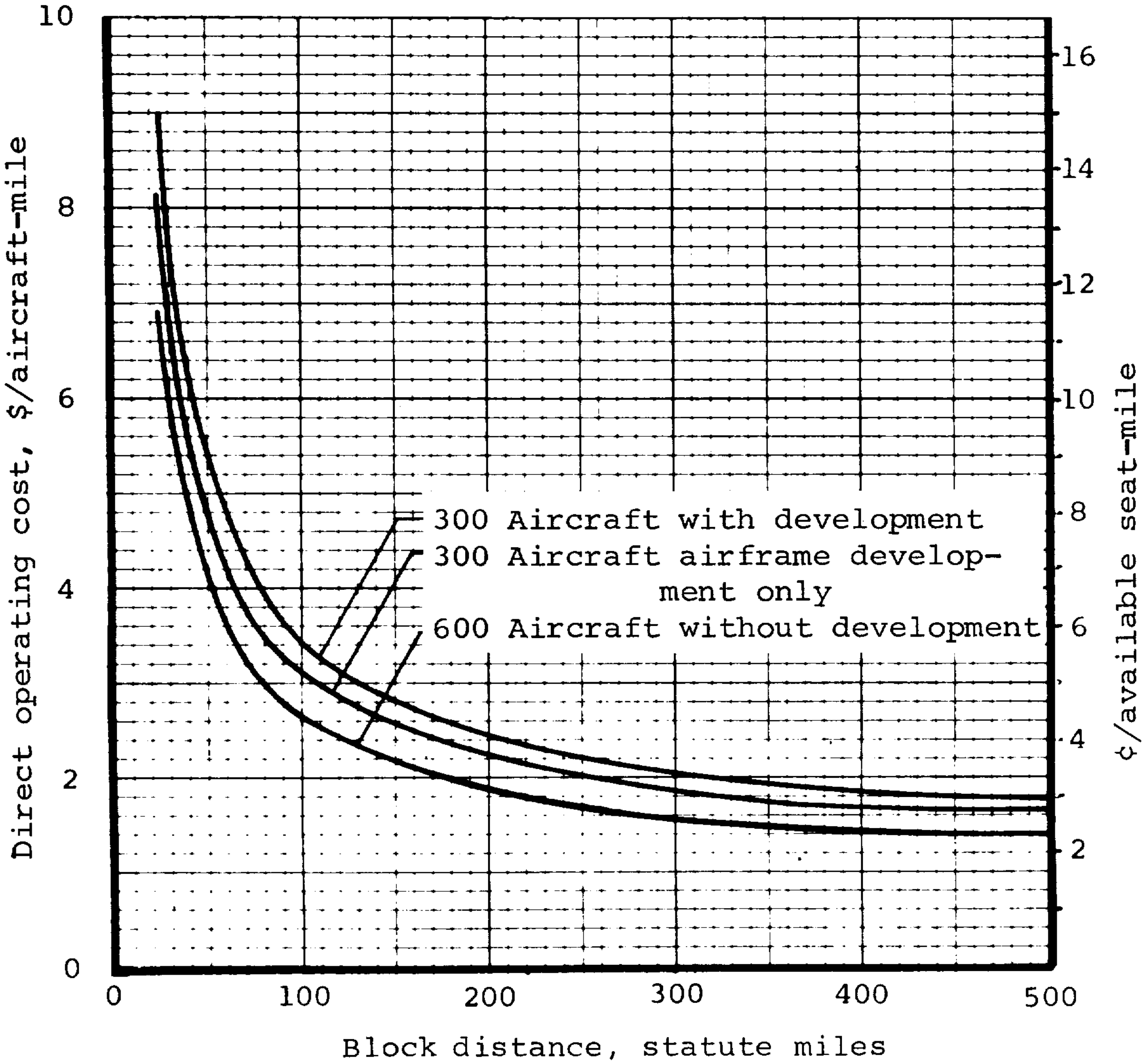


Figure 55. Sensitivity of Lift Fan Direct Operating Costs to Development Costs and Market Size

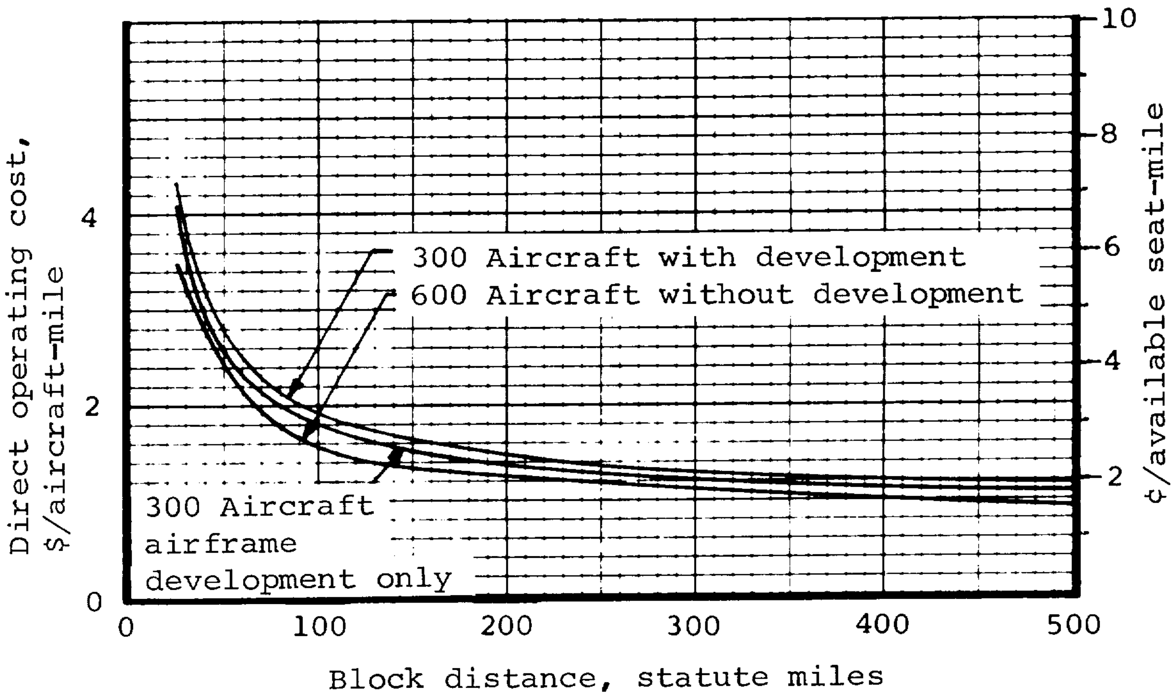


Figure 56. Sensitivity of Turbofan STOL Direct Operating Costs to Development Costs and Market Size

TABLE 18. - DIRECT OPERATING COSTS

SEGMENT	DISTANCE	JET LIFT	TILT WING	LIFT FAN VTOL	TURBOFAN STOL
1	300	$ 650.31	$ 464.76	$ 579.36	$ 362.47
2	50	264.95	117.44	224.86	108.89
3	150	423.99	259.71	269.61	213.65
4	150	426.05	259.74	371.36	214.16
5	35	237.05	94.52	199.14	93.00
6	35	236.67	94.49	198.85	92.93
	720	$2239.02	$1290.66	$1943.18	$1085.10
Average per air-mile $		3.11	1.79	2.70	1.51
Average per seat-mile $		.0518	.0299	.0450	.0251

TECHNICAL RISK AND REQUIRED RESEARCH

Tilt Wing VTOL

The technical feasibility of the tilt wing concept has been firmly established by the three prototypes flown to date. The first tilt wing, the VZ2, was a somewhat crude research aircraft intended to demonstrate the feasibility of the concept. However, it was eventually used to provide tilt wing experience for a large number of pilots. This aircraft was the only one of the early VTOL testbed aircraft with sufficiently good handling qualities to permit such use. The more sophisticated CL-84 and XC-142 aircraft are also successful and their problems are mainly those to which general engineering solutions apply rather than problems particular to the concept.

