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CONCEPTUAL ENGINEERING DESIGN STUDIES OF 1985-ERA COMMERCIAL VTOL AND STOL TRANSPORTS THAT UTILIZE ROTORS

J. P. Magee, R. D. Clark, and C. A. Widdison

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ABSTRACT

This document summarizes conceptual design studies of tandem-rotor helicopter and tilt-rotor aircraft for a short haul transport mission in the 1985 time frame. Vertical takeoff designs of both configurations are discussed, and the impact of external noise criteria on the vehicle designs, performance, and costs are shown. A STOL design for the tilt-rotor configuration is reported, and the effect of removing the vertical takeoff design constraints on the design parameters, fuel economy, and operating cost is discussed.

FOREWORD

The studies summarized in this report were performed by the Boeing Vertol Company for the National Aeronautics and Space Administration, Ames Research Center, under NASA Contract NAS2-8048. Mr. D. Giulianetti and Mr. K. Edenborough were the NASA technical monitors for this work.

Mr. J. P. Magee was the Boeing Vertol program manager. Mr. R. Clark was the project engineer for the VTOL designs, and Mr. C. A. Widdison for the STOL design study.

The contributions made by the following Boeing Vertol Company personnel are acknowledged:

D. Pritchard	-	Weights
W. Eason	-	Flying Qualities
R. Shannon	-	Design
G. Willets	-	Cost Analysis
J. Gibs	-	Acoustics
H. Alexander	-	Technology Manager

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CONCEPTUAL ENGINEERING DESIGN STUDIES OF 1985-ERA COMMERCIAL VTOL AND STOL TRANSPORTS THAT UTILIZE ROTORS

By J. P. Magee, R. D. Clark, and C. A. Widdison
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1. SUMMARY

A conceptual engineering design study has been made to define three aircraft configurations for the short-haul commercial market of the mid 1980's. The vehicle types considered were a tandem-rotor helicopter, a VTOL tilt-rotor aircraft, and a STOL tilt-rotor aircraft. In addition to the baseline designs, two derivative aircraft have been defined for the tandem-rotor helicopter and the VTOL tilt-rotor configurations to examine the impact of external noise criteria on aircraft size, weight, performance, and costs.

A synopsis of the characteristics of the aircraft is shown in Table 1. All of these vehicles are potential contenders for the short-haul commercial market. The following specific conclusions may be drawn from comparisons of the design, performance, and economics data:

- The tandem-rotor helicopter is the lightest configuration and has the lowest acquisition cost of those studied. The VTOL tilt-rotor is the heaviest vehicle and consequently has the highest acquisition cost.
- The VTOL tilt-rotor cruise speed is twice that of the tandem-rotor helicopter which results in a 32-percent lower direct operating cost and an 47.4-percent higher productivity ratio.
- The VTOL tilt-rotor fuel economy results in a fuel usage of 20.19 passenger kilometers per kilogram (47.5 passenger miles per gallon), as compared with 12.24 passenger kilometers per kilogram (28.8 passenger miles per gallon) for the tandem-rotor helicopter.
- The tandem-rotor helicopter noise level is 6 PNdB lower than the tilt-rotor at a 500-foot sideline distance in hover. However, the helicopter affects a noise pollution area of 1.385 square kilometers (0.535 square miles) on landing, as compared with 0.39 square kilometers (0.15 square miles) for the VTOL tilt-rotor and 0.362 square kilometers (0.14 square miles) for the STOL tilt-rotor aircraft.

TABLE I
SUMMARY OF AIRCRAFT DESIGNS

	Baseline Tandem-Rotor Helicopter	+5 PNdB Tandem-Rotor Helicopter	–5 PNdB Tandem-Rotor Helicopter	Baseline VTOL Tilt-Rotor	+5 PNdB VTOL Tilt-Rotor	–5 PNdB VTOL Tilt-Rotor	Baseline STOL Tilt-Rotor
Gross weight, kg (lb)	30 470 (67 175)	29 866 (65 843)	33 669 (74 227)	33 905 (74 749)	33 211 (73 217)	36 143 (99 682)	31 068 (68 493)
Empty weight, kg (lb)	18 226 (40 181)	17 305 (38 152)	21 107 (46 533)	22 710 (50 068)	22 116 (48 757)	24 820 (54 718)	20 422 (45 023)
Cruise speed, KTAS	165	141	181	349	340	355	310
Cruise altitude, m (ft)	1 524 (5 000)	1 524 (5 000)	1 524 (5 000)	4 267 (14 000)	4 267 (14 000)	4 267 (14 000)	4 267 (14 000)
Block time, hr	1.337	1.53	1.24	0.742	0.76	0.73	0.82
Direct operating cost cents/seat-mi	3.21	3.50	3.34	2.19	2.20	2.36	2.09
500-ft Sideline perceived noise, PNdB	92.3	97.2	87.1	98.2	103.2	93.4	101.3
95 PNdB area, takeoff, sq km (sq mi)	0.18 (0.07)	0.49 (0.19)	0.03 (0.01)	0.23 (0.09)	0.40 (0.19)	0.08 (0.03)	0.30 (0.115)
95 PNdB area, landing, sq km (sq mi)	1.39 (0.535)	2.28 (0.88)	.76 (0.295)	.39 (0.15)	.75 (0.29)	.18 (0.07)	0.36 (0.14)
Block fuel, kg (lb)	2 310 (5 093)	2 536 (5 590)	2 541 (5 603)	1 431 (3 157)	1 403 (3 094)	1 618 (3 567)	1 085 (2 392)
Rotor diameter, m (ft)	21 (68.9)	20.8(68.2)	22.1(72.5)	17.16(56.3)	17.0(55.7)	17.74(58.2)	13.53(44.4)
Disc loading, kg/m^2 (lb/ft^2)	43.94 (9.0)	43.94 (9.0)	43.94 (9.0)	73.2 (15)	73.2 (15)	73.2 (15)	108 (22.1)
Wing loading, kg/m^2 (lb/ft^2)	–	–	–	488(100)	488(100)	488(100)	488(100)
Hover tipspeed, m/sec (ft/sec)	221(725)	247(810)	195(640)	236(775)	279(915)	195(640)	244(800)
Cruise tipspeed, m/sec (ft/sec)	221(725)	247(810)	195(640)	165(543)	195(641)	137(448)	171(560)
Installed power, watts (shp)	10.79×10^6 (14 472)	10.27×10^6 (13 770)	12.88×10^6 (17 277)	12.36×10^6 (16 480)	11.98×10^6 (16 072)	14.52×10^6 (19 476)	8.31×10^6 (11 144)

- The effect of more restrictive external noise criteria is an escalation of the vehicle gross weight for both the helicopter and tilt-rotor configurations. Direct operating costs increase as external noise is either increased or decreased.
- Designing the tilt-rotor aircraft for 2000-foot-field-length STOL operation results in a 32-percent saving in mission fuel, giving 26.56 passenger kilometers per kilogram (62.5 passenger miles per gallon) at the design range.
- The STOL tilt-rotor aircraft is slightly higher in productivity, lower in direct operating cost, and slower in speed than the VTOL tilt-rotor aircraft.
- No technological constraint has been identified which limits vehicle size (up to 100 passengers) for any of the configurations. The preponderance of experience for the tandem-rotor helicopter reduces the potential developmental risks. The tilt-rotor vehicles would require a longer-lead component development program approach.

2. INTRODUCTION

The rising costs and diminishing availability of fossil fuels, the increasing congestion at major airports, and the growing need to reduce noise and air pollution are strong motives for evaluating the rotary-wing vehicle for the short-haul air travel market.

The low disc loading of the tandem-rotor helicopter and tilt-rotor configurations allow vertical or STOL takeoff and landing operation for a relatively modest installed horsepower. Improved fuel consumption and air pollution are direct results of decreased power. The capability to operate in a VTOL or STOL mode provides the flexibility of usage necessary to alleviate the air traffic congestion and passenger congestion at the current airport terminals.

The purpose of this study was to develop conceptual designs of VSTOL transports optimized for minimum direct operating cost at a 200-nautical-mile stage length and to assess the effect of external noise criteria on the vehicle design parameters, performance, and operating economics within constraints imposed by structural integrity, flying qualities, and ride qualities criteria.

The design studies summarized in this document were performed under NASA Contract NAS2-8048. Three rotary-wing configurations have been considered, the tandem-rotor helicopter, the VTOL tilt-rotor aircraft, and a STOL tilt-rotor configuration.

The VTOL aircraft have been designed for a 100-passenger load over a design range of 200 nautical miles and the performance, costs, flying qualities and noise levels of the vehicles computed. For each configuration, two additional aircraft have been considered, one 5 PNdB less noisy and one 5 PNdB more noisy. These design data provide a means of assessing the impact of external noise criteria in terms of cost and performance.

In addition to the VTOL designs, a tilt-rotor vehicle was designed to the same payload and range specifically for STOL operation. The removal of the design constraints associated with VTOL operation allow a reduced installed horsepower and resulting improved fuel consumption.

The results of these studies are summarized in this report. The detailed study results are reported in References 1, 2, and 3.

3. CONFIGURATIONS

Three configurations were optimized for the short-haul mission 370 kilometers (200 nautical miles) a tandem-rotor helicopter, a VTOL tilt-rotor aircraft and a STOL tilt-rotor aircraft. The optimization process used computer techniques to assess the impact of the major design parameters on vehicle size, performance, direct operating costs, and external noise signatures. The trend studies which show the results of the parametric design activity are reported in References 2 and 3. In the VTOL vehicle study, six aircraft were defined, a baseline tandem-rotor helicopter and a tilt-rotor aircraft, and in addition, two derivatives of each baseline configuration. The derivative aircraft were designed to show the impact of external noise criteria. For each configuration, one derivative aircraft was designed to be 5 PNdB more noisy and one 5 PNdB less noisy. The STOL tilt-rotor was a derivative of the baseline VTOL tilt-rotor modified for a 609.6-meter (2000-foot) field length takeoff and landing, which allowed the reduction of installed horsepower. Each configuration is described in this section.

3.1 TANDEM-ROTOR HELICOPTER DESIGNS

The tandem-rotor helicopter configuration was selected for this study over other pure helicopter types because of the inherently lower risk of large helicopter development for this type. The primary risks in the development of these aircraft are related to rotor size and transmission and rotor gearbox torque capability. The individual components are generally smaller and more within the manufacturing state of the art for a tandem design than for a single-rotor machine. Other advantages of the tandem configuration include ease of handling large center-of-gravity excursions and the ability to locate the engines away from the passenger cabin. This latter consideration keeps engine noise, fumes, and carbon deposition away from passenger areas. In addition, Boeing experience with tandem-rotor helicopters ranging in size from 2268 to 54 431 kilograms (5000 to 120 000 pounds) gross weights provides a high degree of confidence in prediction and design techniques.

The three tandem-rotor helicopter designs reported include the baseline, or optimized vehicle design, as well as two derivative aircraft whose 152.4-meter (500-foot) sideline perceived noise levels are ±5 PNdB from the baseline case. Their general characteristics are given in Table II.

Design Point Tandem-Rotor Helicopter

The tandem-rotor design point aircraft is shown in Figure 1. The major aircraft dimensions and pertinent data are shown in Table II and compared with the noise derivative vehicles. A threeview is shown in Figure 2.

The design point tandem-rotor vehicle has a 30 470-kilogram (67 175-pound) design takeoff gross weight and the installed power is 3.597×10^6 watts (14 472 shp) at sea level, standard day. The two 21-meter (68.9-foot) rotors are four-bladed articulated rotors with a solidity ratio of 0.099. The selection of rotor solidity was made to provide freedom from stall flutter loads over the entire maneuver envelope. The rotor overlap has been held to zero to eliminate rotor "bang" due to one rotor cutting the trailed vortices of the other, and also to eliminate the possibility of blade collision in the event of a desynchronization failure.

Both rotor shafts are swept forward (7° for the forward rotor and 4° for the aft rotor). This minimizes the rotor loads and cabin attitude range during hover and cruise flight. The pylon heights are arranged to provide a gap-to-stagger ratio of 0.145. This clearance is required to keep noise, rotor loads, and induced power losses at a minimum.

The aircraft has three engines located aft, one on each side of the rear rotor pylon and the third buried in the pylon itself.

The transmission layout is a three-gearbox arrangement where the three engines drives into a combiner gearbox located aft and above the passenger cabin.

Figure 1. Design Point Tandem-Rotor Helicopter

TABLE II
COMPARISON OF TANDEM-ROTOR HELICOPTER AIRCRAFT

	Design Point Tandem-Rotor Helicopter	+5 PNdB Tandem-Rotor Helicopter	–5 PNdB Tandem-Rotor Helicopter
Gross weight, kg (lb)	30 470 (67 175)	29 866 (65 843)	33 669 (74 227)
Empty weight, kg (lb)	18 226 (40 181)	17 305 (38 152)	21 107 (46 533)
Cruise speed, KTAS	165	141	181
Cruise altitude, m (ft)	1 524 (5 000)	1 524 (5 000)	1 524 (5 000)
Block time, hr	1.337	1.53	1.24
Direct operating cost at 200 nmi (3500 hr utilization/$90/lb) cents/seat-mi	3.21	3.50	3.34
500-ft Sideline perceived noise, PNdB	92.3	97.2	87.1
95 PNdB Takeoff area, sq km (sq mi)	0.18 (0.07)	0.49 (0.19)	0.03 (0.01)
95 PNdB Landing Area, sq km (sq mi)	1.39 (0.535)	2.28 (0.880)	0.76 (0.295)
Block fuel, kg (lb)	2 310 (5 093)	2 536 (5 590)	2 541 (5 603)
Rotor diameter, m (ft)	21 (68.9)	20.8 (68.2)	22.1 (72.5)
Disc loading, kg/m^2 (lb/ft^2)	43.94 (9.0)	43.94 (9.0)	43.94 (9.0)
Wing loading, kg/m^2 (lb/ft^2)	—	—	—
Hover tipspeed, m/sec (ft/sec)	221 (725)	247 (810)	195 (640)
Cruise tipspeed, m/sec (ft/sec)	221 (725)	247 (810)	195 (640)
Installed power at sea level, standard day, watts (shp)	10.79x10^6 (14 472)	10.269x10^6 (13 770)	12.882x10^6 (17 277)

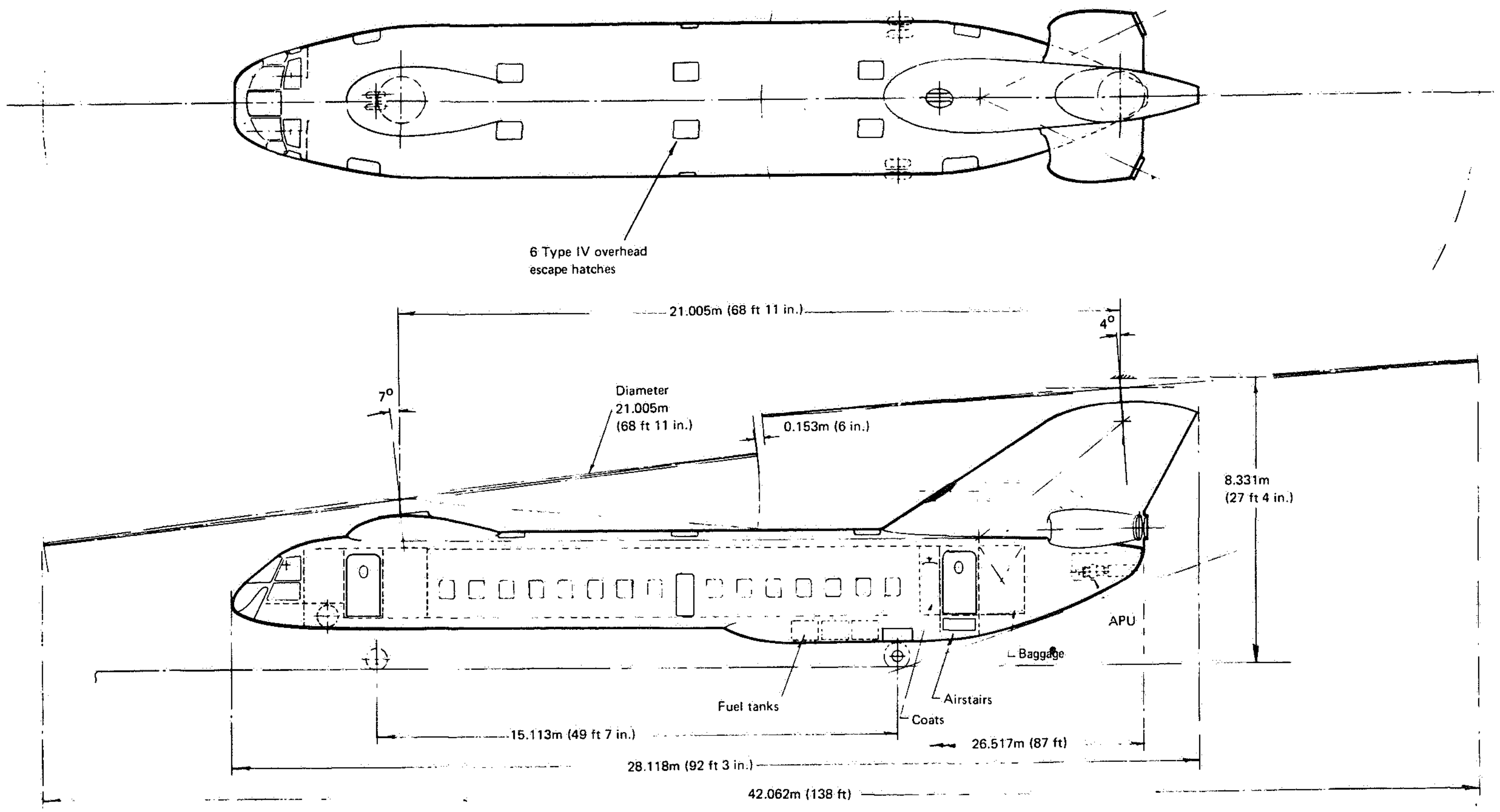


Figure 2. Schematic of Design Point Tandem-Rotor Helicopter

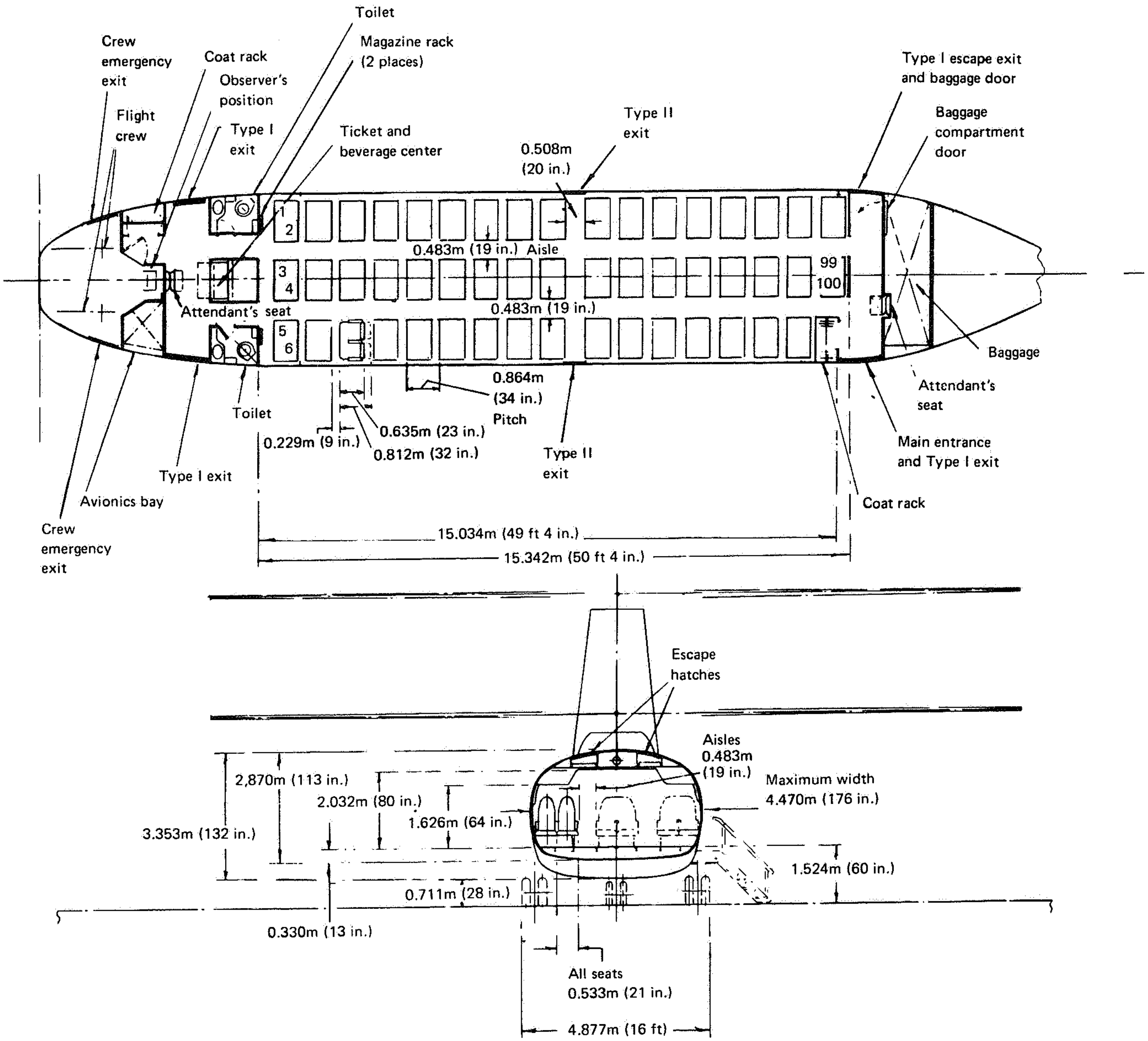


Figure 2. – Concluded

Power is transmitted to the aft rotor by shafting in the rear pylon which drives the aft rotor transmission, and to the forward rotor by shafting along a fuselage tunnel to the forward rotor transmission located forward of the passenger cabin. The auxiliary power unit (APU) is located in the aft fuselage compartment in close proximity to the engines.

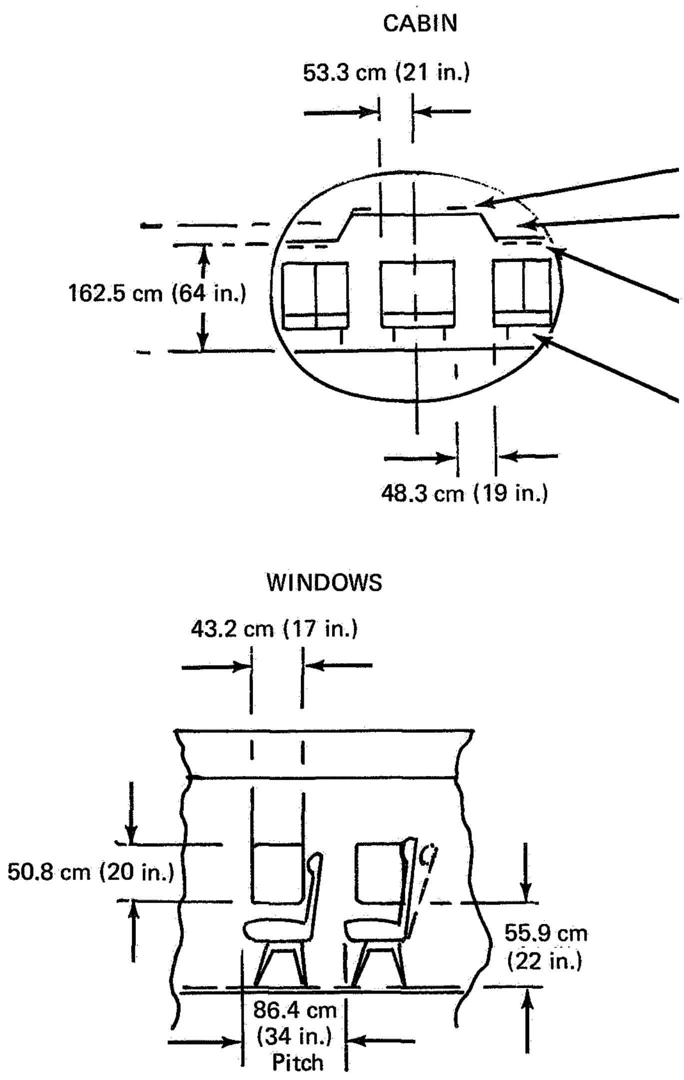
This arrangement has been selected to minimize complexity, cost, weight, and performance losses, as well as the effects of engine and transmission noise and vibration in the passenger cabin.

The fuel tanks are located under the rear cabin floor as shown in Figure 2. These tanks are crashworthy tanks similar to those built and tested by the Boeing Vertol Company for CH-46/47 applications. The design provides adequate tank strength to ensure that no rupture will occur in the event of a 95th-percentile crash. The system is designed for pressure refueling (300 gpm) with crossfeed valving, a fuel pump in each tank, and with fuel pump valves and lines routed away from the landing gear. The dual bleed conditioning system is located in the aft fuselage compartment adjacent to the APU and engine bays.

The landing gear is a retractable tricycle layout providing excellent ground handling characteristics and minimum drag. The system is designed for a 152.4-m/sec (500-fpm) landing rate of sink. The design provides an overturning angle of 27° and adequate fuselage clearance for flared landings.

Cabin layout and passenger accommodation details are shown in Figures 2 and 3. The aircraft cabin has two main entrances located on the port side of the aircraft. The aft entrance is equipped with an airstair in accordance with the study guidelines. The rear entrance is the normal entrance, and the exit is located adjacent to the stowed baggage compartment in the rear of the aircraft. A third entrance is located on the starboard side of the cabin, forward, adjacent to the service facilities; it serves the dual role as a service entrance, and an emergency exit. Another Type I exit is located aft directly opposite the main entrance; it also serves a dual role in that it can be used to load baggage by ground crew and also provides an emergency exit. This additional access provides the operator with flexibility in baggage handling procedures. In addition to these, two Type II emergency exits are located amidships, one on each side. The location of these exits causes the pitch between the ninth and tenth rows of seats to be increased to 1.143 meters (45 inches) to allow a 0.508-meter (20-inch) wide access to the exit. Six Type IV exits are provided in the cabin roof.

The passenger cabin has seats for 100 passengers with an overall seat width of 0.5334 meter (21 inches) and a seat pitch of 0.8636 meter (34 inches). Each passenger has underseat stowage space measuring 0.23x0.41x0.58 meters (9x16x23 inches) and overhead rack stowage with lockable doors. Air vents, individual lights, and a



SYSTEMS

- Air conditioning,
  Dual bleed air
- Unpressurized

ESCAPE PROVISIONS

- Type I exits,
  Two each side
- Type II exits,
  One each side
- Type IV escape hatches,
  Six on top

ENTRANCES

- Main entrances,
  Two left side
- Airstairs,
  Aft at entrance
- Service entrance,
  Right side, Forward

MISCELLANEOUS

- Coat racks for 80 passengers
- Two magazine racks
- Two lavatories
- Beverage service, Forward
- Ticket center, Forward

Figure 3. Tandem-Rotor Helicopter Passenger Accommodations

folding table are provided for each passenger in accordance with normal commercial aircraft practice.

The cabin has dual 0.4826-meter (19-inch) aisles, and the main cabin lights are located over the aisles. Two coatracks are provided, one forward and one aft, with provisions for 80 passengers. Two lavatories are located in the forward end of the cabin. In the center of the forward cabin is the beverage storage and service counter space, which also incorporates ticketing facilities. There are two cabin-attendant seats. One is located forward against the forward passenger cabin bulkhead and close to the forward exits. The second is aft against the baggage hold bulkhead and close to the rear Type I exits.

The aircraft avionics and navigational gear compartment is on the port side of the aircraft just forward of the cockpit/cabin bulkhead. The cockpit space provides adequate accommodation for a flight crew of two with excellent visibility. A third observer seat is provided adjacent to the avionics compartment at the rear of the cockpit. This location provides the observer good forward vision, visibility over the flight crew stations, and also access to the avionics/navigation-aids compartment, if required. The cockpit is provided with two crew emergency exits, one on each side of the cockpit.

+5 PNdB Tandem-Rotor Helicopter Configuration and Layout

The characteristics of the +5 PNdB tandem-rotor helicopter design are given in Table II.

The primary changes in the configuration for the +5 PNdB aircraft result from an increase in rotor tipspeed to 247 m/sec (810 fps) and a decrease in rotor solidity to 0.07. The aircraft gross weight reduced to 29 866 kilograms (65 843 pounds) and the rotor diameter is reduced to 20.8 meters (68 feet 2 inches). The pylon sweep is dictated by the decision to have zero rotor blade overlap. With a smaller rotor diameter, less aft pylon sweep is required than for the baseline aircraft, and this results in a 22.8-centimeter (9-inch) reduction in overall length.

The cabin and cockpit layout is exactly the same as the design point aircraft and meets the same requirements for 100 passengers. The design differences are in the rotor and installed power and transmissions. The installed power decreased to 3.423×10^6 watts (4590 shp) for each of the three engines.

The solidity of 0.07 still meets the criterion of 1.25g maneuver capability with no stall flutter which was selected for the basic aircraft. The reduction in solidity is possible because of the higher tipspeed.

-5 PNdB Tandem-Rotor Helicopter Configuration and Layout

The -5 PNdB tandem-rotor helicopter design also has the same fuselage, cabin, and cockpit arrangement as the baseline helicopter. The major differences in this case are in the rotor and drive system which result from reduced rotor tipspeed and increased solidity required to reduce the external noise by 5 PNdB. The major characteristics of this aircraft are also shown in Table II.

The rotor tipspeed is reduced to 195 m/sec (640 fps) requiring an increased rotor solidity to maintain 1.25g maneuver capability in cruise. The associated increase in aircraft weight required an increase in rotor diameter to 22.1 meters (72.5 feet) to maintain the design disc loading of 43.94 kg/m^2 (9 lb/ft^2).

The drive system configuration is the same as for the baseline aircraft except that the power and torques required are increased. The installed maximum power per engine has increased to 4.294×10^6 watts (5759 shp).

The overall length of the aircraft is increased because, to maintain zero overlap with the increased rotor diameter, the aft pylon is swept more than that of the baseline aircraft.

3.2 VTOL TILT-ROTOR AIRCRAFT DESIGNS

The tilt-rotor concept is unique in that it combines the hover and low-speed efficiency and agility of the helicopter with the cruise advantages of a conventional turboprop transport.

The low-disc-loading rotors are mounted at the wingtips and provide essentially a lateral-twin configuration in hover. The prop/rotors tilt to provide vertical lift in hover and transition to cruise flight. In cruise the prop/rotor propulsive efficiency is high, and this coupled with the high lift-to-drag ratios typical of wingborne aircraft provide an efficient cruising vehicle.

Design Point Tilt-Rotor Configuration and Layout

The design point tilt-rotor aircraft is shown in Figure 4, and a threeview of the vehicle is given in Figure 5. Table III is a list of the major aircraft dimensions and characteristics.

This aircraft has a takeoff gross weight of 33 905 kilograms

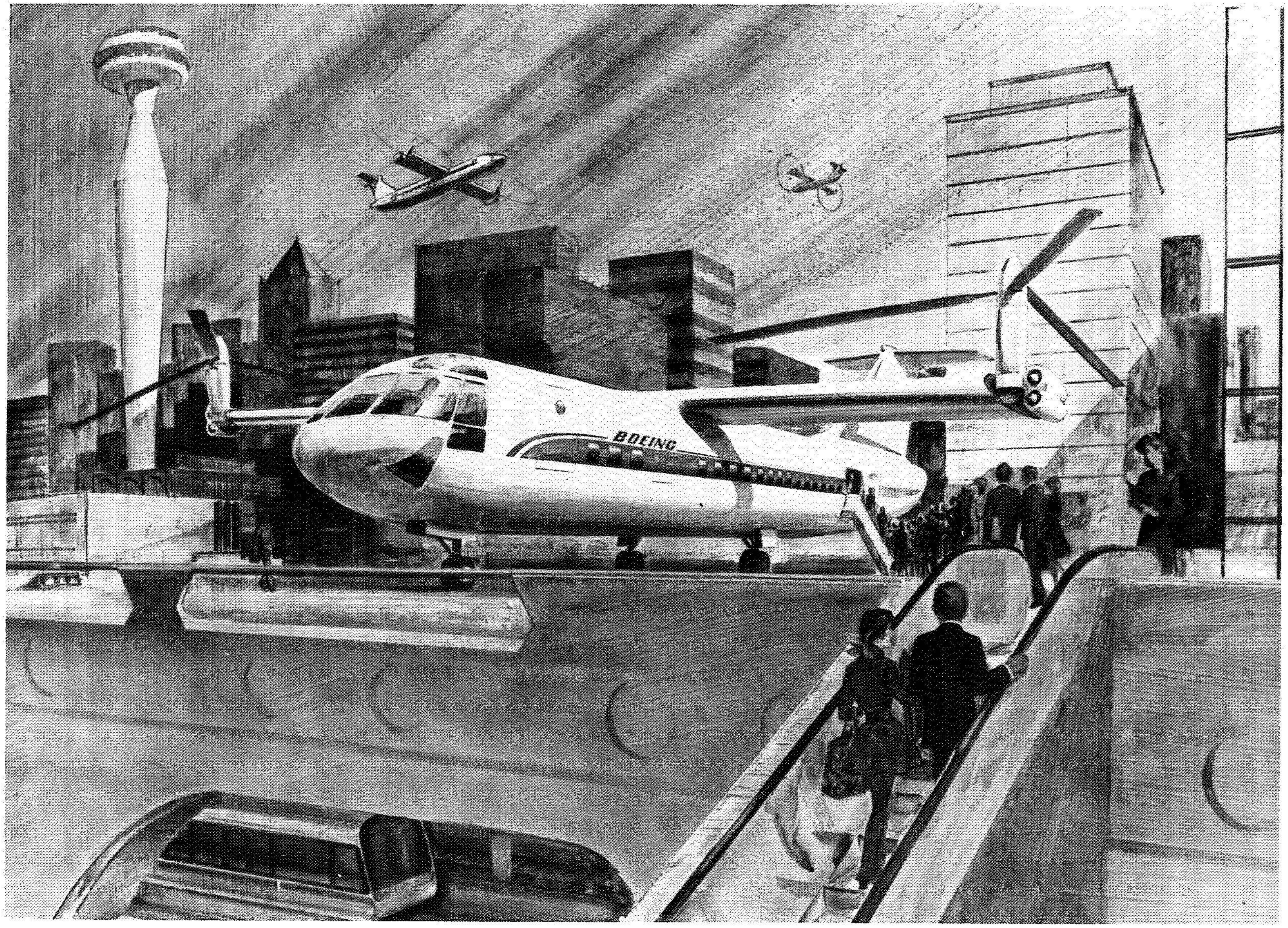


Figure 4. Design Point VTOL Tilt-Rotor Aircraft

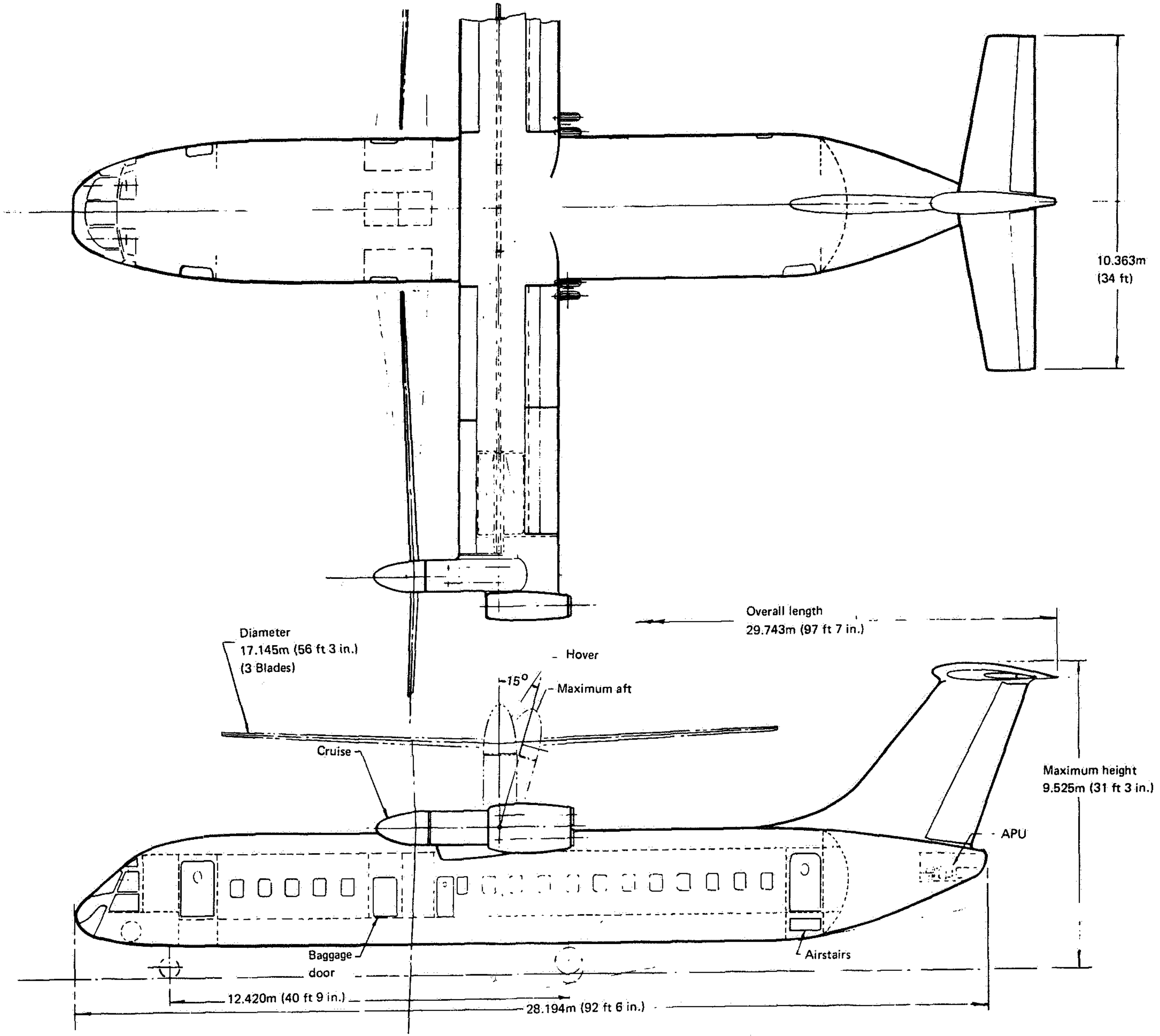


Figure 5. Schematic of Design Point VTOL Tilt-Rotor Aircraft

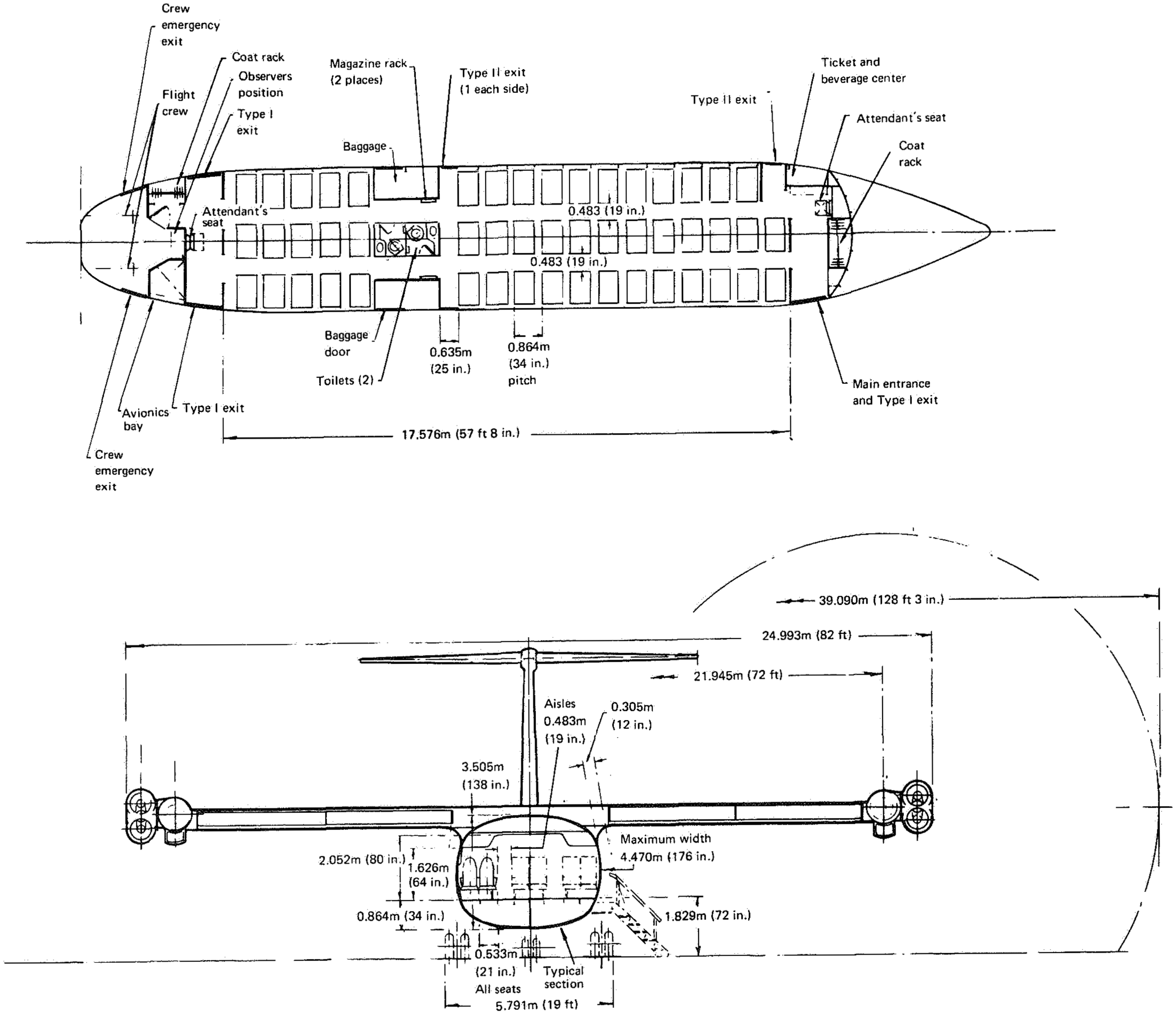


Figure 5. — Concluded

TABLE III
COMPARISON OF VTOL TILT-ROTOR AIRCRAFT

	Design Point Tilt-Rotor	+5 PNdB Tilt-Rotor	−5 PNdB Tilt-Rotor
Gross weight, kg (lb)	33 905 (74 749)	33 211 (73 217)	36 143 (79 682)
Empty weight, kg (lb)	22 710 (50 068)	22 116 (48 757)	24 820 (54 718)
Cruise speed, KTAS	179.5 (349)	175.1 (340)	182.6 (355)
Cruise altitude, m (ft)	4 267 (14 000)	4 267 (14 000)	4 267 (14 000)
Block time, hr	0.742	0.76	0.73
Direct operating cost at 200 nmi (3500 hr utilization/$90/lb) cents/seat-mi	2.19	2.20	2.36
500-ft Sideline perceived noise, PNdB	98.2	103.2	93.4
95 PNdB Takeoff area, sq m (sq mi)	0.23 (0.09)	0.49 (0.19)	0.08 (0.03)
95 PNdB Landing area, sq m (sq mi)	0.39 (0.15)	0.75 (0.29)	0.18 (0.07)
Block fuel, kg (lb)	1 431 (3 157)	1 403 (3 094)	1 618 (3 567)
Rotor diameter, m (ft)	17.16 (56.3)	17.0 (55.7)	17.74 (58.2)
Disc loading, kg/m^2 (lb/ft^2)	73.2 (15)	73.2 (15)	73.2 (15)
Wing loading, kg/m^2 (lb/ft^2)	488 (100)	488 (100)	488 (100)
Hover tipspeed, m/sec (ft/sec)	236 (775)	279 (915)	195 (640)
Cruise tipspeed, m/sec (ft/sec)	165 (543)	195 (641)	137 (448)
Installed power at sea level, standard day, watts (shp)	12.364x10^6 (16 480)	11.984x10^6 (16 072)	14 524x10^6 (19 476)

(74 749 pounds). The rotors are three-bladed and are of hingeless fiberglass composite construction. The rotor diameter is 17.16 meters (56.3 feet) and the solidity ratio is 0.089. In hover and low-speed flight, cyclic pitch control is applied to the rotor to provide control power and trim. These rotors are highly twisted (36 degrees) by comparison with helicopter blades to provide efficient operation at high advance ratio as well as in hover.