Major research and development requirements for the tilt wing configuration presented here are confined to the monocyclic pitch control system. Full scale testing is required in hover and low speed flight to determine the limit of control power which can be obtained and to provide complete stress, aerodynamic, and dynamic load data. Full scale propeller hub and control system hardware also need to be developed. This should include the development of all fiberglass propeller blades. The transition performance trim and stability characteristics of the tilt wing are now well understood and future aerodynamic testing will be confined to detailed development of specific configurations. Looking beyond the level of technology represented by the aircraft presented in this report, future research should be directed towards freeing the present dependence of wing size on propeller diameter. This may be accomplished by relative tilting of the propeller thrust axis and wing chord line in order to control stall in transition during descent and deceleration, or boundary layer control may be used for this same purpose. Development of fly-by-wire control systems is of particular interest to the tilt wing configuration. Phasing and mixing of control system functions and transference of control motions across the wing tilt axis could be accomplished electrically at a great weight saving. Such a system would permit any desired level of control breakout forces and stick forces to be incorporated and stability augmentation systems and automatic landing systems could readily be integrated with the control system. Research for future applications should also include investigation of advanced material such as beryllium for transmission system components.

Jet Lift VTOL

The technical feasibility of the jet lift concept has been well established by the many aircraft of this type, which have been flown. These range from the original Rolls Royce Flying Bedstead to the highly successful Hawker P-1127, for which production quantities are under procurement. The VJ-101 aircraft has successfully proven the concept of jet lift control using thrust modulation.

The airframe is for the most part quite straightforward. The required research effort is in the propulsion area. The most pressing need for research is in the area of noise suppression. High noise level is one of the two major barriers to the use of jet lift aircraft for commercial operation. The other major drawback of the type is the potentially high maintenance cost of the lift engines. Thus, engine research is required to develop engines which are reliable when operated in a high frequency operational environment. Research is also required into the aerodynamic interaction between the propulsion system and airframe (i.e., lift loss and stability in ground effect and transition lift, drag, and trim), and in the design of lift engine intakes when the engine's spin axes are normal to the free stream flow. The problems associated with air starting large numbers of lift engines, the lift engine control systems, and the trim changes which may occur when starting lifting systems must be examined. It is desirable to use high bypass ratio cruise engines on jet lift aircraft in order to obtain the maximum hover lift from engines sized for cruise. Therefore, research is required into the design of deflection nozzles suitable for these high-bypass engines. The lift engine must also be developed to ensure response times satisfactory for control via thrust modulation.

Stowed-Rotor VTOL

The stowed rotor aircraft is a comparatively recent development and is the only aircraft considered in this study for which there is no applicable flight research. Some exploratory wind tunnel tests have been made and the concept must be considered to have higher degree of technical risk than any other configuration.

Development of the convertible fan engines is required although this is largely a matter of integrating proven components. The major problem area is, of course, the conversion process. Research must be conducted in the mechanical, dynamic, aerodynamic and stress problems associated with stowing, stopping, and folding the rotor blades and the reverse process of deploying and spinning up the rotors. Stability during the conversion requires investigation and the phasing and mixing of the helicopter and conventional flight control systems must be determined.

Lift Fan VTOL

The flight experience of this type of aircraft is confined to the XV5A aircraft. However, much of the jet lift experience has some application to this type. The General Electric Company has accomplished a considerable amount of hardware development and NASA has generated a considerable body of data on the aerodynamic characteristics of lift fan aircraft.

Like the jet lift the most pressing need for research is in the noise suppression of the deflected cruise and lift fan thrust, and in this case of the bleed and burn control system also. The control turbocompressors and nozzles, lift fans and associated gas generators and the cruise engines deflector nozzles must also be developed, although most of these items are extensions of existing technology. Further configuration development is desirable to reduce propulsion and control system complexity and afford better flexibility and maintainability.

Fan-in-Wing STOL

All of the foregoing remarks on the lift fan VTOL can be applied to this type of aircraft with the exception of those pertaining to the reaction control system. The handling qualities of the aircraft at STOL speeds may also require further research.

Turbofan STOL

This type of aircraft has obviously a lower degree of technical risk than any of the other concept studies. It is similar in all respects to present day turbofan jet transports with the expection of its externally blown flap system. This system has been extensively investigated in wind tunnel test programs. The major research requirements to this type of aircraft are confined to insuring satisfactory stability and control characteristics in the STOL flight regime.

SELECTION OF MOST PROMISING CONCEPTS

The direct operating costs of the 60-passenger aircraft have been compared in Figure 48 and Table 18, the acquisition costs in Table 16, noise in Figures 44 and 45, and gust sensitivity in Figure 46. The weight summaries are compared in Table 19. These factors together with the technical feasibility and required research have been considered in choosing the most promising concepts.

In choosing the most promising concepts the stowed-rotor VTOL was eliminated first because of its high weight, high degree of technical risk, slow speed, complexity, high first cost, and high direct operating cost. It should be pointed out here that,with the exception of the stowed-rotor concept all of the aircraft have a well-defined technical background and the resulting preliminary designs have a fair degree of confidence. Further investigation may not show the stowed-rotor concept in such an unfavorable light. There is an infinite variety of possible approaches to converting a helicopter into a conventional airplane in flight. A significant breakthrough in this area might change the competitive position of this type of aircraft. Further research may show that a conversion speed well above that assumed in this study is possible. This would reduce the required wing size and flap complexity with a corresponding beneficial effect on the aircraft. Further developments in integrated convertible function propulsion systems may also bring improvements.

The tilt wing aircraft was chosen as one of the most promising concepts since it is the smallest and the least costly of the VTOL aircraft to acquire and operate. It is also the aircraft with the least noise problem, at least in

TABLE 19
60 PASSENGER AIRCRAFT - COMPARISON OF GROUP WEIGHTS

	VTOL					STOL	
	JET LIFT	TILT WING	STOWED ROTOR	LIFT FAN	FAN-IN-WING	FAN-IN-WING	TURBOFAN
Rotors	---	---	9 456	---	---	---	---
Wing	7 000	5 250	5 050	5 774	6 560	5 830	5 895
Tails	2 023	1 937	2 300	2 557	3 220	2 120	1 765
Body	10 450	9 620	13 002	11 890	12 100	10 510	9 990
Alighting Gear	3 230	2 775	3 715	3 155	3 465	2 680	2 591
Flight Controls	1 849	4 172	3 375	2 000	2 000	2 000	2 150
Reaction Controls	---	---	---	2 030	3 180	---	---
Powerplant Installation	(18 321)	(15 605)	(19 104)	(15 411)	(18 235)	(8 860)	(7 638)
Cruise Engine and Nacelle Installation	6 482	5 340	9 454	6 775	6 960	5 520	7 273
Lift Engine or Gas Generator Installation	11 319	---	---	2 661	3 620	660	---
Fan and Duct Installation	---	---	---	5 500	7 150	2 300	---
Fuel System	520	350	550	475	505	380	365
Drive System	---	5 310	9 100	---	---	---	---
Propeller Installation	---	4 605	---	---	---	---	---
Auxiliary Powerplant	530	530	530	530	530	530	530
Instruments and Navigation	770	675	675	700	680	680	675
Hydraulics and Electrical	2 505	2 450	2 450	2 450	2 450	2 450	2 450
Electronics	750	750	750	750	750	750	750
Furnishings and Equipment	5 220	5 120	5 120	5 182	5 140	5 140	5 120
Air Conditioning and Anti-icing	1 450	1 370	1 470	1 430	1 410	1 410	1 370
Weight Empty	54 098	50 254	66 997	53 859	59 720	42 960	40 924
Crew and Crew Baggage	520	520	520	520	520	520	520
Unusable Fuel and Oil	175	175	175	175	175	175	175
Engine Oil	120	100	100	100	100	100	100
Passenger Service Items	655	655	655	655	655	655	655
Operating Weight Empty	55 568	51 704	68 447	55 309	61 170	44 410	42 374
Passenger, Luggage and Revenue Cargo	13 200	13 200	13 200	13 200	13 200	13 200	13 200
Fuel	11 990	6 800	12 808	10 720	11 602	7 721	7 250
Takeoff Gross Weight	80 758	71 704	94 455	79 229	85 972	65 331	62 824

the critical near field area on takeoff and landing. The far field noise is higher than the turbofan types but this is of greater importance to military aircraft where detection rather than annoyance is the problem. The tilt wing has the advantage of simple and continuous conversion process which does not require starting or stopping of engines. It is a well-understood concept with much research and development work behind it. These advantages were felt to outweigh the lower cruise speed and higher gust sensitivity of the tilt wing concept.

The turbofan STOL is an obvious choice in view of its small size, relative simplicity, low technical risk, low acquisition and direct operation cost and high speed.

The fan-in-wing STOL was eliminated because its capability is matched by the less complex turbofan STOL for the 2000 foot field length considered in this study. It would, however, be an excellent configuration for STOL distances below 2000 feet.

The lift fan VTOL was chosen as a most promising concept because of its high speed, low gust sensitivity and excellent transition performance, which stems from the lack of trim change with cruise-engine thrust deflection due to the placement of the cruise engine on the center of gravity. The direct operating cost of the lift fan VTOL is substantially less than either the jet lift or stowed rotor and it has a less severe noise problem than the jet lift. It was selected in preference to the fan-in-wing VTOL because of its greater growth potential.

Although the study requirements were to choose three most promising concepts, the jet lift was retained for further study since, although it has two major shortcomings, in the areas of noise and engine maintenance cost, it is attractive in terms of speed, ride qualities, and simplicity (in number of different major VTOL system components if not in absolute number).

TECHNICAL AND ECONOMIC TRADEOFFS

The sensitivity studies described in this section were made on the basic 60-passenger aircraft selected as the most promising concepts. The study of their direct operating costs over the hypothetical route structure has been described in the "DIRECT OPERATING COSTS" section.

Design Payload

The four aircraft chosen as the most promising concepts were resized to accommodate 120 passengers. The revenue payload of ten percent of the passenger payload was retained, and the number of stewardesses was increased to two.

None of the aircraft changed in configuration as a result of the size increase. However, the control system of the lift fan VTOL required burning at the reaction nozzles to meet the control requirements without excessive gas generator and turbocompressor size. This led to the decision to redesign the 60-passenger aircraft with such a system.

The turbofan STOL and jet lift VTOL aircraft did not present any control problems at the higher weight, but there was some concern over the tilt wing aircraft's ability to meet the pitch control requirements without substituting a tail rotor or other system for monocyclic control. However the pitch control requirements can be met by a combination of monocyclic control and stick authority over wing tilt and flap angles, provided that a small amount of translation control can be permitted. Boeing analysis shows that such a control arrangement is desirable.

The general arrangements of the four 120-passenger aircraft are similar to their 60-passenger counterparts shown in Figures 2, 9, 15 and 29 in the "CONFIGURATION DESIGN ANALYSIS" section. The weight summaries of the 60- and 120-passenger versions of the most promising concepts are compared in Table 20 and the general characteristics in Table 21.

The cruise speed of the tilt wing at cruise power is higher than that of the 60-passenger version since it is aerodynamically cleaner and has an installed power dictated by hover requirements. Doubling the number of passengers required a 46 to 48 percent increase in gross weight for the jet types The increase for the tilt wing was 57 percent which indicates a sizing penalty.

Direct operating costs for the 120-passenger versions are shown in Figure 57. Comparisons of DOC's for the 60 and 120-passenger aircraft, shown in Figure 58, indicate the doubling the design payload lowers the seat-mile costs by about 37 percent. The effect of aircraft size on acquisition cost is shown in Table 22.

TABLE 20
COMPARISON OF 60 AND 120 PASSENGER AIRCRAFT GROUP WEIGHTS

GROUPS	VTOL						STOL	
	JET LIFT		TILT WING		LIFT FAN		TURBOFAN	
Number of Passengers	(60)	(120)	(60)	(120)	(60)	(120)	(60)	(120)
Rotors	---	---	---	---	---	---	---	---
Wing	7 000	10 050	5 250	8 119	5 774	9 559	5 895	9 971
Tails	2 023	3 303	1 937	2 854	2 557	3 447	1 765	2 420
Body	10 450	13 832	9 620	13 196	11 890	14 060	9 990	12 440
Alighting Gear	3 230	4 108	2 775	3 900	3 155	4 483	2 591	3 500
Flight Controls	1 849	2 100	4 172	6 130	2 000	2 210	2 150	2 300
Reaction Controls	---	---	---	---	2 030	2 660	---	---
Power Plant Installation	(18 321)	(25 646)	(15 605)	(24 771)	(15 411)	(21 824)	(7 638)	(9 869)
Cruise Engine and Nacelle Instal.	6 482	9 152	5 340	8 166	6 775	9 640	7 273	9 394
Lift Eng. or Gas Generator Instal.	11 319	15 814	---	---	2 661	3 720	---	---
Fan and Duct Installation	---	---	---	---	5 500	7 864	---	---
Fuel System	520	680	350	475	475	600	365	475
Drive System	---	---	5 310	8 802	---	---	---	---
Propeller Installation	---	---	4 605	7 328	---	---	---	---
Auxiliary Powerplant	530	530	530	530	530	530	530	530
Instruments and Navigation	770	770	675	675	700	700	675	675
Hydraulics and Electrical	2 505	2 775	2 450	2 775	2 450	2 775	2 450	2 775
Electronics	750	750	750	750	750	750	750	750
Furnishings and Equipment	5 220	8 438	5 120	8 278	5 182	8 318	5 120	8 258
Air Conditioning and Anti-Icing	1 450	1 595	1 370	1 495	1 430	1 555	1 370	1 495
Weight Empty	54 098	73 897	50 254	73 473	53 859	72 871	40 924	54 983
Crew and Crew Baggage	520	660	520	660	520	660	520	660
Unusable Fuel and Oil	175	175	175	175	175	175	175	175
Engine Oil	120	120	100	100	100	100	100	100
Passenger Service Items	655	750	655	750	655	750	655	750
Operating Weight Empty	55 568	75 602	51 704	75 158	55 309	74 556	42 374	56 668
Pass., Luggage and Revenue Cargo	13 200	26 400	13 200	26 400	13 200	26 400	13 200	26 400
Fuel	11 990	16 964	6 800	10 400	10 720	14 541	7 250	9 943
Takeoff Gross Weight	80 758	118 966	71 704	111 958	79 229	115 497	62 824	93 011

TABLE 21
COMPARISON OF 60 AND 120 PASSENGER AIRCRAFT GENERAL CHARACTERISTICS

	VTOL							
	JET LIFT		TILT WING		LIFT FAN		TURBOFAN STOL	
PASSENGERS	60	120	60	120	60	120	60	120
Physical Data								
Wing								
Area (sq ft)	712	1 030	787	1 200	1 055	1 445	749	1 094
Span (ft)	55	66	79.5	97.2	58.6	75	67	81
Aspect Ratio	4.25	4.25	8.03	7.86	3.20	3.90	6.0	6.0
Sweep at ¼ Chord (Degrees)	Fwd.25	Fwd.25	Zero	Zero	35	30	25	25
t/c (Root) ℄ Fuselage (%)	17	17	18	18	14.5	14.5	13.6	13.6
t/c (Tip) (%)	11	11	9	9	10	10	8.2	8.2
Horizontal Tail Area (sq ft)	186	268	238	310	360	410	180	258
Vertical Tail Area (sq ft)	177	279	178	250	188	240	146	219
Fuselage Length (ft)	80.5	103	79.5	102.75	82.5	106	80	101
Design Cruise Condition								
Cruise Speed (kt TAS)	466	466	380	397	466	466	472	472
Cruise Altitude (ft)	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000
Structural Limits								
V_{MO} (kts EAS)	400	400	390	390	400	400	400	400
M_{MO}	.83	.83	.72	.72	.83	.83	.83	.83
V_D (kts EAS)	450	450	425	425	450	450	450	450
N_{LIMIT}	2.50	2.50	3.09	3.09	2.50	2.50	2.80	2.80
Rotors or Propellers								
Diameter (ft)	-	-	21.05	26.33	-	-	-	-
Number of Blades	-	-	4	4	-	-	-	-
Solidity	-	-	.25	.25	-	-	-	-
Maximum Tip Speed (fps)	-	-	850	850	-	-	-	-
(All Power at Sea Level Standard)								
Cruise Powerplant								
Number	4	4	4	4	4	4	4	4
Maximum Thrust (Ea, lbs)	6 950	9 520	-	-	6 960	10 110	7 500	10 880
Maximum Power (Ea, SHP)	-	-	6 741	10 487	-	-	-	-
Bypass Ratio	3	3	-	-	3	3	3	3
Pressure Ratio	16	20	14	16	20	20	20	20
T_4 (°R)	2 600	2 600	2 600	2 600	2 600	2 600	2 600	2 600
Lift Powerplant								
Number	10	10	-	-	4 Lift Fans	4 Lift Fans	-	-
Maximum Thrust (Ea lbs)	9 970	14 920	-	-	17 600	25 250	-	-
Bypass Ratio	2.5	2.5	-	-	8	8	-	-
Pressure Ratio	7.0	7.0	-	-	-	-	-	-
T_4 (°R)	2 360	2 360	-	-	-	-	-	-