The rotors and forward rotor transmission tilt; however, the engines, mounted outboard of the tilt package, remain stationary. This arrangement does not require the engines to be requalified for vertical operation and reduces the inertia of the tilt package.

The aircraft has four engines, two on each wing tip. The rotors and engines are connected by means of a cross-shaft which provides the torque transmission across the aircraft in event of engine failure. The location of the engines outboard of the tilt package provides easy access to the engine bays for maintenance or engine removal.

The span of the aircraft is 25 meters (82 feet) measured from outboard of one nacelle to outboard of the other. The wing is straight and untapered with a NACA 63_4221 section with a wing setting angle of 2° relative to the fuselage. The wing aspect ratio is 7.14.

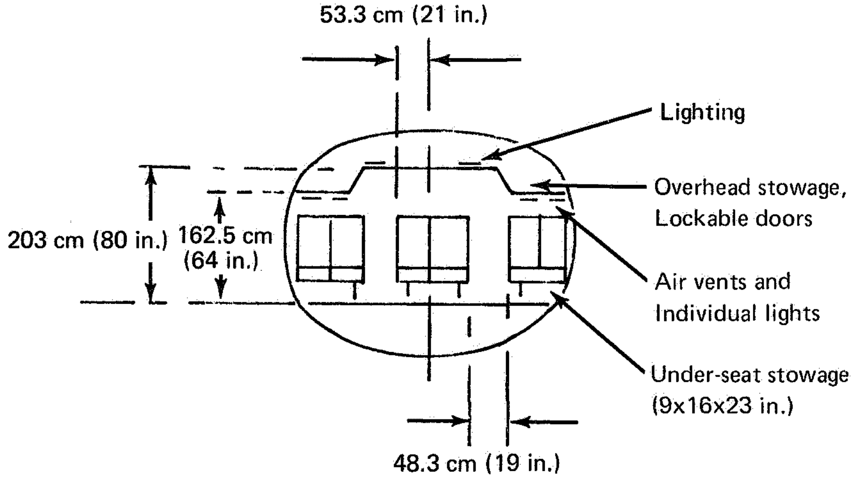
The wing has full-span 30-percent-chord plain flaperons used as both flaps and ailerons. A leading edge umbrella flap is provided which opens for hover and low-speed helicopter-type flight to alleviate the rotor download on the wing. This device is also used to ensure that wing unstalling at end of transition occurs simultaneously on both wings.

The empennage T-tail configuration was selected to reduce the impact of rotor downwash on the horizontal stabilizer in transition flight. The horizontal tail volume ratio is 1.47, and the vertical tail volume ratio is 0.159.

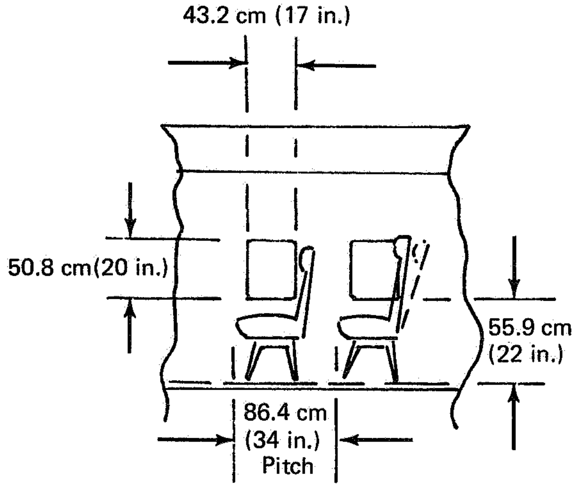
The tricycle landing gear configuration provides good ground handling characteristics and is retractible. The undercarriage provides an overturning angle of 27°.

Cabin layout and passenger accommodation details are shown in Figures 5 and 6. The aircraft cabin has two main entrances located on the port side. The aft entrance is equipped with an airstair in accordance with NASA guidelines and is the normal entrance and exit. A third Type I exit is located on the starboard side of the forward cabin. Two Type II exits are provided midcabin immediately aft of the baggage/toilet facilities, and a further Type II exit is located aft directly opposite the main entrance.

CABIN



WINDOWS



SYSTEMS

- Air conditioning,
  Dual bleed air
- Pressurized
- Emergency oxygen

ESCAPE PROVISIONS

- Type I exits,
  Two left side, One right side
- Type II exits,
  One left side, Two right side

ENTRANCES

- Main entrances,
  Two left side
- Airstairs,
  Aft at entrance
- Service entrance,
  Right side, Forward

MISCELLANEOUS

- Coat racks for 80 passengers
- Two magazine racks
- Two lavatories
- Beverage service, Aft
- Ticket center, Aft

Figure 6. Tilt-Rotor Aircraft Passenger Accommodations

The passenger cabin has seats for 100 passengers with an overall seat width of 0.5334 meter (21 inches) and a seat pitch of 0.8636 meter (34 inches). Each passenger has underseat stowage space measuring 0.23x0.41x0.58 meters (9x16x23 inches) and overhead rack stowage with lockable doors. Air vents, individual lights, and a folding table are provided for each passenger in line with normal commercial aircraft practice.

The cabin has dual 0.4826 meter (19 inch) aisles and the main cabin lights are located over the aisles. Two coat racks are provided, one forward and one aft, with provisions for 80 passengers. Two lavatories are provided in the center of the cabin in line with the baggage stowage area. The location of the baggage and toilet facilities in this area keeps passenger seats away from the prop/rotor tip-path plane in cruise to minimize noise and vibration. External baggage loading doors are provided to give ground crew access, if desired.

The beverage storage and service facilities are located aft. This unit is located adjacent to the service door/emergency exit which is larger than the minimum required Type II exit. Ticketing facilities are located in the same service unit. Two cabin-attendants seats are provided, one against the forward passenger cabin bulkhead and close to the forward exits, the second aft against the rear bulkhead and close to the rear exits.

The aircraft avionics and navigational gear compartment is on the port side of the aircraft just aft of the cockpit. The cockpit space provides adequate accommodation for a flight crew of two with excellent visibility. A third observer seat is provided at the rear of the cockpit adjacent to the avionics bay. This location provides the observer good forward vision, visibility over the flight crew stations, and access to the avionics/nav-aids bay, if required. The cockpit is provided with two crew emergency exits.

+5 PNdB Tilt-Rotor Configuration and Layout

The characteristics of the +5 PNdB tilt-rotor aircraft are given in Table III. The cabin layout and passenger and crew accommodations for the derivative vehicles are the same as those of the baseline aircraft.

The design parameters changed to obtain the increased noise level for the +5 PNdB aircraft were rotor tipspeed and solidity; tipspeed was increased to 279 m/sec (915 fps) in hover, and solidity was reduced to 0.081. Wing loading and disc loading were maintained, so that the improvement in vehicle design gross weight results in reduced rotor diameter and wing span and reduced installed power. Gross weight was reduced to 33 211 kilograms (73 217 pounds), the rotor diameter to 16.98 meters (55.7 feet), and installed power to 2.99×10^6 watts (4018 shp) per engine.

-5 PNdB Tilt-Rotor Configuration and Layout

The characteristics of the -5 PNdB tilt-rotor are given in Table III. The cabin layout and the passenger and crew accommodations for the derivative vehicles are the same as those of the baseline aircraft.

The design parameters changed to obtain the -5 PNdB are solidity and tipspeed. The rotor disc loading was held at 73.2 kg/m^2 (15 lb/ft^2) and the rotor diameter increased to 17.74 meters (58.2 feet). The wingspan, dictated by the rotor radius and rotor/fuselage clearance, also increases to 22.83 meters (74.9 feet).

The wing loading of 488 kg/m^2 (100 lb/ft^2) was maintained, and as a result, wing area was increased to 73.8 m^2 (796.8 ft^2), and the aspect ratio was reduced to 7.04.

The increased aircraft gross weight demands a higher installed power 3.63×10^6 watts (4869 shp) per engine which, in combination with reduced tipspeed and therefore higher torque levels, implies a larger and heavier transmission.

The change in cruise rpm reduces the nose-up pitching moment effect of the rotor and results in a lower horizontal tail volume ratio (1.31).

The increased installed power and decreased rpm (i.e., increased rotor efficiency) improve the cruise performance a little to give a normal rated power speed of 355 knots at 4267 meters (14 000 feet) altitude.

3.3 STOL TILT-ROTOR DESIGN

The STOL tilt-rotor vehicle is a derivative of the baseline VTOL tilt-rotor aircraft. The payload, fuselage, passenger accommodations, and fixed equipment are the same as in the VTOL design, and the aircraft was sized to carry 100 passengers over the same 370-kilometer (200-nautical-mile) range. The basic difference in the two vehicles arises out of the relaxation of the VTOL requirement. For the STOL design a takeoff field length of less than 609.6

meters (2000 feet) at sea level, 32°C (90°F) ambient condition replaced the vertical takeoff. This allows a reduction in installed power and rotor diameter which contribute to improved fuel economy.

STOL Tilt-Rotor Characteristics and Layout

A general view of the design point STOL tilt-rotor aircraft is shown in Figure 7 and a threeview drawing is given in Figure 8. Table IV provides a list of the major aircraft dimensions and characteristics.

The aircraft has a takeoff gross weight of 31 068 kilograms (68 493 pounds) and an empty weight of 20 422 kilograms (45 023 pounds). The two three-bladed rotors are of hingeless fiberglass construction. The rotor diameter is 13.53 meters (44.4 feet), and the solidity ratio is 0.082. In low-speed flight, cyclic pitch control is applied to the rotor to provide control power and trim.

The span of the aircraft is 23.93 meters (78.5 feet) measured between rotor axes. The wing is straight and untapered with an aspect ratio of 9. The wing section is a NACA 63_4221 airfoil set at an incidence angle of 2° relative to the fuselage reference line.

Full-span trailing-edge flaperons of 30-percent chord are provided for use as both flaps and ailerons. The leading edge of the wing carries a full span 15-percent-chord Kruger flap.

The empennage consists of a trimmable horizontal stabilizer (whose tail volume ratio is 1.46) mounted atop the vertical tail (of volume ration 0.145). The T-tail configuration minimizes the effect of rotor downwash on the horizontal tail during transition.

4. WEIGHTS

4.1 BASELINE DESIGN POINT AIRCRAFT

The component weight breakdown for the three baseline aircraft is shown in Table V. Each of these configurations have the same design payload and range.

The tandem-rotor helicopter is the lightest vehicle, with a design gross weight of 30 469.9 kilograms (67 175 pounds), and the VTOL

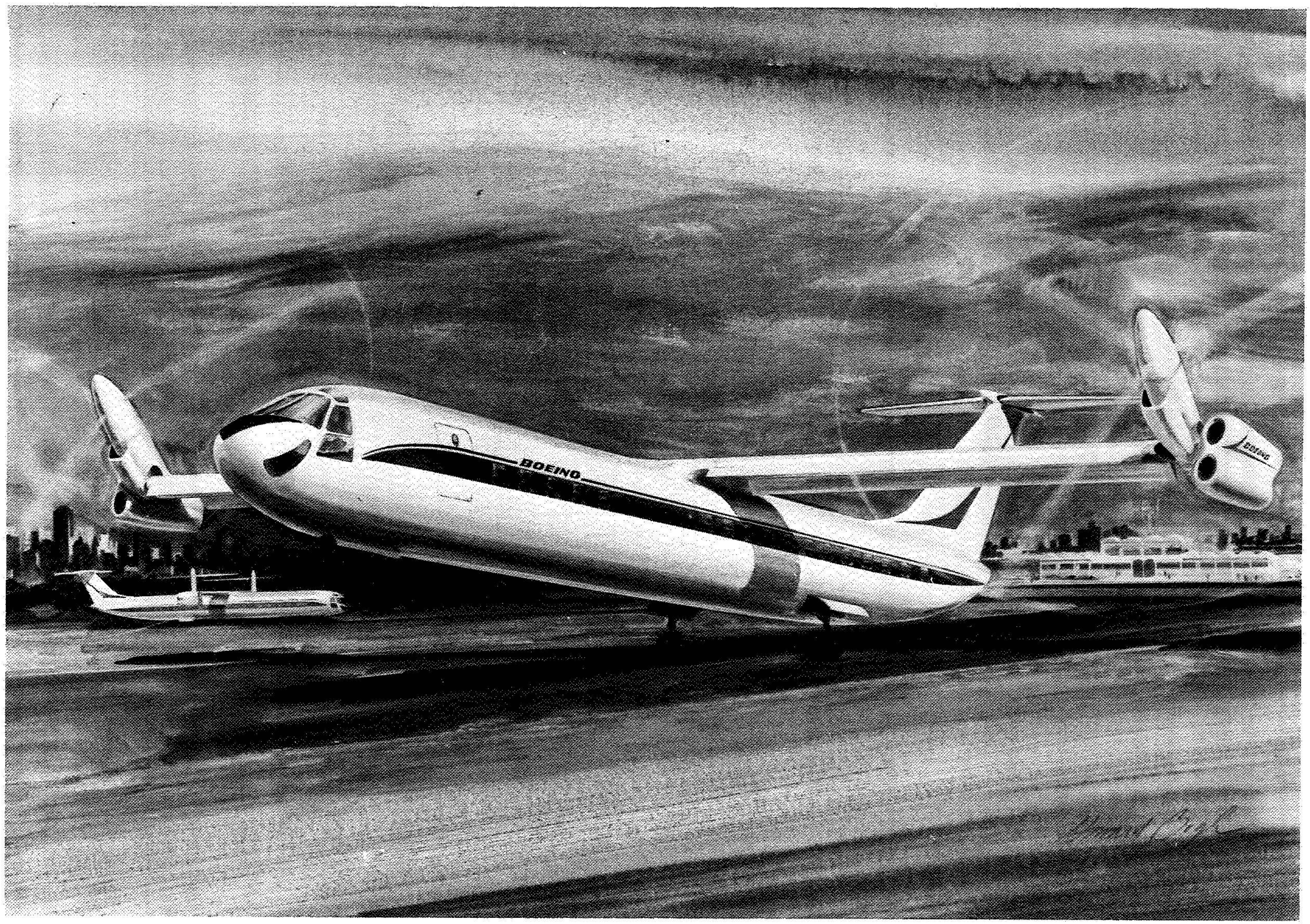


Figure 7. Design Point STOL Tilt-Rotor Aircraft

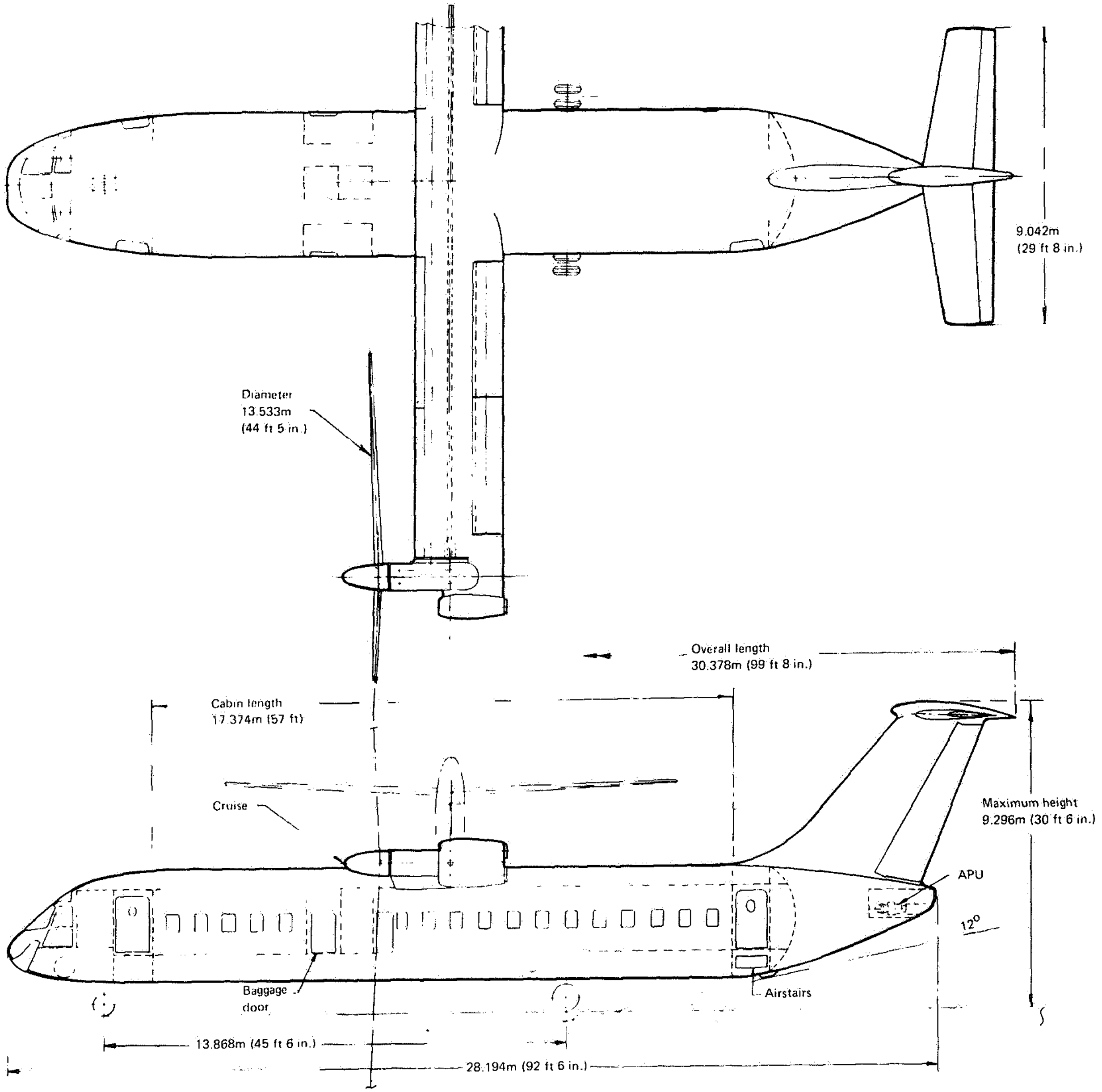


Figure 8. Schematic of Design Point STOL Tilt-Rotor Aircraft

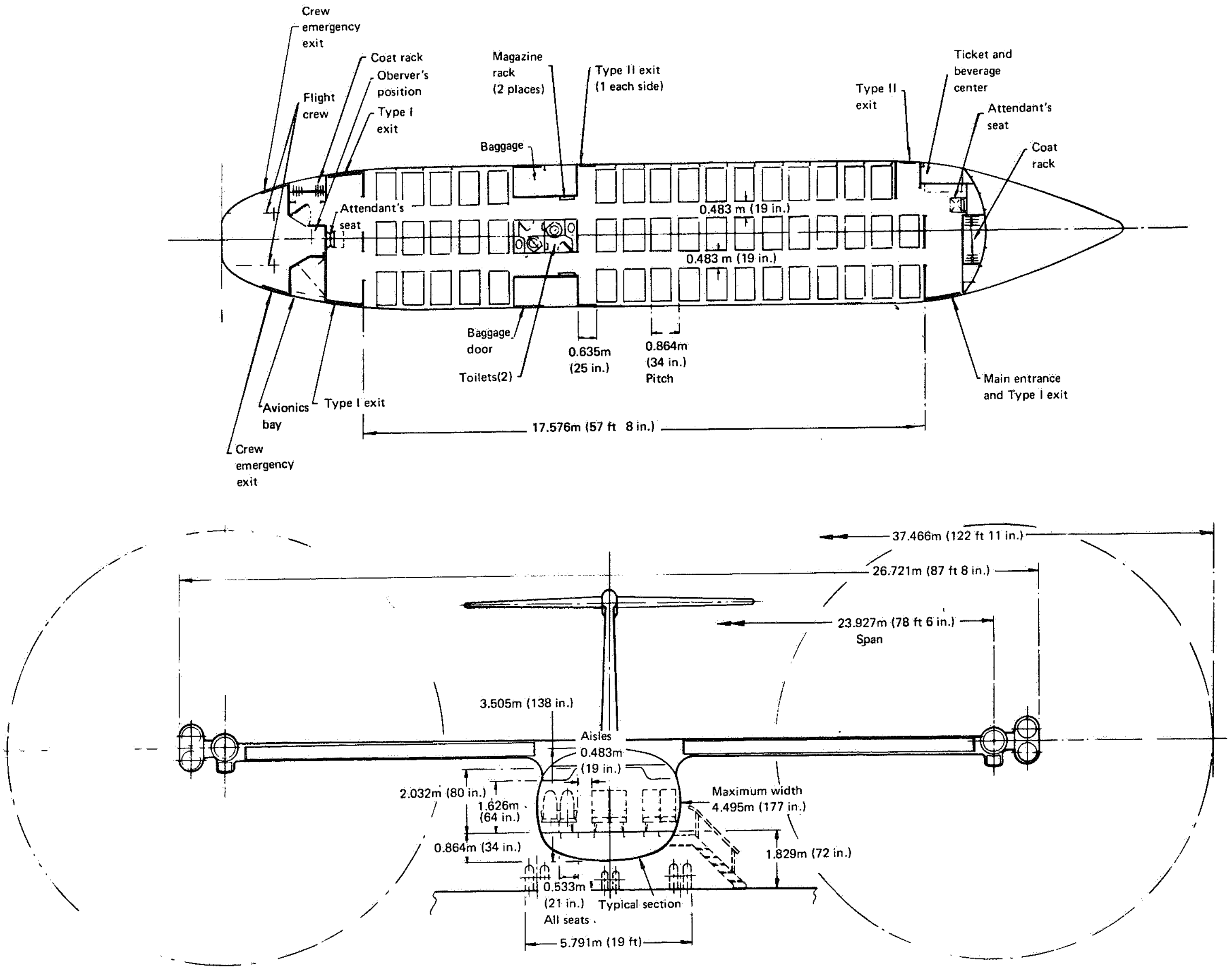


Figure 8. – Concluded

TABLE IV
STOL TILT-ROTOR AIRCRAFT SUMMARY

	Design Point STOL Tilt Rotor
Gross weight, kg (lb)	31 068 (68 493)
Empty weight, kg (lb)	20 422 (45 023)
Cruise speed, kt	310
Cruise altitude, m (ft)	4 267 (14 000)
Block time, hr	0.82
Direct operating cost at 200 nmi (3500 hr utilization/$90/lb) cents/seat-mi	2.09
500-ft Sideline perceived noise, PNdB	101.3
95 PNdB Takeoff area, sq km (sq mi)	0.30(0.115)
95 PNdB Landing area, sq km (sq mi)	0.36 (0.14)
Block Fuel, kg (lb)	1 085 (2 392)
Rotor diameter, m (ft)	13.53 (44.4)
Wing loading, kg/m^2 (lb/ft^2)	488 (100)
Disc loading, kg/m^2 (lb/ft^2)	108 (22.1)
Takeoff tipspeed, m/sec (ft/sec)	244 (800)
Cruise tipspeed, m/sec (ft/sec)	171 (560)
Installed power at sea level, standard day, watts (shp)	8.31x10^6 (11 144)

TABLE V
BASELINE AIRCRAFT WEIGHTS

	Tandem-Rotor Helicopter Weights		VTOL Tilt-Rotor Aircraft Weights		STOL Tilt-Rotor Aircraft Weights	
	(kg)	(lb)	(kg)	(lb)	(kg)	(lb)
WING	–	–	1 960.9	4 323	34 977.7	5 286
ROTOR	3 029.1	6 678	2 379.5	5 246	1 877.4	4 139
TAIL	–	–	636.8	1 404	520.3	1 147
SURFACES	–	–	636.8	1 404	520.3	1 147
ROTOR	–	–	–	–	–	–
BODY	2 950.1	6 504	3 853.2	8 495	3 889.5	8 575
BASIC	–	–	–	–	–	–
SECONDARY	–	–	–	–	–	–
ALIGHTING GEAR GROUP	1 218.8	2 687	1 356.2	2 990	1 242.8	2 740
ENGINE SECTION	222.7	491	430.0	948	288.9	637
	–	–	–	–	–	–
PROPULSION GROUP	4 401.2	9 703	4 751.8	10 476	3 000.9	6 616
ENGINE INST'L	997.9	2 200	1 184.3	2 611	796.1	1 755
EXHAUST SYSTEM *	–	–	–	–	–	–
COOLING	–	–	–	–	–	–
CONTROLS *	–	–	–	–	–	–
STARTING *	–	–	–	–	–	–
PROPELLER INST'L	*82.6	*182	*367.4	*810	*246.8	*544
LUBRICATING *						
FUEL	219.1	483	99.3	219	76.2	168
DRIVE	3 101.6	6 838	3 100.8	6 836	1 881.9	4 149
FLIGHT CONTROLS	1 031.9	2 275	1 835.2	4 046	1 567.2	3 455
AUX. POWER PLANT	288.5	636	288.5	636	288.5	636
INSTRUMENTS	191.9	423	191.9	423	191.9	423
HYDR. & PNEUMATIC	308.4	680	308.4	680	308.4	680
ELECTRICAL GROUP	378.3	834	378.3	834	423.7	934
AVIONICS GROUP	293.9	648	293.9	648	293.9	648
ARMAMENT GROUP						
FURN. & EQUIP. GROUP	3 206.9	7 070	3 273.6	7 217	3 273.6	7 217
ACCOM. FOR PERSON.						
MISC. EQUIPMENT						
FURNISHINGS						
EMERG. EQUIPMENT						
AIR CONDITIONING	521.6	1 150	612.3	1 350	612.3	1 350
ANTI-ICING GROUP	181.4	400	254.0	560	254.0	560
LOAD AND HANDLING GP.						
WEIGHT EMPTY	18 224.8	40 179	22 804.7	50 276	20 431.0	45 043
CREW	299.4	660	299.4	660	299.4	660
TRAPPED LIQUIDS	52.2	115	52.2	115	52.2	115
ENGINE OIL	59.9	132	59.9	132	59.9	132
CREW ACCOMMODATIONS	68.0	150	68.0	150	68.0	150
EMERGENCY EQUIPMENT	7.3	16	23.6	52	23.6	52
PASSENGER ACCOMO.	415.5	916	415.5	916	416.6	916
PASSENGERS (100)	8 164.6	18 000	8 164.6	18 000	8 164.6	18 000
FUEL	3 178.3	7 007	2 017.6	4 448	1 553.5	3 425
GROSS WEIGHT	30 469.9	67 175	33 905.4	74 749	31 057.7	68 493

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tilt-rotor is the heaviest with a design gross weight of 33 905.4 kilograms (74 749 pounds). The STOL tilt-rotor aircraft is lighter than the VTOL tilt-rotor as a direct result of reduced power and thrust required for takeoff. The STOL vehicle has a design gross weight of 31 067.7 kilograms (68 493 pounds).

The weight items which make up the useful load (i.e., the difference between the design gross weight and the weight empty) are common to all three aircraft, with two exceptions. First, the fuel weights vary as a function of the fuel efficiency of the vehicle to perform the design mission and according to the specified reserve fuel requirements. And second, the emergency equipment weight assumed for the tandem-rotor helicopter is 16.3 kilograms (36 pounds) lighter than for the tilt-rotor because of design altitude is low enough, 1524 meters (5000 feet), that emergency oxygen for all passengers is not required.

The STOL tilt-rotor wing weight is heavier than the VTOL aircraft because of increased aspect ratio despite the reduced wing area. The STOL wing weight is defined by the aeroelastic stiffness requirements to provide an adequate margin from whirl flutter and reverse bending loads on landing, whereas the jump takeoff criteria predominates for the VTOL aircraft.

The helicopter rotor system is heavier than either of the tilt-rotor designs. This is dictated by the rotor size, tipspeed, and thrust requirement and the maneuver load factor at design cruise speed which sets rotor solidity. The landing gear is taken as a fixed percentage of the vehicle gross weight and varies accordingly. The engine weights are defined by a fixed engine specific weight and are a direct result of the installed power required.

The propulsion group weights are primarily a function of installed power, rotor size, and torque requirements. The tandem-rotor helicopter transmissions are designed to take the installed power at sea level, standard day. The tilt-rotor aircraft reduce the rotor rpm in cruise, and therefore the transmissions are sized at the normal rated power condition at cruise rpm at 4267 meters (14 000 feet) altitude. This torque limit exceeds the sea level installed power requirement at takeoff rpm.

The auxiliary powerplant, instruments, hydraulic and pneumatic systems, and electrical and avionics system weights are the same for each configuration. Some small differences exist between the tandem-rotor helicopter and the tilt-rotor vehicles in the furnishings and equipment, environmental systems, and anti-icing systems weights which result from differences in operating altitudes.

These differences in design requirements define the variations in weight empty for the three configurations and result in a payload-to-gross-weight ratio of 26.7 percent for the tandem-rotor helicopter, 24.1 percent for the VTOL tilt-rotor, and 26.4 percent for the STOL tilt-rotor.

The weight-empty-to-gross-weight ratios for the vehicles are 59.7 percent for the tandem-rotor helicopter, 62.3 percent for the VTOL tilt-rotor, and 65.6 percent for the STOL tilt-rotor. The aerodynamic efficiency is indicated by the fuel-to-gross-weight ratios which are 10.4 percent for the tandem-rotor helicopter, 5.95 percent for the VTOL tilt-rotor, and 5 percent for the STOL tilt-rotor.

4.2 EFFECT OF EXTERNAL NOISE CRITERIA ON VEHICLE WEIGHTS

Derivative aircraft designs were studied for both VTOL configurations which would show the impact of external noise criteria on the vehicle weights. Table VI shows the component weight breakdown for the baseline tandem-rotor helicopter aircraft compared with two derivative tandem-rotor vehicles. Each of these designs has a difference of 5 PNdB in the 152.4-meter (500-foot) sideline perceived noise at takeoff from the baseline aircraft case. One is 5 PNdB more noisy and one 5 PNdB less noisy.

The effect of reducing external noise is to increase the aircraft gross weight, and increasing noise allows a reduction in gross weight.

The major differences in weight between the +5 PNdB design and the baseline helicopter are in the rotor and drive systems. The reduction in diameter and solidity of the rotors reduces the rotor system weight to 2745 kilograms (6052 pounds). The reduction in diameter also allows the distance between rotor centers to be reduced which, coupled with a lighter overall gross weight, reduces the bending moments in the fuselage structure and allows a reduction in body weight compared with the baseline aircraft.

The propulsion system weight is reduced by virtue of the lower installed power. The weight of the rotor flight controls is also reduced, since the rotor size and inertias are smaller. The fuel required to fly the design mission is reduced, since the engines are operating at a higher fraction of maximum power in cruise flight.

The -5 PNdB helicopter design is heavier than the baseline aircraft. This increase in weight is caused by the larger rotor diameter and solidity which increases the rotor system weight to 3729.9 kilograms (8223 pounds). The body weight increases as a result of the increase in the distance between the rotor hubs,

TABLE VI
EFFECT OF EXTERNAL NOISE CRITERIA ON HELICOPTER WEIGHTS

	Baseline Tandem-Rotor Helicopter Weights		+5 PNdB Tandem-Rotor Helicopter Weights		−5 PNdB Tandem-Rotor Helicopter Weights	
	(kg)	(lb)	(kg)	(lb)	(kg)	(lb)
WING						
ROTOR	3 029.1	6 678	2 745.1	6 052	3 729.9	8 223
TAIL						
SURFACES						
ROTOR						
BODY	2 950.1	6 504	2 840.4	6 262	2 996.9	6 607
BASIC						
SECONDARY						
ALIGHTING GEAR GROUP	1 218.8	2 687	1 194.8	2 634	1 346.3	2 968
ENGINE SECTION	222.7	491	222.7	491	222.7	491
PROPULSION GROUP	4 401.2	9 703	4 211.6	9 285	5 705.3	12 578
ENGINE INST'L	997.9	2 200	949.4	2 093	1 191.1	2 626
EXHAUST SYSTEM *						
COOLING						
CONTROLS *						
STARTING *						
PROPELLER INST'L	*82.6	*182	*78.5	*173	*98.4	*217
LUBRICATING *						
FUEL	219.1	483	241.3	532	241.3	532
DRIVE	3 101.6	6 838	2 942.4	6 487	4 174.4	9 203
FLIGHT CONTROLS	1 031.9	2 275	718.5	1 584	1 733.6	3 822
AUX. POWER PLANT	288.5	636	288.5	636	288.5	636
INSTRUMENTS	191.9	423	191.9	423	191.9	423
HYDR. & PNEUMATIC	308.4	680	308.4	680	308.4	680
ELECTRICAL GROUP	378.3	834	378.3	834	378.3	834
AVIONICS GROUP	293.9	648	293.9	648	293.9	648
ARMAMENT GROUP						
FURN. & EQUIP. GROUP	3 206.9	7 070	3 206.9	7 070	3 206.9	7 070
ACCOM. FOR PERSON.						
MISC. EQUIPMENT						
FURNISHINGS						
EMERG. EQUIPMENT						
AIR CONDITIONING	521.6	1 150	521.6	1 150	521.6	1 150
ANTI-ICING GROUP	181.4	400	181.4	400	181.4	400
LOAD AND HANDLING GP.						
WEIGHT EMPTY	18 224.8	40 179	17 304.0	38 149	21 105.5	46 530
CREW	299.4	660	299.4	660	299.4	660
TRAPPED LIQUIDS	52.2	115	52.2	115	52.2	115
ENGINE OIL	59.9	132	59.9	132	59.9	132
CREW ACCOMMODATIONS	68.0	150	68.0	150	68.0	150
EMERGENCY EQUIPMENT	7.3	16	7.3	16	7.3	16
PASSENGER ACCOM.	415.5	916	415.5	916	415.5	916
PASSENGERS (100)	8 164.6	18 000	8 164.6	18 000	8 164.6	18 000
FUEL	3 178.3	7 007	3 494.9	7 705	3 496.2	7 708
GROSS WEIGHT	30 469.9	67 175	29 865.7	65 843	33 668.6	74 227

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since the bending moments carried by the fuselage structure increase requiring a higher structural strength and weight. The landing gear weight is governed by the change in aircraft weight and grows with the aircraft to 1346.3 kilograms (2968 pounds). The engine section weights are increased owing to the increased engine size. The increased installed power and weight require a larger transmission reflected by the increased drive system weight.

The increased flight controls weight is a function of the increase in rotor size and weight.

A similar comparison is drawn in Table VII for the VTOL tilt-rotor aircraft. The weights breakdown for the two noise derivative tilt-rotor aircraft are compared with the design point tilt-rotor aircraft weights.

The +5 PNdB tilt-rotor has a design gross weight of 33 210.5 kilograms (73 217 pounds). The increase in tipspeed results in a reduction in transmission weight to 2627 kilograms (5791 pounds). The rotor system weight is not much less than the baseline aircraft. This is due to the effect of increased tipspeed on rotor system weight, which tends to counteract the savings expected from reduced diamter and solidity. The rotor flight control weights are governed to a large extent by the rotor weights and as a result do not reduce significantly at the higher tipspeed. The lighter gross weight dictates a slightly lower installed power which shows as a small weight saving in the engine section and installations.

The design takeoff gross weight for the -5 PNdB tilt-rotor is 36 143 kilograms (79 682 pounds) an increase of nearly 2268 kilograms (5000 pounds) over the baseline aircraft. This is due to the reduction in rotor tipspeed and increase in rotor solidity and diameter.

The reduction in tipspeed tends to reduce rotor weight, but this effect is more than offset by the increase due to solidity and diameter, and the net result is a slightly heavier rotor system.

The flight controls weight increases with the rotor weight, because the upper control design is set by rotor blade size, weight, and pitch inertia. The governing parameter in the drive system weight is the reduction in tipspeed which increases the torque requirements. This coupled with the larger power requirement of the -5 PNdB tilt-rotor causes a substantial increase in the drive system weight. The larger power requirement also implies higher engine and installation weights. The result is a 29.5-percent increase in propulsion group weights over the baseline aircraft. The landing gear is taken as a percentage of gross weight and increases accordingly.

TABLE VII
EFFECT OF NOISE CRITERIA ON TILT-ROTOR WEIGHTS

	Design Point Tilt-Rotor Weights		+5 PNdB Tilt-Rotor Weights		–5 PNdB Tilt-Rotor	
	(kg)	(lb)	(kg)	(lb)	(kg)	(lb)
WING	1 960.9	4 323	1 932.7	4 261	2 018.0	4 449
ROTOR	2 379.5	5 246	2 323.1	5 126	2 566.0	5 657
TAIL	636.8	1 404	618.7	1 364	695.8	1 534
SURFACES	636.8	1 404	618.7	1 364	695.8	1 534
ROTOR						
BODY	3 853.2	8 495	3 849.2	8 486	3 863.7	8 518
BASIC						
SECONDARY						
ALIGHTING GEAR GROUP	1 356.2	2 990	1 328.6	2 929	1 445.6	3 187
ENGINE SECTION	430.0	948	416.8	919	504.8	1 113
PROPULSION GROUP	4 751.8	10 476	4 225.2	9 315	6 145.2	13 548
ENGINE INST'L	1 184.3	2 611	1 148	2 531	1 391.6	3 068
EXHAUST SYSTEM *						
COOLING						
CONTROLS *						
STARTING *						
PROPELLER INST'L	*367.4	*810	*356.1	*785	*431.4	*951
LUBRICATING *						
FUEL	99.3	219	94.3	208	105.2	232
DRIVE	3 100.8	6 836	2 626.7	5 791	4 217.0	9 297
FLIGHT CONTROLS	1 835.2	4 046	1 818.0	4 008	1 979.5	4 364
AUX. POWER PLANT	288.5	636	288.5	636	288.5	636
INSTRUMENTS	191.9	423	191.9	423	191.9	423
HYDR. & PNEUMATIC	308.4	680	308.4	680	308.4	680
ELECTRICAL GROUP	378.3	834	378.3	834	378.3	834
AVIONICS GROUP	293.9	648	293.9	648	293.9	648
ARMAMENT GROUP						
FURN. & EQUIP. GROUP	3 273.6	7 217	3 273.6	7 217	3 273.6	7 217
ACCOM. FOR PERSON.						
MISC. EQUIPMENT						
FURNISHINGS						
EMERG. EQUIPMENT						
AIR CONDITIONING	612.3	1 350	612.3	1 350	612.3	1 350
ANTI-ICING GROUP	254.0	560	254.0	560	254.0	560
LOAD AND HANDLING GP.						
WEIGHT EMPTY	22 804.7	50 276	22 115.2	48 756	24 819.5	54 718
CREW	299.4	660	299.4	660	299.4	660
TRAPPED LIQUIDS	52.2	115	52.2	115	52.2	115
ENGINE OIL	59.9	132	59.9	132	59.9	132
CREW ACCOMMODATIONS	68.0	150	68.0	150	68.0	150
EMERGENCY EQUIPMENT	23.6	52	23.6	52	23.6	52
PASSENGER ACCOM.	415.5	916	415.5	916	415.5	916
PASSENGERS (100)	8 164.6	18 000	8 164.6	18 000	8 164.6	18 000
FUEL	2 017.6	4 448	2 012.1	4 436	2 240.3	4 939
GROSS WEIGHT	33 905.4	74 749	33 210.5	73 217	36 143.0	79 682

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The increase in takeoff gross weight of this aircraft requires an increase in mission fuel to 2240.3 kilograms (4939 pounds), 11 percent more than the baseline aircraft.

The details of basic fuselage, cabin, and cockpit accommodations, etc., are the same for all three VTOL tilt-rotor aircraft.

4.3 WEIGHTS GUIDELINES

The weight of each component and system has been computed using the HESCOMP or VASCOMP sizing programs (References 4 and 5) which use statistical and semiempirical weight trend equations based on known aircraft weights. The sizing procedure is an iterative process in which the aircraft weight is varied until the mission fuel required is equal to the allocated fuel weight.

Weights of all structural components have been reduced by 25 percent from the trend curve data, in keeping with the guideline directive on the use of composite materials.

Several standard item weights were also specified, as shown in Table VIII.

The 544.2 kilograms (1200 pounds) allocated for APU, instruments, electrical, and electronics has been assumed to be an uninstalled weight and an additional 440.8 kilograms (9721 pounds) has been included to account for installation. The engine weights are based on a projected specific weight of 0.15 lb/shp which is expected to be available for application to a 1985 commercial aircraft. The control system is a fly-by-wire system and the weight estimate for the controls is based upon recent Boeing experience with fly-by-wire controls on the Model 347 helicopter. The rotor gearboxes are designed for maximum engine power and torque under sea level, standard day conditions.

The landing gear is designed for a 152.4-m/min (500 ft/min) rate descent and is 4 percent of the design gross weight.

Passenger and crew accommodations are based on Boeing 737 aircraft data, since it will be necessary to provide passenger comfort to at least this standard by 1985.

The overall aircraft is sized for a maneuver load factor of 3.5 and an ultimate load factor of 5.25, as recommended in FAR Part 29 for helicopter aircraft. The tilt-rotor vehicles are sized for a maneuver load factor of 2.5 and an ultimate load factor of 3.75, as recommended in FAR Part 25.