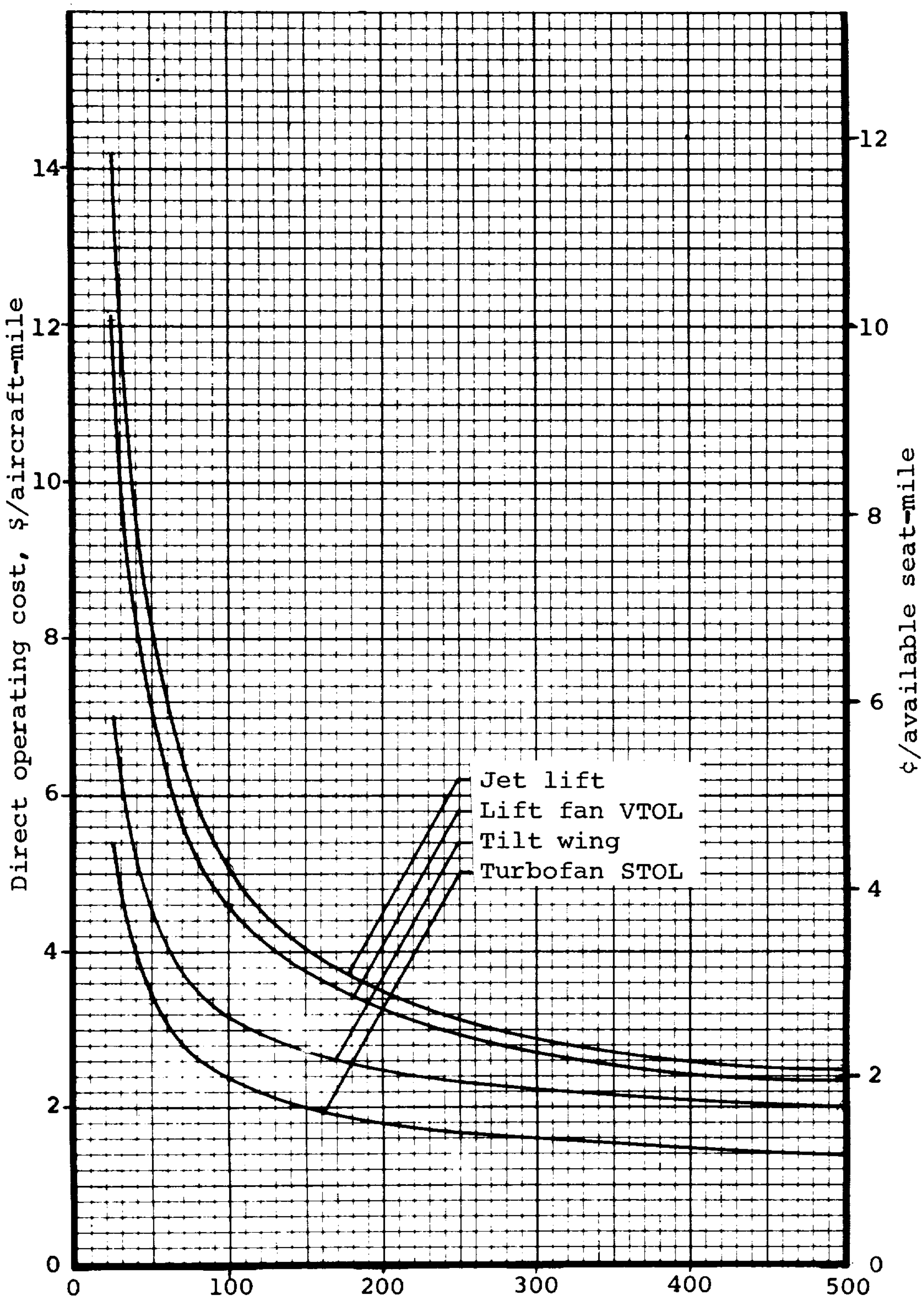


Figure 57. Comparison of Direct Operating Costs of Four 120-Passenger Configurations, Long Pattern

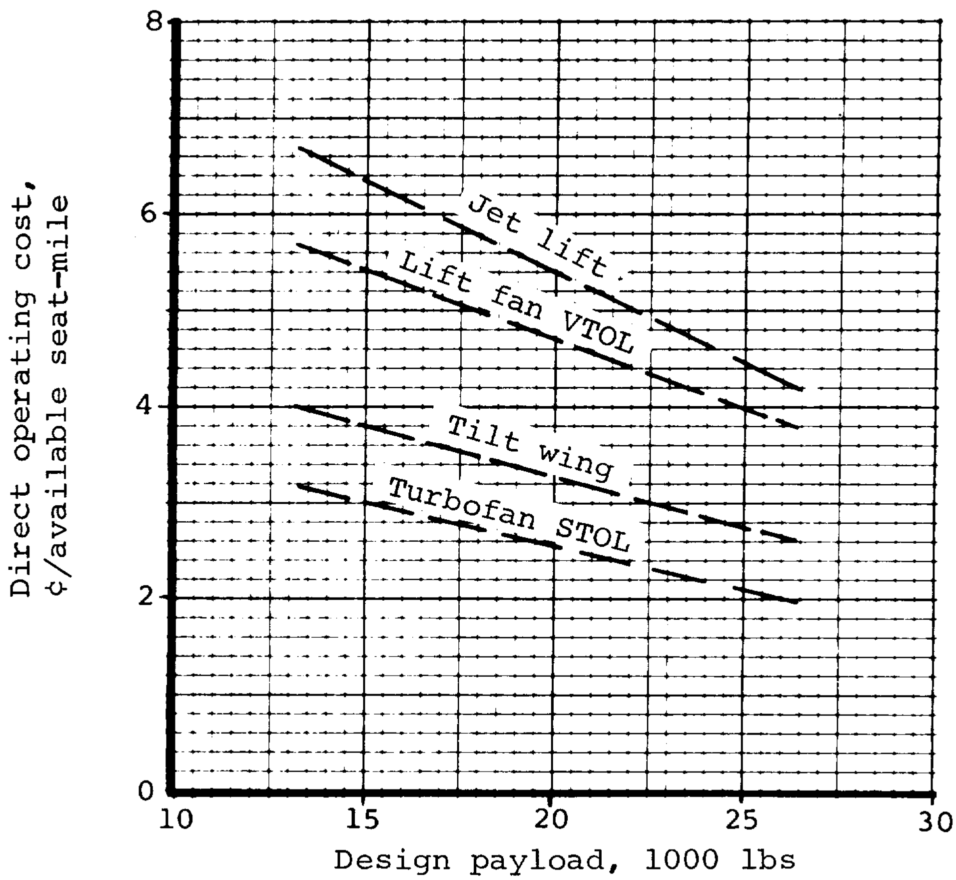


Figure 58. Sensitivity of Direct Operating Cost per Available Seat-Mile to Design Payload for 100 Mile Block Distance, Long Pattern

TABLE 22

COST RELATIONSHIP VS. WEIGHT RELATIONSHIP

60 Passenger vs 120 Passenger

(300A/C Program)

	JET LIFT VTOL	TILT WING VTOL	LIFT FAN VTOL	TURBO-FAN STOL
60 PASSENGER				
WEIGHT:				
Gross	80,758	71,704	79,229	62,824
Empty	54,098	50,254	53,859	40,924
% Empty to Gross	67	70	68	65
RECURRING COST ('000s)	$3,600	$3,100	$3,300	$2,200
120 PASSENGER				
WEIGHT:				
Gross	118,966	111,958	115,497	93,011
Empty	73,897	73,473	72,871	54,983
% Empty to Gross	62	66	63	59
RECURRING COST ('000s)	$4,400	$4,200	$4,300	$2,700
% INCREASE 120 PASSENGER VS 60 PASSENGER				
WEIGHT:				
Gross	47	56	46	48
Empty	37	46	35	34
RECURRING COST	22	35	30	23

This tabulation indicates that the increase in weight empty of the 60 Passenger aircraft ranges from 35% to 46% for the 120 passenger and that the effect of this weight increase, increases the cost from 22% to 35%. The difference of these increases is due to the effect of the application of the regression curves for costing.

The four most promising 60-passenger aircraft have been analyzed to determine the sensitivity of design gross weight to the level of control power provided. The results of this analysis show sensitivity for doubling and halving the required initial angular acceleration rates.

Tilt wing VTOL. - The control power of the tilt wing aircraft can be reduced by decreasing the differential collective pitch and cyclic pitch of the propellers, and by using smaller spoilers and reducing their deflection angles. While the reduced control authority over blade angle might result in lower control loads and the spoiler installation might be slightly lighter, halving the control power does not signifiicantly effect the airplane's size or weight.

Differential collective pitch can be increased to double the control power in roll without a weight penalty. Yaw control can also be increased without a significant weight penalty by augmenting the spoiler system with some downward flap deflection. This was done on the basic 60-passenger aircraft to provide the desired level of control, which is twice the required value. Pitch control could be increased 40 percent by providing large amounts of wing authority on the stick, but doubling the control power would require reconfiguring the aircraft with larger propellers or by changing the control method to tail rotor or other device. To evaluate the effect of the former solution would require extensive tradeoff studies. The latter solution could incur a penalty of some 1500 pounds on gross weight to maintain the same payload and range capability.

Jet Lift VTOL. - The effect of changing control power on this aircraft is simply one of changing the size of the lift engines to suit the new levels of thrust modulation required for control. Doubling and halving the control powers would change the thrust per lift engine from 9950 pounds to 10 800 and 9645 pounds, respectively. The corresponding iterated gross weights are 80 758, 82 500 and 79 540 pounds, respectively.

Lift fan VTOL. - This aircraft requires resized gas generators, turbocompressors, ducting, and reaction nozzles for changes in control power. The tabulation below shows there is relatively little gain realized from reduction of the requirements. This is because the critical control conditions are engine-out cases. However, as the control requirements increase, the critical conditions change and the penalty becomes somewhat more severe. Refer to Table 23.

TABLE 23
Control Accelerations - rad/sec^2

Pitch/Roll/Yaw	.15/.3/.125	.3/.6/.25	.6/1.2/.5
Maximum Thrust			
Pitch nozzles	2520 lb	3190 lb	5850 lb
Roll nozzles	2420 lb	2980 lb	4220 lb
Maximum Nozzle Vector Angle	16.9°	37.4°	44°
Gas Generator Weight	560 lb	560 lb	660 lb
Turbocompressor Weight	150 lb	150 lb	180 lb
Duct Weight			
Turbocompressor	340 lb	340 lb	460 lb
Nozzle Supply	470 lb	530 lb	660 lb
Nozzle Weight	180 lb	230 lb	370 lb
Δ O.W.E.	-110 lb	0 lb	+520 lb
Iterated Design Gross Weight	78 850 lb	79 191 lb	80 800 lb

Turbofan STOL. - Halving the control requirements for this aircraft would merely change the total surface control movements, and no significant weight change would result. Increasing the control requirements would necessitate the installation of a boundary layer control blowing system on all control surfaces. This system would give a weight penalty of approximately 1100 pounds on the gross weight of the aircraft.

1980 Propulsion Technology

The 1980 state of the art in propulsion technology is a matter of considerable conjecture, but definite trends may be observed in turbomachinery design. The maximum turbine inlet temperature will increase, resulting in increased specific thrust (thrust/airflow) or a smaller engine for the same thrust requirement. This will increase the takeoff thrust specific fuel consumption for the cruise fan engine, although the thrust SFC at altitude cruise conditions increases only slightly. The engine pressure ratio will increase, resulting in a decreased specific fuel consumption, but only a minor effect on output specific thrust because of the increase in compressor power. For the turbofan engine, an increase in bypass ratio (fan air/primary air) is possible, which results in a substantial thrust increase at takeoff, a lesser increase at cruise, but an increase in engine weight.

Relatively minor changes in component efficiencies may be anticipated in projecting the engine technology in 1980. Turbomachinery design now provides compressor polytropic efficiency of 90 percent, turbine adiabatic efficiency of 91 percent, burner efficiency of 98 percent, and fan efficiency of 85 percent, which suggests limited possibilities for improvement in the future. Rather, the emphasis will be on increasing the performance of each stage of each component and, consequently, reducing engine weight.

Increased turbine inlet temperature. - Analysis of production and study engine specs, Boeing correlations, and a general knowledge of cooled-turbine technology, would seem to confirm that 2140°F (2600°R) is a suitable estimate of 1970 turbine technology (first delivery of prototype engines in 1970), and that 2740°F (3200°R) is a reasonable estimate of the 1980 state of the art.

The increased specific thrust resulting from this increase in turbine inlet temperature permits a smaller engine for the same thrust requirement. Offsetting this weight saving is an increase in engine weight due to the higher turbine inlet temperatures, but the net result is approximately a 7-percent decrease in engine weight.

The higher turbine inlet temperature results in an increased specific fuel consumption at the takeoff rating and a smaller increase in thrust at the altitude cruise condition. The net effect of this increased thrust is a 3 percent increase in specific fuel consumption due to the change in turbine inlet temperature.

Increased engine pressure ratio. - Improvements in compressor technology which are indicated by extrapolating the present generation of development engines with transonic stages to moderately higher stage pressure ratios result in increased pressure ratio compressors with a reduced number of stages for 1980 engines. Engine pressure ratio is limited only by the size of the blades in the latter stages of the compressor, then. The size of the T64 compressors' rear stage has been used as an arbitrary limit since the polytropic efficiency of the T64 compressor is approximately .9. For the larger thrust engines, an engine pressure ratio of 28 is indicated in 1980 state of the art engines.

At the anticipated turbine inlet temperature of 2740°F (3200° R), an increase in engine pressure ratio from 20 to 28 increases the specific thrust, which decreases engine weight 8 percent and specific fuel consumption about 12 percent.

Increased bypass ratio. - An increase in bypass ratio for the turbofan engine would result in an improved thrust specific fuel consumption and a decreased weight of fuel. To offset this, however, the engine weight, and hence the aircraft weight, would increase, producing a larger thrust requirement and a greater increase in engine weight. Increased bypass ratio would be of questionable benefit for a limited range, high subsonic cruise aircraft.

State of the art improvements. - Reference 4 proposed a 4-percent decrease in weight per year to account for improvements in material and design refinements, based on correlation of more than 40 production and study turbofan and and turbojet engines. This correlation is valid to 1970. From 1970 to 1980, improvements in materials technology includes the use of lighter materials such as titanium and beryllium for compressors and shafts. With minimum improvements in materials in the hot end, a weight saving of 16 percent seems reasonable for 1980 engines.