TABLE VIII
WEIGHTS SPECIFIED BY STUDY GUIDELINES

Item		Weight	
		(lb)	(kg)
Wheels, tires, and brakes		Company optimum	
Instruments (flight and navigation)		1200 lb	544.3 kg
Electrical (excluding generating equipment)			
Electronics (communication, flight, and navigation)			
Auxiliary power unit installation			
Seats and belts			
Passenger:	Double	16 lb/Passenger	7.26 kg/Passenger
	Triple	16 lb/Passenger	7.26 kg/Passenger
Crew seats:	Cabin crew	16 lb/Crew member	7.26 kg/Passenger
	Flight crew	40 lb/Crew member	7.26 kg/Passenger
Lavatory		300 lb/Unit	136 kg/Unit
Beverage only		200 lb Total	90.72 kg Total
Air stair		400 lb	181.4 kg

4.4 CENTER-OF-GRAVITY RANGES AND VEHICLE GROWTH FACTORS

The longitudinal center-of-gravity range of the vehicle is of note since it defines whether restricted or unrestricted passenger seating is necessary. The tandem-rotor helicopter is unique in this respect in that no restrictions are necessary from a vehicle stability or trim standpoint. The longitudinal disposition of the rotors provides this advantage. The permissable cg envelopes for the three baseline aircraft are shown in Figure 9 as a function of aircraft weight.

In the VTOL tilt-rotor case, a restricted seating arrangement has been assumed. In Figure 9 this assumption is indicated by three "bubbles" for each flight condition. The lower one defines the maximum excursion in cg at various weights assuming that window seats are initially occupied. The second assumes every other aisle seat is occupied, and the third assumes that the remaining aisle seats are also occupied. The reason for the two different envelopes, one for hover and one for forward flight, is because the tilting of the nacelle mass shifts the aircraft cg between these flight modes. In fixed-wing airplane terms, the cg range is 14.3 percent to 32 percent of the mean aerodynamic chord (M.A.C.) and provides a 5-percent minimum static margin with most-aft cg.

The STOL tilt-rotor case is also shown in Figure 9 and resembles the VTOL tilt-rotor. The cg excursion due to nacelle tilt is not so severe in this case, since a nacelle incidence of 66° is used at takeoff rather than 90°, as in the VTOL case. The cg range in cruise in this case is from 9.8 percent to 33.5 percent M.A.C. In interpreting these ranges, note that the STOL aircraft wing chord is smaller than the VTOL aircraft.

In order to provide ready comparison of these aircraft design weights with other designs with different fixed weights, the aircraft growth data are shown in Figure 10. These curves allow an aircraft gross weight to be obtained for a variation in a fixed empty weight item and allow reasonable comparison of weight with other designs based on assumptions of different fixed equipment, etc.

5. PERFORMANCE

This section summarizes the performance of each of the seven aircraft designed during the study. First, each aircraft is assessed on the basis of its performance of the design mission, and second, the detail performance capability is examined in each phase of the mission.

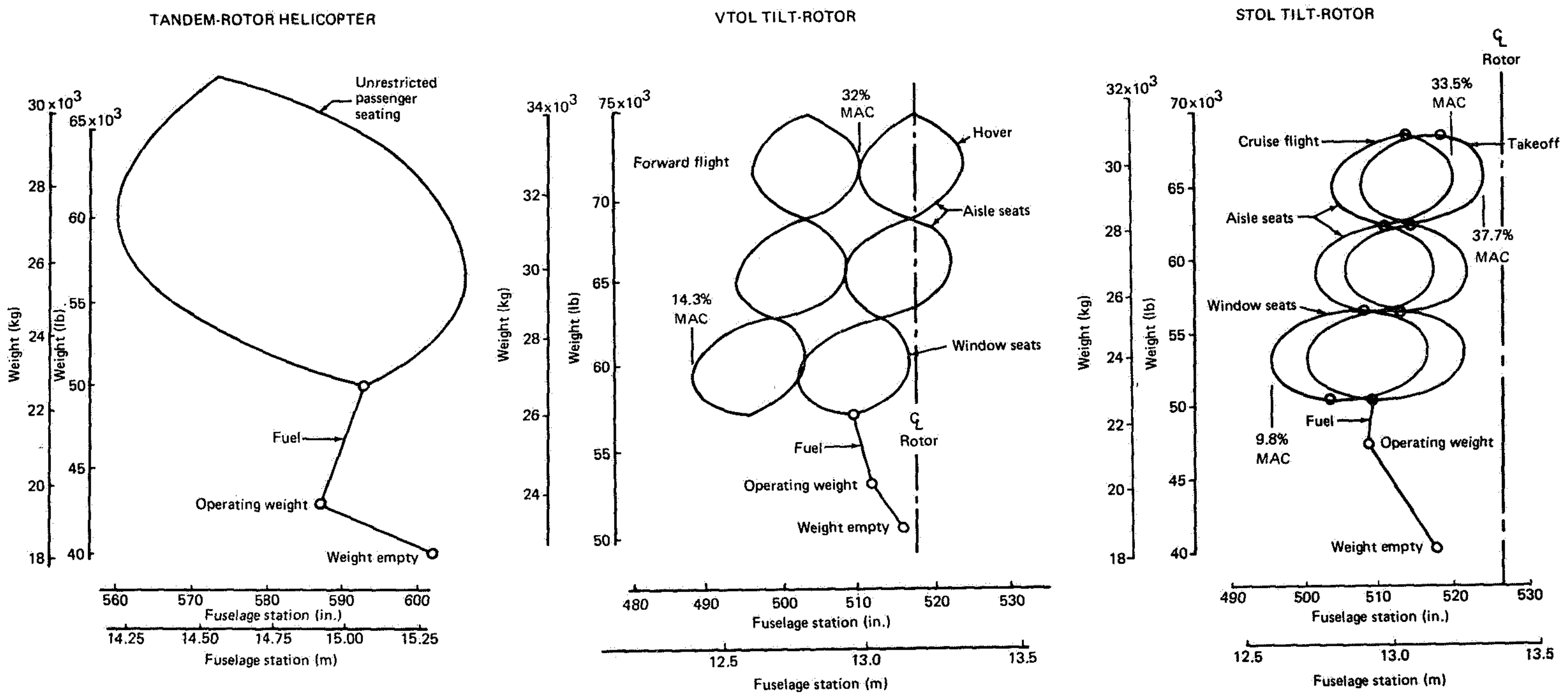


Figure 9. Comparison of Center-of-Gravity Envelopes

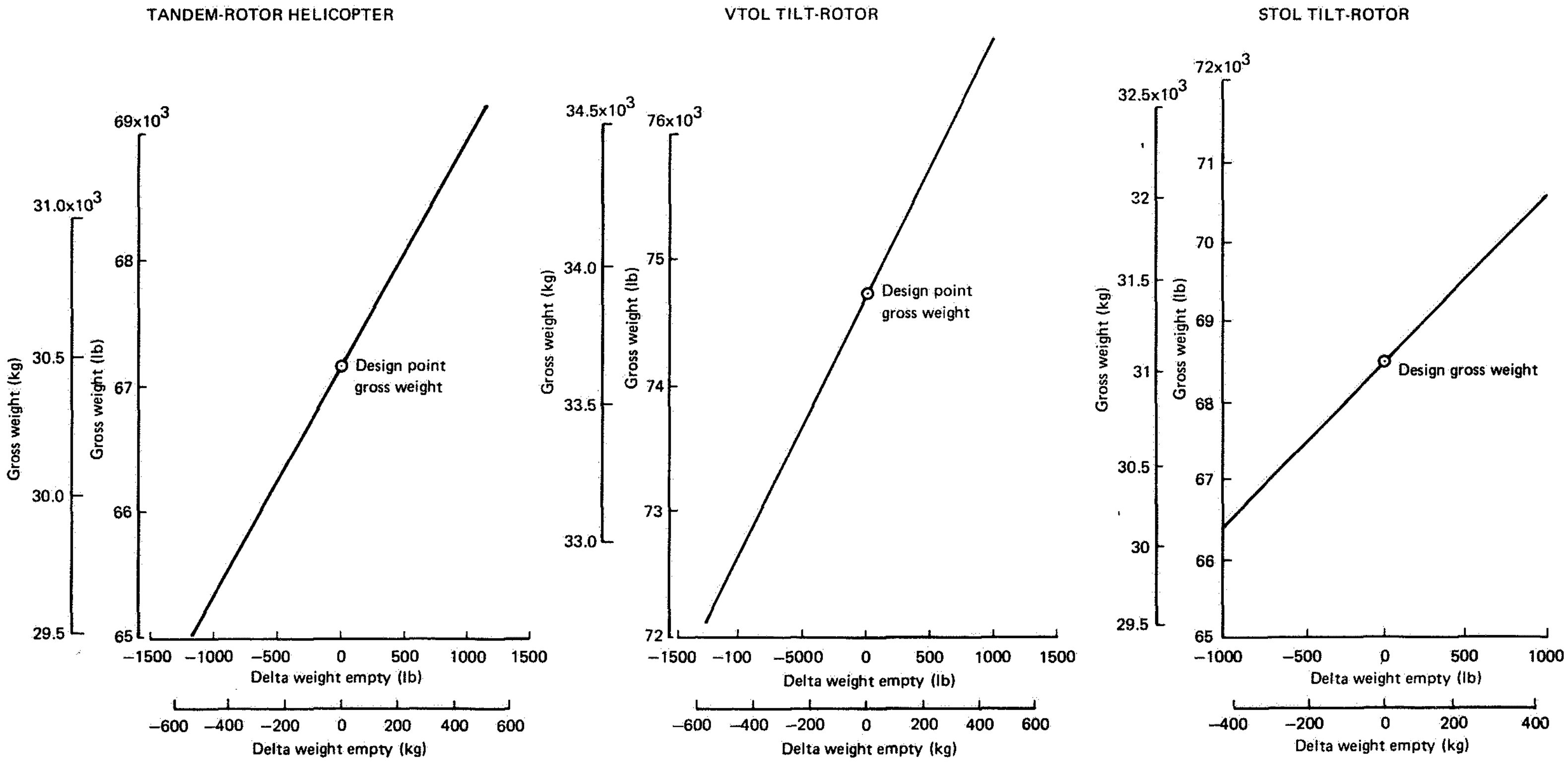


Figure 10. Growth Factor Data for the Baseline Configurations

The mission requirement is that the aircraft should carry 100 passengers with baggage to a destination 370 kilometers (200 nautical miles) from the starting point. Fuel reserves are to be sufficient to allow for a 93-kilometer (50-nautical-mile) diversion and a 20-minute loiter at a 1524-meter (5000-foot) altitude. Details of the design mission are shown in Figure 11 and Table IX.

5.1 MISSION PERFORMANCE

The mission performance of each aircraft is presented in the form of a time history showing the progress of the aircraft throughout the mission in terms of elapsed time, fuel used, distance covered, speed, and altitude. The tabulated data are grouped for convenient comparison among different concepts and among baseline and noise derivative aircraft.

Baseline Aircraft

Tables X and XI contain the mission performance history of the baseline tandem-rotor helicopter, the VTOL tilt-rotor, and the STOL tilt-rotor in S.I. units and U.S. units.

The baseline tandem helicopter consumes a total of 2311 kilograms (5094 pounds) of fuel not including the reserves remaining at the end of the mission. The VTOL tilt-rotor uses 1433 kilograms (3157 pounds), whereas the STOL tilt-rotor requires only 1085 kilograms (2391 pounds). Expressed in terms of fuel economy, the STOL tilt-rotor has the best performance, producing 34.2 passenger km per kg fuel (62.5 passenger miles per gallon). The VTOL tilt-rotor uses 32 percent more fuel and produces 25.9 passenger-km/kg fuel (47.3 passenger-mi/gal) and the tandem helicopter requires 121 percent more fuel than the STOL tilt-rotor and has a fuel consumption of 16.1 passenger-km/kg (29.4 passenger-mi/gal).

The cruise speed of the tandem-rotor helicopter at its cruise altitude of 1524 meters (5000 feet) is 168 knots. This is slower than either of the tilt-rotor aircraft. The cruise speed of the VTOL tilt-rotor at 4267 meters (14 000 feet) is 350 knots, while that of the STOL tilt-rotor is 311 knots. The extra 39 knots of cruise speed capability of the VTOL over the STOL tilt-rotor is due to its higher installed power required to meet the vertical lift requirement.

Since the cruise is the major part of the mission, the cruise speed largely determines the time to complete the mission. The baseline tandem-rotor helicopter has a block time of 1.337 hours

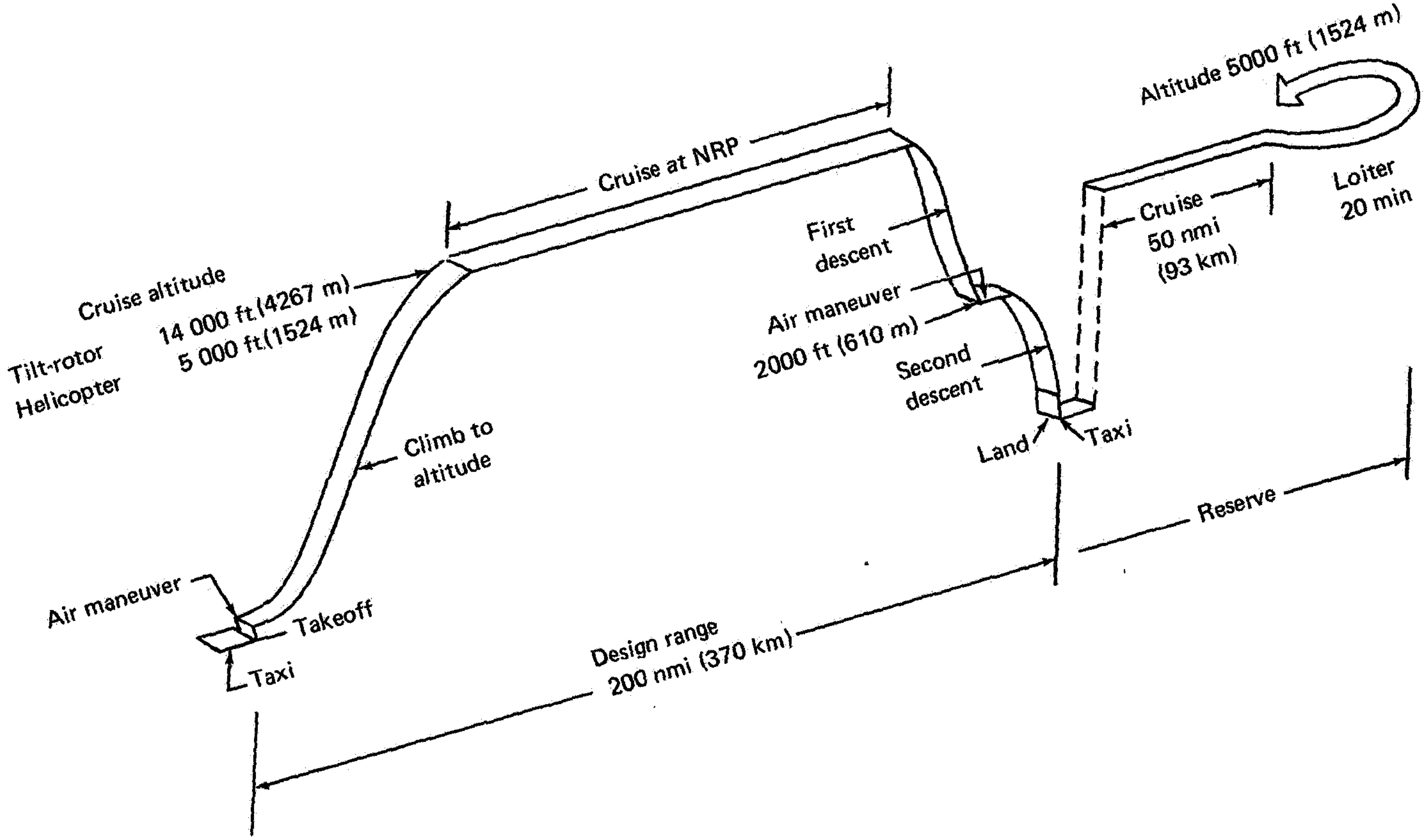


Figure 11. Design Short-Haul Mission

TABLE IX
VSTOL MISSION PROFILE DEFINITION

Segment	Time VTOL	Distance VTOL	Remarks
Taxi out	1 min	0	– – –
Takeoff, transition, and conversion to conventional flight	0.5 min	0	– – –
Air maneuver (origin)	0.5 min	0	– – –
Acceleration to climb speed	As calculated		
Climb	As calculated		At optimum climb speed
Cruise	As calculated		At constant integral 1000 ft altitudes (no enroute altitude change
Descent to 2000 ft	As calculated		5000 fpm maximum rate of descent
Air maneuver at 2000 ft (destination)	1.5 min	0	– – –
Decelerating approach and conversion to powered lift flight 2000 ft to 1000 ft	As calculated	0	1000 fpm maximum rate of descent
Transition and landing from 1000 ft to touchdown	As calculated	0	1000 fpm maximum rate of descent down to 35 ft 600 fpm maximum rate of descent below 35 ft
Taxi in	1 min	0	– – –

TABLE X
MISSION SUMMARIES FOR BASELINE TANDEM-ROTOR HELICOPTER, VTOL TILT-ROTOR, AND STOL TILT-ROTOR AIRCRAFT (S.I. UNITS)

BASELINE TANDEM-ROTOR HELICOPTER

	Time (hr)	Distance (km)	Weight (kg)	Fuel (kg)	V (kt)	Rate of Climb (m/sec)
	0	0	30 470			
Taxi				6	———	———
	0.017	0	30 464			
Takeoff				49	———	———
	0.042	0	30 416			
Climb				87	92	9.1
	0.088	7.97	30 329			
Cruise				2165	168	———
	1.242	366.34	28 251			
Descent				11	115	−12.5
	1.262	370.60	28 240			
Air Maneuver				29	92	———
	1.287	370.60	28 210			
Descent				16	70	− 5.1
	1.304	372.45	28 194			
Landing				29	———	———
	1.321	372.45	28 165			
Taxi				6	———	———
	1.337	372.45	28 159			
Reserve				869	150/93	———
	2.004	463.25	27 290			

BASELINE VTOL TILT-ROTOR

	Time (hr)	Distance (km)	Weight (kg)	Fuel (kg)	V (kt)	Rate of Climb (m/sec)
	0	0	33 905			
Taxi				6	———	———
	0.017	0	33 899			
Takeoff				82	———	———
	0.050	0	33 817			
Climb				185	178	16.7
	0.121	23	33 632			
Cruise				998	351	———
	0.576	319	32 634			
Descent				63	275	−10.6
	0.672	371	32 571			
Air Maneuver				29	138	———
	0.697	371	32 542			
Descent				6	255	———
	0.705	374	32 536			
Landing				58	———	−10.6
	0.730	374	32 478			
Taxi				6	———	———
	0.747	374	32 472			
Reserve				685	143/242	———
	1.228	463.2	31 787			

STOL TILT-ROTOR

	Time (hr)	Distance (km)	Weight (kg)	Fuel (kg)	V (kt)	Rate of Climb (m/sec)
	0	0	31 068			
Taxi				4	———	———
	0.017	0	31 064			
Takeoff				64	———	———
	0.050	0	31 000			
Climb				176	167	11.6
	0.152	30.26	30 823			
Cruise				728	312	0
	0.657	322.03	30 095			
Descent				39	316	−11.4
	0.746	370.40	30 056			
Air Maneuver				20	143	———
	0.771	370.40	30 036			
Descent				4	255	−10.6
	0.779	373.96	30 033			
Landing				46	———	———
	0.804	373.96	29 987			
Taxi				4	———	———
	0.820	373.96	29 983			
Reserve				474	150/212	———
	1.373	463.00	29 509			

TABLE XI
MISSION SUMMARIES FOR BASELINE TANDEM-ROTOR HELICOPTER VTOL TILT-ROTOR, AND STOL TILT-ROTOR AIRCRAFT (U.S. UNITS)

BASELINE TANDEM-ROTOR HELICOPTER

	Time (hr)	Distance (nmi)	Weight (lb)	Fuel (lb)	V (kt)	Rate of Climb (ft/min)
	0	0	67 175			
Taxi				12	–––	–––
	0.017	0	67 163			
Takeoff				107	–––	–––
	0.042	0	67 056			
Climb				191	92	1810
	0.088	4.3	66 865			
Cruise				4582	168	–––
	1.242	197.7	62 283			
Descent				25	115	−2460
	1.262	200	62 258			
Air Maneuver				65	92	–––
	1.287	200	62 193			
Descent				35	70	−1000
	1.304	201	62 158			
Landing				65	–––	–––
	1.321	201	62 093			
Taxi				12	–––	–––
	1.337	201	62 081			
Reserve				1916	150/93	–––
	2.004	250	60 165			

BASELINE VTOL TILT-ROTOR

	Time (hr)	Distance (nmi)	Weight (lb)	Fuel (lb)	V (kt)	Rate of Climb (ft/min)
	0	0	74 749			
Taxi				14	–––	–––
	0.017	0	74 735			
Takeoff				179	–––	–––
	0.050	0	74 556			
Climb				408	178	+3280
	0.121	12.45	74 148			
Cruise				2200	351	–––
	0.576	171.82	71 948			
Descent				139	275	−2080
	0.672	200	71 809			
Air Maneuver				365	138	–––
	0.697	200	71 744			
Descent				12	255	−2080
	0.705	202	71 732			
Landing				128	–––	–––
	0.730	202	71 604			
Taxi				14	–––	–––
	0.747	202	71 590			
Reserve				1511	143/242	–––
	1.278	250	70 079			

STOL TILT-ROTOR

	Time (hr)	Distance (nmi)	Weight (lb)	Fuel (lb)	V (kt)	Rate of Climb (ft/min)
	0	0	68 493			
Taxi				9	–––	–––
	0.017	0	68 484			
Takeoff				141	–––	–––
	0.050	0	68 343			
Climb				389	167	2280
	0.152	16.34	67 954			
Cruise				1605	312	–––
	0.657	173.88	66 349			
Descent				87	316	−2245
	0.746	200	66 262			
Air Maneuver				43	143	–––
	0.771	200	66 219			
Descent				8	255	−2085
	0.779	201.92	66 211			
Landing				101	–––	–––
	0.804	201.92	66 110			
Taxi				9	–––	–––
	0.820	201.92	66 101			
Reserve				1044	150/212	–––
	1.373	250	65 057			

whereas the VTOL tilt-rotor takes only 0.747 hours. Thus, the high speed of the VTOL tilt-rotor leads to a saving in block time of 35 minutes relative to the helicopter. On the other hand, although the STOL tilt-rotor is about 39 knots slower than the VTOL tilt-rotor, it takes slightly more than 4 minutes longer to complete the mission.

The performance levels of these aircraft for similar missions with ranges other than 370 kilometers (200 nautical miles) have been calculated and are presented in Figure 12 as payload range graphs. For ranges greater than the design range, additional fuel was included to allow a maximum range of at least 740 kilometers (400 nautical miles). The weight of the additional tankage amounted to less than the weight of one passenger with baggage. The slope of the payload radius curve is strongly dependent on the fuel consumption of the aircraft. That is why the payload capability degrades most rapidly for the helicopter and least for the STOL tilt-rotor. At the extended range of 740 kilometers (400 nautical miles), the passenger load is limited to 72 on the tandem-rotor helicopter, 84 on the VTOL tilt-rotor, and 88 on the STOL tilt-rotor aircraft.

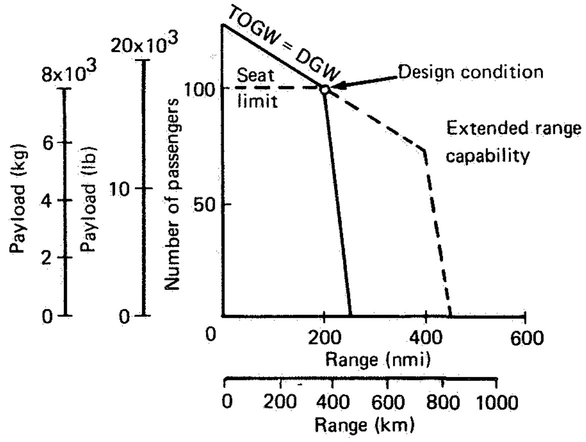
Figure 13 shows payload radius curves for the same three aircraft operating with one engine inoperative (OEI) during the cruise segment of the mission. This enables the remaining engines to operate at a level nearer the optimum specific fuel consumption level, thus producing a more economical mission in terms of fuel used. However, the speed is significantly lower so that operating cost increases and productivity decreases. The range with full passenger load is increased by flying the mission in this condition to 460 kilometers (250 nautical miles) for the helicopter and the VTOL tilt-rotor, and 410 kilometers (220 nautical miles) for the STOL tilt-rotor.

Baseline and Noise Derivative Helicopters

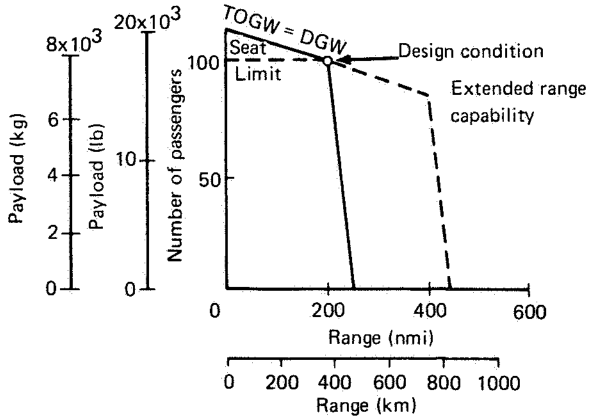
The mission performance of the baseline tandem-rotor helicopter and its noise derivatives is presented in Tables XII and XIII in S.I. units and U.S. units, respectively.

The mission fuel required by the baseline helicopter is 2311 kilograms (5094 pounds). Both of the noise derivative helicopters consume about 220 kilograms (500 pounds) more fuel than the baseline version. This indicates that designing for the lower noise level incurs roughly a 10-percent fuel consumption penalty and that relaxing the noise constraint by +5 PNdB incurs about the same loss of economy. This represents a degradation in fuel consumption from 16.1 passenger-km/kg (29.4 passenger-mi/gal) down to 14.61 passenger-km/kg (26.7 passenger-mi/gal).

BASELINE TANDEM-ROTOR HELICOPTER, 92.3 PNdB
Design Mission Profile and Reserves



BASELINE VTOL TILT-ROTOR, 98.2 PNdB
Design Mission Profile and Reserves



STOL TILT-ROTOR
Design Mission Profile and Reserves

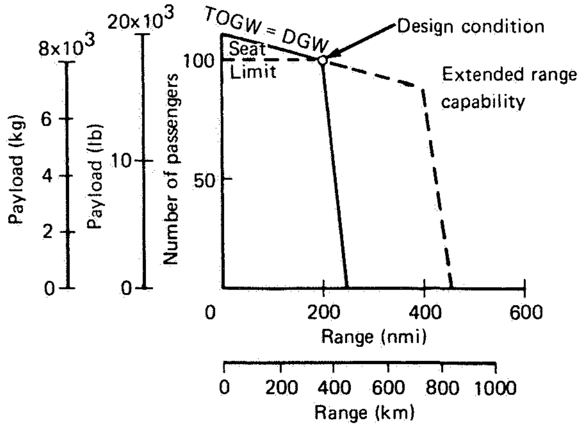
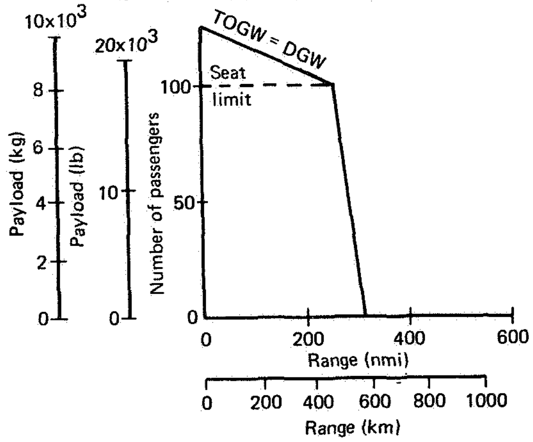


Figure 12. Payload-Range Capability with All Engines Operating

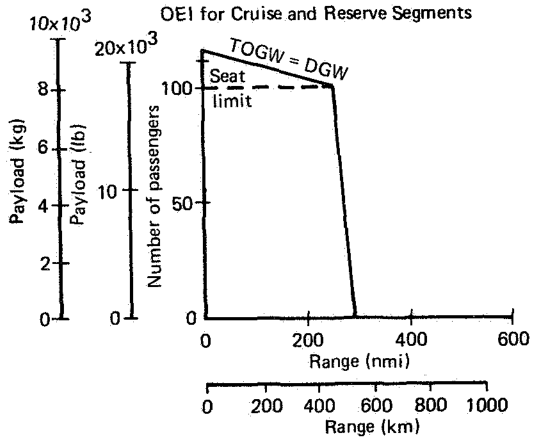
BASELINE TANDEM-ROTOR HELICOPTER, 92.3 PNdB

Design Mission Profile and Reserves
OEI for Cruise and Reserve Segments



BASELINE VTOL TILT-ROTOR, 98.2 PNdB

Design Mission Profile and Reserves
OEI for Cruise and Reserve Segments



STOL TILT-ROTOR

Design Mission Profile and Reserves
OEI for Cruise and Reserve Segments

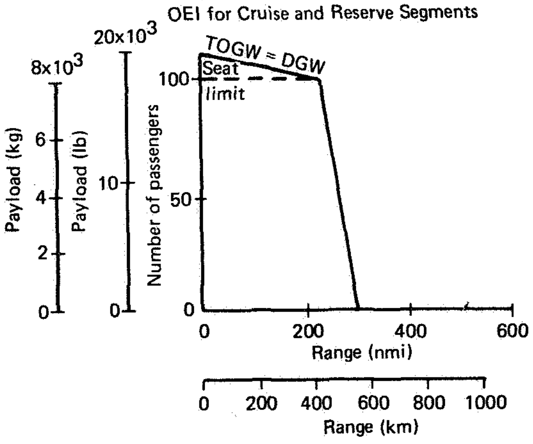


Figure 13. Payload-Range Capability with One Engine Inoperative

TABLE XII
MISSION SUMMARIES FOR BASELINE AND DERIVATIVE TANDEM-ROTOR HELICOPTERS (S.I. UNITS)

BASELINE TANDEM-ROTOR HELICOPTER

	Time (hr)	Distance (km)	Weight (kg)	Fuel (kg)	V (kt)	Rate of Climb (m/sec)
	0	0	30 470			
Taxi				6	---	---
	0.017	0	30 464			
Takeoff				49	---	---
	0.042	0	30 416			
Climb				87	92	9.2
	0.088	7.97	30 329			
Cruise				2165	168	---
	1.242	366.34	28 251			
Descent				11	115	−12.5
	1.262	370.60	28 240			
Air Maneuver				29	82	---
	1.287	370.60	28 210			
Descent				16	70	− 5.1
	1.304	372.45	28 194			
Landing				29	---	---
	1.321	372.45	28 165			
Taxi				6	---	---
	1.337	372.45	28 159			
Reserve				869	150/93	---
	2.004	463.25	27 290			

+5 PNdB TANDEM-ROTOR HELICOPTER

	Time (hr)	Distance (km)	Weight (kg)	Fuel (kg)	V (kt)	Rate of Climb (m/sec)
	0	0	29 874			
Taxi				5	---	---
	0.017	0	29 869			
Takeoff				46	---	---
	0.042	0	29 823			
Climb				105	81	7.2
	0.101	9.1	29 718			
Cruise				2292	145	---
	1.434	367.3	27 426			
Descent				9	115	−15.7
	1.451	370.6	27 417			
Air Maneuver				30	80	---
	1.476	370.6	27 387			
Descent				16	70	− 5.1
	1.492	374.3	27 371			
Landing				28	---	---
	1.509	374.3	27 343			
Taxi				5	---	---
	1.526	374.3	27 338			
Reserve				1005	140/81	---
	2.217	463.3	26 333			

−5 PNdB TANDEM-ROTOR HELICOPTER

	Time (hr)	Distance (km)	Weight (kg)	Fuel (kg)	V (kt)	Rate of Climb (m/sec)
	0	0	33 669			
Taxi				6	---	---
	0.017	0	33 662			
Takeoff				58	---	---
	0.042	0	33 604			
Climb				91	95	10.3
	0.083	7.2	33 513			
Cruise				2277	182	---
	1.143	366.2	31 236			
Descent				14	115	−12.0
	1.164	370.6	31 222			
Air Maneuver				34	95	---
	1.189	370.6	31 187			
Descent				18	70	− 5.1
	1.206	374.3	31 169			
Landing				35	---	---
	1.223	374.3	31 134			
Taxi				7	---	---
	1.240	374.3	31 127			
Reserve				956	164/96	---
	1.877	463.3	30 171			

TABLE XIII
MISSION SUMMARIES FOR BASELINE AND DERIVATIVE TANDEM-ROTOR HELICOPTERS (U.S. UNITS)

BASELINE TANDEM-ROTOR HELICOPTER

	Time (hr)	Distance (nmi)	Weight (lb)	Fuel (lb)	V (kt)	Rate of Climb (ft/min)
	0	0	67 175			
Taxi				12	---	---
	0.017	0	67 163			
Takeoff				107	---	---
	0.042	0	67 056			
Climb				191	92	1810
	0.088	4.3	66 865			
Cruise				4582	168	---
	1.242	197.7	62 283			
Descent				25	115	−2460
	1.262	200	62 258			
Air Maneuver				65	92	---
	1.287	200	62 193			
Descent				35	70	−1000
	1.304	201	62 158			
Landing				65	---	---
	1.321	201	62 093			
Taxi				12	---	---
	1.337	201	62 081			
Reserve				1916	150/93	---
	2.004	250	60 165			

+5 PNdB TANDEM-ROTOR HELICOPTER

	Time (hr)	Distance (nmi)	Weight (lb)	Fuel (lb)	V (kt)	Rate of Climb (ft/min)
	0	0	65 843			
Taxi				11	---	---
	0.017	0	65 832			
Takeoff				102	---	---
	0.042	0	65 730			
Climb				231	81	1410
	0.101	4.9	65 499			
Cruise				5053	145	---
	1.434	198.20	60 446			
Descent				18	115	−3078
	1.451	200	60 428			
Air Maneuver				67	80	---
	1.476	200	60 361			
Descent				35	70	−1000
	1.492	202	60 326			
Landing				61	---	---
	1.509	202	60 265			
Taxi				8	---	---
	1.526	202	60 253			
Reserve				2107	140/81	---
	2.217	250	58 038			

−5 PNdB TANDEM-ROTOR HELICOPTER

	Time (hr)	Distance (nmi)	Weight (lb)	Fuel (lb)	V (kt)	Rate of Climb (ft/min)
	0	0	74 227			
Taxi				15	---	---
	0.017	0	74 213			
Takeoff				128	---	---
	0.042	0	74 085			
Climb				200	95	2020
	0.083	3.9	73 885			
Cruise				5021	182	---
	1.143	197.6	68 864			
Descent				31	115	−2363
	1.164	200	68 833			
Air Maneuver				176	95	---
	1.189	200	68 757			
Descent				41	70	−1000
	1.206	202	68 716			
Landing				78	---	---
	1.223	202	68 638			
Taxi				15	---	---
	1.240	202	68 623			
Reserve				2107	164/96	---
	1.877	250	66 516			

The cruise speed of the baseline tandem-rotor helicopter is 168 knots. When the lower noise requirement is imposed, the speed increases despite the larger gross weight of the -5 PNdB derivative helicopter; the speed increases by 8 percent to 182 knots. The loss in cruise speed resulting from relaxing the noise level by +5 PNdB is almost 14 percent, or a cruise speed of 145 knots.

The cruise speeds resulting from the noise design changes are reflected in the mission block times achieved. The baseline helicopter completes the mission in 1 hour and 20 minutes, the +5 PNdB derivative takes 1 hour and 32 minutes, while the -5 PNdB helicopter, the fastest of the three helicopters, completes the mission in 1 hour and 14 minutes.

Baseline and Noise Derivative VTOL Tilt-Rotors

Tables XIV and XV give details of the mission performance history for the baseline VTOL tilt-rotor aircraft and its noise derivatives.

The baseline VTOL tilt-rotor uses a total mission fuel of 1433 kilograms (3157 pounds). Allowing the design noise level to increase by 5 PNdB results in an aircraft that has a better fuel consumption, using only 1404 kilograms (3095 pounds) of fuel to complete the mission. The -5 PNdB derivative, on the other hand, uses 1620 kilograms (3569 pounds) of fuel, an increase of 13 percent over the baseline aircraft.

The fuel economy of the baseline VTOL tilt-rotor is 25.9 passenger-km/kg (47.3 passenger-mi/gal) compared with an improved 26.4 passenger-km/kg (48.3 passenger-mi/gal) for the +5 PNdB aircraft and a value of only 22.9 passenger-km/kg (41.9 passenger-mi/gal) for the quieter -5 PNdB noise derivative tilt-rotor.

5.2 VEHICLE PERFORMANCE

This section includes a description of the performance capabilities of the design point aircraft for various flight conditions. The different regimes of flight are grouped into takeoff and landing performance and performance in forward flight.

Takeoff and Landing Performance

Baseline and noise derivative tandem-rotor helicopter. - The takeoff and landing performance of VTOL aircraft is expressed in terms

TABLE XIV
MISSION SUMMARIES FOR BASELINE AND NOISE DERIVATIVE VTOL TILT-ROTOR AIRCRAFT (S.I. UNITS)

DESIGN POINT VTOL TILT-ROTOR

	Time (hr)	Distance (km)	Weight (kg)	Fuel (kg)	V (kt)	Rate of Climb (m/sec)
	0	0	33 905			
Taxi				6	---	---
	0.017	0	33 899			
Takeoff				82	---	---
	0.050	0	33 817			
Climb				185	178	16.7
	0.121	23	33 632			
Cruise				998	351	---
	0.576	319	32 634			
Descent				63	275	−10.6
	0.672	371	32 571			
Air Maneuver				29	138	---
	0.697	371	32 542			
Descent				6	255	---
	0.705	374	32 536			
Landing				58	---	−10.6
	0.730	374	32 478			
Taxi				6	---	---
	0.747	374	32 472			
Reserve				685	143/242	---
	1.228	463.2	31 787			

+5 PNdB VTOL TILT-ROTOR

	Time (hr)	Distance (km)	Weight (kg)	Fuel (kg)	V (kt)	Rate of Climb (m/sec)
	0	0	33 211			
Taxi				6	---	---
	0.017	0	33 205			
Takeoff				79	---	---
	0.050	0	33 126			
Climb				176	178	16.9
	0.120	22.7	32 950			
Cruise				988	341	---
	0.587	319	31 962			
Descent				61	286	−10.6
	0.683	370	31 901			
Air Maneuver				26	150	---
	0.708	370	31 875			
Descent				5	255	−10.6
	0.716	374	31 870			
Landing				57	---	---
	0.741	374	31 813			
Taxi				6	---	---
	0.757	374	31 807			
Reserve				531	155/224	---
	1.304	463	31 276			

−5 PNdB VTOL TILT-ROTOR

	Time (hr)	Distance (km)	Weight (kg)	Fuel (kg)	V (kt)	Rate of Climb (m/sec)
	0	0	36 143			
Taxi				7	---	---
	0.017	0	36 136			
Takeoff				96	---	---
	0.050	0	36 040			
Climb				165	190	22
	0.104	19	35 875			
Cruise				1162	356	---
	0.553	315	34 713			
Descent				79	282	−10
	0.655	371	34 634			
Air Maneuver				28	152	---
	0.680	371	34 606			
Descent				6	255	− 9.7
	0.689	374	34 600			
Landing				68	---	---
	0.714	374	34 532			
Taxi				8	---	---
	0.730	374	34 524			
Reserve				639	154/233	---
	1.268	463	33 885			

TABLE XV
MISSION SUMMARIES FOR BASELINE AND NOISE DERIVATIVE VTOL TILT-ROTOR AIRCRAFT (U.S. UNITS)

DESIGN POINT VTOL TILT-ROTOR	Time (hr)	Distance (nmi)	Weight (lb)	Fuel (lb)	V (kt)	Rate of Climb (ft/sec)
	0	0	74 749			
Taxi				14	–––	–––
	0.017	0	74 735			
Takeoff				179	–––	–––
	0.050	0	74 556			
Climb				408	178	3280
	0.121	12.45	74 148			
Cruise				2200	351	–––
	0.576	171.82	71 948			
Descent				139	275	–2080
	0.672	200	71 809			
Air Maneuver				65	138	–––
	0.697	200	71 744			
Descent				12	255	–2080
	0.705	202	71 732			
Landing				128	–––	–––
	0.730	202	71 604			
Taxi				14	–––	–––
	0.747	202	71 590			
Reserve				1511	143/242	–––
	1.278	250	70 079			

+5 PNdB VTOL TILT ROTOR	Time (hr)	Distance (nmi)	Weight (lb)	Fuel (lb)	V (kt)	Rate of Climb (ft/min)
	0	0	73 217			
Taxi				13	–––	–––
	0.017	0	73 204			
Takeoff				174	–––	–––
	0.050	0	73 030			
Climb				389	178	+3330
	0.120	12.25	72 641			
Cruise				2178	341	–––
	0.587	172	70 463			
Descent				134	286	–2085
	0.683	200	70 329			
Air Maneuver				58	150	–––
	0.708	200	70 271			
Descent				11	255	–2080
	0.716	202	70 260			
Landing				125	–––	–––
	0.741	202	70 135			
Taxi				13	–––	–––
	0.757	202	70 122			
Reserve				1171	155/224	
	1.304	250	68 951			

–5 PNdB VTOL TILT ROTOR	Time (hr)	Distance (nmi)	Weight (lb)	Fuel (lb)	V (kt)	Rate of Climb (ft/min)
	0	0	79 682			
Taxi				16	–––	–––
	0.017	0	79 666			
Takeoff				211	–––	–––
	0.050	0	79 455			
Climb				364	190	+4320
	0.104	9,98	79 091			
Cruise				2561	356	–––
	0.553	170	76 530			
Descent				174	282	–1960
	0.655	200	76 356			
Air Maneuver				62	152	–––
	0.680	200	76 294			
Descent				14	255	–1900
	0.689	202	76 280			
Landing				150	–––	–––
	0.714	202	76 130			
Taxi				17	–––	–––
	0.730	202	76 113			
Reserve				1403	154/233	–––
	1.268	250	74 710			

of the gross weight lifting capability in hover, For any given hover condition, the net lift-to-weight ratio is held greater than unity in order that a margin of thrust (or power) is available for vertical climb, maneuvering, and control.