Conclusions. - These improvements in propulsion technology are expected to reduce the weight of the cruise engines by 29 percent.

Although the anticipated increases in component efficiencies are negligible, a 10-percent decrease in specific fuel consumption is to be expected from the higher engine pressure ratio, which offsets the effect of higher turbine inlet temperature.

The changes in design gross weight of the four 60-passenger most promising concepts due to those engine technology improvements have been assessed. The following assumptions have been made:

1. The 29-percent decrease in engine weight and 10-percent improvement in specific fuel consumption would be achieved for the lift propulsion systems.

2. The tilt wing propellers would decrease in weight by 10 percent due to improved design and materials

3. Transmission system weights would decrease 10-percent, because of material improvements increasing allowable gear tooth pressures and allowable stresses generally.

The resulting design gross weights are as follows:

	1970	1980
1. Tilt wing VTOL	71 704	64 450
2. Jet lift VTOL	80 758	68 490
3. Lift fan VTOL	79 191	66 970
4. Turbofan STOL	62 824	57 550

It can be seen that the jet and lift fan VTOL types have the greatest potential gains for the projected technology improvements.

The powerplant sizes and costs, airframe costs, fuel flows, and other data required to calculate direct operating costs were determined, using cost trend curves and scaling factors similar to those described before. The reductions in direct operating costs achieved by designing for 1980 technology are presented in Table 24 and compared with the 1970 technology aircraft. As would be expected the jet lift and lift fan aircraft derive more benefit from improved propulsion technology than the tilt wing and turbofan STOL.

TABLE 24
EFFECT OF 1980 ENGINE TECHNOLOGY
ON DIRECT OPERATING COST, LONG PATTERN

Statute miles	Aircraft	DOC $ per aircraft mile 1970	DOC $ per aircraft mile 1980	Ratio 1980/1970
25	Jet Lift VTOL	10.82	9.72	.898
	Tilt Wing VTOL	5.23	4.92	.941
	Lift Fan VTOL	8.99	8.14	.905
	Turbofan STOL	4.33	4.16	.961
100	Jet Lift VTOL	4.02	3.61	.898
	Tilt Wing VTOL	2.41	2.27	.942
	Lift Fan VTOL	3.42	3.10	.906
	Turbofan STOL	1.92	1.84	.958
500	Jet Lift VTOL	2.02	1.81	.896
	Tilt Wing VTOL	1.56	1.46	.936
	Lift Fan VTOL	1.79	1.63	.911
	Turbofan STOL	1.18	1.13	.958

The effect of this technological tradeoff on the acquisition costs, less spares in a 300 aircraft program is given in Table 25.

TABLE 25
EFFECT OF 1980 ENGINE TECHNOLOGY ON ACQUISITION COSTS

AIRCRAFT	1970	1980	
Jet Lift VTOL	$4.6 million	$4.1 million	(89%)
Tilt Wing VTOL	4.1	3.8	(93%)
Lift Fan VTOL	4.5	4.1	(91%)
Turbo-Fan STOL	2.9	2.8	(97%)

Austere Approach

The ground rules of this study were not conducive to low direct operating costs, especially at low stage length. The aircraft were required to be self-supporting, have the conveniences associated with current commercial aircraft, carry fuel for conventional approach and landing patterns, and be designed for the not-so-short stage length of 500 statute miles. Despite these requirements, the operating costs are no higher than those of current transport helicopters at 25 miles stage length, and little greater than conventional short haul transports at the longer stage lengths. However, these costs must be reduced if air transport is to compete with surface travel in the short-haul intercity market.

Therefore the design requirements must be scrutinized closely. It has become customary for short-haul aircraft to be self-supporting. However, conventional aircraft only require two to three pounds of thrust for every ten pounds of weight added. The VTOL requires about twelve pounds. Such items as stairs, auxiliary power units, and air conditioning could be built into landing pads without affecting turnaround time, and VTOL aircraft need not carry galleys, multiple toilets, or deluxe furnishings. Fuel requirements can be tailored for the short approach and landing patterns of which the VTOL is capable. A go-around fuel reserve is probably not required. VTOL aircraft can make final approach adjustments at very low speeds. Applying this philosophy, the design gross weight of the tilt wing aircraft in this study could be reduced from 71 704 pounds to 56 500 pounds for the same payload and range, with corresponding reductions in direct operating cost of approximately 20 percent.

The group weight summaries and general characteristics of the 60-passenger tilt wing designed to the study ground rules and those of the austere aircraft are compared in Tables 26 and 27, respectively. The specific changes reflected in this table are:

1. Deletion of airstairs and auxiliary power unit

2. Deletion of cargo hold (six passengers substituted to maintain payload)

TABLE 26

TILT WING VTOL

EFFECT OF AUSTERE DESIGN PHILOSOPHY ON GROUP WEIGHTS

Weights	STUDY GROUND RULES	AUSTERE APPROACH
Rotors	-	-
Wing	5 250	3 950
Tail	1 937	1 580
Body	9 620	7 100
Alighting Gear	2 775	1 977
Flight Controls	4 172	3 200
Reaction Controls	-	-
Powerplant Installation	(15 605)	(12 100)
Engine Section - Cruise - Lift	1 250	1 000
Engine Installation - Cruise - Lift	3 820	3 030
Lift Gas Generators	-	-
Drive System	5 310	3 900
Fuel System	350	300
Engine Controls	100	80
Starting System	170	130
Propeller Installation	4 605	3 660
Auxiliary Power Unit	530	-
Instruments and Navigation	675	650
Hydraulics Electrical	2 450	1 992
Electronics	750	750
Furnishings and Equipment	(5 120)	(3 054)
Flight Provisions	515	332
Passenger Accommodations	3 838	2 428
Cargo Handling	473	-
Emergency Equipment	294	294
Air Conditioning and Anti-icing	1 370	1 370
Weight Empty	50 254	37 723
Crew and Crew Luggage	520	520
Unusable Fuel and Oil	175	175
Engine Oil	100	100
Passenger Service Items	655	110
Operating Weight Empty	51 704	38 628
Passengers and Luggage	12 000	12 000
Revenue Cargo	1 200	1 200
Fuel	6 800	4 700
Takeoff Gross Weight	71 704	56 528

TABLE 27

TILT WING VTOL

EFFECT OF AUSTERE DESIGN PHILOSOPHY ON GENERAL CHARACTERISTICS

	TILT WING VTOL	66 PASSENGER AUSTERE TILT WING
Physical Data		
Wing		
Area (sq ft)	787	626
Span (ft)	79.5	71
Aspect Ratio	8.03	8.05
Sweep @ ¼ Chord (degrees)	0	0
(t/c) Root ℄ Fuselage	.18	.18
(t/c) Tip	.09	.09
Horizontal Tail Area (sq ft)	238	136
Vertical Tail Area (sq ft)	178	178
Fuselage Length (ft)	79.5	76
Design Cruise Conditions		
Cruise Speed (kt TAS)	380	380
Cruise Altitude (ft)	30 000	30 000
Structural Limits		
V_{MO} (kts EAS)	390	390
M_{MO}	.72	.72
V_D (kts EAS)	425	425
N_{LIMIT}	2.9	2.9
Rotors or Propellers		
Diameter (ft)	21.05	18.8
Number of Blades	4	4
Solidity	.25	.25
Maximum Tip Speed (fps)	850	850
Cruise Powerplants		
Number	4	4
Maximum Power/Engine (ESHP)	6740	5270
Bypass Ratio	-	-
Pressure Ratio	14	14
T_4	2600°R	2600°R

3. Deletion of galley and one of the two washrooms

4. Substitution of ultra-lightweight seats and a generally austere approach to other furnishings. However, soundproofing was not changed.

5. Reduction of fuel by eliminating go-around fuel reserve and tailoring approach and landing fuel to the revised pattern shown in Figure 32. Taxi fuel was also eliminated.

AIRWORTHINESS REQUIREMENTS

V/STOL airworthiness standards can be defined by minor modifications and additions to the airplane and rotorcraft transport category standards. However, since the aircraft in question have a strong resemblance (in physical shape) to conventional wing-body-tail airplanes, the comments contained herein will be suggested revisions to FAR part 25 (although a large percentage of the revisions are derived from FAR part 29) and will be presented in a paragraph-by-paragraph description.

FAR 25.33 Propeller Speed and Pitch Limits

(c) The low pitch blade stop, or other means used to limit the low pitch position of the propeller blades, must be set so that the engine speed does not exceed 103 percent of maximum allowable engine r.p.m. with -

(1) The propeller blades at the low pitch limit and governor inoperative; and

(2) Takeoff manifold pressure with the airplane stationary under standard atmospheric conditions.

It is suggested that a provision for secondary pitch control to allow for low angles normally used for VTOL propellers be incorporated. This requirement arises from the takeoff situation of a VTOL aircraft, namely that the VTOL must be capable of developing full power and keep the T/W ratio less than 1. In this situation, the pilot must be able to keep the aircraft in static trim both vertically and longitudinally.

FAR 25.105 Takeoff

(a) The takeoff speeds, accelerate - stop distance, and takeoff path, must be determined.

(2) In the selected configuration for takeoff.

(b) No takeoff, made to determine the data required by the section, may require exceptional piloting skill or alertness.

Fixing the configuration with constant flap position and power setting may tend to compromise VTOL operation, and, therefore, another sub-heading covering V/STOL aircraft takeoff operations should be written.

FAR 25.107 Takeoff Speeds

Minimum control speed, V_{MC}, must not exist for VTOL aircraft. This section, or a separate and distinct section, requires definition of a critical decision point whereby the pilot can either abort the takeoff and stop safely in the takeoff area or continue the takeoff with one engine out when the critical engine becomes inoperative. This requirement is related to the definition of the engine out height-speed diagram for rotorcraft.

FAR 25.121 Climb: One Engine Inoperative

This section covers performance with the engine out, propeller either stopped or windmilling, but there should also be some consideration for the effects of engine out when the propellers are cross-shafted whereby the propeller would still be delivering thrust. Also, this would be an appropriate section to mention limiting high-speed envelopes as per FAR part 29. If there is any combination of height and forward speed (including hover) under which a safe landing cannot be made, a limiting height-speed envelope must be established for that condition.

FAR 25.111 Takeoff Path

This is another appropriate section for mention of the height-speed envelope and also for clarification of takeoff speeds, configuration, and order of operation in the STOL and VTOL modes. For example:

(a) (2) The airplane must be accelerated on the ground to V_1 at which point the critical engine must be made inoperative and remain inoperative for the rest of the takeoff.

(b) During the acceleration to V_2, the nose gear may be raised off the ground at a speed not less than V_r.

(c) (2) The airplane must reach V_2 before it is 35 feet above the takeoff surface and must continue at a speed as close as practical to, but not less than V_2, until it is 400 feet above the takeoff surface.

(c) (4) Except for gear retraction and propeller feathering, the airplane configuration may not be changed until the airplane is 400 feet above the takeoff surface.

This paragraph and the subheadings which stipulate that the segments of the takeoff path must be clearly defined in terms of configuration changes, etc. would have to be completely rewritten for STOL and VTOL operations.

FAR 25.173 Static Longitudinal Stability

The requirements in paragraph .173 should exist above a defined transition speed (V_{tr}), and below V_{tr} should delete reference to elevator but retain the stick force/knot requirement. For these requirements a V_{tr} would have to be defined in some way, possibly by a height-speed envelope. Thus for VTOL aircraft below V_{tr}:

(1) A rearward movement of the control is necessary to obtain airspeeds less than trim speed; and

(2) A forward movement of the control is necessary to obtain airspeeds greater than trim.

There should be a required minimum airspeed increment from trim per unit stick force during transition and hover.

FAR 25.337 Maneuvering Loads

The maneuvering envelope must be extended to cover speeds between hover and V_{stall}, and possibly beyond where the load factor caused by the lifting thrust is greater than the aerodynamic lift. Suggested limitations might be as per FAR part 29, which stipulates rotorcraft must be designed for a limit maneuvering load factor of 3.5 and -1, or 2 and -.05 if it can be shown that the probability of exceeding the lesser limits is very small because of inherent design features.

In the case of pure VTOL mode, and some instances of STOL where the lifting thrust axis moves independently of the fuselage axis, it would be necessary to include a limit maneuvering envelope for axial as well as normal load factor. For instance, in the case of a tilt wing aircraft the pilot may accelerate forward by changing wing incidence, or he may decelerate to a stop in the same manner.

FAR 25.341 Gust Loads

Here, as in the preceding section on maneuver loads, provisions must be made for loads in the hover mode and for velocities from zero (0) to V_{stall}. For the hover mode, rotorcraft must be designed to withstand loads resulting from horizontal and vertical gusts of 30 feet per second, but for speeds greater than zero the aircraft requirements are more stringent.

FAR 25.925 Propeller Clearance

FAR part 25 stipulates that there must be at least one inch between the blade tips and the airplane structure, plus any additional clearance necessary to prevent harmful vibration. This requirement, however, may tend to compromise VTOL configuration utilizing the principle of the ducted fan where tip clearances less than one inch may be needed for optimum performance.

FAR 25.1121 Exhaust System

For V/STOL aircraft, there is a strong possibility that there may be a hot air ducting system passing through the fuselage contour connecting the extremities of the aircraft; i.e., wing to wing, nose to tail, and/or wing to nose and tail. Under these circumstances a paragraph should be included covering the ability of these ducts, within the fuselage contour, to resist rupture and retain hot air under the inertia forces prescribed for the emergency landing conditions in 25.561.

FAR 25.1149 Propeller Speed and Pitch Control

(a) There must be a separate propeller speed and pitch control for each propeller.

For VTOL configurations, it may not be necessary to have separate propeller speed and pitch controls if the propellers are interconnected. However, separate pitch trim for each propeller will be required.

(b) The propeller speed and pitch controls must be to the right of, and at least one inch below, the pilot's throttle controls.

For VTOL configurations which incorporate the left hand flight control, this section is not applicable since it spells out the location of the propeller speed and pitch controls must be on a center mounted pedestal. Also, for cross-shafted prop VTOL configuration declutching may be required for propeller failure and feathering.

CONCLUSIONS AND RECOMMENDATIONS

The study has shown that, from the vehicle technology standpoint, commercial V/STOL short haul transportation is feasible in the early 1970's. Furthermore, development of such vehicles does not require any technological breakthrough. The required research and development will be based on extension of present technology.

The direct operating costs predicted in the study are within the realm of economic acceptability. The costs predicted on the hypothetical route structure, which give the most meaningful yardstick of economy, range from 2.51 to 5.18 cents per available seat-mile for an average stage length of 120 statute miles. Reference 7 indicates that costs below 4.4 cents per available seat-mile will result in profitable operation.

It is concluded that the most promising types of aircraft among those studied are the Turbofan STOL and the Tilt Wing, Lift Fan and Jet Lift VTOL concepts. The other two concepts studied were the Fan-in-Wing STOL and Stowed Rotor VTOL. The Fan-in-Wing STOL was not considered inferior to the types mentioned above, but more suited to shorter balanced field lengths than the 2000 foot distance stipulated in the study ground rules. The Stowed Rotor design was less promising than the other types. However, this concept is a comparatively recent development and further research may improve its competitive position.

It cannot be emphasized too strongly that reduction in noise propagation is the key to acceptance of V/STOL aircraft into commercial operations. Therefore noise reduction of V/STOL systems, and to a lesser extent of turbofan engines for STOL operation into city center or suburban areas, is the most urgent and important item of research.

Further work is required into the optimization of V/STOL short haul transport with respect to range, reserves, degree of equipment and furnishing austerity and payload requirements. The results of such optimization could well be a substantial reduction in direct operating cost at low stage lengths.

Vertol Division,
The Boeing Company
Morton, Pennsylvania, May 6, 1966

Drag Data

The drag data developed in this study is summarized by Figure 59, Table 28, and Table 29.