Figure 14 summarizes the hover capability of the three tandem-rotor helicopters, showing the variation with ambient temperature and altitude for the case of all engines operating. The degradation of hover capability with temperature and altitude, which is largely due to the effect of these parameters on engine performance, is almost identical for the three helicopters. The capability at high power levels is limited by the torque carrying capacity of the transmission.

The one engine inoperative (OEI) hover capability is shown in Figure 15. The design condition, which is at sea level and a temperature of 32°C (90°F) is indicated on each graph by a circle. At the design condition, the hover capability is exactly equal to the design gross weight. Again, the degradation of performance with ambient conditions is the same for each of the three helicopters. For the range of variables considered, the transmission capacity is not a limiting factor when operating OEI.

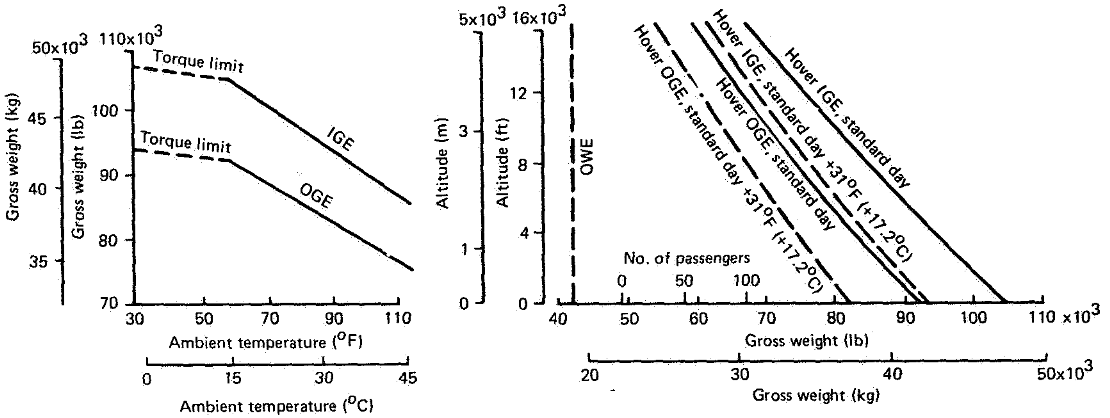
The hover performance curves indicate that lifting capabilities far in excess of the design gross weight are possible for all of the helicopters under certain conditions. These capabilities cannot be utilized as additional gross weight, however, as the takeoff gross weight is limited by the design load factor. The excess capability could be used for additional maneuverability or increased vertical rate of climb.

A significant increase in hover capability is achieved by operating in ground effect. Again the excess capability is not useable as payload, but may be used for more agility close to the ground or as a ground cushion in a landing flare.

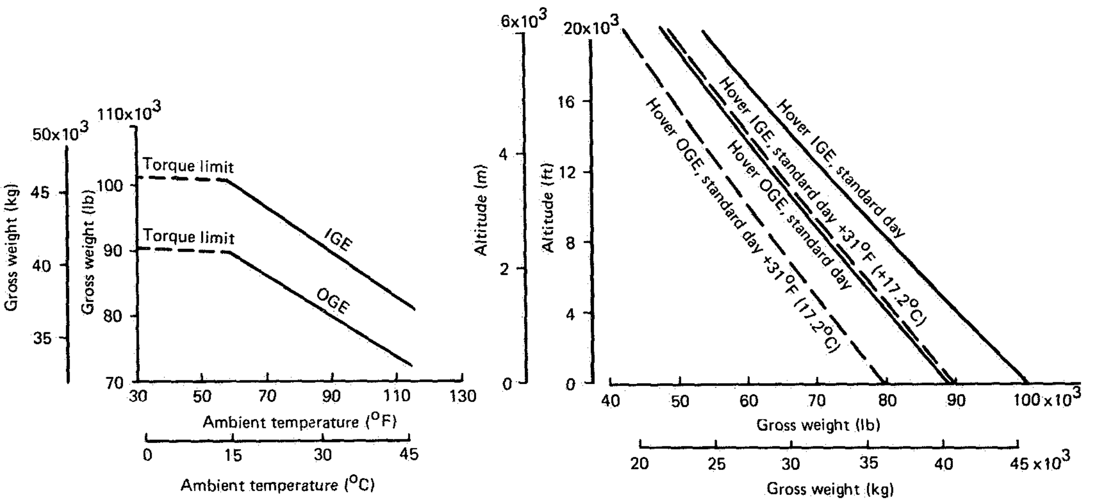
Baseline and noise derivative VTOL tilt-rotor aircraft. - The takeoff and landing performance of the VTOL tilt-rotor aircraft is presented in Figures 16 and 17 for the cases of all engines operating and one engine inoperative, respectively. The design condition is shown on the graphs for the OEI case; at this point the hover capability is exactly equal to the design gross weight. As for the helicopters, there is an excess of hover capability due to the fact that the aircraft were sized to hover OEI at sea level 32°C (90°F). Again this excess capability cannot be employed to carry payload or extra fuel.

STOL tilt-rotor aircraft. - Since the takeoff and landing performance of STOL aircraft depends strongly on the manner in which these maneuvers are executed, the groundrules governing their estimation are presented in Table XVI. The resulting performance levels and takeoff and landing field lengths are shown in Figures 18 and 19 as they vary with certain important parameters.

BASELINE TANDEM-ROTOR HELICOPTER AEO



+5 PNdB TANDEM-ROTOR HELICOPTER



–5 PNdB TANDEM-ROTOR HELICOPTER

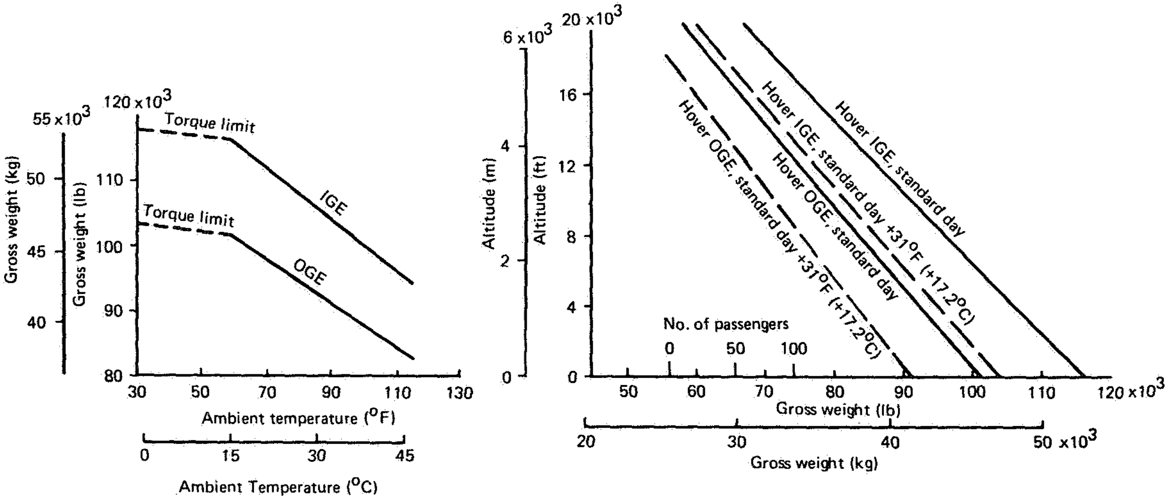
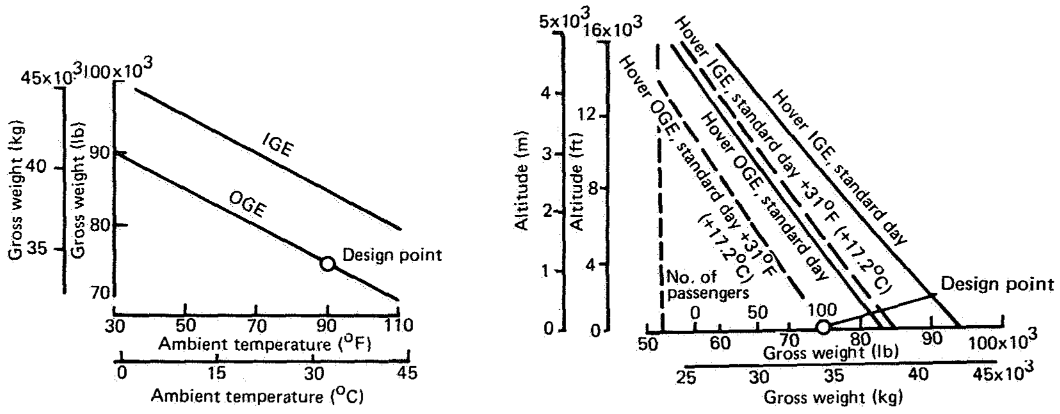
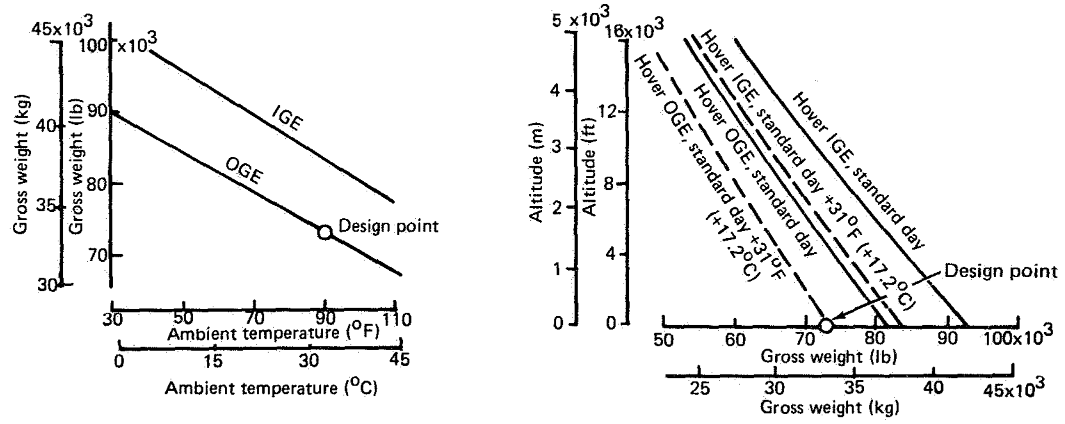


Figure 14. Effect of Ambient Temperature and Altitude on Hover Performance of Tandem-Rotor Helicopter with All Engines Operating

BASELINE VTOL TILT-ROTOR OEI



+5 PNdB VTOL TILT-ROTOR



–5 PNdB VTOL TILT-ROTOR

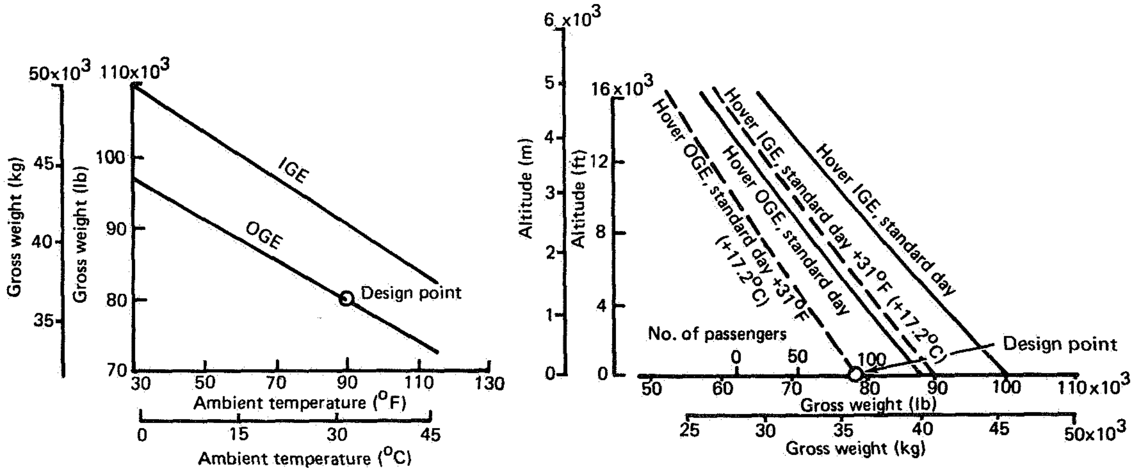


Figure 15. Effect of Ambient Temperature and Altitude on Hover Performance of Tandem-Rotor Helicopter with One Engine Inoperative

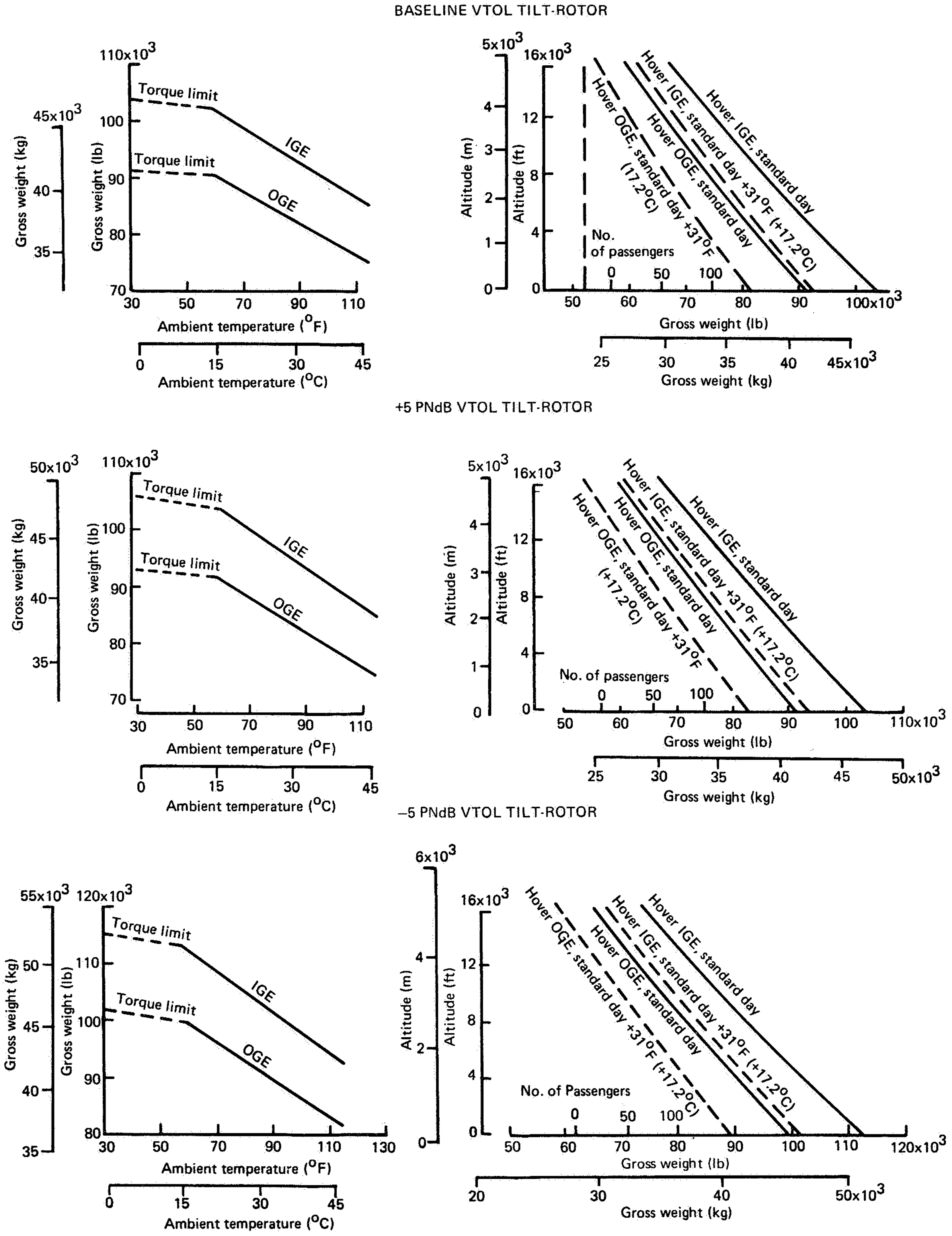
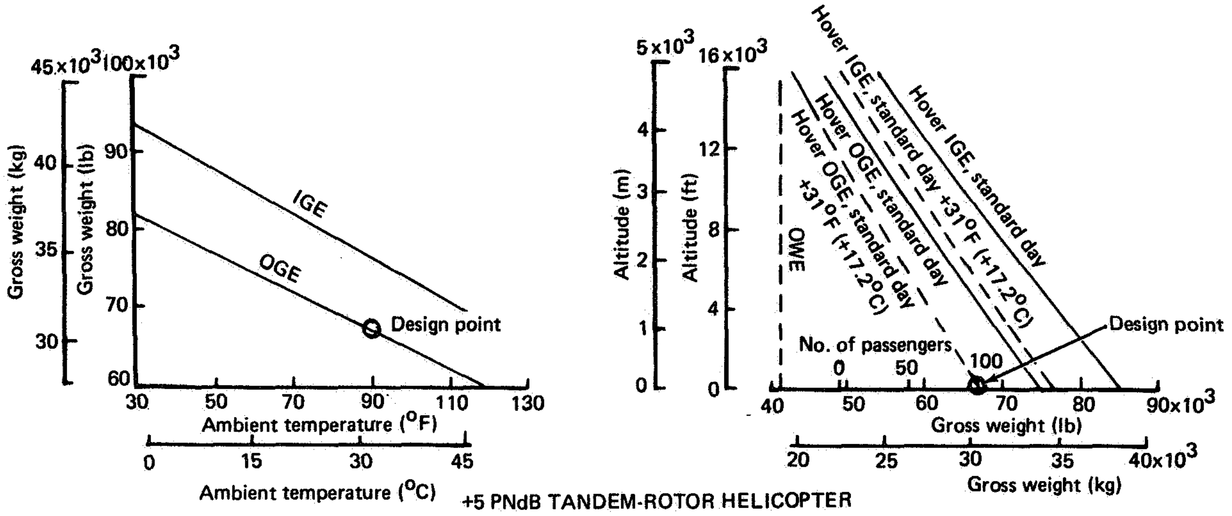
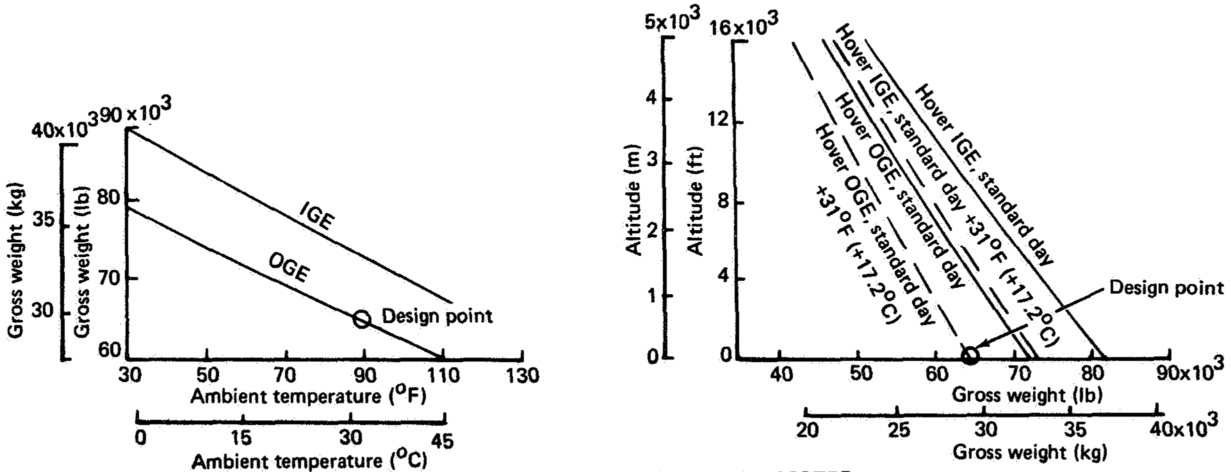


Figure 16. Effect of Ambient Temperature and Altitude on Takeoff and Landing Performance of VTOL Tilt-Rotor Aircraft with All Engines Operating

BASELINE TANDEM-ROTOR HELICOPTER



+5 PNdB TANDEM-ROTOR HELICOPTER



–5 PNdB TANDEM-ROTOR HELICOPTER

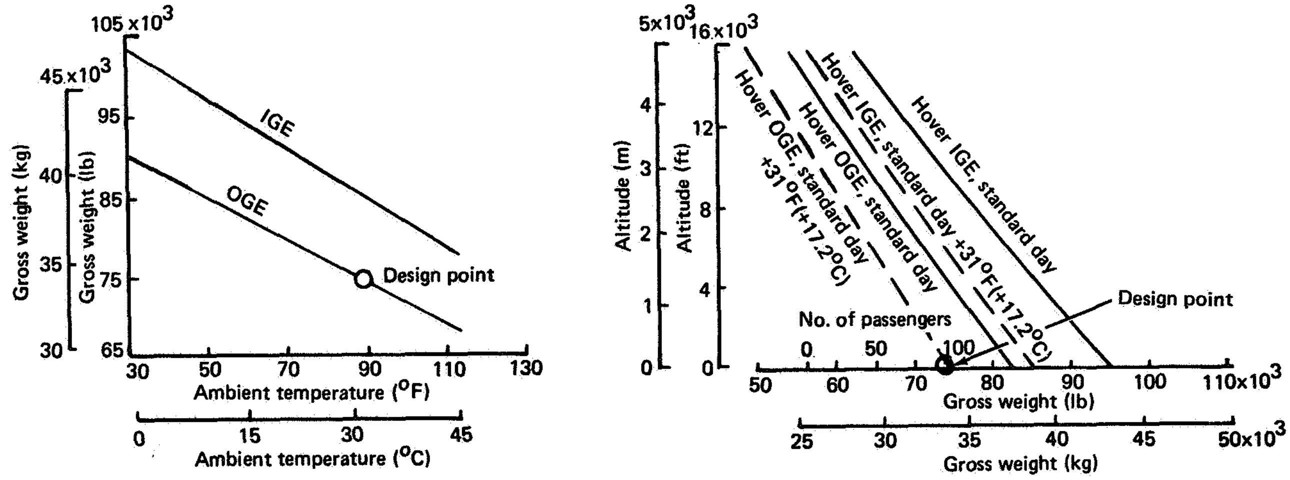


Figure 17. Effect of Ambient Temperature and Altitude on Takeoff and Landing Performance of VTOL Tilt-Rotor Aircraft with One Engine Inoperative

TABLE XVI
TAKEOFF AND LANDING GROUND RULES FOR STOL TILT-ROTOR AIRCRAFT

TAKEOFF (Sea level, 90°F)	LANDING (Sea level, 90°F)
Acceleration: Rolling friction coefficient, $\mu = 0.03$ All engines operating Liftoff speed: $V_{LOF} \geqslant 1.05$ (V_{MCA} and V_{MCG}) Rotation: 8 deg/sec maximum Climbout conditions to 35-ft obstacle: • AEO: Climb gradient $\geqslant$ 6.7%(15:1) (gear down) • OEI: **Climb gradient** $\geqslant$ 6.7%(15:1) (gear up) $\alpha \leqslant (\alpha_{STALL} - 10^\circ)$ (gear down) Speed at obstacle: $V_2 \geqslant V_{LO} \geqslant 1.15\, V_{MCA} \geqslant V_{MCA} + 10$ kt Factors for field length: 1.15 for AEO 1.00 for engine cut at liftoff 1.00 for accelerate-stop	Approach speed: (Speed at 35-ft obstacle) $V_{AP} \geqslant 1.15\, V_{MCA} \geqslant V_{MCA} + 10$ kt $\alpha \leqslant (\alpha_{STALL} - 10^\circ)$ *Landing climbout gradient:* • AEO: Climb gradient = 3.33% (30:1) (gear down) • OEI: Climb gradient = 3.33% (30:1) (gear up) Flight path from 35 ft: Maximum rate of descent at 35 ft = 800 fpm Maximum rate of descent at touchdown = 300 fpm Rotation: 8 deg/sec maximum Deceleration: 1 sec time delay Braking friction coefficient, $\mu = 0.35$ 0.4g maximum deceleration on ground Factor for field length: Landing distance from 35 ft divided by 0.7

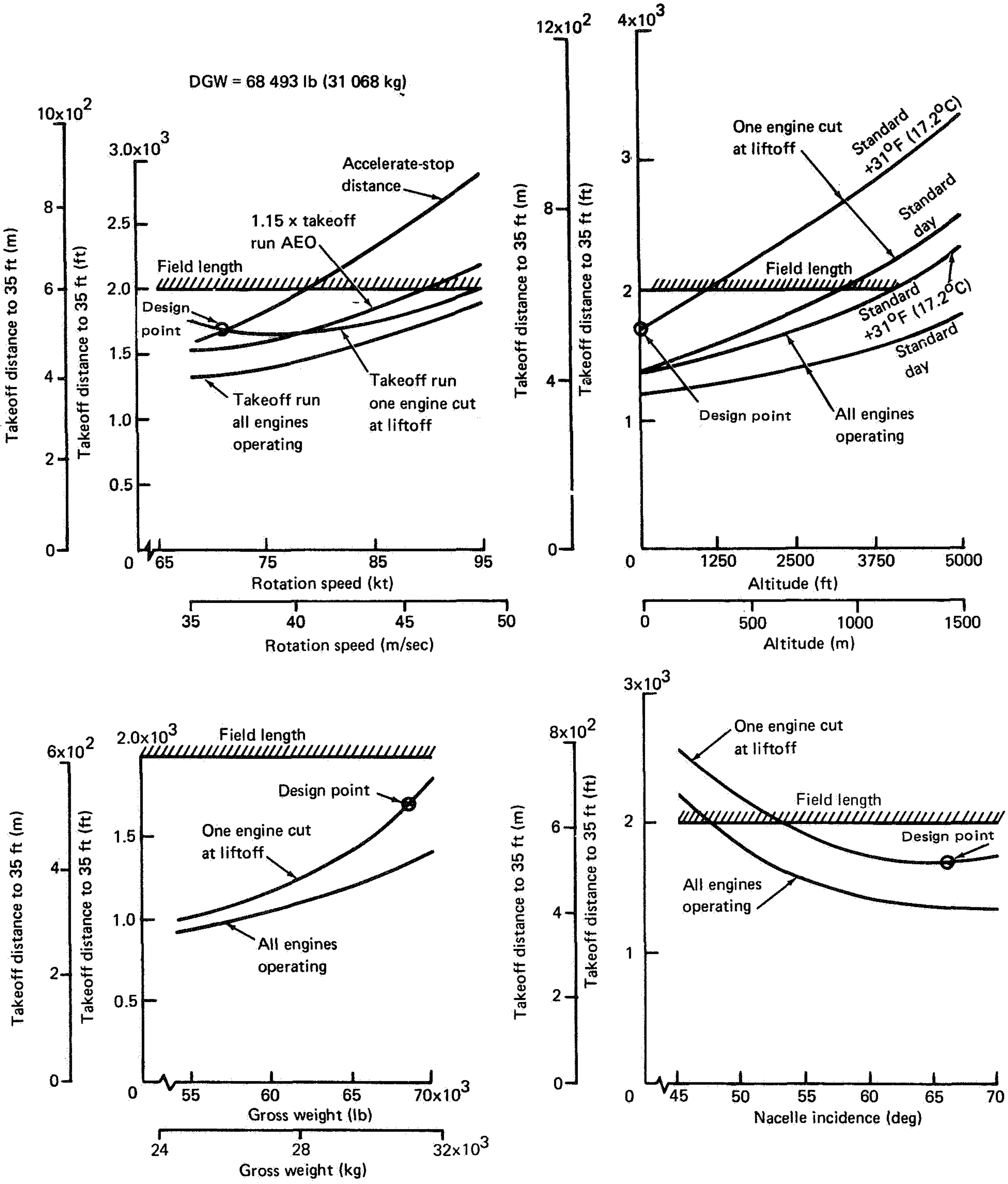


Figure 18. Takeoff Performance of STOL Tilt-Rotor Aircraft

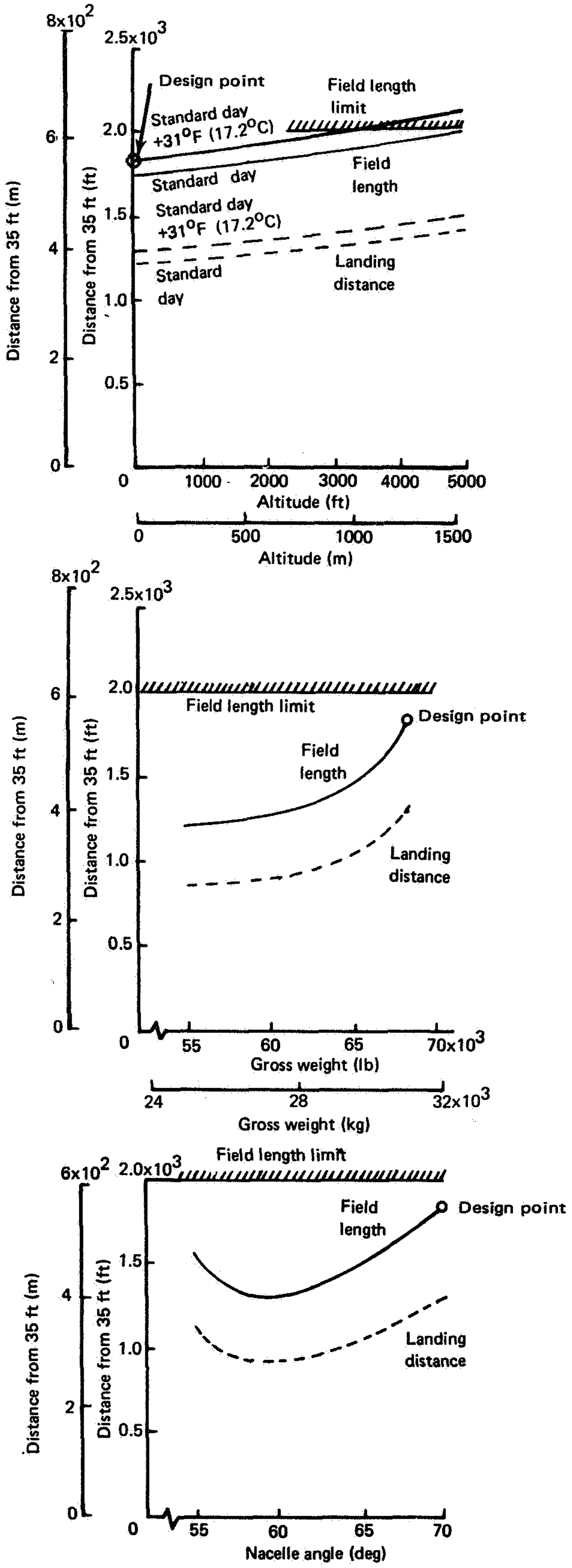


Figure 19. Landing Performance of STOL Tilt-Rotor Aircraft

Most of the groundrules in Table XVI are self-explanatory, but those related to liftoff and approach speeds and those defining field length will be explained here. The stall margin on angle of attack is to prevent sudden changes of lift that require large rapid control applications.

The minimum control speeds V_{MCA} (air) and V_{MCG} (ground) were mentioned merely for convention; in this context they have little significance. The control of the aircraft at very low speeds is effected by means of rotor cyclic pitch, differential cyclic pitch, and differential collective pitch adjustments. As speed is increased the normal flight controls are phased in so that at cruise speed conventional control surfaces are sufficient. The control system design is an exercise beyond the scope of this study, and it is sufficient to note that enough control can be designed into the system at any given minimum speed. The VTOL tilt-rotor is, of course, controllable at all speeds down to the hover condition.

Three eventualities are considered in determining the takeoff field length. First, a completely normal takeoff is assumed and the distance to achieve a wheel height of 10.67 meters (35 feet) is estimated. Second, an estimate is made of the distance to achieve 10.67 meters (35 feet) above the ground in the event that one engine fails at the liftoff point. Emergency operation of the remaining three engines at a 9-percent increased power level is assumed. In the third case, the distance covered when the takeoff is aborted at the liftoff point is estimated. The calculation assumes there is a one-second time delay between the liftoff point and the application of brakes and that an average deceleration of 0.35g may be achieved on the ground. The takeoff field length is then defined as the most critical of 115 percent of the normal takeoff distance, the engine out at liftoff distance, and the accelerate-stop distance.

The landing field length is simply a factor of the distance required to land from 10.67 meters (35 feet). This factor is 1/0.7, allowing for variations in pilot technique, local conditions, etc.

The upper part of Figure 18 shows the takeoff performance (field length) as it varies with rotation speed, ambient conditions, gross weight, and nacelle incidence. On each graph the selected design condition has been indicated.

Figure 18 shows the variation with rotation speed of the takeoff distance to 35 feet with all engines operating and the three candidate distances for field length. It will be seen that the design condition lies close to the minimum field length defined by the intersection of the accelerate-stop and one-engine-out distances. The aircraft can apparently operate from a 609.6-meter (2000-foot) field with a wide tolerance on the rotation speed. The design liftoff speed of 71 knots, however, is the minimum speed at which sufficient moment is obtained from the horizontal tail to rotate the aircraft about its main landing gear.

The performance degrades with altitude and with temperature, and the effect of increasing gross weight is also adverse as shown in Figure 18. Figure 18 also shows that the aircraft could takeoff within the 609.6-meter (2000-foot) field length at gross weights higher than the design value, but this does not happen in practical cases as the load factor limitation would be exceeded.

The variation of takeoff distance with rotor nacelle incidence is given in Figure 18. The design condition was chosen to be near optimum with respect to nacelle incidence.

The landing performance, as shown in Figure 19 is degraded by increasing altitude and temperature and by increasing gross weight. The maximum landing weight is constrained to be no greater than the takeoff gross weight.

The effect of nacelle angle on landing performance is shown in Figure 19. The design condition is far from the apparent optimum incidence setting; however, in order to land with a lower nacelle setting fuselage attitude would have to be increased to an abnormally nose-high attitude. Such a landing configuration would be impractical because of the unwieldly landing gear that would be required and the poor pilot visibility that would result.

Forward Flight Performance

The economics of aircraft operations are dictated to a large extent by the forward flight efficiency of the configuration. During the study the vehicle configurations and performance were optimized to achieve high forward flight speed to minimize direct operating costs, aircraft size, and initial acquisition costs. The optimization study had the minimum direct operating cost requirement as the primary objective. The details showing the impact of cruise altitude, design cruise speed, and fundamental configuration parameters on direct operating costs are detailed in References 1 and 3.

Rate of Climb Performance

Climb performance as a function of altitude is given in Figure 20 (for the baseline vehicles). Data for conditions of all engines operating and one engine inoperative at design gross weight and operating weight empty are shown. This performance is calculated with the engines at the 30-minute-rating power level. The data

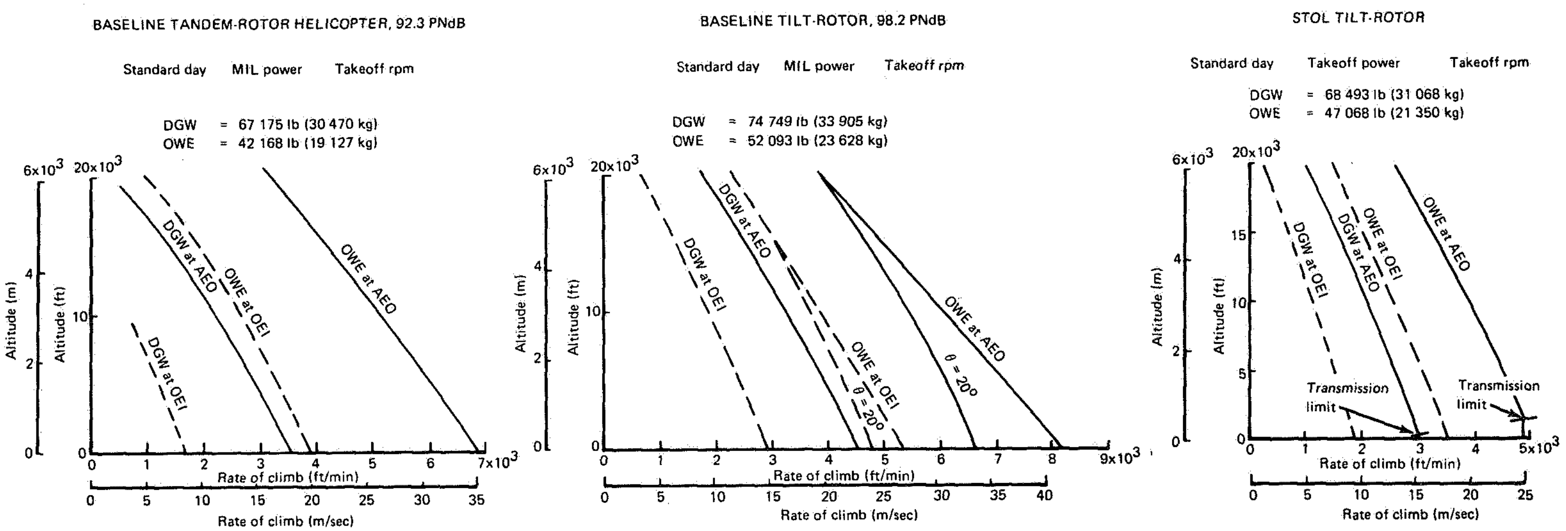


Figure 20. Climb Performance as a Function of Altitude for the Baseline Vehicles with All Engines Operating and with One Engine Inoperative

for the tilt-rotor vehicles show the climb performance at a fuselage attitude restricted to 20° in addition to the maximum climb capability.

At design gross weight at sea level condition, the tandem-rotor helicopter climb capability is 1082 m/min (3550 ft/min), the VTOL tilt-rotor is 1402 m/min (4600 ft/min), and the STOL tilt-rotor is 914 m/min (3000 ft/min). The rate of climb advantage for the VTOL tilt-rotor results from its lower minimum power required and its greater installed power. The reduced installed power of the STOL tilt-rotor is reflected in its reduced rate of climb relative to the VTOL tilt-rotor.

Climb performance of the noise criteria derivative helicopters is given in Figure 21. The -5 PNdB helicopter's rate of climb is improved relative to the baseline vehicle by 122 m/min (400 ft/min), while the +5 helicopter's is reduced by 122 m/min (400 ft/min) at sea level. This is a result of the changes to the induced power of the rotor due to higher and lower rotor solidity used to obtain the takeoff noise levels and maintain an adequate maneuver margin in cruise.

Climb performance of the noise derivative VTOL tilt-rotors is given in Figure 22. A comparison of these data with the baseline VTOL aircraft indicates that the -5 PNdB aircraft has the same rate of climb capability at design gross weight as the baseline, while the quieter -5 PNdB aircraft has a 213 m/min (700 ft/min) improvement. This is because the quieter vehicle has increased installed power while the noisier vehicle has essentially the same installed power as the baseline VTOL tilt-rotor.

Cruise Performance

Cruise performance as indicated by the vehicle specific range is shown in Figures 23 through 25. These data for the helicopters are for sea level and 1524-meter (5000-foot) altitudes, standard day conditions. For the STOL and VTOL tilt-rotor, data is calculated for 1524-meter (5000-foot) and 4267-meter (14 000-foot) altitudes. All data are for all-engines-operating conditions.

Figure 23 shows that the baseline helicopter has a peak specific range at design gross weight of 0.077 km/kg (0.065 n mi/lb). The comparable value for the VTOL tilt-rotor is 0.0947 km/kg (0.080 n mi/lb), while the STOL tilt-rotor has a peak value of 0.122 km/kg (0.103 n mi/lb). This comparison at 1524 meters (5000 feet) is indicative of the configuration characteristics. The 2:1 ratio of the VTOL tilt-rotor compared to the tandem-rotor helicopter is a result of the advantage of the tilt-rotor in cruise lift-to-drag ratio.