Stability Augmentation Requirements

An assessment of the requirements for stability augmentation systems in the various aircraft studied was made, based on experience with the VTOL aircraft flown to date. Obviously a considerable amount of work involving simulation would be needed to make a proper assessment of these requirements, but outlined below is a first-order estimate:

	Roll	Pitch	Yaw
Tilt Wing VTOL	**	**	*
Jet Lift VTOL	**	**	*
Stowed Rotor VTOL	**	**	**
Lift Fan VTOL	**	**	*
Fan-in-Wing VTOL	**	**	*
Fan-in-Wing STOL	--	--	*
Turbofan STOL	--	--	*

* Single SAS system
** Dual SAS system with triplicated sensors and majority vote system

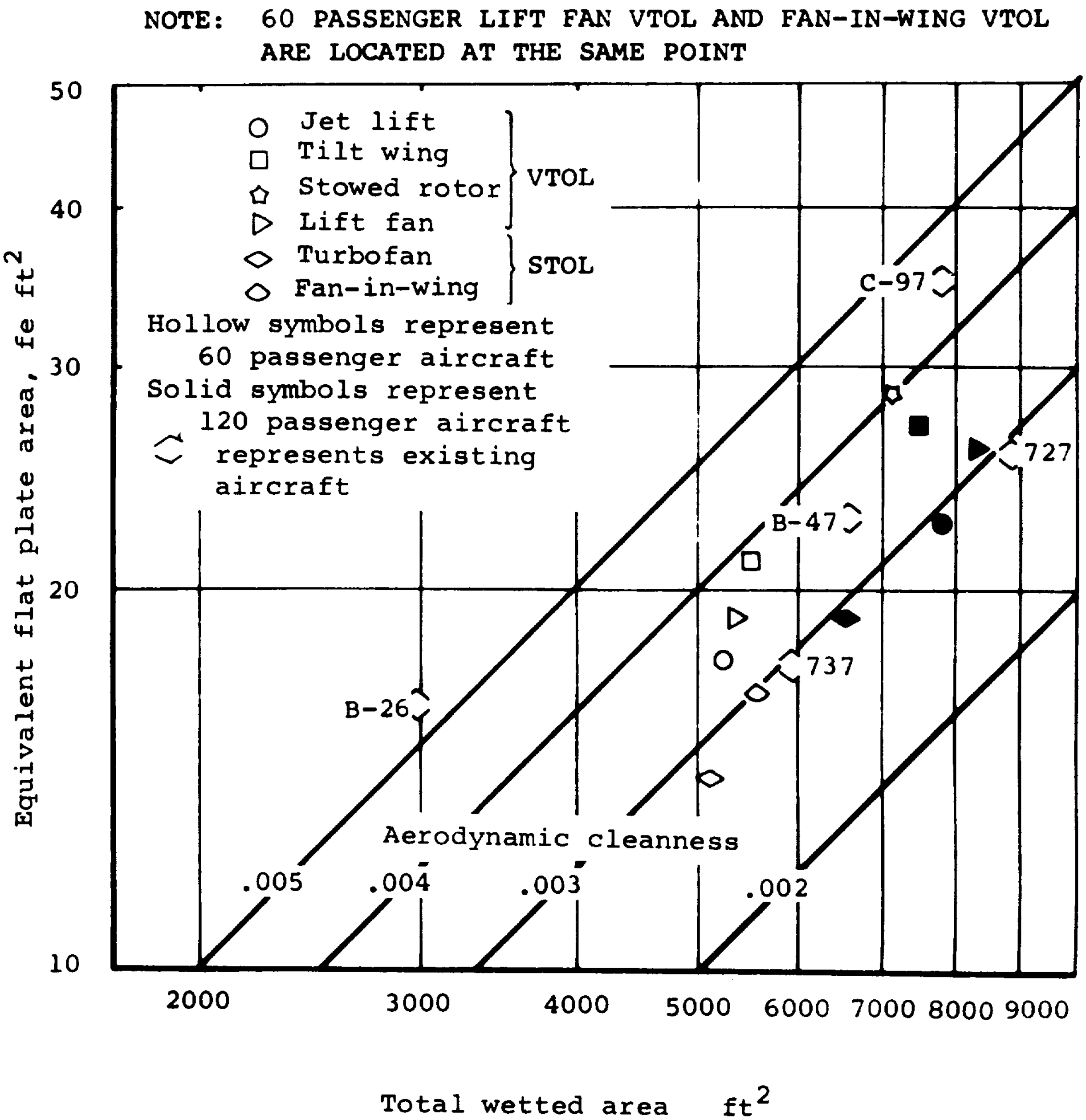


Figure 59. Comparison of Total Equivalent Flat Plate Area

TABLE 28

EQUIVALENT FLAT PLATE DRAG AREA COMPARISON (fe) FT^2

	60 PASSENGER							120 PASSENGER			
	JET LIFT VTOL	TILT WING VTOL	STOWED ROTOR VTOL	LIFT FAN VTOL	FAN-IN-WING VTOL	FAN-IN-WING STOL	TURBOFAN STOL	JET LIFT VTOL	TILT WING VTOL	4-FAN VTOL	TURBOFAN STOL
Body	6.031	7.73**	8.03	8.74	8.79	6.432	6.65	8.55	8.92**	10.69	8.57
Wing	3.848	5.41	5.55	5.49	5.015	4.597	4.36	4.80	8.29	8.25	6.50
Engine Nacelles	1.860	4.88	5.11	1.14	1.101	2.441	.74	1.960	5.67	2.07	.85
Engine Struts	.552	---	1.67	.55	.679	.464	.42	.540	---	1.15	.44
Lift Engine Pods	2.190	---	---	---	---	---	---	3.00	---	---	---
Vertical Tail	1.496	1.38	4.73*	3.09	3.526	2.605	2.04	1.75	1.87	3.79	2.72
Horizontal Tail	1.571	1.75	1.83					2.00	2.17		
Total fe	17.548	21.15	26.92	19.01	19.111	16.539	14.210	22.60	26.92	25.95	19.08
C_{Do}	.0249	.0269	.0308	.0180	.0186	.0201	.0190	.0219	.0224	.0180	.0174

* Includes Aft Rotor Fairing
** Includes Landing Gear Housing

NOTE: Interference drag is included with appropriate components

TABLE 29

COMPARISON OF INDUCED DRAG FACTORS (C_{D_i}/C_L^2) AND LIFT COEFFICIENT SLOPES (C_{L_α})

CONFIGURATION	C_{D_i}/C_L^2	C_{L_α} (deg^{-1})
Tilt Wing VTOL		
60-passenger	.0466	.0850
120-passenger	.0480	.0844
Jet Lift VTOL		
60-passenger	.0749	.0733
120-passenger	.0749	.0733
Stowed-Rotor VTOL		
60-passenger	.0567	.0816
Lift Fan VTOL		
60-passenger	.1145	.0570
120-passenger	.960	.646
Fan-in-Wing VTOL		
60-passenger	.1210	.0591
Fan-in-Wing STOL		
60-passenger	.0720	.0707
Turbofan STOL		
60-passenger	.0607	.0732
120-passenger	.0607	.0732

TABLE 30

60 PASSENGER AIRCRAFT COMPARISON OF FUEL WEIGHTS

	VTOL					STOL	
500 ST MI MISSION	JET LIFT	TILT WING	STOWED ROTOR	LIFT FAN	FAN-IN WING	FAN-IN WING	TURBO-FAN
Mission							
Taxi Out	206	86	68	64	80	60	26
Takeoff	790	140	170	576	584	365	231
Climb	1 960	740	2 292	2 040	2 200	1 628	1 077
Cruise	3 484	3 287	5 754	3 272	3 460	2 521	2 551
Descent	184	331	200	228	248	193	312
Approach and Landing	1 637	430	732	1 565	1 538	766	300
Taxi In	56	86	68	24	26	20	26
Reserves							
Loiter	2 100	1 310	2 830	2 116	2 316	1 595	2 565
Go-Around	1 573	390	694	835	1 150	573	162
Total	11 990	6 800	12 808	10 720	11 602	7 721	7 250

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