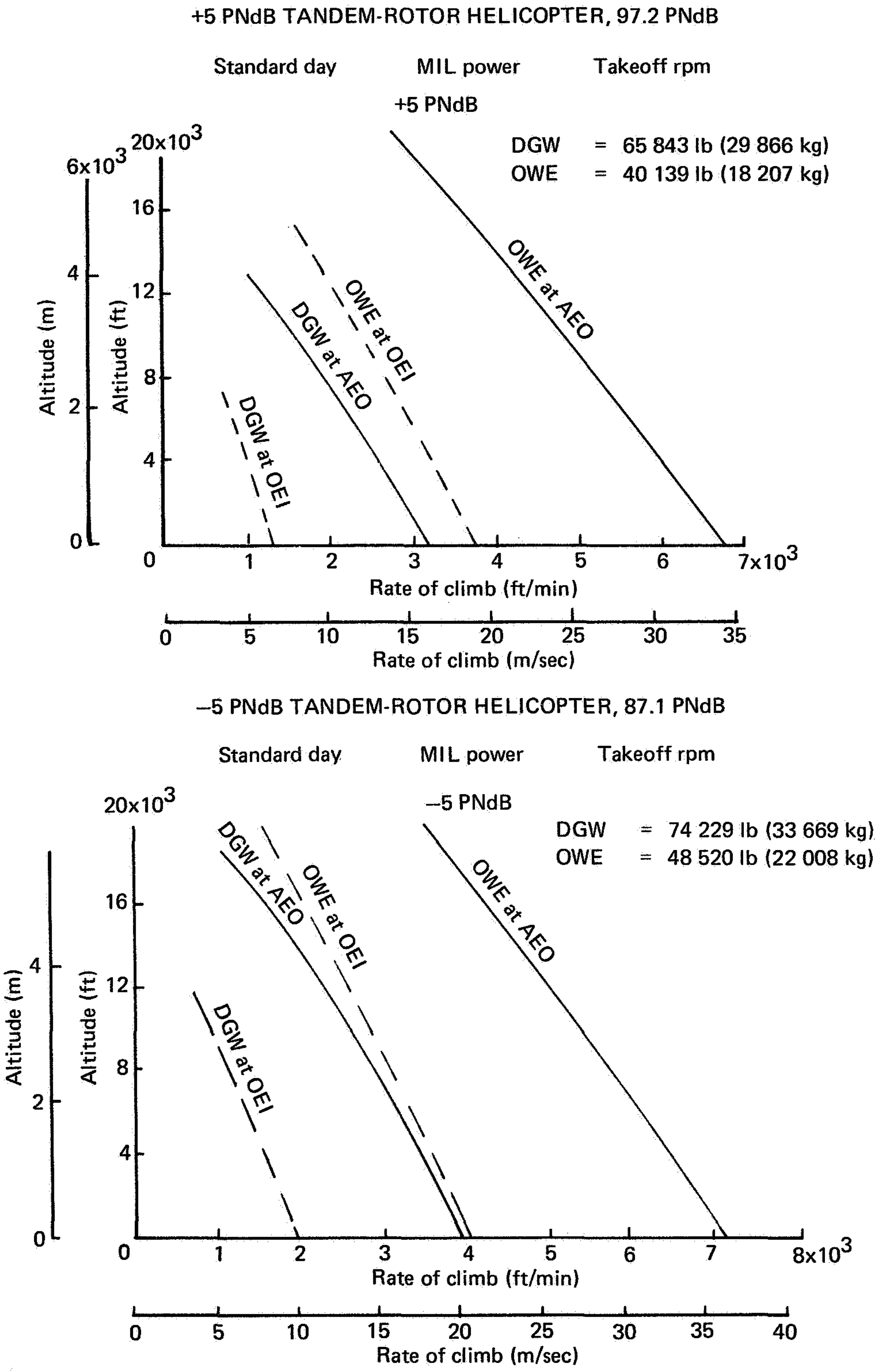
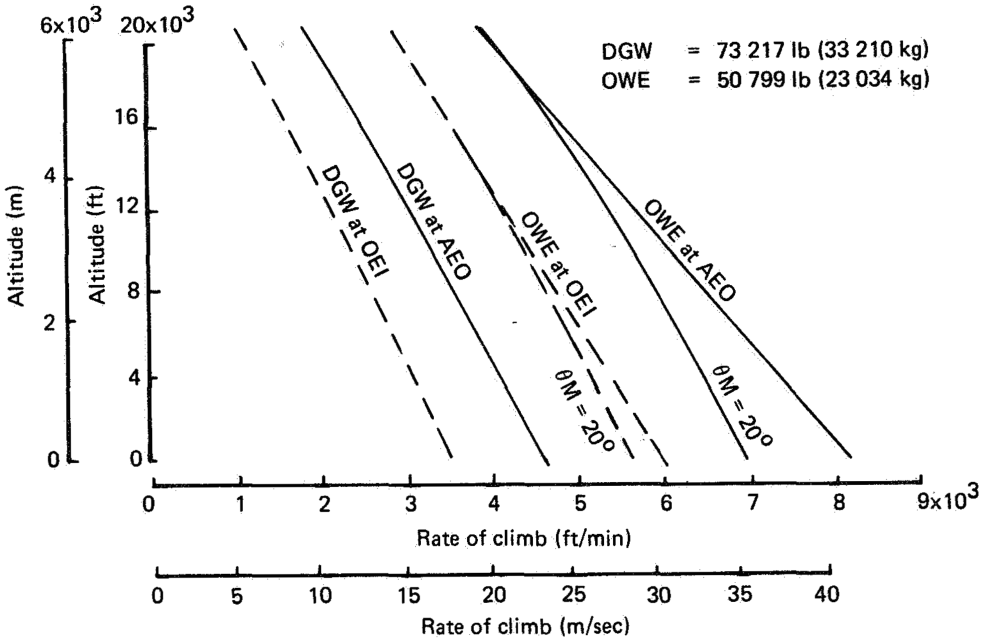


Figure 21. Climb Performance of the Noise Derivative Tandem-Rotor Helicopters with All Engines Operating and with One Engine Inoperative

+5 PNdB TILT-ROTOR, 103.2 PNdB

Standard day MIL power Takeoff rpm



−5 PNdB TILT-ROTOR, 93.4 PNdB

Standard day MIL power Takeoff rpm

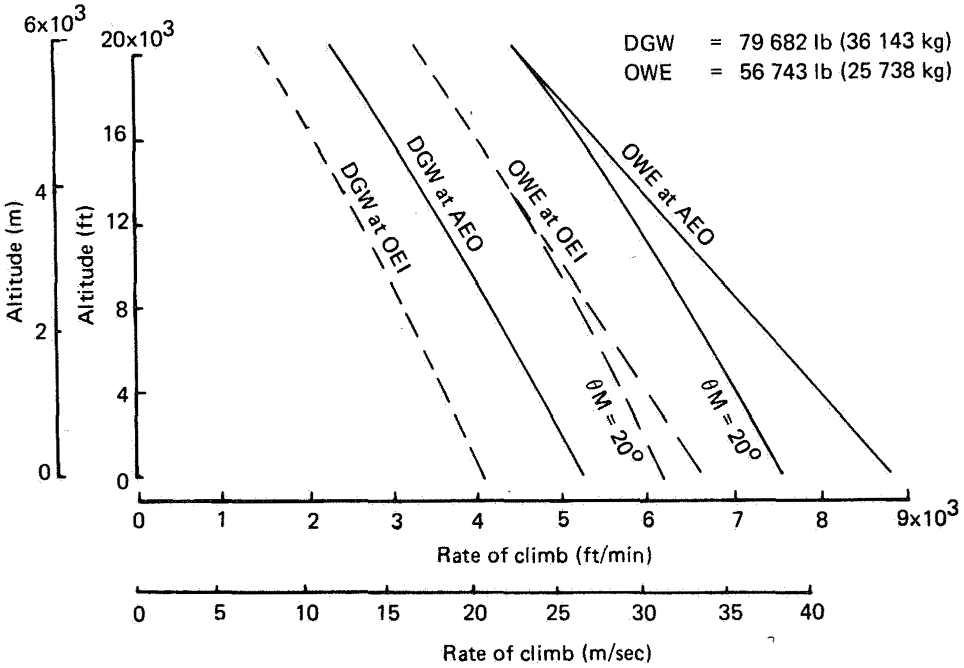


Figure 22. Climb Performance of the Noise Derivative Tilt-Rotor Aircraft with All Engines Operating and with One Engine Inoperative

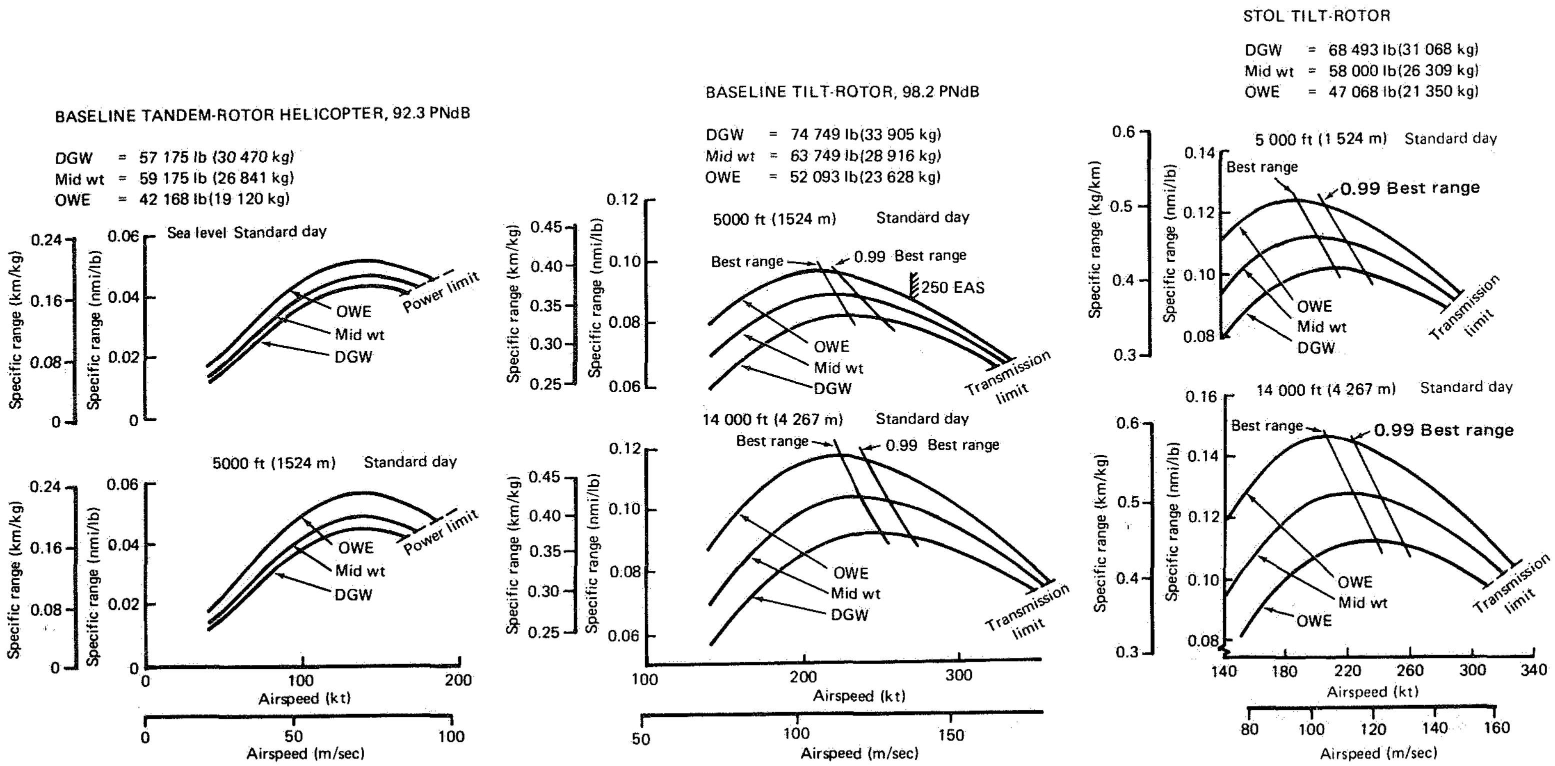


Figure 23. Cruise Performance as Indicated by Vehicle Specific Range for the Baseline Aircraft, All Engines Operating

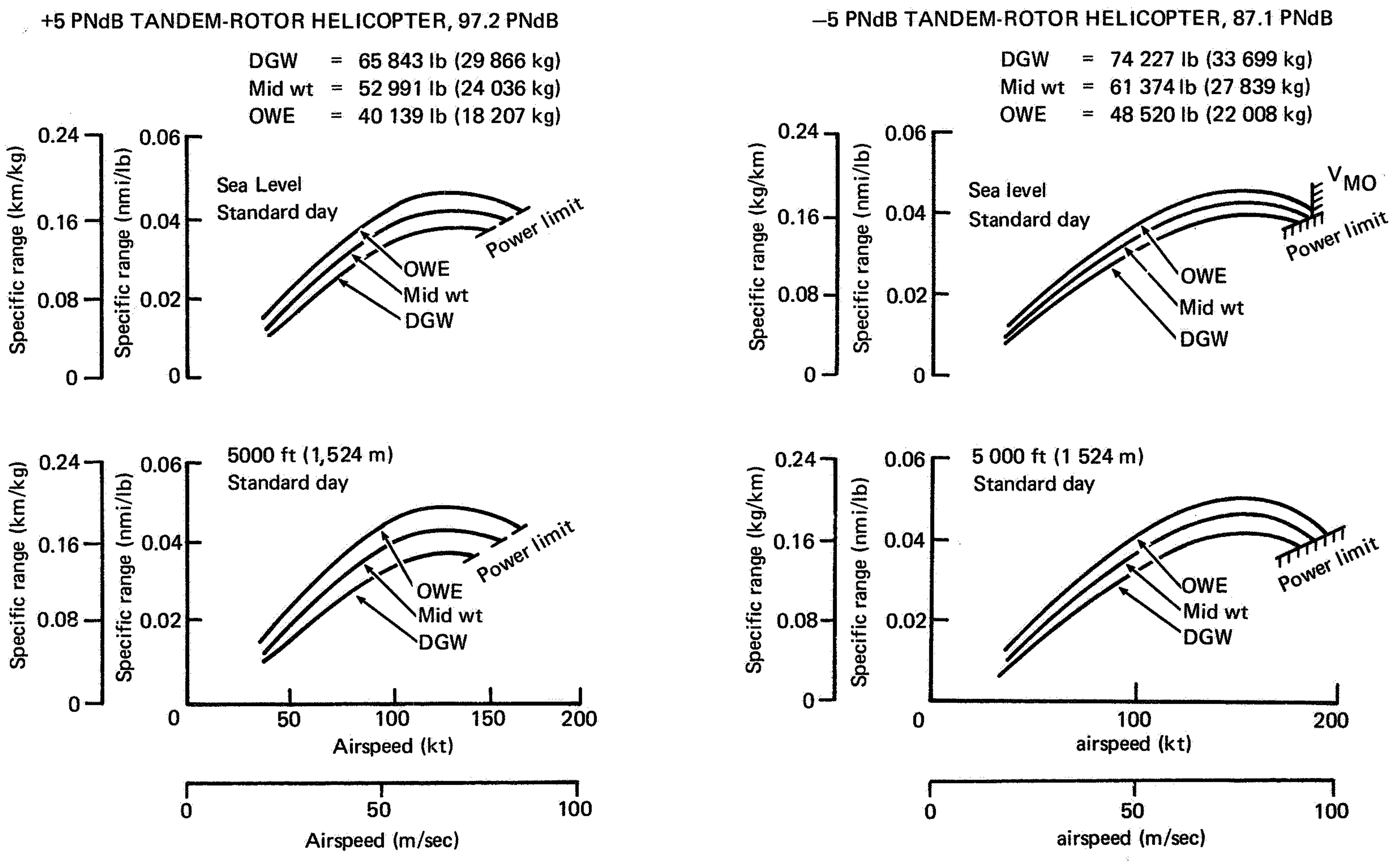


Figure 24. Cruise Performance as Indicated by Vehicle Specific Range for the Noise Derivative Tandem-Rotor Helicopters, All Engines Operating

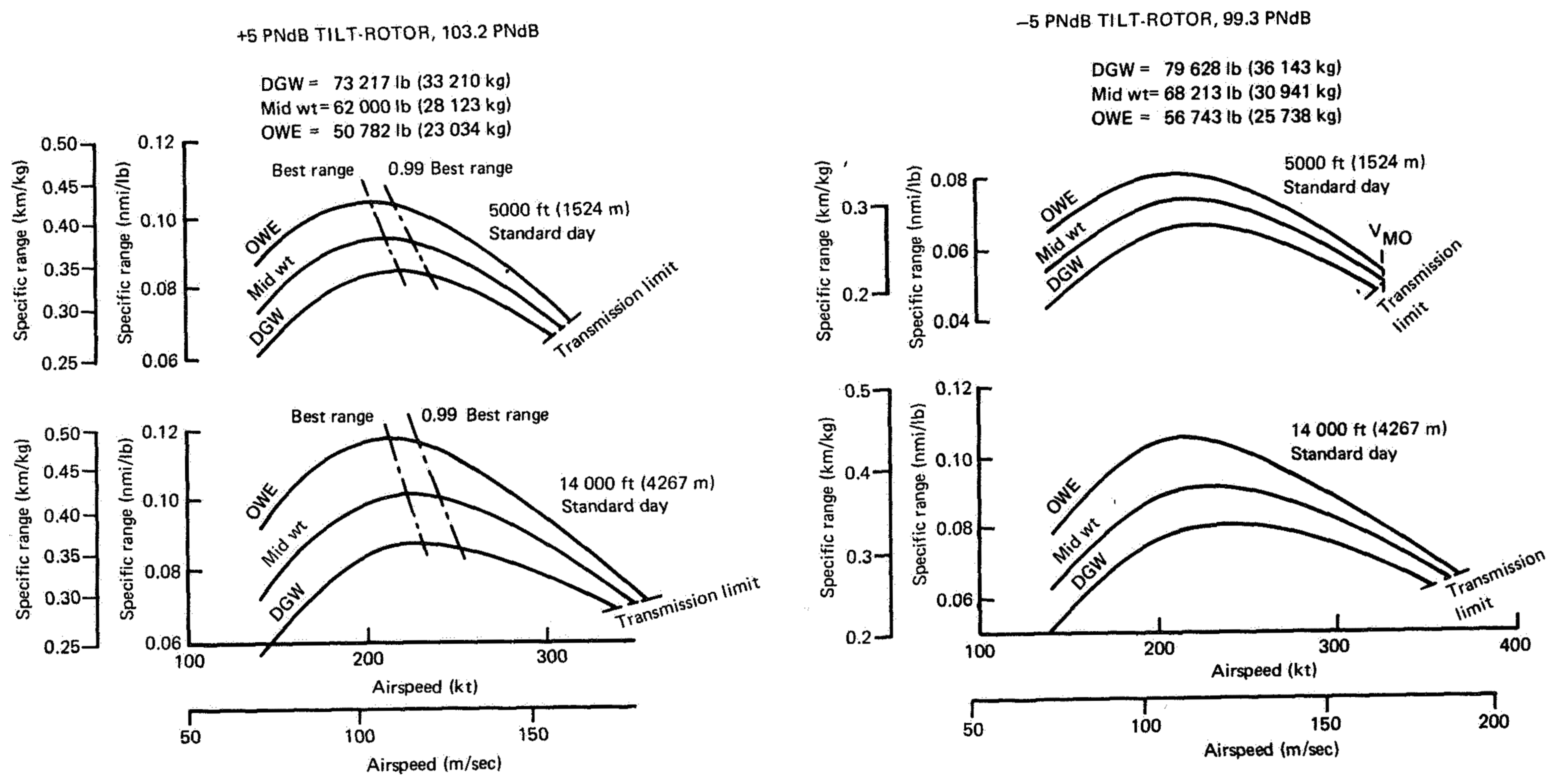


Figure 25. Cruise Performance as Indicated by Vehicle Specific Range for the Noise Derivative Tilt-Rotor Aircraft, All Engines Operating

The STOL tilt-rotor has a higher specific range than the VTOL tilt-rotor due to an improved lift-to-drag ratio, higher aspect ratio, and lower specific fuel consumption that results from lower installed power and higher power fractions in cruise.

The specific range performance of the noise criteria derivative aircraft are shown in Figures 24 and 25. The fuel consumption of the ±5 PNdB vehicle is slightly worse than the baseline aircraft for both helicopter and tilt-rotor configurations.

The level flight maximum speed as a function of cruise altitude data is given in Figures 26 through 28. These data are for the vehicles operating at normal rated power setting, rotor cruise rpm, and design gross weight and operating weight empty. Speed capability with all engines operating and one engine inoperative is presented.

The baseline helicopter at a design gross weight of 30 470 kilograms (67 175 pounds) can achieve 165 knots at the design cruise altitude of 1524 meters (5000 feet). With one engine inoperative the speed attainable is 148 knots. At this altitude the maximum speed achieved is 181 knots at operating weight empty.

The baseline VTOL tilt-rotor maximum level flight speed is 346 knots at design gross weight and 4267 meters (14 000 feet). Below this altitude speed is limited by the transmission torque capacity. With one engine inoperative, the maximum speed is reduced to 304 knots.

At design gross weight, the STOL tilt-rotor has a maximum speed with all engines operating of 310 knots at 4267 meters (14 000 feet). Below this altitude the speed is limited by the transmission torque capability and above this altitude by the normal rated power available. At the operating empty weight, the transmission limit extends to an altitude of 4420 meters (14 500 feet), and the maximum speed is 326 knots with all engines operating.

With one engine inoperative, the cruise performance is not transmission limited at any altitude. At design gross weight the maximum speed with one engine inoperative of 270 knots occurs at sea level. The reduction in speed capability at higher altitudes reflects the degradation of engine performance (power available) with altitude.

The increased speed of the tilt-rotor aircraft over the helicopter is a result of the lift-to-drag advantage and the high propulsive efficiency of the tilt-rotor. The VTOL tilt rotor's 38 knot advantage over the STOL vehicle results from the higher installed power required by the hover takeoff sizing criterion.

The speed-altitude performance of the noise derivative helicopters is given in Figure 27. These data indicate that the quieter

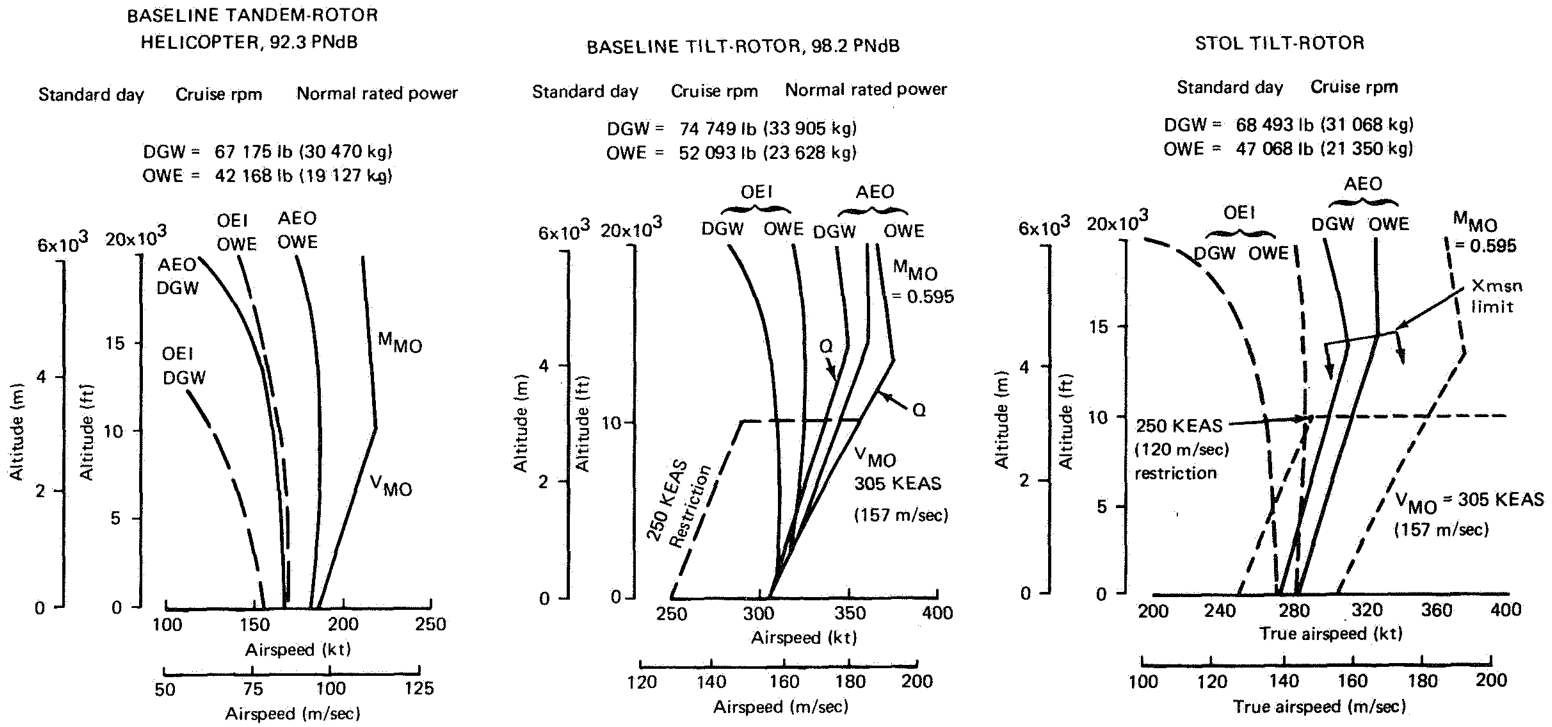


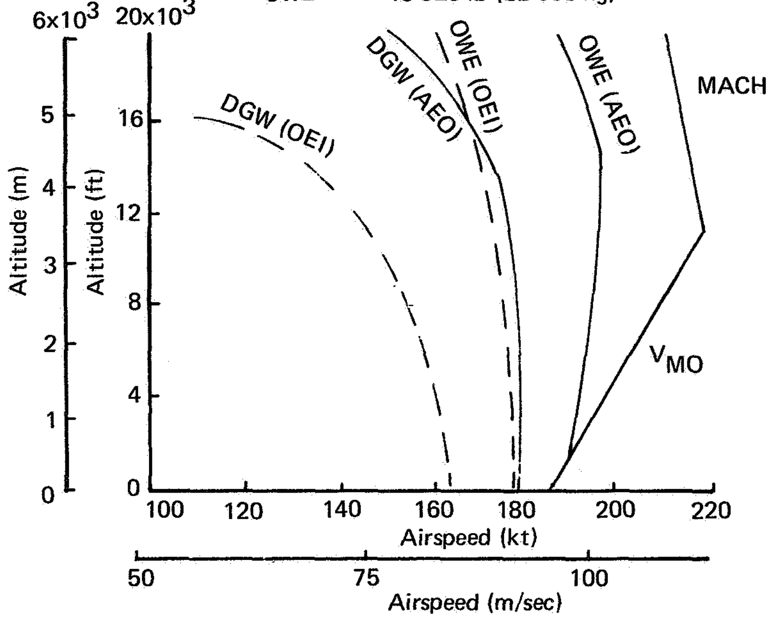
Figure 26. Cruise Performance as a Function of Altitude for STOL Tilt-Rotor Aircraft with All Engines Operating and with One Engine Inoperative

–5 PNdB TANDEM-ROTOR HELICOPTER, 87.1 PNdB

Standard Day   Normal rated power   Cruise rpm

DGW = 74 227 lb (33 669 kg)

OWE = 48 520 lb (22 008 kg)



+5 PNdB TANDEM-ROTOR HELICOPTER, 97.2 PNdB

Standard day   Normal rated power   Cruise and hover rpm

DGW = 65 843 lb (29 866 kg)

OWE = 40 139 lb (18 207 kg)

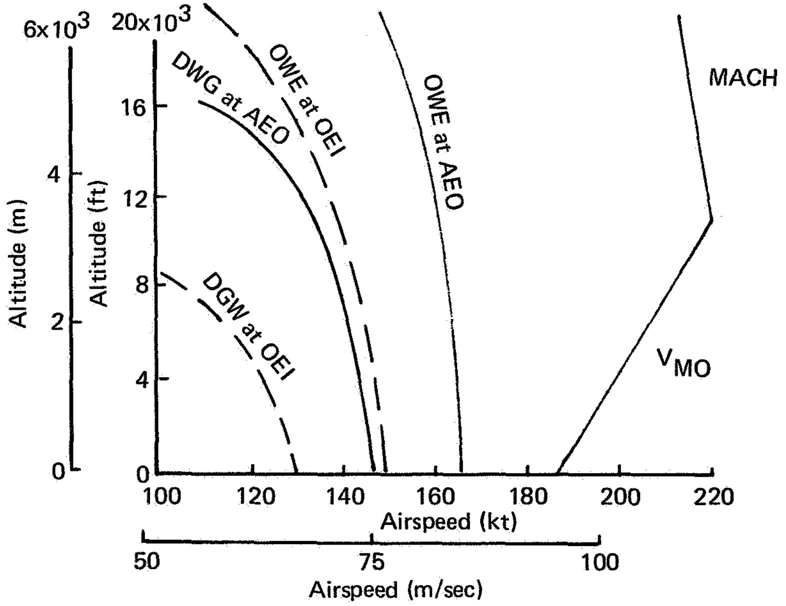
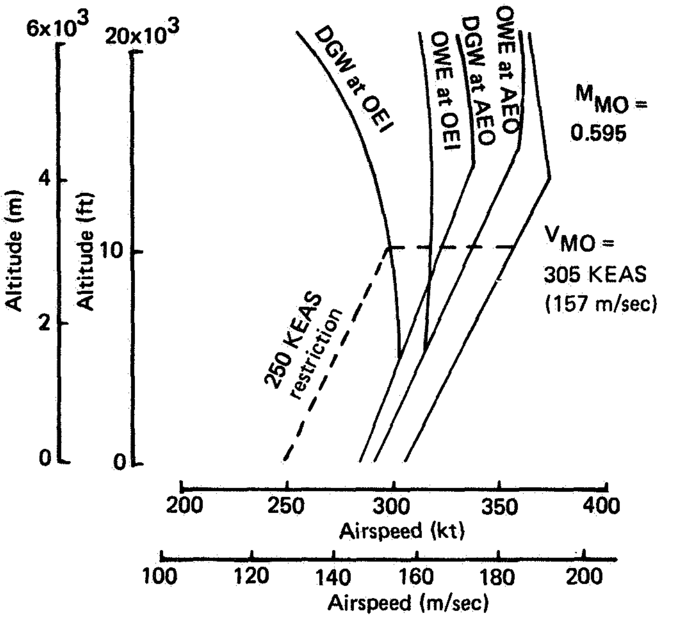


Figure 27. Speed/Altitude Performance of Noise Derivative Tandem-Rotor Helicopters with All Engines Operating and with One Engine Inoperative

+5 PNdB TILT-ROTOR, 103.2 PNdB

Standard day Normal rated power Cruise rpm

DGW = 73 217 lb (33 210 kg)
OWE = 50 782 lb (23 034 kg)



−5 PNdB TILT-ROTOR, 93.4 PNdB

Standard day Normal rated power Cruise rpm

DGW = 79 682 lb (36 143 kg)
OWE = 56 743 lb (25 738 kg)

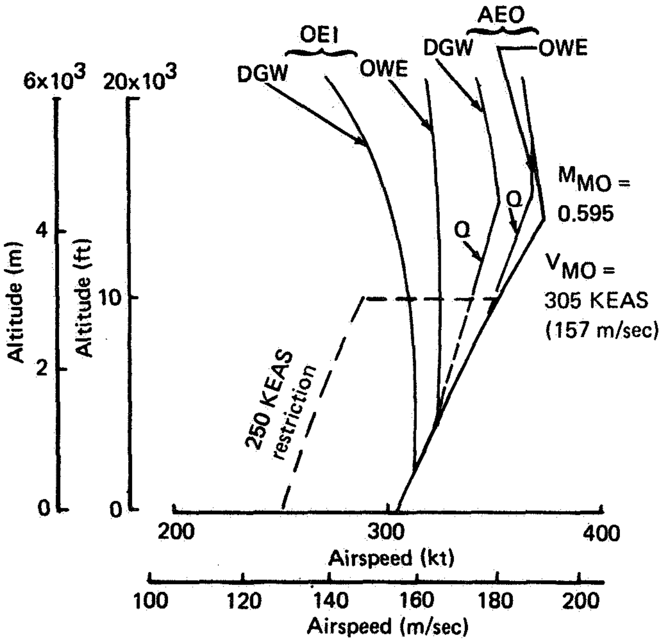


Figure 28. Speed/Altitude Performance of Noise Derivative

helicopter cruise speed is increased by 19 knots at cruise altitude while the noisier vehicle is reduced 20 knots relative to the baseline aircraft.

Noise derivative tilt-rotor aircraft speed-altitude performance is given in Figure 28. These vehicles exhibit the same effect of noise criteria on level flight speed capability as do the helicopters; namely, the quieter vehicle is somewhat faster and the noisier vehicle somewhat slower than the baseline VTOL tilt-rotor. The normal-rated-power speeds are ±8 knots relative to the baseline vehicle at design gross weight and 4267 meters (14 000 feet) cruise altitude.

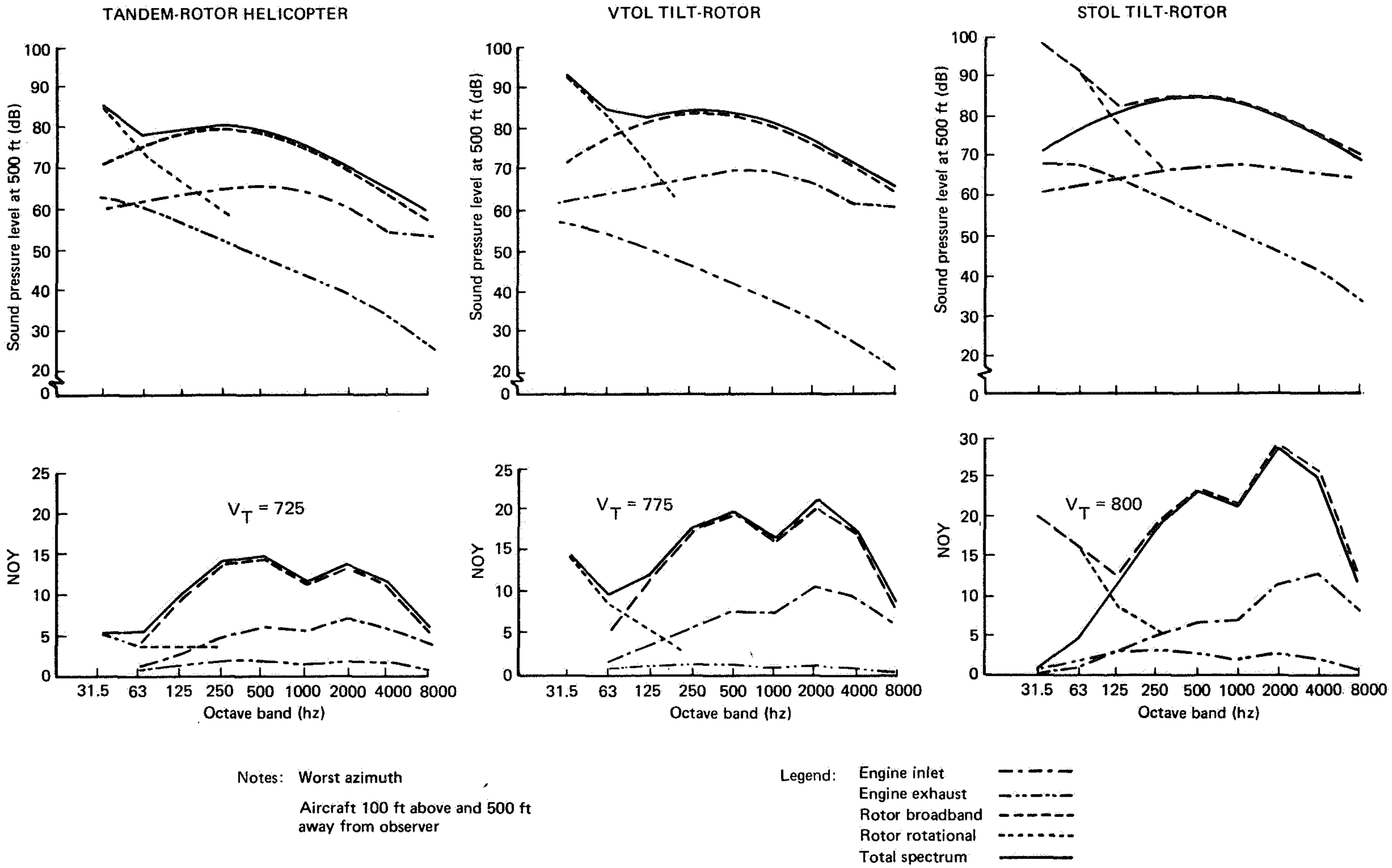
6. EXTERNAL NOISE

Noise pollution is one of the most important parameters to be considered in assessing community acceptance of future air vehicles for commercial operation. This is especially true of vehicles which, by virtue of their V/STOL performance, can operate from dispersed terminals close to areas of high population density.

Several different measures of assessing noise pollution have been suggested, and no universally accepted method exists. In order to provide a data base from which future comparisons can be drawn, the external noise levels of the aircraft have been assessed in three ways. The fundamental sound pressure level spectra are presented at the static thrust or maximum noise condition, and the corresponding perceived noise level is computed at a 152.4-meter (500-foot) sideline distance. The noise footprint areas or contours during takeoff and landing have also been estimated, and finally the perceived noise time histories along the vehicle flight path are shown.

6.1 EXTERNAL NOISE COMPARISON OF BASELINE CONFIGURATIONS

The sound pressure level spectra for the three baseline configurations are shown in Figure 29. These data are calculated at a 152.4-meter (500-foot) sideline distance in hover or at takeoff conditions. The overall sound pressure level for the tandem-rotor helicopter is set for most of the frequency range by the rotor to broadband noise, though at the very low frequencies the rotor rotational noise becomes dominant. Thus, the 92.3 PNdB value at 152.4-meter (500-foot) sideline is set primarily by rotor noise.



Notes: Worst azimuth

Aircraft 100 ft above and 500 ft away from observer

Figure 29. Sound Pressure Levels for the Baseline Aircraft

Unless special noise suppression measures are adopted, the engine inlet noise becomes dominant in the 4 kHz to 8 kHz octave bands. The engine inlet is therefore assumed to be treated for noise reduction by installing acoustic absorption linings. The inlet absorption lining has been tuned to two bands with centers of frequencies at 4 kHz and 8 kHz. This matched the engine signature to that of the rotor such that the rotor signature sets the perceived noise level value.

The noise spectra for the VTOL tilt-rotor vehicle, Figure 29, shows very similar characteristics. The rotor broadband noise is again the predominant contribution to the noise level. The engine inlet noise is considered to be suppressed by absorbtion linings in this case also. The increase in tipspeed and blade loading and the reduction in solidity of the tilt-rotor compared with the tandem-rotor helicopter result in higher sound pressure levels and a higher perceived noise level 98.2 PNdB at 152.4-meter (500-foot) sideline in hover.

The STOL tilt-rotor vehicle was considered at the start of the takeoff roll (i.e., maximum thrust) in order to provide a comparison. The sound pressure level data, shown in Figure 29, indicate the same fundamental spectrum shape and increased sound pressure levels. This is due to a further increase in tipspeed and reduction in solidity, by comparison with the tilt-rotor, although the reduction in thrust loading has a beneficial effect.

An alternate method of comparison of noise annoyance of the three aircraft types is to examine the area over which high noise levels will be experienced in takeoff and landing. The contour plots of constant perceived noise levels are shown for the three baseline aircraft in Figure 30. Although the tandem-rotor helicopter has a lower perceived noise level at 152-meter (500-foot) sideline in hover than either of the tilt-rotor configurations, the noise pollution area is significantly worse. Several factors influence this comparison. On takeoff the vehicle rate of climb has a large impact on the area of the contours. The tilt-rotor vehicles benefit from this by virtue of superior climb performance compared with the helicopter.

The landing cases are performed at the same descent rate for all three configurations although the some variations occur in the last 152.4-meter (500-feet) of altitude as a function of flare requirements and mode of landing. The two tilt-rotor configurations have lower noise areas in this case primarily resulting from the variation of nacelle incidence in the descent and the corresponding rpm changes.

The tandem-rotor helicopter rotor attitude is fairly constant, by comparison, and the definite directionality of the rotor noise elongates the ground noise contours. In the tilt-rotor cases, the aircraft are quiet in the cruise mode (i.e., nacelles down) and

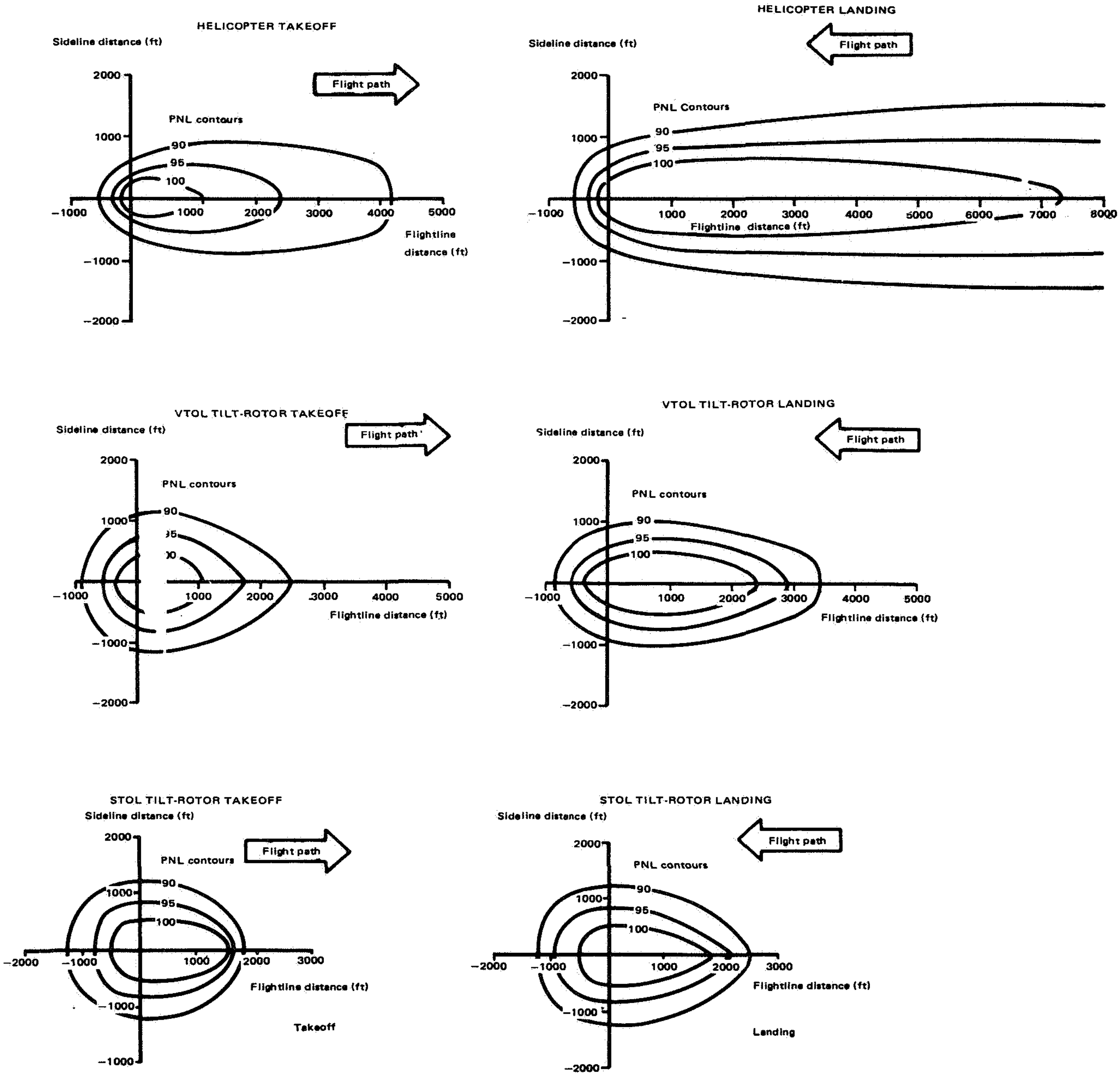


Figure 30. Perceived Noise Level Contours of Baseline Aircraft on Takeoff and Landing

the noise level increases as the nacelle incidence and rotor thrust are increased to the landing conditions.

The takeoff and landing profiles are shown in Figures 31 and 32, and time histories of perceived noise along the aircraft flight path are included. The peak noise values of the perceived noise time histories fall off faster for the tilt-rotor than for the helicopter on takeoff. This is again due to conversion and the low noise level of the tilt-rotor configuration in cruise. The reverse of this procedure on landing shows as a sharp rise in peak noise level during conversion to the landing case, and explains the shorter noise contours of the tilt-rotor aircraft.

6.2 EXTERNAL NOISE CRITERIA DERIVATIVE DESIGNS

The noise derivative aircraft were designed to be 5 PNdB more and less noisy than the baseline aircraft at the 152.4-meter (500-foot) sideline distance in hover. The sound pressure level data in this condition for the three tandem-rotor helicopters is shown in Figure 33. The overall sound pressure levels are set primarily by the broadband rotor noise. The increased rotor tipspeed and solidity of the +5 PNdB tandem-rotor helicopter increases the broadband and rotational noise components and results in a higher sound pressure level. The impact of the higher frequency end of the spectrum plays the largest role in increasing the perceived noise level as a result of the NOY weighting.

The -5 PNdB tandem-rotor helicopter has reduced tipspeed and increased solidity. These effects reduce the broadband noise especially in the high-frequency range and account for the 5 PNdB decrease in static thrust noise level.

The baseline VTOL tilt-rotor and the two noise derivative tilt-rotors are compared on the same basis in Figure 34. The characteristics are much the same as the tandem-rotor helicopter vehicles with the increase and decrease in sound pressure level and perceived noise level being dictate by the variations in tipspeed and solidity.

The perceived noise level contours on takeoff and landing for both tandem-rotor helicopters and VTOL tilt-rotors are compared in Figures 35 and 36. The area included in the constant noise contour decreases as the static perceived noise level decreases.

The areas enclosed by the 95 PNdB contours for the tilt-rotor aircraft are about the same size or a little larger than for the tandem-rotor helicopters, as shown in Table XVII. In the landing case, the areas are much less for the tilt-rotor aircraft than for the tandem-rotor helicopter.

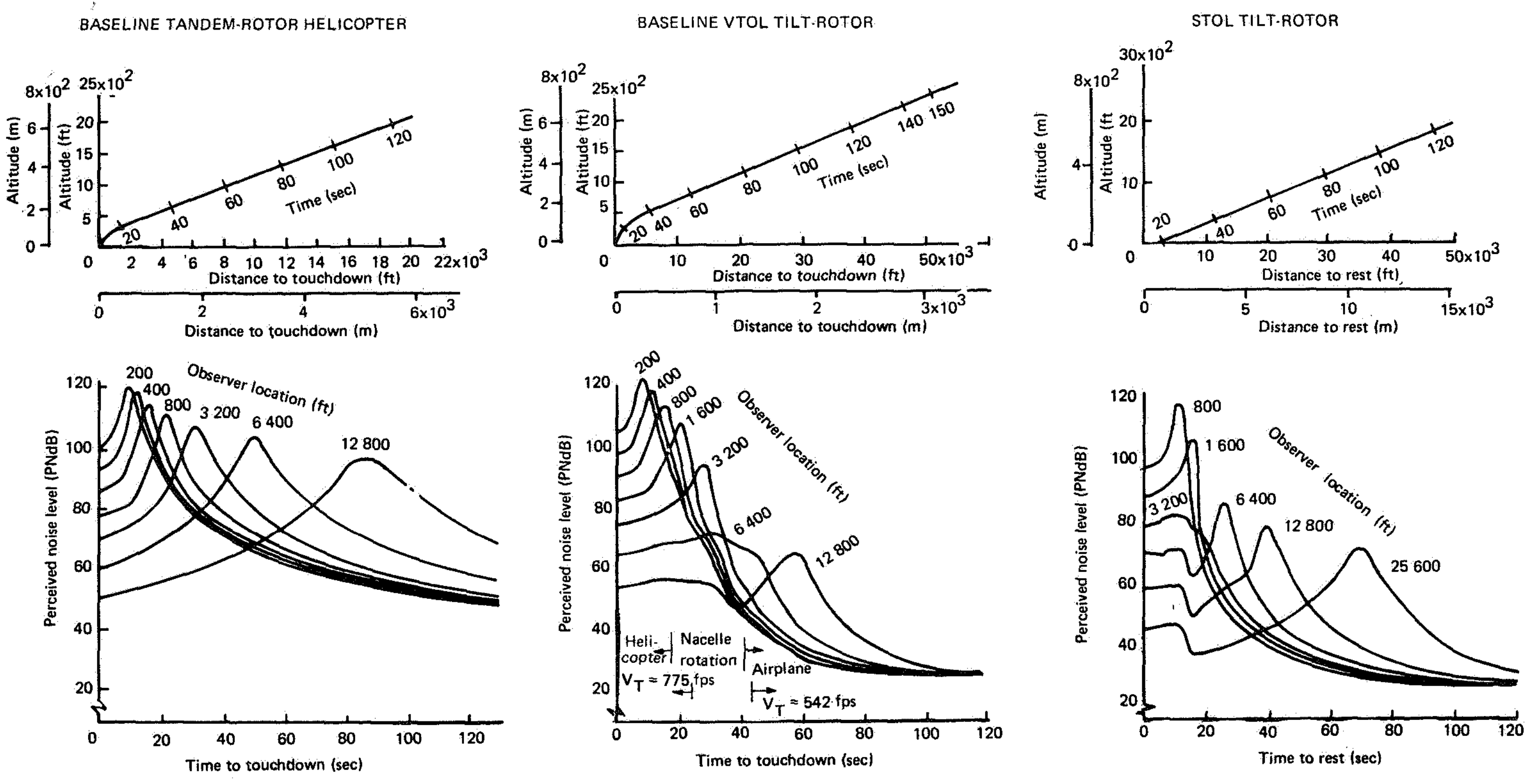


Figure 31. Landing Noise Profiles for the Baseline Aircraft

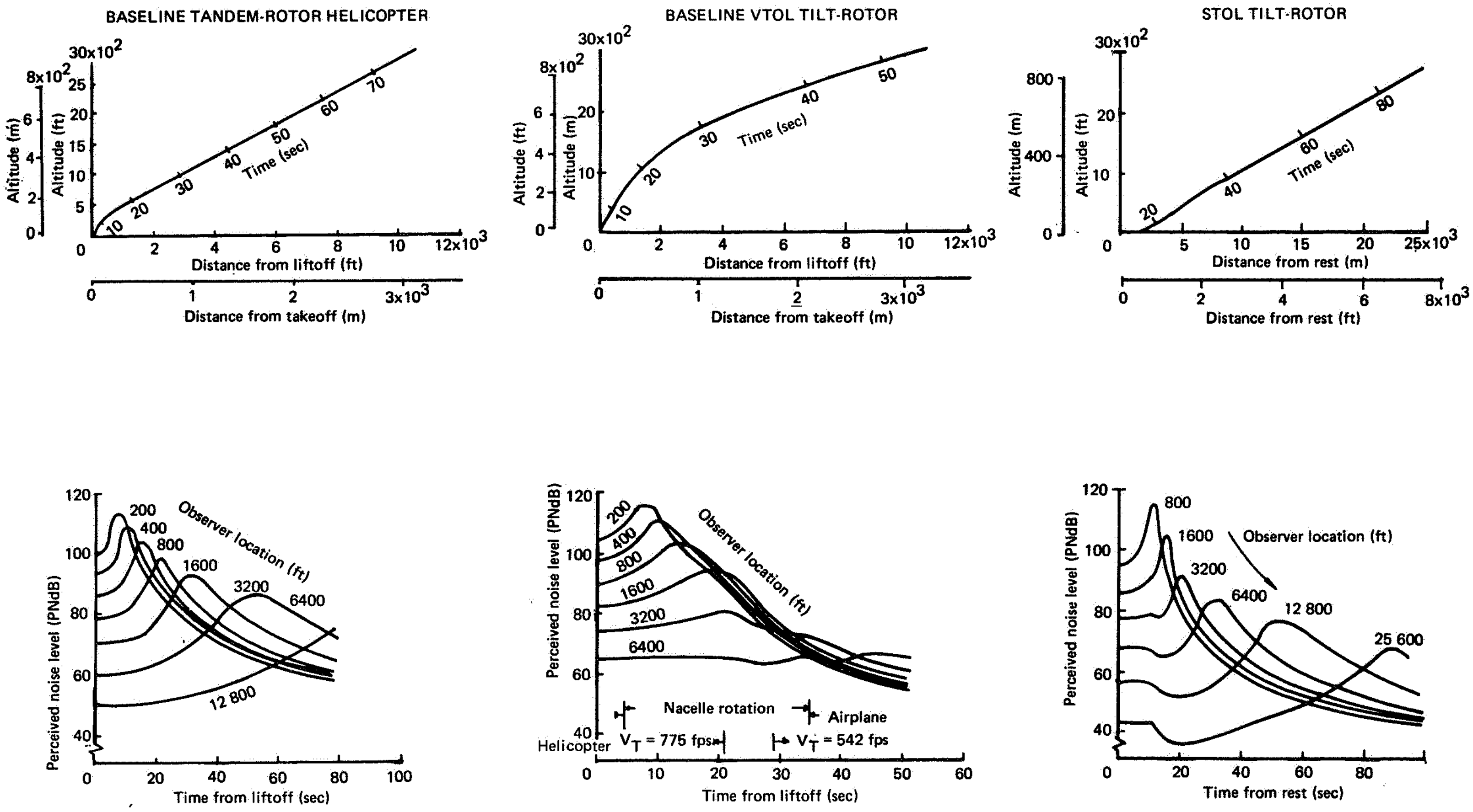


Figure 32. Takeoff Noise Profiles for the Baseline Aircraft

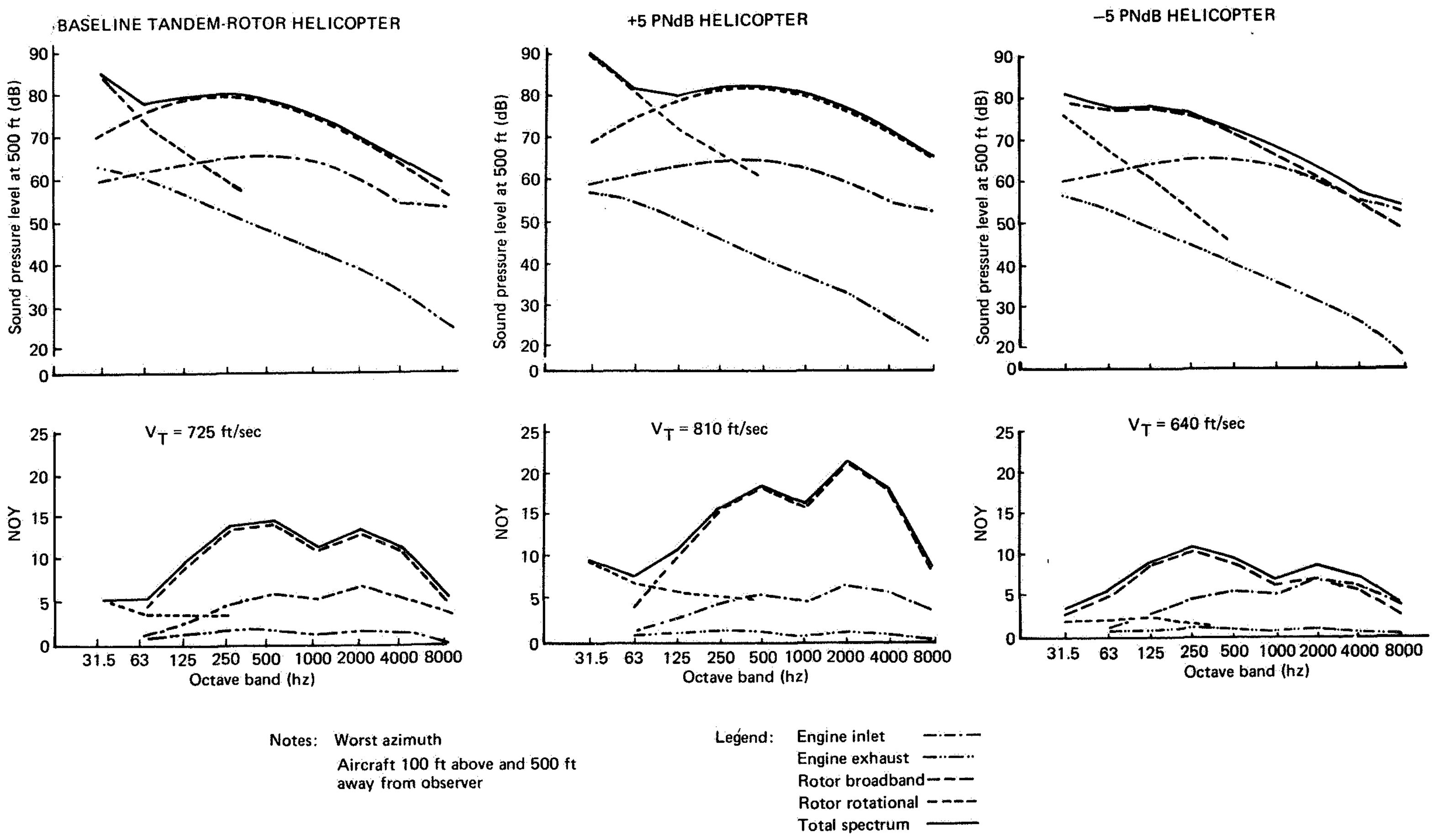
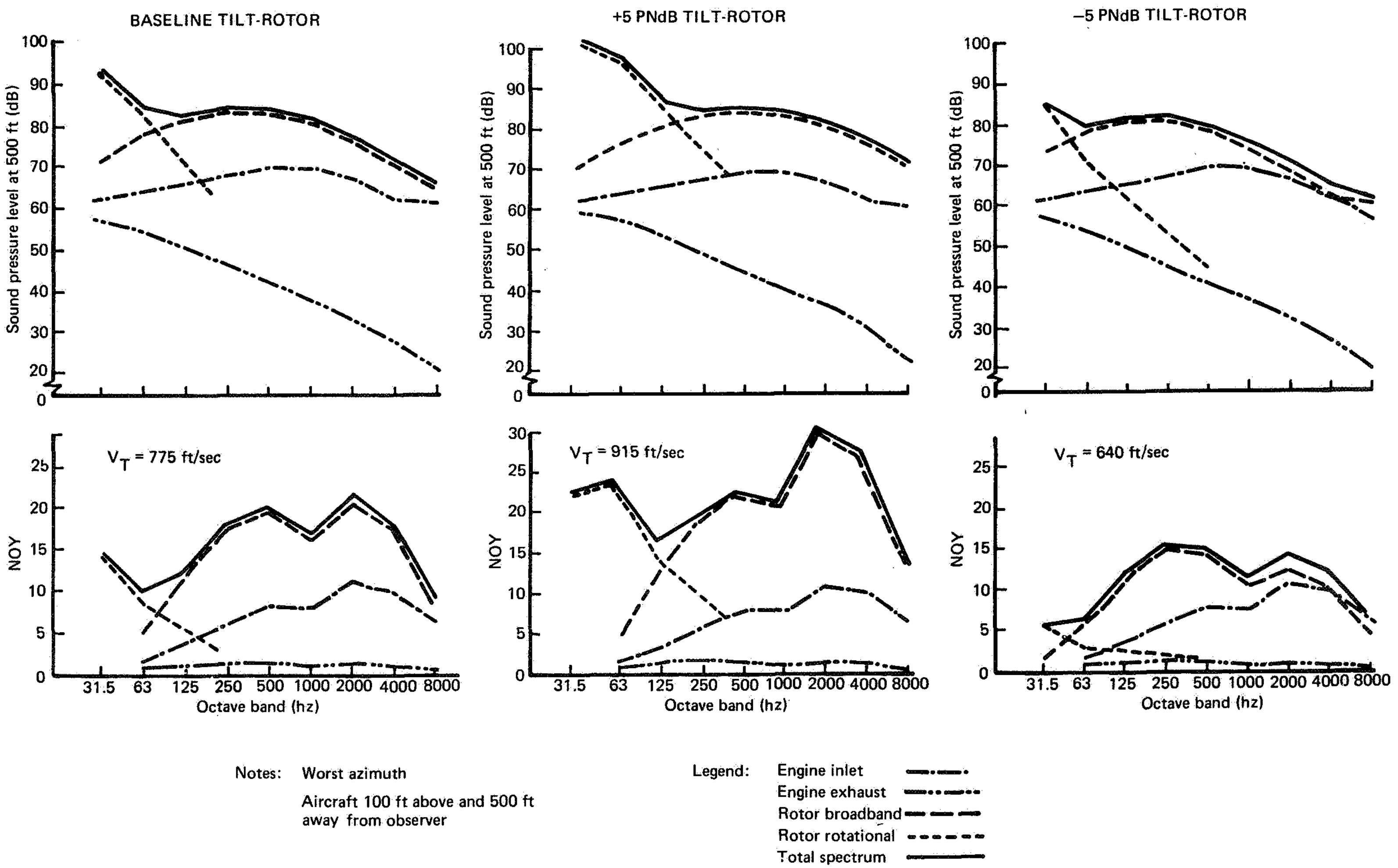


Figure 33. Sound Pressure Levels for the Noise Derivative Tandem-Rotor Helicopters



Notes: Worst azimuth

Aircraft 100 ft above and 500 ft away from observer

Legend: Engine inlet

Engine exhaust

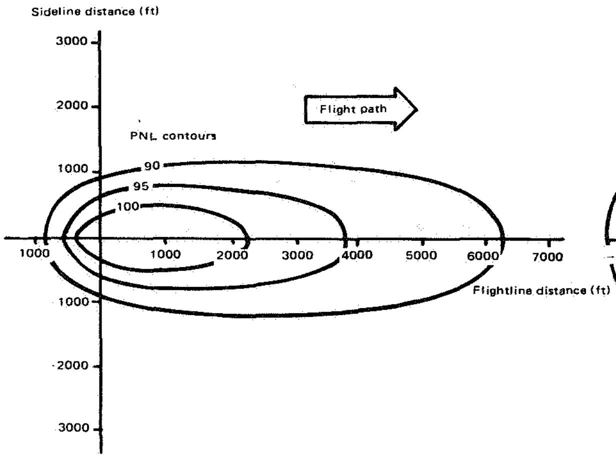
Rotor broadband

Rotor rotational

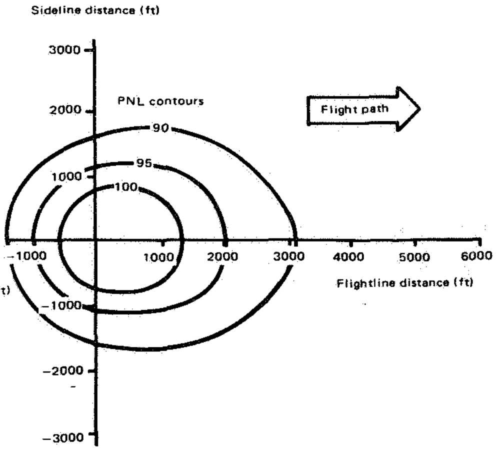
Total spectrum

Figure 34. Sound Pressure Levels for the Noise Derivative Tilt-Rotor Aircraft

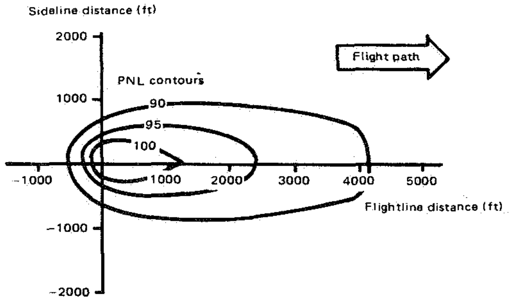
+5 PNdB HELICOPTER DESIGN POINT STANDARD TAKEOFF



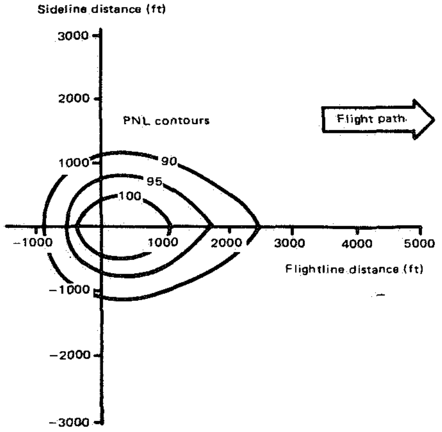
+5 PNdB TILT-ROTOR DESIGN POINT – STANDARD TAKEOFF



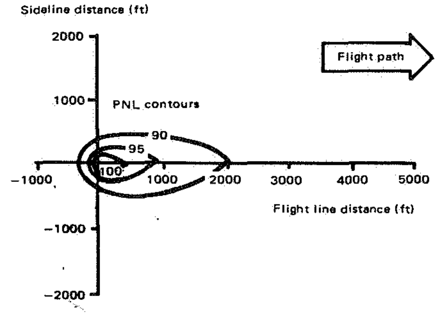
BASELINE HELICOPTER DESIGN POINT – STANDARD TAKEOFF



BASELINE TILT-ROTOR DESIGN POINT – STANDARD TAKEOFF



–5 PNdB DESIGN POINT HELICOPTER – STANDARD TAKEOFF



-5 PNdB TILT-ROTOR DESIGN POINT – STANDARD TAKEOFF

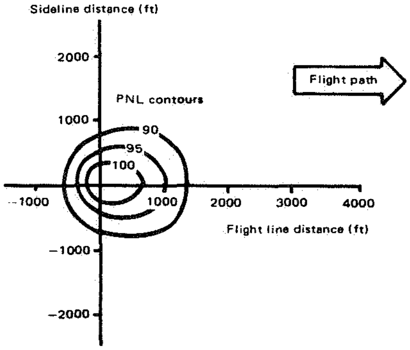


Figure 35. Perceived Noise Level Contours of Baseline and Noise Derivative Aircraft on Takeoff

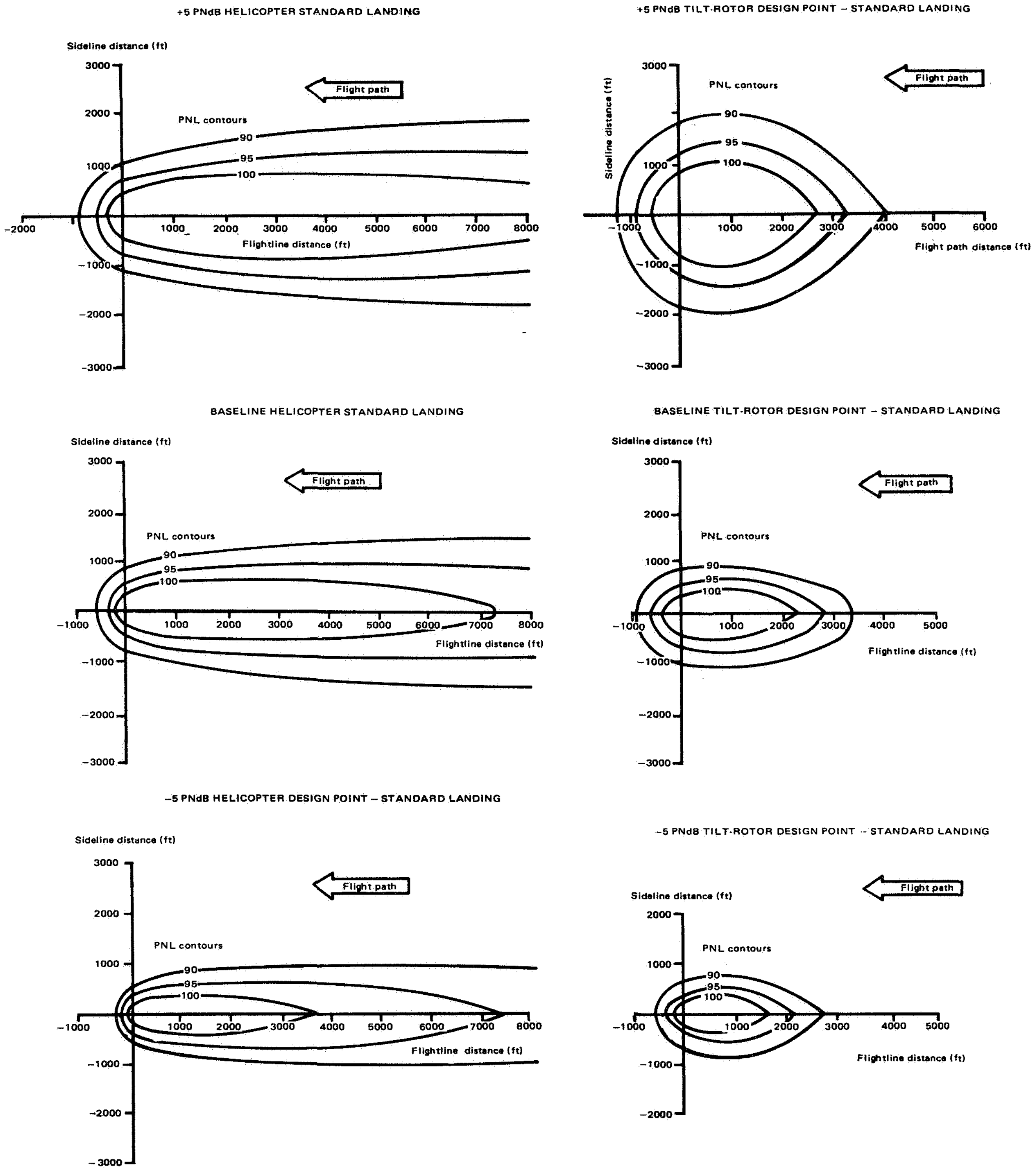


Figure 36. Perceived Noise Level Contours of Baseline and Noise Derivative Aircraft on Landing

TABLE XVII
AREA ENCLOSED BY A 95 PNdB CONTOUR ON TAKE OFF AND LANDING

Configuration	Takeoff		Landing	
	(sq km)	(sq mi)	(sq km)	(sq mi)
Baseline helicopter	0.18	0.07	1.39	0.535
+5 PNdB helicopter	0.49	0.19	2.28	0.88
–5 PNdB helicopter	0.03	0.01	0.76	0.295
Baseline tilt-rotor	0.23	0.09	0.39	0.15
+5 PNdB tilt-rotor	0.49	0.19	0.75	0.29
–5 PNdB tilt-rotor	0.08	0.03	0.18	0.07
STOL tilt-rotor	0.3	0.115	0.36	0.14

7. GUST SENSITIVITY

In commercial operation the ride qualities of the aircraft take on a larger significance than in military operation, for which current rotary-wing vehicles are primarily designed. This, coupled with the relatively low operating altitudes for these aircraft, requires a low sensitivity to gusts and turbulence. The acceleration response of the design vehicles due to gust disturbances is compared in Figure 37 at their cruise velocities and altitudes. Since the vehicle response is a function of weight, a range is shown from operating weight empty to design gross weight. The tandem-rotor helicopter has a relatively low response compared with the tilt-rotors due, for the most part, to its lower cruise speed. Both tilt-rotor aircraft have higher response's than the criteria line established by NASA. These vehicles would require a direct lift control system to reduce this gust sensitivity. A preliminary analysis of such a control system was performed and established that the control requirements in terms of actuator response and authority were well within the design ranges normally available for control. This system needs to be developed, and it should include the rotor controls as well as the wing. In this area the tandem helicopter has an advantage over the tilt-rotor.

8. COSTS

The initial or flyaway costs and the direct operating costs of the configurations studied have been computed based upon NASA guidelines for cost estimation. The guidelines are summarized in Table XVIII.

Initial costs data for the three baseline configurations are shown in Table XIX. The aircraft costs have been computed for two levels of airframe cost, \$198/kg (\$90/lb) and \$243/kg (\$110/lb). The largest component of the vehicle cost is the airframe cost, which is a strict function of weight and varies between configurations accordingly. The dynamics system costs are also weight-dependent and are estimated at \$176/kg (\$80/lb). Engine costs are a function of maximum horsepower; the avionics package has been assumed to be a constant cost for all configurations.

The VTOL tilt-rotor total cost is \$4.15 million and is 23.5 percent more expensive than the design point tandem helicopter. This difference is due to the increment in weight and installed power

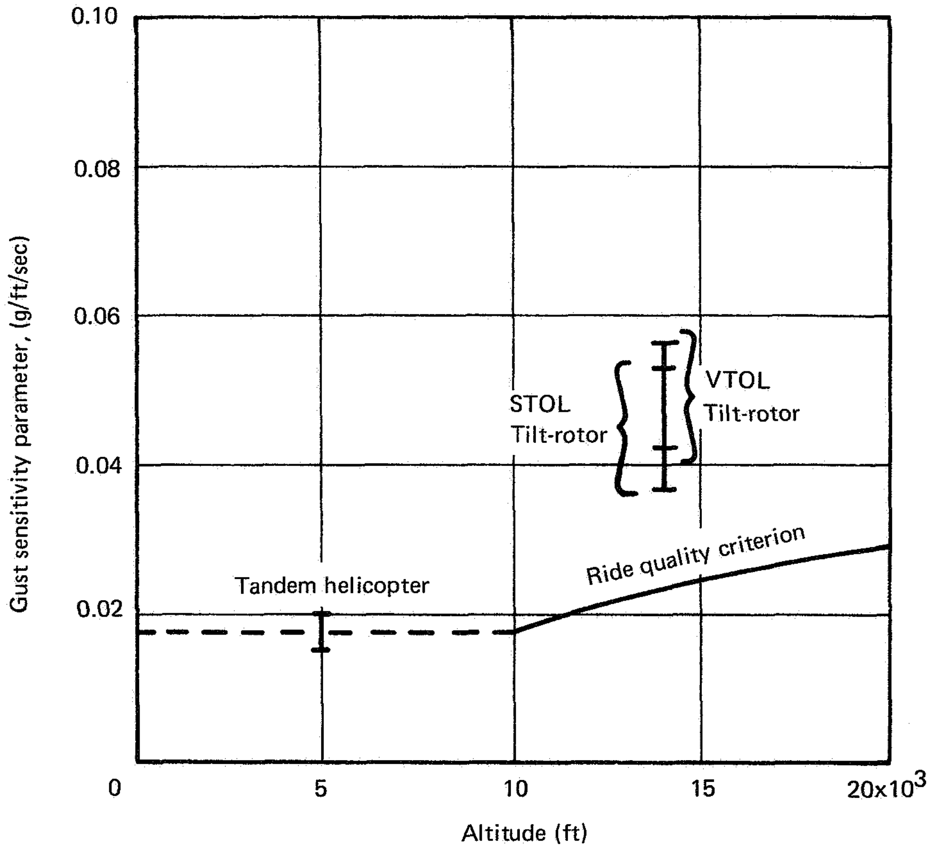


Figure 37. Gust Sensitivity at Maximum Cruise Speed

TABLE XVIII

GROUND RULES FOR COST CALCULATIONS

Item	
Year dollars	1974
Avionics price,$/acft	250 000
Airframe price, $/lb	90 and 110
Dynamic system price, $/lb	80
Engine price, $/rated shp	280 $(HP^{.785})$
Crew costs, $/hr	$\frac{0.067\ GW}{1000} + 134$
Fuel, $/lb	0.02
Oil, $/lb	1.24
Nonrevenue factor, %	2
Labor rate, $/hr	6.0
Airframe labor, mh/fh	1.0 AIA
Airframe material, $/fh	1.0 AIA
Engine labor, mh/fh	0.65 AIA
Engine material, $/fh	0.65 AIA
Engine TBO, hr	4 500
Dynamic system labor, mh/fh	AIA
Dynamic system material, $/fh	AIA
Dynamic system TBO, hr	3 000
Maintenance burden	150% Direct labor
Depreciation period, yr	12
Spares – %	
Airframe	8
Engines	40
Dynamic system	25
Utilization, hr	2 500 and 3 500

TABLE XIX
INITIAL COSTS OF DESIGN POINT CONFIGURATIONS

Baseline Tandem-Rotor Helicopter

Airframe Cost	$90/lb	$110/lb
Airframe	$2 199 510	$2 688 290
Dynamic system	1 063 040	1 063 040
Engines	654 265	654 265
Avionics	250 000	250 000
Total	$4 166 815	$4 655 595

Baseline VTOL Tilt-Rotor

Airframe Cost	$90/lb	$110/lb
Airframe	$3 179 430	$3 885 970
Dynamic system	949 920	949 920
Engines	774 416	774 416
Avionics	250 000	250 000
Total	$5 153 766	$5 860 306

Baseline STOL Tilt-Rotor

Airframe Cost	$90/lb	$110/lb
Airframe	$3 244 230	$3 965 170
Dynamic system	557 440	557 440
Engines	566 928	566 928
Avionics	250 000	250 000
Total	$4 618 598	$5 339 538

between the two configurations. The STOL tilt-rotor initial cost is $4.618 million, which is $535 168 less than the VTOL aircraft but still 11 percent more expensive than the baseline tandem-rotor helicopter design.

The initial costs of the external noise criteria aircraft designs are shown in Table XX. For the tandem-rotor helicopter the initial cost decreases from $4.166 million to $3.982 million (4.4 percent) as the 152.4-meter (500-foot) sideline noise level increases 5 PNdB. When the static thrust external noise is reduced 5 PNdB, the aircraft initial cost increases to $4.76 million (14.2 percent).

If the VTOL tilt-rotor external noise is allowed to increase 5 PNdB, the aircraft initial costs decrease from $4.15 million to $5.034 million (23 percent). Reducing the external noise to 5 PNdB less than the baseline tilt-rotor aircraft results in an increase in cost to $5.604 million, an 8.74-percent increase.

The costs referred to in the discussion are the values computed at $198/kg ($90/lb) airframe weight. Similar conclusions are apparent if the data for $243/kg ($110/lb) of airframe weight are considered.

The direct operating costs of the three baseline aircraft are shown in Table XXI at the design block range of 370 kilometers (230 statue miles). The data are computed for two values of aircraft utilization, 2500 hr/yr and 3500 hr/yr, for aircraft priced at both $198/kg ($90/lb) airframe weight and $243/kg ($110/lb) airframe weight.

The effect of increasing aircraft utilization is to decrease the direct operating costs, since the aircraft insurance and depreciation costs can be spread over more passenger miles. The direct operating cost increases with airframe cost due to increased insurance, maintenance material, and depreciation costs.

For the purpose of comparison, the 3500 hr/yr and $198/kg ($90/lb) airframe weight is used. The tandem-rotor helicopter, at 3.21 cents per seat-mile, is the most expensive aircraft to operate. The VTOL tilt-rotor is next at 2.19 cents per seat-mile. The effect of designing the tilt-rotor for STOL is to reduce the direct operating cost to 2.09 cents per seat-mile.

The parameters which primarily define the direct operating costs are aircraft weight and cruise speed. The VTOL tilt-rotor is cheaper to operate than the tandem-rotor helicopter despite its higher weight because of lower fuel consumption and because the cruise speed achieved is approximately twice that of the tandem-rotor helicopter. This increases the productivity of the aircraft and crew, thereby reducing costs/seat-mile for depreciation, insurance, crew, and maintainance.

TABLE XX
INITIAL COSTS OF NOISE DERIVATIVE AIRCRAFT DESIGNS

	+5 PNdB Tandem-Rotor Helicopter		–5 PNdB Tandem-Rotor Helicopter	
Airframe Costs	$90/lb	$110/lb	$90/lb	$110/lb
Airframe	$2 144 700	$2 621 300	$2 408 670	$2 943 930
Dynamic system	958 080	958 080	1 351 200	1 351 200
Engines	629 220	629 220	751 887	751 887
Avionics	250 000	250 000	250 000	250 000
Total	$3 982 000	$4 458 600	$4 761 757	$5 297 017

	+5 PNdB VTOL Tilt-Rotor		–5 PNdB VTOL Tilt-Rotor	
Airframe Costs	$90/lb	$110/lb	$90/lb	$110/lb
Airframe	$3 154 950	$3 856 050	$3 279 780	$4 008 620
Dynamic system	873 360	873 360	1 196 320	1 196 320
Engines	755 728	755 728	878 736	878 736
Avionics	250 000	250 000	250 000	250 000
Total	$5 034 038	$5 735 138	$5 604 836	$6 333 676

TABLE XXI
DIRECT OPERATING COST OF THE BASELINE CONFIGURATION

STOL Tilt-Rotor

Utilization (hr/yr)	2500		3500	
Airframe Cost ($/lb)	90	110	90	110
Flying operations				
Flight crew	0.0048	0.0048	0.0048	0.0048
Fuel and oil	0.0026	0.0026	0.0026	0.0026
Hull insurance	0.0013	0.0015	0.0009	0.0011
Total flying operations	0.0087	0.0089	0.0083	0.0085
Direct maintenance				
Airframe - Labor	0.0014	0.0014	0.0014	0.0014
– Material	0.0012	0.0015	0.0012	0.0015
Engines – Labor	0.0006	0.0006	0.0006	0.0006
– Material	0.0006	0.0006	0.0006	0.0006
Dynamic System - Labor	0.0003	0.0003	0.0003	0.0003
Material	0.0005	0.0005	0.0005	0.0005
Total direct maintenance	0.0047	0.0050	0.0047	0.0050
Maintenance burden	0.0036	0.0036	0.0036	0.0036
Total maintenance	0.0083	0.0085	0.0083	0.0085
Depreciation	0.0061	0.0070	0.0044	0.0050
Total direct costs	0.0231	0.0244	0.0209	0.0220

Baseline VTOL Tilt-Rotor

Utilization (hr/yr)	2500		3500	
Airframe Cost ($/lb)	90	110	90	110
Flying operations				
Flight crew	0.0044	0.0044	0.0044	0.0044
Fuel and oil	0.0033	0.0033	0.0033	0.0033
Hull insurance	0.0013	0.0015	0.0009	0.0011
Total flying operations	0.0090	0.0092	0.0086	0.0088
Direct maintenance				
Airframe – Labor	0.0013	0.0013	0.0013	0.0013
– Material	0.0011	0.0014	0.0011	0.0014
Engines – Labor	0.0006	0.0006	0.0006	0.0006
– Material	0.0008	0.0008	0.0008	0.0008
Dynamic system – Labor	0.0005	0.0005	0.0005	0.0005
– Material	0.0008	0.0008	0.0008	0.0008
Total direct maintenance	0.0051	0.0054	0.0051	0.0054
Maintenance burden	0.0037	0.0037	0.0037	0.0037
Total maintenance	0.0088	0.0091	0.0088	0.0091
Depreciation	0.0063	0.0071	0.0045	0.0051
Total direct costs	0.0241	0.0254	0.0219	0.0230

Baseline Tandem-Rotor Helicopter

Utilization (hr/yr)	2500		3500	
Airframe Cost ($/lb)	90	110	90	110
Flying operations				
Flight crew	0.0081	0.0081	0.0081	0.0081
Fuel and oil	0.0045	0.0045	0.0045	0.0045
Hull insurance	0.0019	0.0022	0.0014	0.0015
Total flying operations	0.0145	0.0148	0.0140	0.0141
Direct maintenance				
Airframe – Labor	0.0013	0.0013	0.0013	0.0013
– Material	0.0010	0.0012	0.0010	0.0012
Engines – Labor	0.0007	0.0007	0.0007	0.0007
– Material	0.0009	0.0009	0.0009	0.0009
Dynamic system – Labor	0.0011	0.0011	0.0011	0.0011
– Material	0.0017	0.0017	0.0017	0.0017
Total direct maintenance	0.0067	0.0069	0.0067	0.0069
Maintenance burden	0.0047	0.0047	0.0047	0.0047
Total maintenance	0.0114	0.0116	0.0114	0.0116
Depreciation	0.0094	0.0105	0.0067	0.0075
Total direct costs	0.0353	0.0369	0.0321	0.0332

Notes: Direct Operating Costs
Dollars/Seat-Mi
Block Distance = 230 Stat Mi

The STOL tilt-rotor aircraft is slower than the VTOL tilt-rotor because of lower installed power. However, the decrease in gross weight and fuel consumption is just large enough to negate the effect of speed on direct operating cost and results in the small improvement shown.

The total direct operating costs at 370 kilometers (230 statute miles) for the aircraft designed to ±5 PNdB are compared with the direct operating costs of the baseline vehicles in Table XXII and Figure 38.

The direct operating cost of the +5 PNdB tilt-rotor is almost identical to the baseline aircraft, and no cost advantage is gained by allowing increased noise levels. However, decreasing the noise level by 5 PNdB results in an increased direct operating cost by approximately 8 percent due to the increased gross weight and fuel consumption.

The tandem-rotor helicopter data shows that, as the perceived noise level varies ±5 PNdB away from the baseline aircraft, the direct operating costs increase. For the +5 PNdB case the overall decrease in weight is negated by the slower cruise speed and the direct operating cost increases by 9.2 percent. The increased speed of the -5 PNdB helicopter is not sufficient to affect the sharply increasing gross weight, and again the direct operating cost increases, by 4.2 percent.

The effect of operating range on the aircraft direct operating costs is shown in Figure 39 for the three baseline vehicles. The data shown in each case up to the design range is for the aircraft as designed. The data shown at more than 370 kilometers (200 nautical miles) is for a modified aircraft. For the design mission aircraft the direct operating costs increase as operating range is reduced. The fundamental difference between the aircraft is in the overall level of direct operating cost as reflected in the design range data shown earlier.

The extended range aircraft shown in Figure 39 assumes in each case that additional tankage is provided for 740-kilometer (400-nautical-miles) range with no increase in overall takeoff gross weight. That is to say that the allowable payload is reduced to the nearest whole passenger to account for increased tank weight and increased fuel weight. This assumption causes the discontinuity at the design range between the design mission aircraft and the extended range vehicle data. The fuel usage of the tandem-rotor helicopter is higher than the tilt-rotors and requires more payload reduction to achieve the 740-kilometer (400-nautical-miles) range. This reduction in allowable available seats causes the direct operating cost to increase as the range is increased. The baseline tandem-rotor helicopter can carry 72 passengers over a 740-kilometer (400-nautical-mile) range.

TABLE XXII

COMPARISON OF DIRECT OPERATING COST FOR EXTERNAL NOISE CRITERIA DESIGNS

VTOL Tilt-Rotor				
Utilization (hr/yr)	2500		3500	
Airframe Cost ($/lb)	90	110	90	110
Baseline	0.0241	0.0254	0.0219	0.0230
+5 PNdB	0.0242	0.0255	0.0220	0.0231
–5 PNdB	0.0260	0.0272	0.0236	0.0245

Tandem-Rotor Helicopter				
Utilization (hr/yr)	2500		3500	
Airframe Cost ($/lb)	90	110	90	110
Baseline	0.0353	0.0369	0.0321	0.0332
+5 PNdB	0.0386	0.0402	0.0350	0.0362
–5 PNdB	0.0363	0.0384	0.0334	0.0345

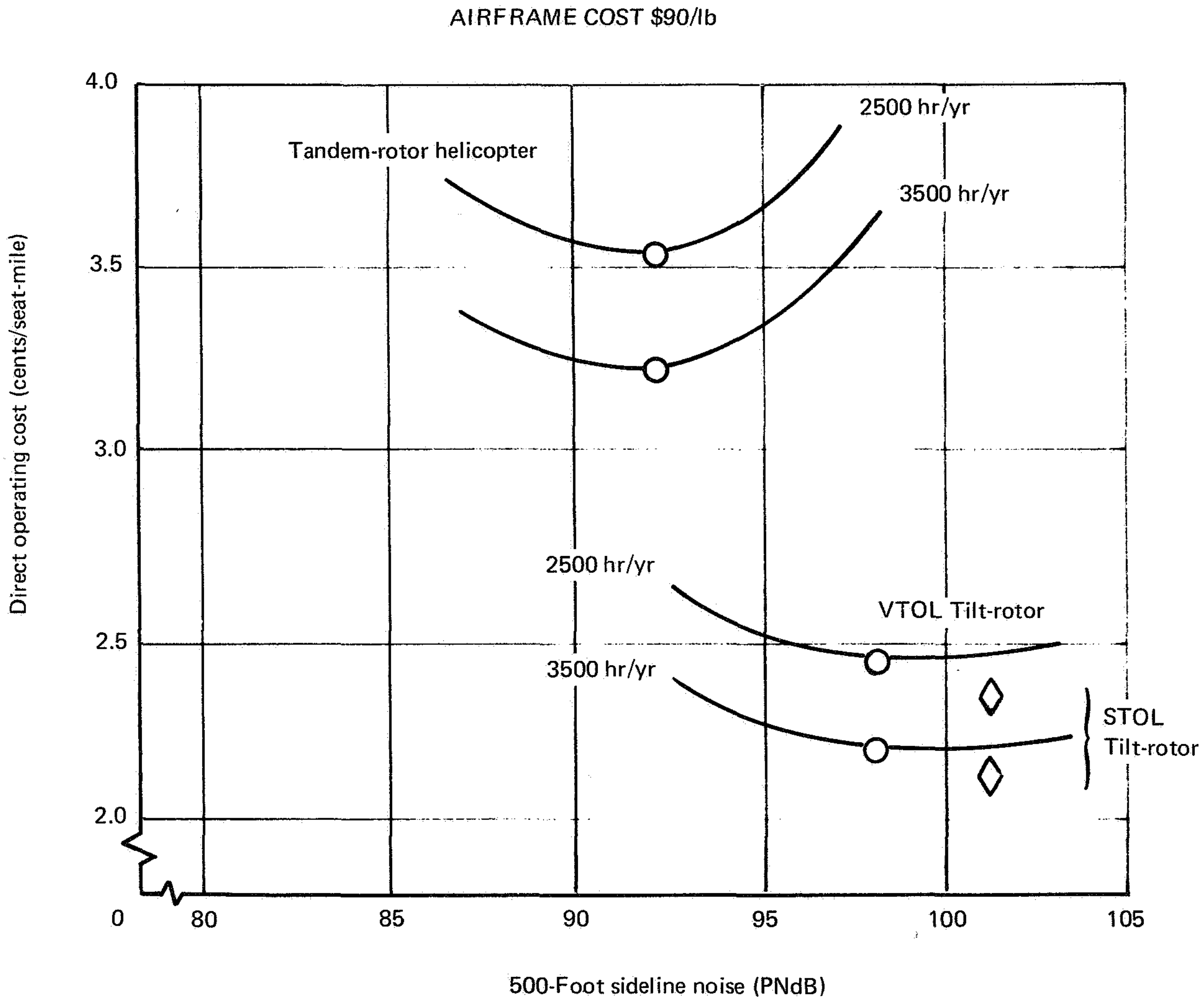


Figure 38. Effect of External Noise Criteria on Direct Operating Cost at a Range of 230 Statute Miles

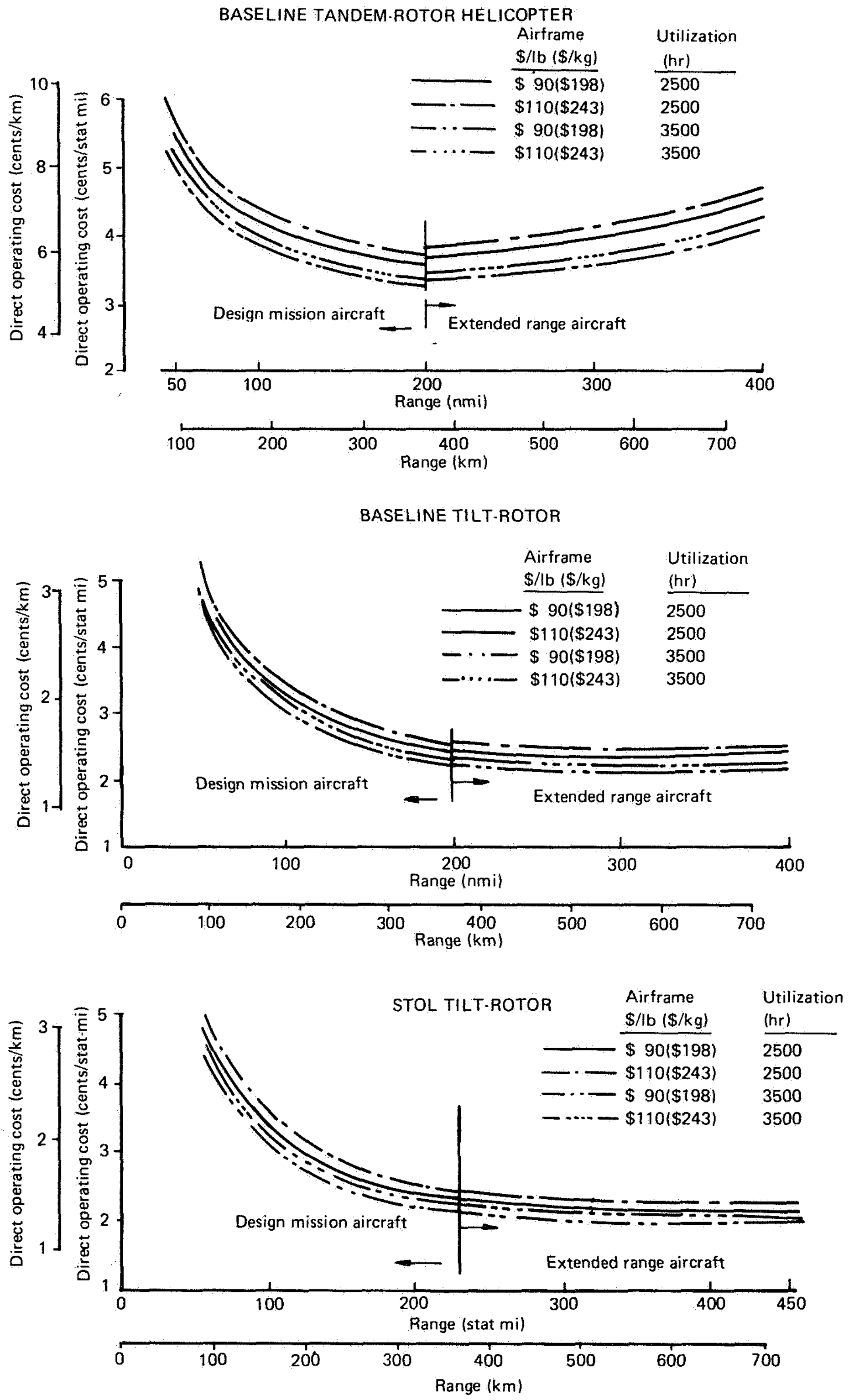


Figure 39. Effect of Operating Range on Direct Operating Cost for the Baseline Aircraft

The VTOL and STOL tilt-rotors do not exhibit the same large increase in direct operating cost as range is increased. This is largely due to the fuel economy of this configuration in its cruise flight condition. The extended range VTOL tilt-rotor carries 84 passengers and the STOL tilt-rotor carries 88 passengers over the 740-kilometer (400-nautical-mile) range.

The characteristics of the noise derivatives are almost identical to the baseline vehicles except for the incremental differences at the design range.

9. MAXIMUM SIZE AND TECHNICAL RISK

One of the items in the statement of work for this study which has provoked much thought and discussion is that pertaining to the number of passengers for which the aircraft were to be designed. This stated that the maximum payload should not exceed 100 passengers and that restrictions to a lower number should be governed by technological constraint only. Economic factors such as minimum operating cost per available seat-mile were not to be considered in setting a size limit for the aircraft. The study has been fully responsive to this groundrule, which might under some circumstances have forced the selection of uneconomic designs. However, careful examination of technology issues has not resulted in the identification of any serious impediments to the maximum size aircraft. In fact, only the 100-passenger constraint has been found to be more restrictive than either technological or economic considerations in both the helicopter and tilt-rotor configurations. In both configurations the optimum operating costs occur around the 100-passenger mark, and there is no specific evidence of technological phenomena or difficulties with fabrication techniques or component manufacture which would limit the helicopter or tilt-rotor to some intermediate number of passengers. The 100-passenger-size vehicles were accordingly selected for detailed study.

Having arrived at this aircraft size, it may be worthwhile to review some of the other issues which might be involved in the selection of an aircraft to build. A large sized aircraft requires more development funds and more time to bring into service than a smaller aircraft. This might provide a persuasive argument for the development of a smaller design which fell within some set of budgetary and schedule constraints. Another factor to be considered is the credibility of the size selected and support among the technical community. It will be more difficult to generate and sustain support for a larger development. Other issues which intrude into the area of economics are such questions as passenger density, frequency of schedule, and availability of the initial capital costs to the commercial carrier. For example, the advantages of low direct operating cost could be overcome if the acquisition cost of the aircraft is more than the commercial carrier has at its disposal.

On the other hand an aircraft that is too small will be uneconomical to operate and will require a premium fare structure which may preclude use by the desired market. Some of these issues are not readily quantified and are in many cases outside the defined scope of the study.

9.1 TANDEM-ROTOR HELICOPTER

No limitation of tandem-rotor helicopter size exists within one 100-passenger range, based on technical risk. This conclusion is based upon examination of the elements of the tandem-rotor helicopter and comparison with current industrial experience.

The components and systems of a tandem-rotor helicopter to which a size-dependent technical risk might be ascribed are the rotor system and the drive train.

Rotor System

The rotor system used in the design point tandem-rotor helicopter is a four-bladed 21-meter (68.9-foot) diameter rotor with a solidity of 0.099. The rotor is fully articulated and of conventional design. Table XXIII shows the rotor characteristics compared with existing rotor designs. The design point aircraft rotor diameter is 2.71 meters (8.9 feet) larger than the CH-47 aircraft and considerably smaller than the other examples shown.

The rotor solidity, 0.099, is almost identical to the 0.092 rotor solidity of the XCH-62 heavy-lift helicopter (HLH). Rotor blades for the XCH-62 have already been fabricated using composite structures; this demonstrates that the rotor size is a minimal risk from a fabrication viewpoint. The only risk element in the rotor system is whether or not an adequate weight allowance has been made in the aircraft design. The rotor system weight is shown on a statistical weights trend comparison in Reference 2 and demonstrates that the weight allowance used is consistent with actual weights of existing large rotors in this size class.

TABLE XXIII
TANDEM-ROTOR HELICOPTER: ROTOR SYSTEM

Aircraft	Diameter (ft)	Solidity (σ)	Chord (in.)	Twist θ (deg)	Tipspeed (ft/sec)	V_{NRP} (K_{TAS})
Design point	68.0	0.099	31.72	12	725	165
+5 PNdB	68.2	0.07	22.5	12	810	131
–5 PNdB	72.5	0.159	54.32	12	640	181
XCH-62	92	0.09226	40	12	750	146
CH-47C	60	0.062	25.25	9	770	165
Model 347	60	0.0827	25.25	9	691	169
CH-53A	72	0.115	26	8	698	170
YCH-53E	79	0.136	29	10.6	700	191

Drive Train

The drive train used in the tandem-rotor helicopter design is modelled on the XCH-62 helicopter system designed by Boeing Vertol and currently undergoing development testing. The design point aircraft installed power is lower than the XCH-62, and the torque levels required in the combiner gearbox are modest by comparison with the existing design. The rotor transmission is required to transmit a maximum of 207 847 foot-pounds of torque which is comparable to the CH-53A (210 000 foot-pounds) and much less than the XCH-53E (342 000 foot-pounds) and the XCH-62 (358 000 foot-pounds).

The critical components of the lift/propulsion package are therefore within the range of experience of the Boeing Vertol Company.

One method of reducing the risks in the development of large aircraft is by a component development program approach such as the ongoing HLH Advanced Technology Components Program. The critical components developed in this program will produce a prototype aircraft of much larger size than the tandem-rotor helicopter design selected for the short-haul mission. In view of this experience, the risks for a vehicle whose fabrication is to start in 1980 must be considered small, provided that the experience gained at Boeing Vertol in large tandem-rotor helicopter designs is utilized in the design and fabrication of the commercial aircraft defined in this study.

The only element of risk associated with the designs is the structural weight reduction of 25 percent to allow for advanced composite materials design. This reduction is thought to be optimistic; a maximum weight reduction of 16 percent is considered to be more appropriate based on Boeing experience. However, the 25-percent reduction was used, after discussions with NASA, to preserve common groundrules between these designs and those produced by other contractors.

9.2 VTOL AND STOL TILT-ROTOR DESIGNS

The evaluation of risk and the selection of maximum capacity for the tilt-rotor transports require careful reasoning and are approached under a number of groundrules which rely on certain assumptions including the successful completion of the NASA-Army XV-15 program.

The directive of the study guidelines was to select the largest aircraft (up to 100 passengers), limited only by technical risk. An examination of the risk elements associated with a 100-

passenger-size vehicle is summarized here in this context, to meet the guideline directive.

The fundamental assumption in the evaluation of risk for the tilt-rotor aircraft has been that the XV-15 program will be successful. That is to say that the XV-15 performance, handling qualities, and structural integrity are demonstrated to be within an acceptable and predictable range. Specifically, it is assumed that the behavior of currently identified phenomena which define design conditions peculiar to the configuration (such as whirl flutter and rotor dynamic interactions with the flight mode dynamics) will be as predicted by analysis and model and component testing.

In summary, it is assumed that configuration problems will be resolved by the XV-15 program, and, therefore, the discussion of risk for the 1985 tilt-rotor transport may be limited to those issues which are functions only of size.

Technical Evaluation of Risk

Speculating on the possible emergence of new phenomena and design difficulties as size is increased is not considered to be a useful exercise, since if such difficulties are not predicted, quantification and evaluation is impossible. The potential for such development problems is recognized, but it is proposed that the development plan for the commercial transport vehicle should be structured to obtain an orderly resolution of design problems to minimize their impact. Before discussing a development program which ensures against the intangible risks, it is necessary to examine the known problem areas such as dynamic system design and predictable phenomena to determine whether any predictable limits exist.

The potential for risk in the fuselage, empennage, and aircraft systems must be considered minimal, since structure and systems of this type are not significantly different from existing aircraft practice. The wealth of information in these areas, for aircraft in the 100-passenger size range as well as for much larger aircraft, provides a solid basis for design and development.

In previous experience, where large steps in size have been made in rotary wing design, the developmental difficulties have been related to the aircraft dynamic systems. For this reason it is useful to briefly examine these areas in tilt-rotor design.

The following components and systems have the highest potential for developmental risk:

- Drive System - Can large transmission with large torques and low rotional frequencies be successfully designed?
- Rotor System - Does the rotor-blade strength keep pace with rotor loads as size is increased?
- Rotor, Nacelle, and Wing Aeroelastic Consideration - As size is increased, do the design constraints of wing strength and frequency become more or less restrictive?

Each of these areas are addressed in the following discussion.

The structural weight reductions of 25 percent used in the study is thought to constitute a technical risk. A maximum weight reduction of 16 percent is more in line with Boeing experience.

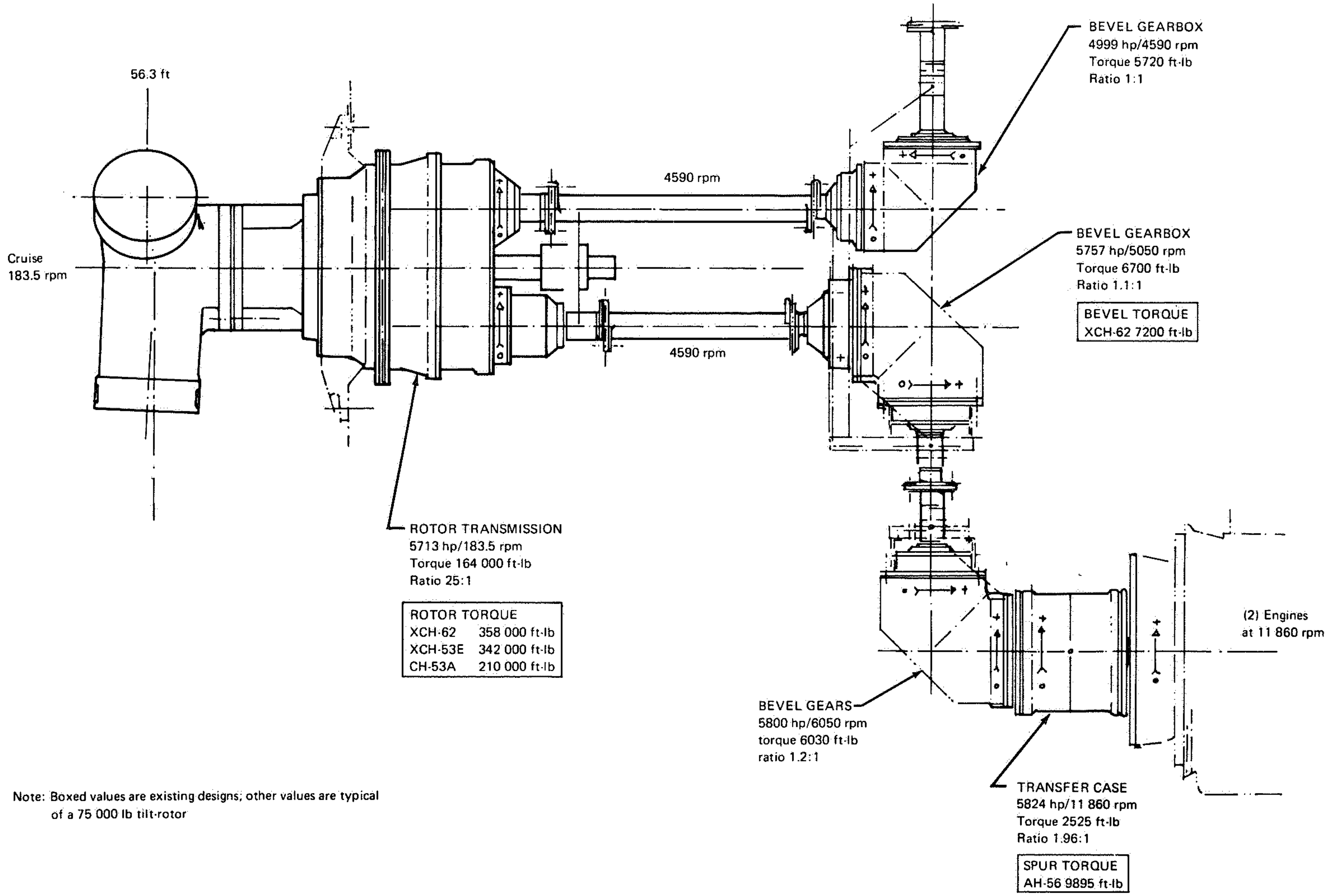
Drive train. - The drive train required by the design point VTOL tilt-rotor aircraft is shown schematically in Figure 40. The technical risks may be evaluated by comparing each transmission box or gear train with existing hardware.

The engine transfer case critical mesh torque is 2525 foot-pounds. A similar spur torque mesh exists in the AH-56 transmission, which is designed to 9895 foot-pounds. The largest of the bevel boxes requires the transmission of 6700 foot-pounds of torque. This can be compared to a bevel set in the transmission of the XCH-62, which is designed to 7200 foot-pounds. The main rotor transmission requires a maximum torque of 165 000 foot-pounds, which is much smaller than the CH-53A, at 210 000 foot-pounds, the XCH-53E, at 342 000 foot-pounds, or the XCH-62, at 358 000 foot-pounds. The spur torque which drives the cross-shaft from the main transmission collector is sized at 7200 foot-pounds, which is again less than the AH-56 spur torque of 9895 foot-pounds.

The rotor transmission requires a reduction ratio of 25:1. The XCH-53E main rotor transmission reduction ratio is 35.8:1, and the CH-53A is 32.5:1. The XCH-62 reduction ratio is 51.2:1. The maximum reduction ratio required for the bevel boxes is 1.2:1, which is quite low. Typically, bevel boxes can be designed up to 3:1, and at low power, even 5:1 reduction ratios are not uncommon. The transfer case spur gearing has a 1.96:1 reduction ratio, which again is modest by industry experience (up to 5:1 ratios).

These comparisons indicate that the elements of the drive system are well within industry experience in terms of size, torque transfer, and reduction ratio.

The design of the individual gearboxes and shafting cannot be considered a size-limiting risk item, although the operation of these components in the configuration specific to the tilt-rotor would require development, as is the case for any new transmission. The VTOL tilt-rotor transmission design was selected for



Note: Boxed values are existing designs; other values are typical of a 75 000 lb tilt-rotor

Figure 40. Transmission Design Technology for Tilt-Rotor Aircraft

this discussion because the STOL design is an identical layout, but smaller in terms of size, torque, and reduction ratios, and is therefore inherently a lower risk.

Rotor blade design. - The design of a hingeless rotor for a tilt-rotor aircraft requires the compromise of blade root strength and blade root stiffness in order to provide a finished design which has acceptable rotating blade frequencies as well as adequate blade fatigue bending strength. The detailed design of the rotor is beyond the scope of this conceptual design study; however, estimates of blade load and strength have been made to show that such a design is feasible. Based on experience with the Boeing Model 222 design, the 8.5 percent radial station on the blade is the probable fatigue critical section.

The rotor loads have been computed from the measured 7.92-meter (26-foot) diameter loads using Mach scaling and accounting for the difference in rotor solidity. Cyclic pitch is assumed to be input as a function of longitudinal stick. Figure 41 shows the estimated normal load factor at which endurance limit loads on the blade root occur for the VTOL tilt-rotor design. For speeds in excess of 216 knots, the aircraft can pull its design maneuver limit with no fatigue damage, and at the worst case, can pull 1.8g before fatigue damage occurs.

The criterion used in the past for conventional propeller design is that the blade should be able to tolerate loads corresponding to 1200 Aq (i.e., angle of attack times dynamic pressure) with no damage. This line is also shown in Figure 41 to provide a comparison.

The maximum normal maneuver in hover requires 5.6° cyclic. A normal maneuver is defined by passenger comfort levels quoted in the study guidelines (i.e., 0.1g lateral and 0.4g vertical). At this condition, the resulting blade stresses are approximately 84 percent of the fatigue allowable.

Normal hover loads with worst cyclic to trim produce blade bending loads of about 32 percent of the fatigue allowable level.

Figure 42 shows the estimated normal load factor at which endurance limit loads occur in the STOL rotor design. In this case the aircraft can pull its design maneuver load factor at speeds in excess of 223 knots with no fatigue damage, and at the worst case, can pull 2.1g before any fatigue damage occurs.

Detailed design of the blade and the aircraft control system in transition would be required in both configurations to compute the blade fatigue life. However, the magnitude of the loads estimated in relationship to the fatigue endurance limit provides a reasonable indication that these blades could be designed to give an adequate fatigue life in commercial service.

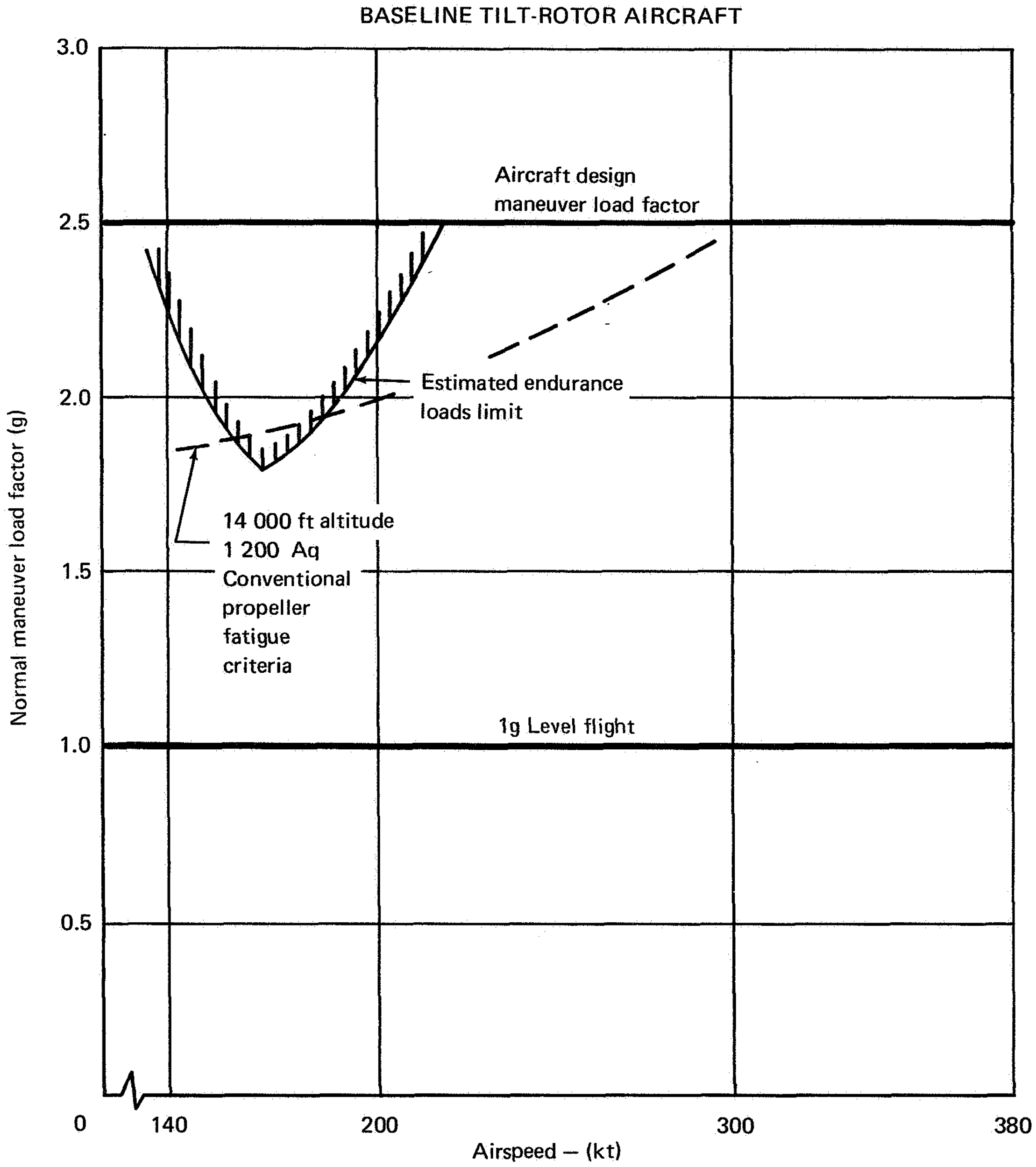


Figure 41. Maneuver Load Factor Envelope for Baseline VTOL Tilt-Rotor, Blade Load Limits

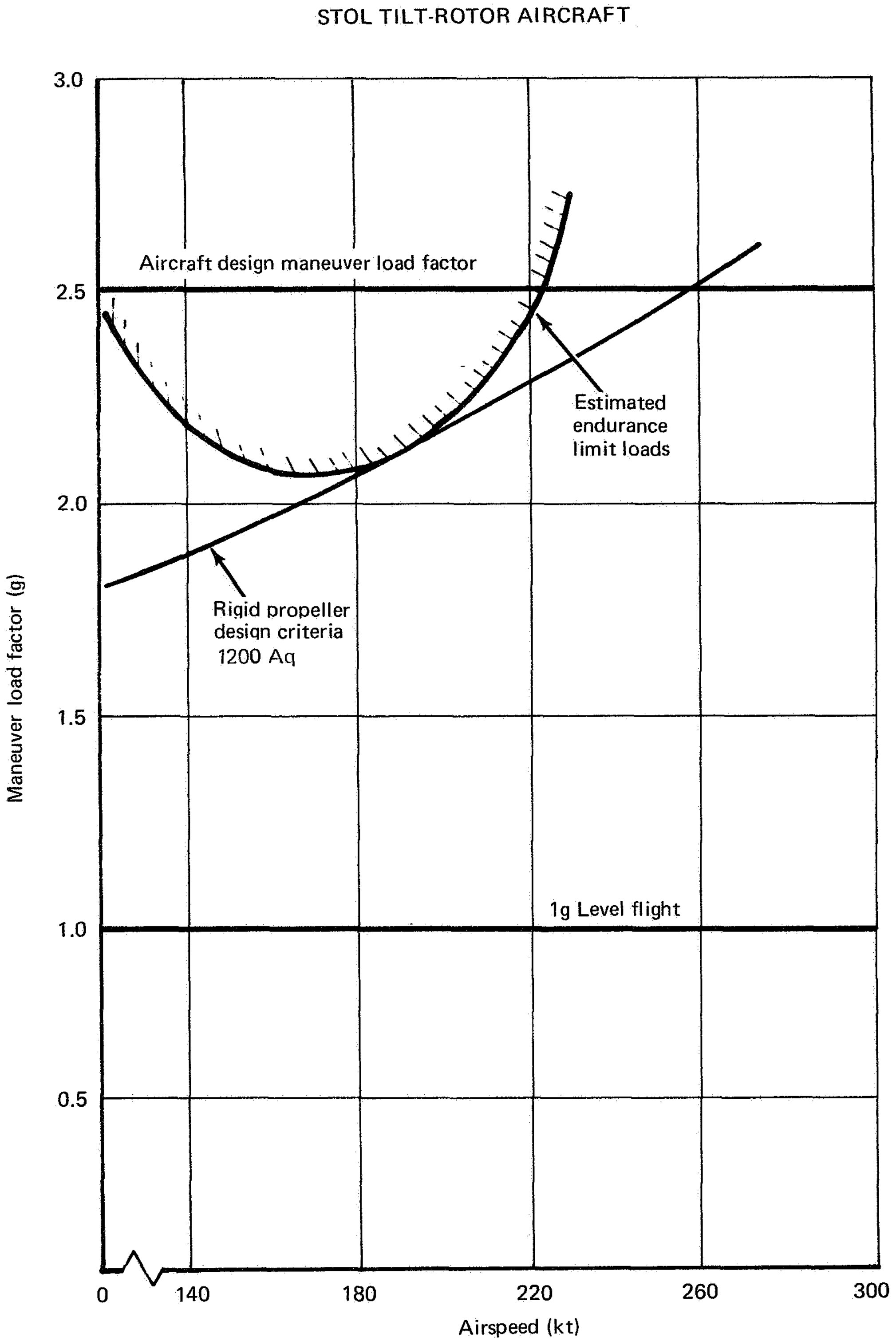


Figure 42. Maneuver Load Factor Envelope for STOL Tilt-Rotor, Blade Load Limits

Scaling. - In discussing possible problems which may be a function of size, the question will be asked whether XV-3 and XV-15 experience, as well as the growing body of full-scale component and scaled-model test data, can be extrapolated or scaled up to the size associated with the 100-passenger tilt-rotor aircraft. Boeing Vertol's position is that experience gained in any well conducted tilt-rotor test program is indeed relevant to others of larger scale and that the series of results of tests of scaled models and full-scale rotors which have been conducted in support of the NASA-Army research vehicle competition and subsequently may be applied in two ways. The first is by direct application using scaling laws and the second by validating general methods and procedures which may be applied in widely different situations.

The validity of scaling model data to full scale has been demonstrated at Boeing Vertol by experience with the 1/9th-scale version of the 26-foot-diameter rotor which was tested in the NASA-Ames 40- by 80-foot wind tunnel. This experience is summarized in Figure 43 and shows that the small-scale test was an adequate indicator of the aeroelastic behavior of the full-scale wing and rotor system.

A relatively smaller jump is involved in going from the 7.62- or 7.92-meter (25- or 26-foot) diameter level to a 17.07-meter (56-foot) diameter rotor system. The more general question of validation of methodology has been addressed at length in other Boeing documents (e.g., Reference 6) and will not be repeated here, except to state that good predictive capability has been shown in all technology areas including blade loads, rotor derivatives, and aeroelastic stability.

Aeroelastic stability. - At an early stage of the study, aeroelastic stability was reviewed as a potential area of risk as aircraft size grew from levels which had been studied in depth (e.g., Boeing Vertol Model 222 and Bell Model 301). The concern was that the parameters which determine aeroelastic behavior might grow in such a manner that aeroelastic requirements would become governing, and that the structural weights required would be substantially higher than these indicated by the usual sizing and weight trend procedures.

In growing a hingeless rotor from the 7.92-meter (26-foot) diameter size to 17.07 meters (56 feet) in diameter, tipspeed is held constant, and blade-per-rev frequency is maintained at the values selected for the Model 222. These stiffness characteristics can be provided for an acceptable structural weight.

An increased margin could be provided for the cost of additional structural weight; however, the 1.2 V_{dive} criterion already provides a 44-percent margin over the speeds at which the aircraft is designed to operate. And this is considered adequate in an aircraft intended for civil commercial operation.

FULL-SCALE AND 1/9-SCALE TESTING FOR HINGELESS ROTOR AEROELASTIC STABILITY

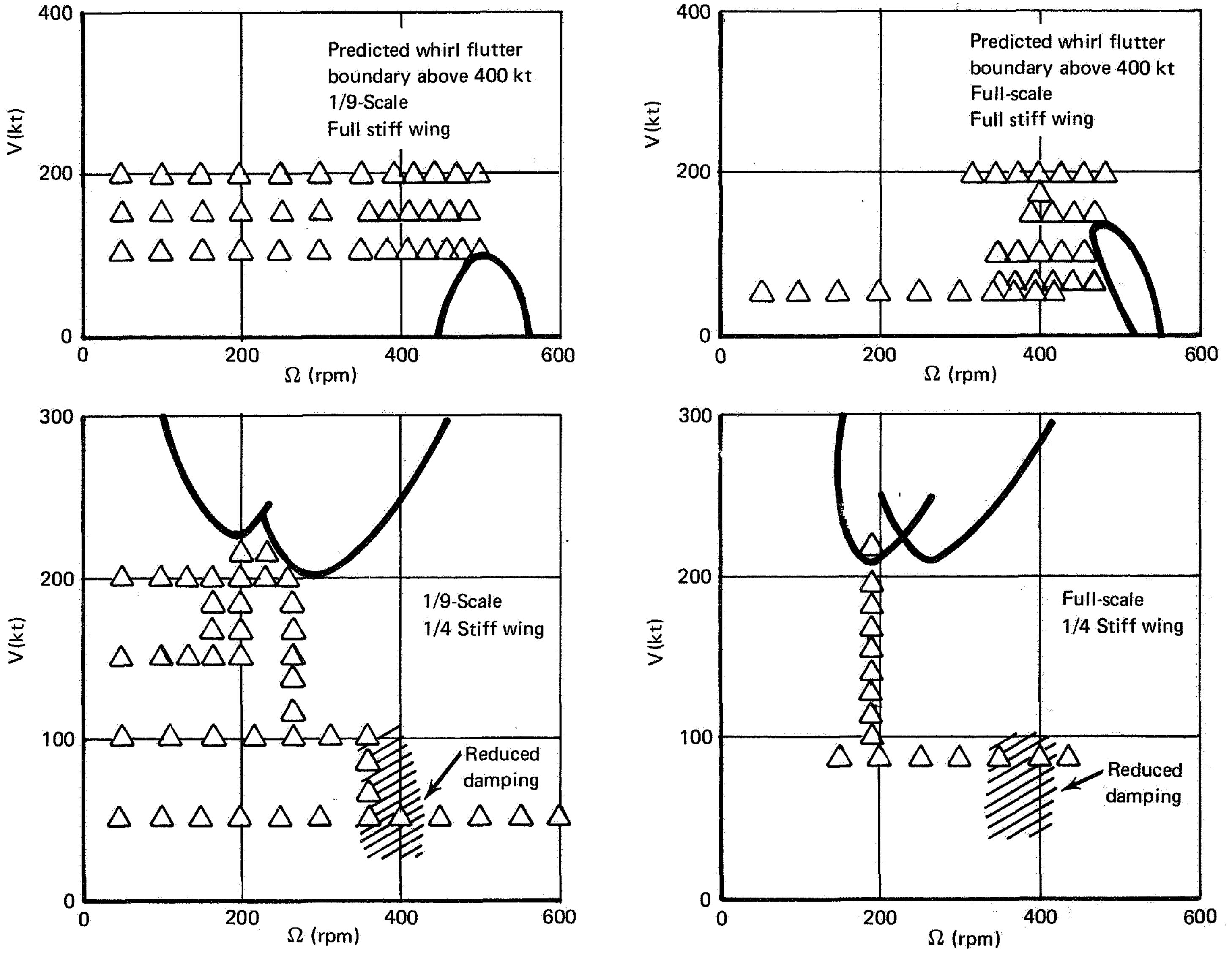


Figure 43. Scaling Summary

Economics

The single most important parameter in selecting a successful commercial vehicle is cost.

As the payload (i.e., number of passengers) and size of the aircraft increase, the direct operating costs decrease. This is illustrated by Figure 44. For example, the costs of operation per passenger mile of a 50-passenger aircraft would be 43 percent higher than its 100-passenger counterpart.

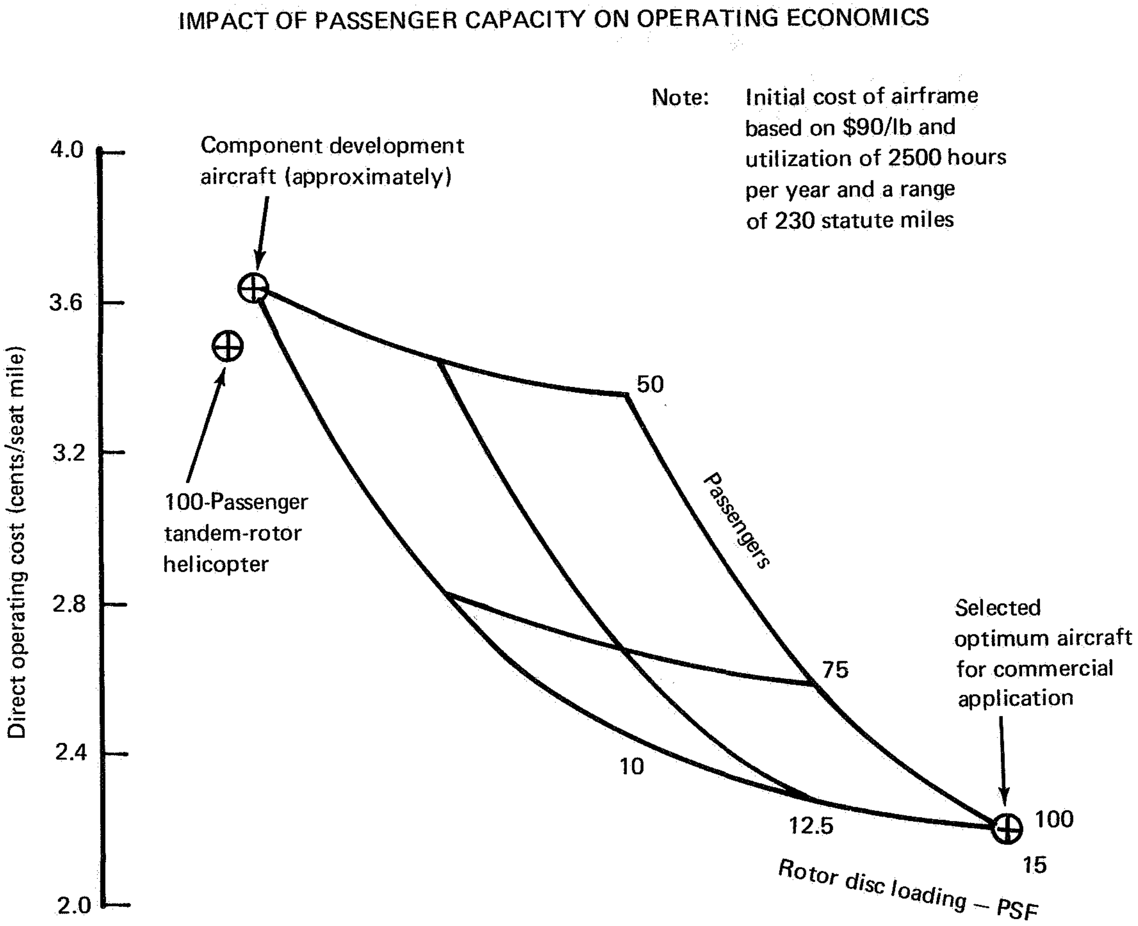
Since no major technology issues are identified limiting size in the study range, the optimization of vehicle cost clearly indicates that a 100-passenger vehicle (maximum allowed by the study guidelines) must be selected. A compromise decision to offer commercially an intermediate sized aircraft may set back the acceptance of the concept. For example, a 50-passenger vehicle would demonstrate economics which are slightly worse than the 100-passenger helicopter, which can almost be considered within the current state-of-the-art. This comparison would therefore tend to eliminate the tilt-rotor from contention.

In the commercial situation, the economic facts require that, unless compelling technical and engineering reasons are clearly identified which will limit the size of the aircraft, the selected vehicle must be of the 100-passenger size if the aircraft concept is to realize its potential and sucessfully compete in the short-haul market place. This position does not preclude the construction of an intermediate sized vehicle for component development and technology demonstration purposes. A program of this sort involving component development and testing is the most effective method of risk reduction.

To meet a 1985 deadline for the 100-passenger transport, a development program would require initiation in 1978, with laboratory work and whirl tests during 1979 and 1980. The fuselage for an intermediate sized aircraft would be selected from the existing inventory, since cruise performance would not be critical on the test-bed vehicle. This phase would need to be started in 1979 to produce flight data by 1981. The orderly development of hardware in this this way and the acquisition of flight experience will provide a necessary background to fly commercially successful passenger tilt-rotor aircraft by 1985.

10. DESIGN DATA COMPARISONS

The information generated as a result of the design studies summarized in this report allows several comparisons to be drawn.



IMPACT OF PASSENGER CAPACITY ON OPERATING ECONOMICS

Note: Initial cost of airframe based on $90/lb and utilization of 2500 hours per year and a range of 230 statute miles

Figure 44. Tilt-Rotor Direct Operating Costs as a Function of Disc Loading and number of Passengers

The tandem-rotor helicopter and the VTOL and STOL tilt-rotor aircraft display differences in size, weight, performance, and economics which are functions of the intrinsic properties of the configurations. The impact of noise criteria on the vehicle designs can also be summarized. The following discussion provides a brief analysis of the vehicle properties and the general conclusions which may be drawn.

The fundamental parameters used to compare configurations are weight, mission fuel, and installed power. These data are compared in Figure 45 for all of the vehicles considered in this study. The comparison of baseline aircraft weights shows the tandem-rotor helicopter to be the lightest vehicle. The VTOL tilt-rotor is heavier as a result of higher disc loading and the additional weight associated with the wing structure. Designing the tilt-rotor configuration for STOL allows a lower installed power and reduced rotor size which decrease the gross weight to almost the tandem-rotor helicopter level.

The influence of external noise criteria expressed in terms of the perceived noise level at the 152.4-meter (500-foot) sideline distance is apparent from Figure 45. The reduction in external perceived noise causes the design gross weight and weight empty to escalate.

The wing weight penalty paid by the tilt-rotor configurations provides a payoff in cruise flight and lift-to-drag ratio, and this is reflected in the comparison of mission fuel requirements. The tilt-rotor vehicles require significantly less fuel than the tandem-rotor helicopters. Designing for STOL reduces the tilt-rotor fuel consumption by 25 percent. The effect of increasing or decreasing noise levels is an increase in the mission fuel required.

The installed power is primarily a function of disc loading and thrust-to-weight ratio. The tandem-rotor helicopters are designed at a disc loading of 43.9 kg/m^2 (9 lb/ft^2) compared with 73.2 kg/m^2 (15 lb/ft^2) for the VTOL tilt-rotors. This difference is the primary reason for the higher installed power in the tilt-rotor case. The reduced thrust-to-weight ratio of the STOL aircraft resulting from the relaxation of vertical lift constraints results in an installed power less than that of the tandem-rotor helicopter.

The normal-rated-power cruise speeds and the design mission block times of the aircraft are shown in Figure 46. The low drag and high propulsive efficiency of the tilt-rotor result in cruise speed capability approximately twice that of the tandem-rotor helicopters. The reduction in cruise speed of the STOL tilt-rotor as compared with the VTOL design is due to the reduced installed power. The block times are calculated over the entire mission, of which the cruise segment is a large part. The tilt-rotor speed

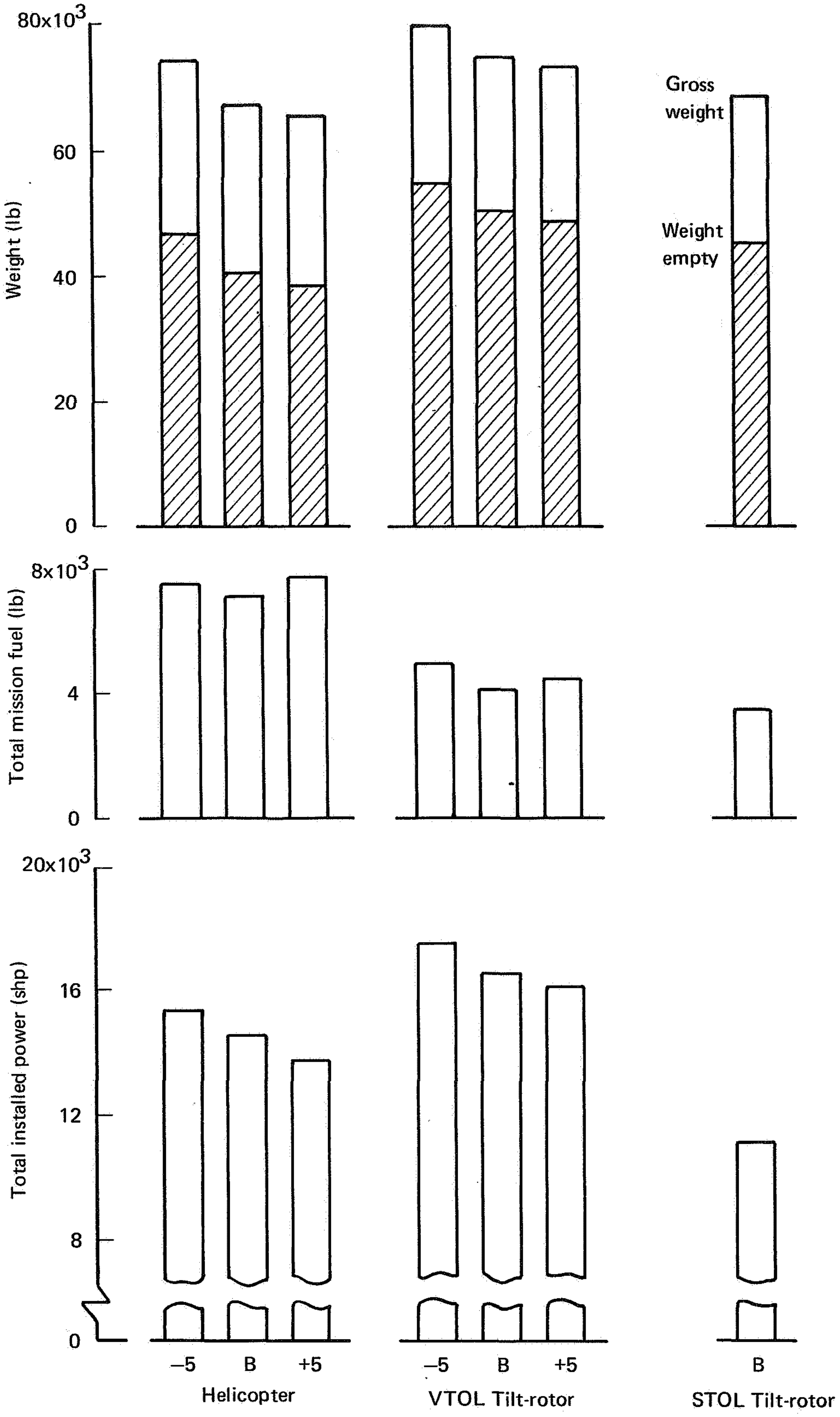


Figure 45. Effect of Design Noise Criteria on Total Installed Power, Mission Fuel, and Weight

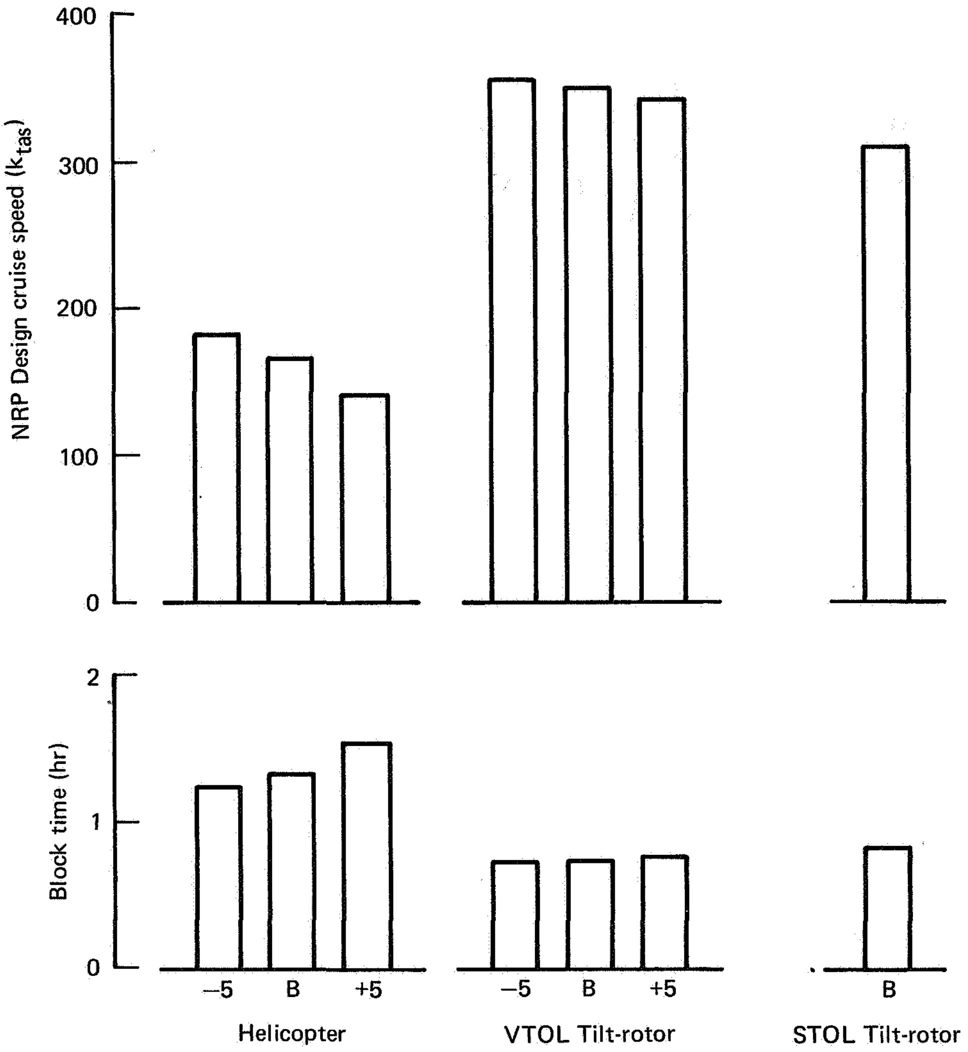


Figure 46. Effect of Design Noise Criteria on Block Time and NRP Cruise Speed

advantage results in lower block times than the helicopter. The STOL tilt-rotor has a slightly longer block time than the VTOL design. The general trend of speed capability with external perceived noise shows that, for both tandem-rotor and tilt-rotor aircraft, reduced external noise coincides with higher cruise speed capability and lower block times.

The index of community acceptance or annoyance of aircraft noise is a fluid and debateable issue and one not addressed in this study. Two parameters have been used to provide a comparison of the relative merits of the configurations. The perceived noise levels at the 152.4-meter (500-foot) sideline distance in hover are shown in Figure 47 for the VTOL aircraft. The value shown for the STOL aircraft is at static thrust at the start of the takeoff roll. The baseline helicopter is approximately 6 PNdB less noisy than the baseline tilt-rotor; this is largely due to the lower tipspeed and blade loading of the helicopter. The STOL tilt-rotor has the highest perceived noise level at static thrust due to its high tipspeed and low solidity. The noise derivative vehicles are by definition ±5 PNdB from the appropriate baseline aircraft.

An alternate index of community acceptance is the area exposed to high noise levels on takeoff and landing. The areas within a 95 PNdB contour are shown for both takeoff and landing in Figure 47. The tandem-rotor helicopter affects a much larger area (1.39 square kilometers, 0.535 square miles) than the VTOL tilt-rotor aircraft (0.39 square kilometers, 0.15 square miles) in the landing case and is slightly better in takeoff. The STOL tilt-rotor affects about the same areas (0.36 square kilometers, 0.14 square miles as the VTOL tilt-rotor. These data, however, demonstrate that the choice of index of community acceptance can radically affect the comparison of configurations.

The initial acquisition cost of the aircraft is dictated, to a large extent, by the vehicle weight. These data are compared in Figure 48. These data are based on airframe costs of $90 lb, as dictated by the study guidelines. The baseline tilt-rotor costs 26 percent more than the baseline helicopter, while the STOL tilt-rotor costs 11 percent more. The noise derivative vehicles exhibit an increase in cost as noise level is reduced and a slight improvement as noise criteria is relaxed.

Direct operating costs reverse the economic advantages of the helicopter, as shown in Figure 48. The speed and fuel advantage of the tilt-rotors, shown in Figures 45 and 46, have a greater impact on direct operating cost than higher acquisition cost. The direct operating cost of the baseline VTOL tilt-rotor is 69 percent of the baseline helicopter cost, while the baseline STOL tilt-rotor direct operating cost is 62 percent of the tandem-rotor helicopter cost. The STOL tilt-rotor direct operating cost is reduced, relative to the VTOL tilt-rotor, because of the reduction in aircraft weight and mission fuel, which offset the 30-knot speed advantage of the VTOL vehicle.

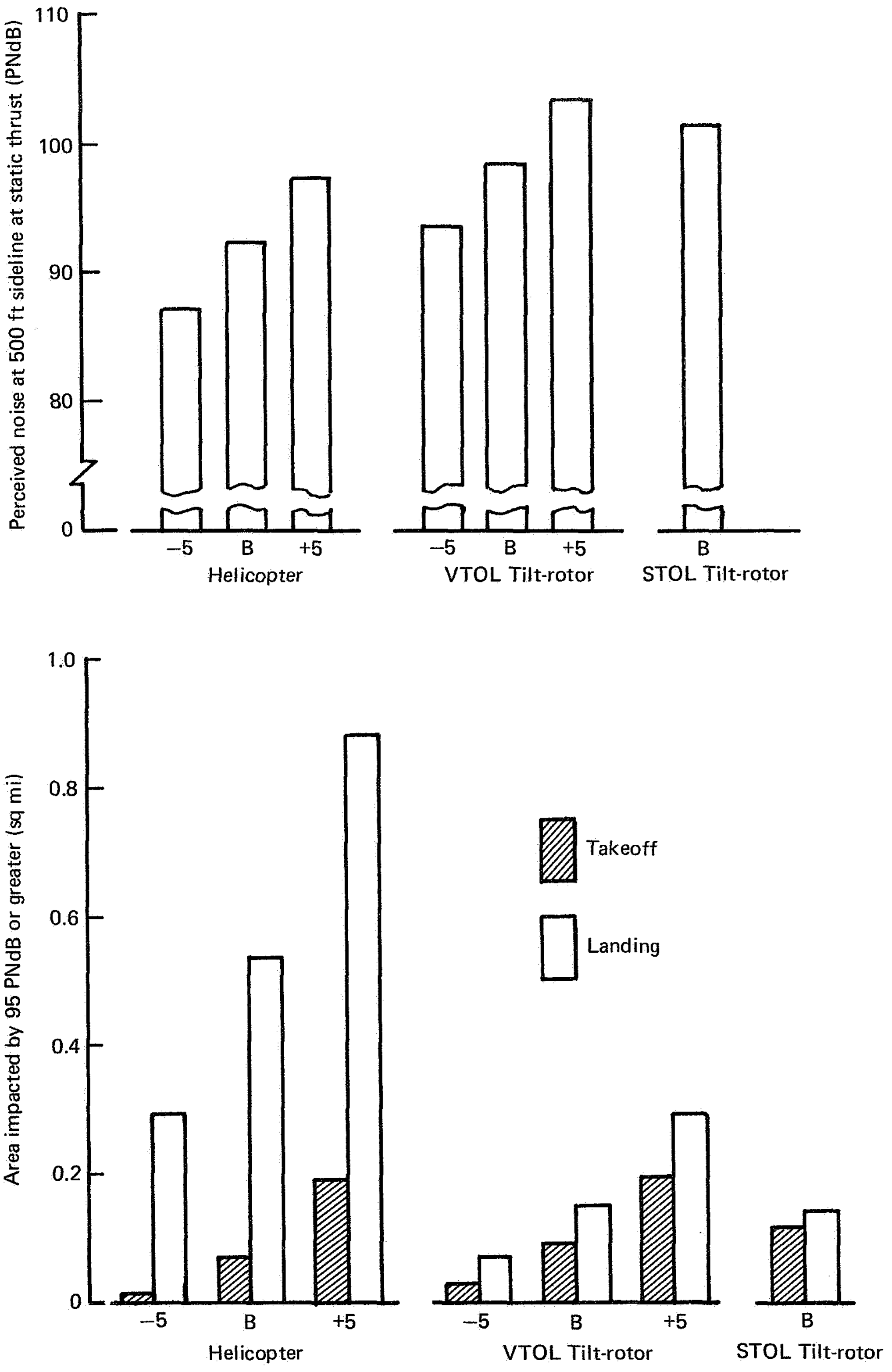


Figure 47. Area Impacted by 95 PNdB or Greater and Perceived Noise at 500-Foot Sideline Distance for Baseline and Noise Derivative Aircraft

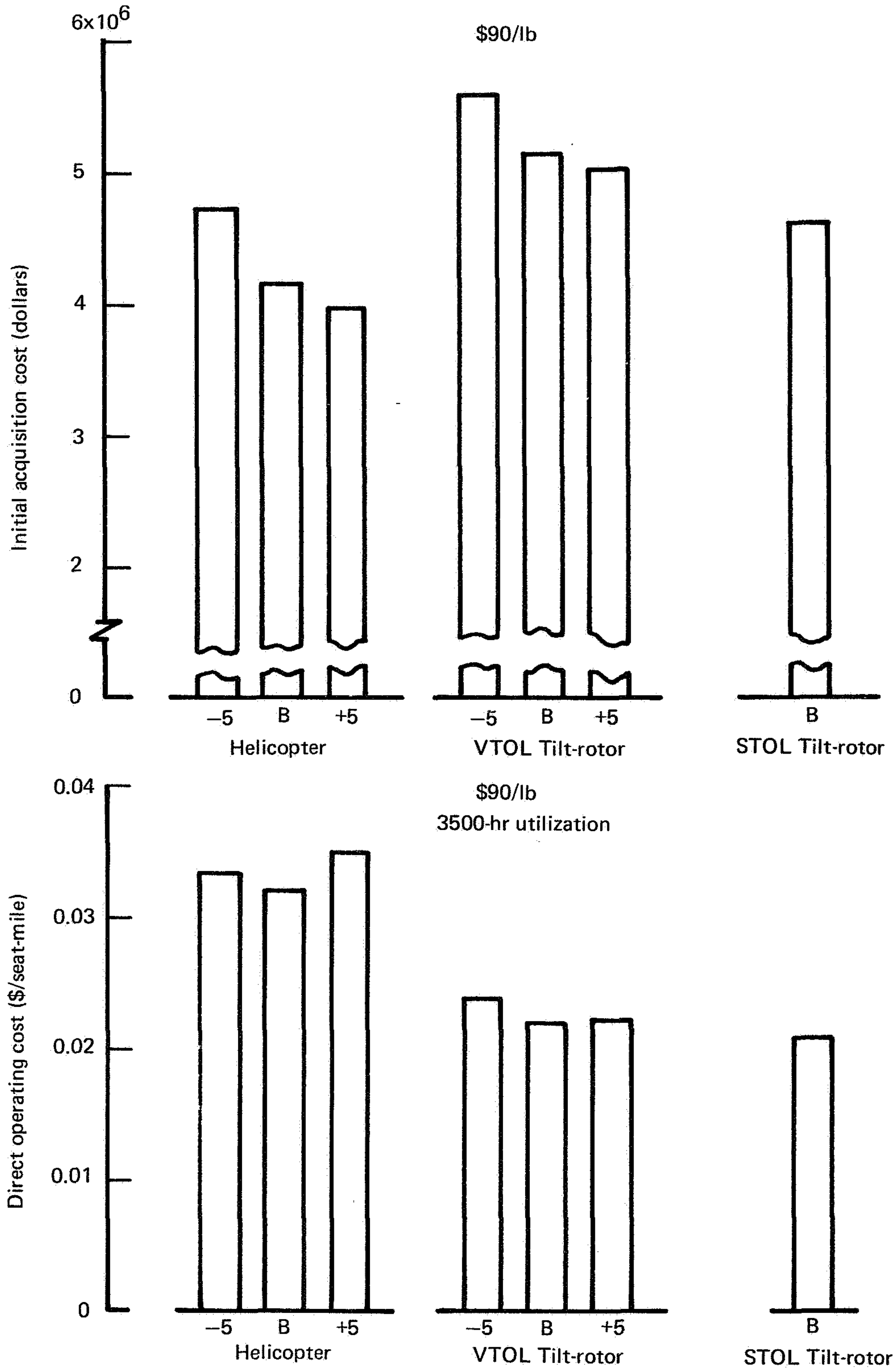


Figure 48. Initial Acquisition Cost and Direct Operating Cost for Baseline and Noise Derivative Aircraft

Direct operating costs for the noise derivative VTOL vehicles show no economic advantage relative to the baseline vehicles.

The block speed of the three baseline aircraft is shown in Figure 49 for mission ranges of 92.5 to 740 kilometers (50 to 400 nautical miles). Because the time taken for terminal maneuvers is the same for each aircraft, the block speed of any given aircraft largely reflects its cruise speed. Both STOL and VTOL tilt-rotor aircraft are much faster than the tandem-rotor helicopter. The helicopter loses less time during the climb and descent phases of the mission than do the tilt-rotors because it cruises at 1524 meters (5000 feet) rather than 4267 meter (14 000 feet). At large values of range the block speed approaches the cruise speed asymptotically.

Closely related to the block speed performance of the aircraft is the direct operating cost, which is shown in Figure 50 as it varies with range. For each of the baseline aircraft, two curves are shown representing extreme combinations of airframe cost, $90/lb and $110/lb, with utilizations of 3500 and 2500 hours per year. The comparison of the vehicles for constant utilization is biased in favor of the slower aircraft. If the utilization were defined by block speed, the faster aircraft would have a higher utilization than the slower one, and a larger difference in direct operating cost would result. For all except the very shortest range considered, the tandem-rotor helicopter has a much higher direct operating cost than either of the tilt-rotor configurations. The STOL tilt-rotor is slightly less expensive to operate than the VTOL aircraft. For ranges greater than the design value of 200 nautical miles, a modification was required in order to maintain constant gross weight. This consisted of extra fuel tanks installed at the expense of payload capability, thus increasing the range capability. The extended range of the helicopter increases direct operation cost, but for the tilt-rotors, the direct operating cost continues to decrease with range (or at worst, remains constant).

The fuel consumption of the baseline aircraft as a function of cruise speed is illustrated in Figure 51 for each of the three concepts. The fuel consumption is expressed in passenger miles per gallon of fuel used. It can be seen that both of the tilt-rotor configurations show a greater economy of fuel than does the helicopter, and in addition, they fly much faster. It should also be noted that, for the design condition, the cruise altitude was optimum for each configuration. The design points indicated on the graph correspond to the maximum cruise speed with the cruise power setting anc cruise rpm, and as such do not coincide with optimum fuel consumption. In each case an improvement of about 10 percent can be achieved in fuel consumption by flying the cruise part of the mission at the optimum speed. This would, however, impose a higher direct operating cost and lower productivity. For any given cruise speed, the STOL tilt-rotor has by

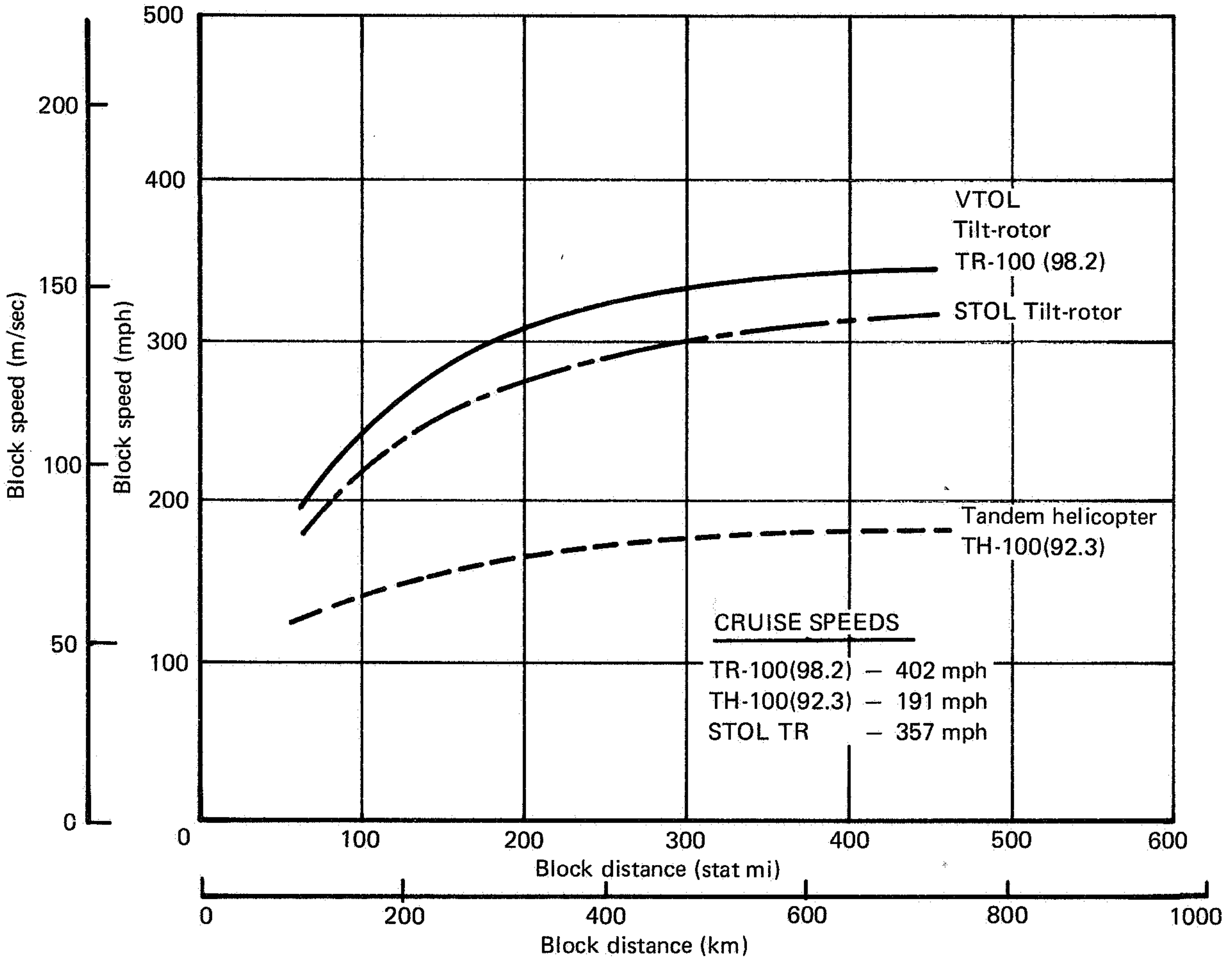


Figure 49. Block Speed and Distance for Baseline Aircraft

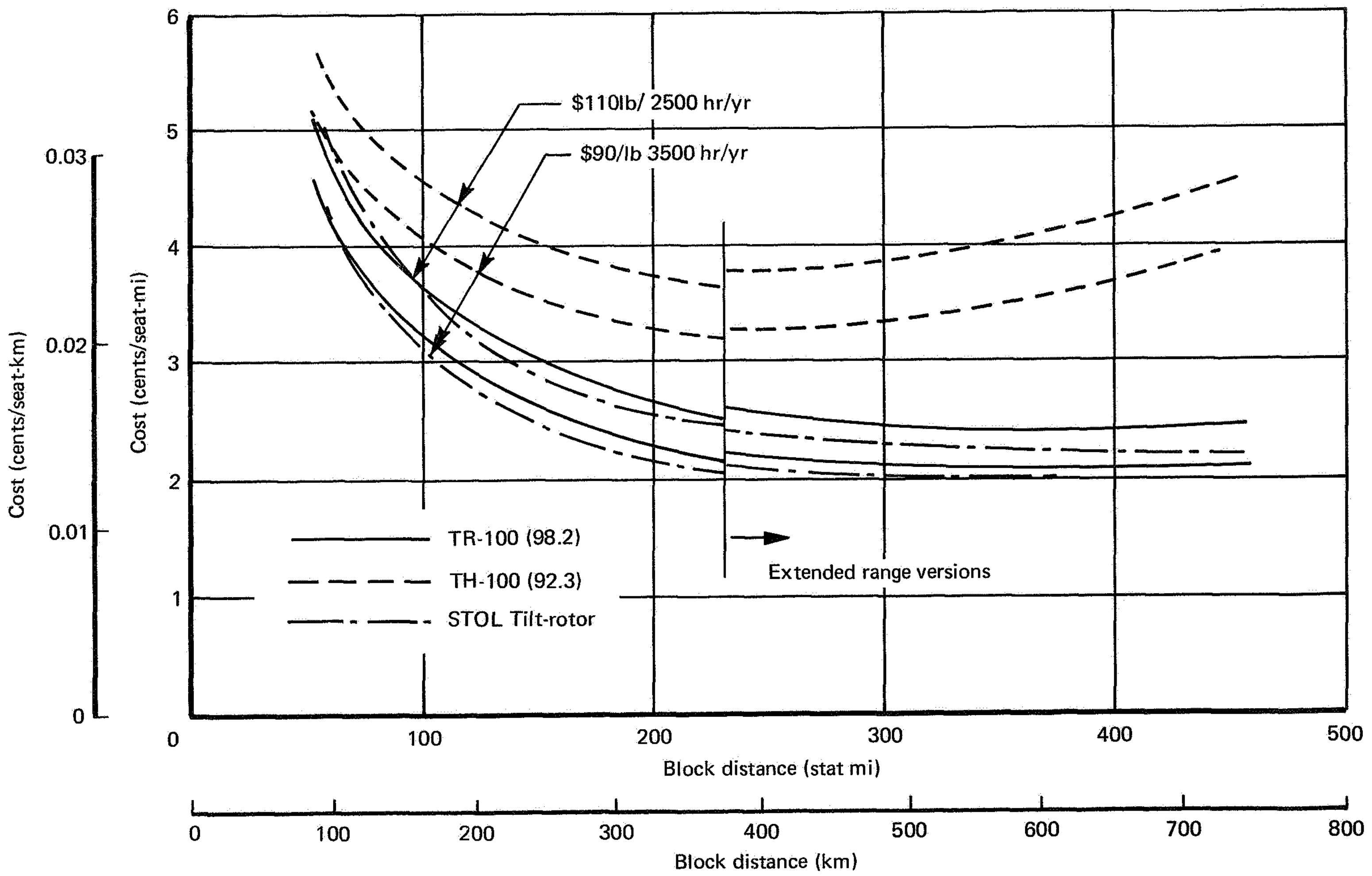


Figure 50. Direct Operating Costs for Baseline Aircraft

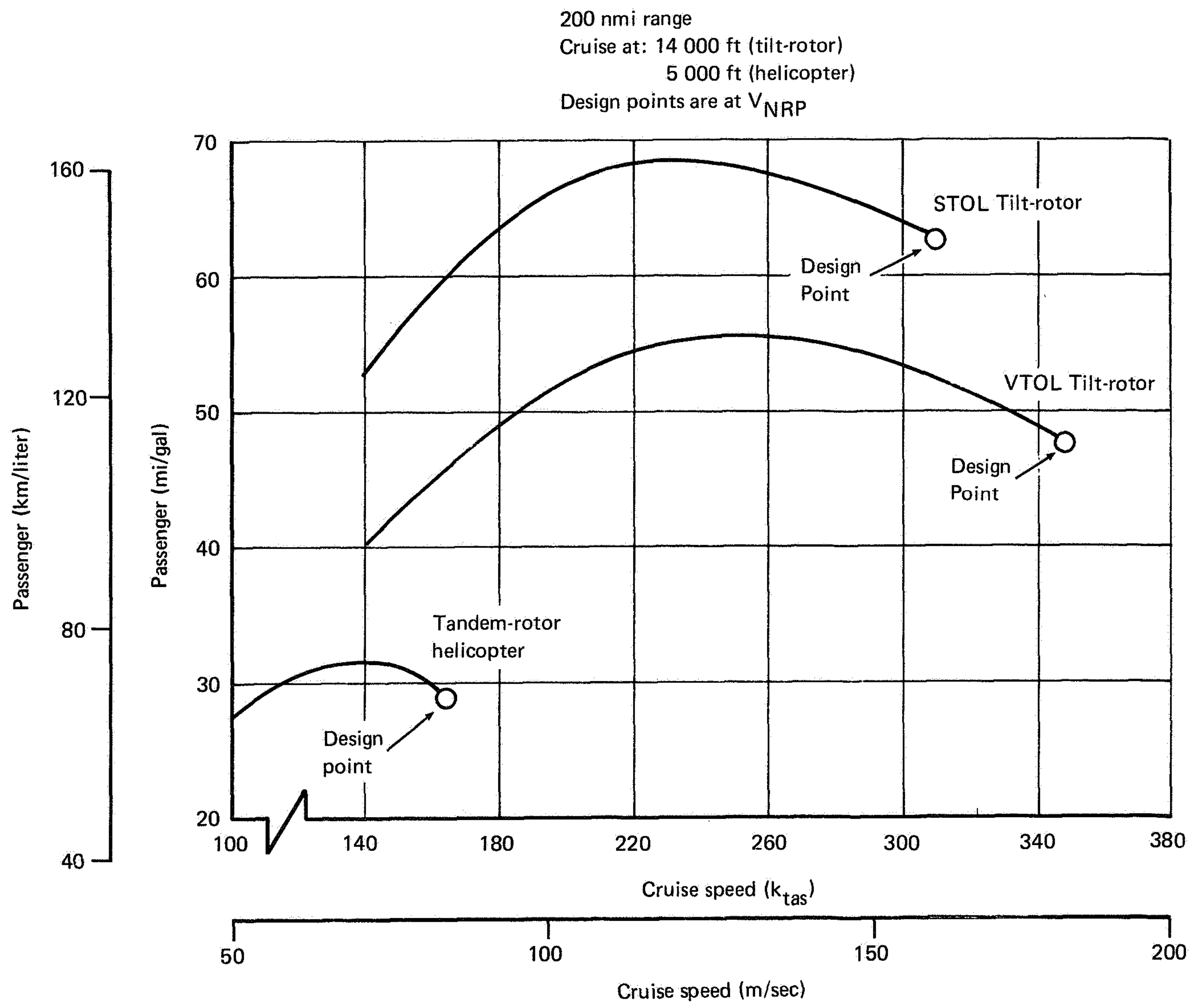


Figure 51. Variation of Fuel Consumption with Cruise Speed

far the best fuel economy by a margin of at least 10 passenger miles per gallon. By accepting the penalty of 17 percent increased direct operating cost due to cruising at the speed for best fuel consumption, an improvement from 62.5 to 68.8 passenger miles per gallon could be achieved. The VTOL tilt-rotor's higher fuel consumption is due to its larger gross weight, power, and drag. In addition, at any given speed the STOL tilt-rotor operates at a more nearly optimum engine power fraction than does the VTOL.

For the design mission, Figure 52 shows the fuel consumption of the three baseline aircraft in comparison with that of a selection of conventional airplanes and helicopters. Each airplane shows considerably better fuel economy than the corresponding trends; this is due in part to the savings in weight (and, therefore, drag and installed power) resulting from the use of 1980 technology in the aircraft design.

In Figure 53 the productivity ratio (payload times block speed/ weight empty) is shown for the baseline aircraft as a function of range. Both of the tilt-rotor aircraft are about 50 percent more productive than the baseline tandem-rotor helicopter at the design range. The difference is due mainly to their relatively higher speed. The STOL tilt-rotor is slightly more effective than the VTOL because its empty weight is lower. The lower speed of the STOL almost cancels out the effect of the reduced empty weight.

11. CONCLUDING REMARKS

The vehicles defined in this study are potential competitors for the short-haul air traffic market of the mid 1980's. The increasing frustration of the air traveller with the congestion at existing airports, along with the current awareness of urban communities in the area of noise pollution, must ultimately be met by new concepts in air travel which provide the operator with the flexibility necessary to meet the market requirements. Rotary-wing aircraft have the potential for providing such a solution.

The tandem-rotor helicopter has an advantage over the more advanced tilt-rotor concept insofar as it is lighter and has a lower acquisition cost. The preponderance of experience with in the helicopter industry makes the development of this aircraft a low risk, although technology improvements in the field of ride qualities and vibration must be found.

The VTOL tilt-rotor would require a more intensive developmental program than the helicopter, since flight hardware experience is limited. The large advantages of high speed, low fuel

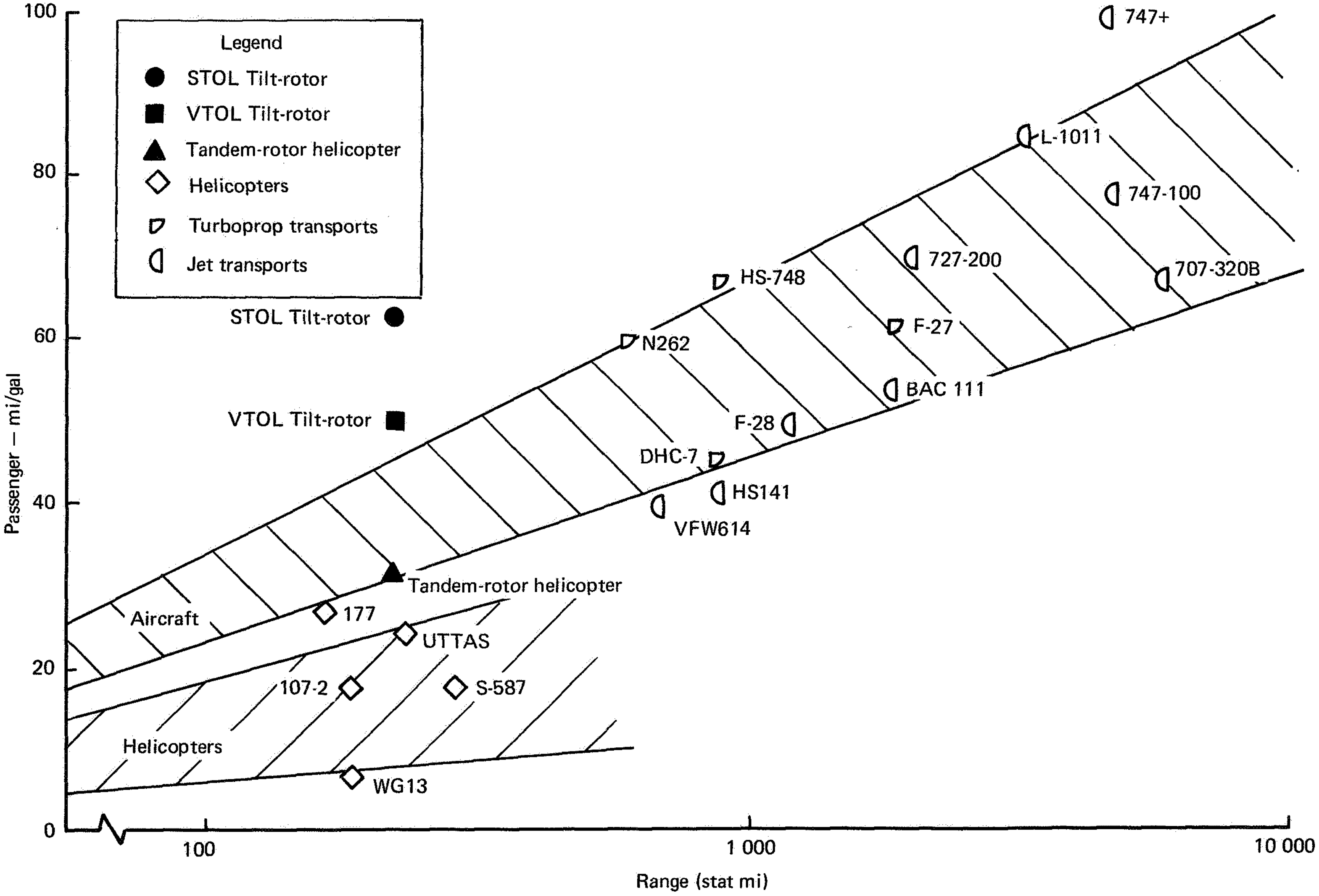


Figure 52. Fuel Consumption of Baseline Aircraft and Production Aircraft

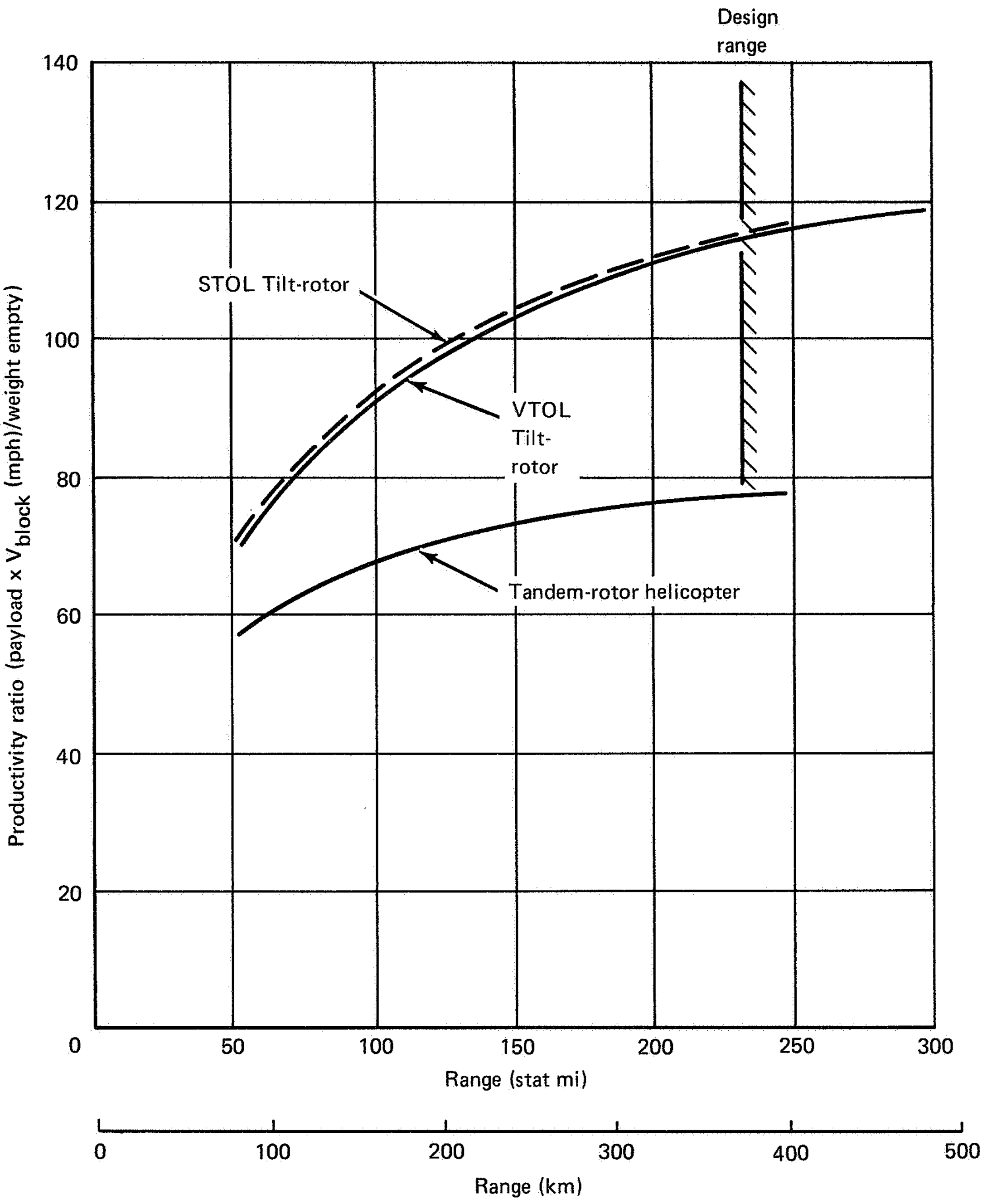


Figure 53. Productivity Ratios for Baseline Aircraft

consumption, and low operating costs are extremely attractive and require the continued research and development of this concept to provide large scale flight hardware expertise.

The fuel economy of the tilt-rotor vehicle can be further improved by designing for STOL operation; however, this performance gain is at the cost of loss of VTOL flexibility, and this tradeoff must be made in a realistic operational environment.

The practical considerations of terminal area operation need to be examined in some detail to establish practical modes of approach and operation. In this respect an index of community acceptance to noise pollution needs definition in order that noise abatement groundrules may be considered.

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February 3, 1975

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